

Fragipans



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A Proposal for Establishing Soil Classification Criteria for Two Kinds of Fragipans and for their Placement into Soil Taxonomy at the Great group and Subgroup Levels

I. BACKGROUND

Soils identified as having fragipans occur throughout the world. Fragipans have important effects on the use of these soils for agricultural and non-agricultural purposes. Crop production is affected by both the root restriction and perching of water caused by fragipans. Non-agricultural uses such as building sites are affected by the perching water.

Scientific studies of these kinds of horizons have not been conclusive. In spite of a plethora of investigations, only a small amount of definitive data on soil genesis or common soil properties have been developed. The identification of fragipans also is very much a field problem. Soil scientists must make decisions in the field on the basis of soil properties they observe and record at each observation point. The vagaries of the criteria in *Soil Taxonomy* have resulted in the placement of soils with fragic properties into a wide variety of taxonomic categories. In some places soils without pedogenic properties of fragipans were classified in fragic Great groups.

The National Cooperative Soil Survey is in the initial stages of updating modern soil surveys to a common standard in order to bring uniformity and continuity to soil interpretations. The establishment of definitive criteria for the identification of fragipans is necessary if those goals are to be attained.


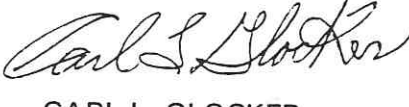
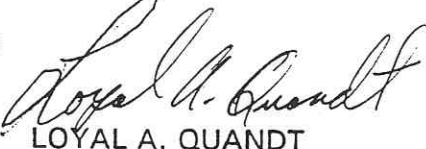




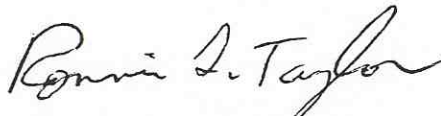

In 1991 Loyal Quandt and Carl Glocker embarked on a project to bring all of the knowledge of all of the National Cooperative Soil Survey soil scientists together to address this challenge and to develop the criteria for fragipans that are part and parcel to this proposal.

Background research has been conducted as follows:

- | | |
|-------------|---|
| Fall 1991 | Loyal Quandt and Carl Glocker assembled all available literature on fragipans. These data were analyzed and then summarized. |
| Spring 1992 | They prepared a preliminary set of criteria for identification and classification of fragipan soils at the great group and subgroup levels of Soil Taxonomy. The criteria were circulated to all states and cooperators for critique. |
| Sept. 1992 | Idaho-Washington Fragipan Tour--primary objective was to develop criteria that will identify fragipans in northwestern United States. |
| Nov. 1992 | Revised definitions and criteria were circulated and replies used for fine tuning. States in the southcentral part of the United States tested a kind of fragipan high in exchangeable aluminum. |
| Oct. 1992 | Tri-State Fragipan Tour (Ohio, Indiana, and Kentucky)--primary objective was to observe and describe classic fragipans. Criteria were circulated to all states and cooperators for critique. |

- Feb. 1993 Prepared and distributed a compendium of papers on fragipans entitled What's Up in Fragipans. This publication summarizes all field trip reports and most of the important research papers concerning fragipans.
- May 1993 Missouri Fragipan Tour--primary objective was to observe and describe dense, brittle albic horizons.
- June 1993 Developed definition for this kind of fragipan. Circulated definition and criteria. Used replies for further fine tuning.
- Oct. 1993 New England Fragipan-Dense Till Study (New York, Connecticut, Massachusetts)--primary objective was to identify fragipans and to review dense till soil properties.
- Jan. 1994 Circulated revised definitions and criteria to states with substantial acreages of fragic soils.
- April 1994 Prepared this proposal for the identification, description, and classification of two kinds of fragipans, and soils with fragic properties.

This proposal is the culmination of these activities. Examination of existing research and critique of proposed criteria involved the skills and talents of at least 150 field, research, and laboratory soil scientists in the NCSS. We, the undersigned, fully support the proposal presented herein.

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3rd Edition on Fragipans, 1994

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II. PREAMBLE

In the course of this study one fact about fragipans became evident. That is, that there is an unknown number of kinds of soil horizons that perch water and exclude roots. Some of the constraining soil properties are chemical and some are physical. This proposal sets out definitive soil properties and the parameters that can be used to identify and classify only two of these kinds of horizons. Others, if desired, can be defined and added to this family of fragipans as their criteria become evident. Some seven major clues and 16 minor clues to identification have been chronicled in *Soil Taxonomy* and the literature. It is proposed that the present definition for fragipans be redefined in *Soil Taxonomy* to include Fragalfic pans, and Fragalbic pans and that they be entered into *Soil Taxonomy* at the Great group level. It is proposed that the definition for Soils with Fragic Properties be used to enter soils into *Soil Taxonomy* at the subgroup level. The Keys to Soil Taxonomy will make sure that both Fragipans key out before Soils with Fragic Properties.

FRAGIPAN

III. PROPOSAL

A fragipan in its simplest form is a soil horizon that perches water and restricts the entry of feeder roots into the soil matrix. Fragipans, (L. fragilis, meaning brittle pan) have a variety of forms of expression, both physical and chemical. Definitive criteria for these two kinds of fragipans are related to soil structural units, bulk density, redoximorphic features and evidence of pedogenesis. Primary soil structure is either, prismatic, columnar or platy. Size of peds and strength or integrity of their faces is such that avenues for root or water penetration are severely limited in areal extent. Bulk densities are usually near or greater than those densities determined by researchers to be root restrictive. Redoximorphic features such as iron and manganese accumulations and iron and clay depletions, give evidence to perching water and soil development. Additionally, the presence of inped oriented clay, clay films, iron, or organic coats on faces of peds, or uncoated sand or silt grains give evidence to pedogenesis. Brittleness is an ancillary property that has not, to date, been attributed either to physical or chemical conditions in the fragipan. It could be caused by interparticle binding by amorphous oxides of silica, iron and aluminum, clay bridging of mineral grains or by close packing of mineral grains during dewatering of the parent material. Low base saturation and low reaction class (pH) are also common properties. See figure 1.

A. DEFINITION: FRAGIPANS

Two kinds of physically restrictive fragipans are FRAGALFIC pans and FRAGALBIC pans.

1. Fragalfic fragipans have all of the following properties:

- a. Primary soil structure is very coarse prismatic or columnar in more than 60 percent of the volume. Horizontal diameter of very coarse prisms or columns is 10 to 75 cm. Diameter is measured along the shortest horizontal distance of a closed loop formed by the faces of a ped. Intrusions of cracks or seams into, but not through the ped are ignored. An irregularly shaped prism or column is considered to be very coarse if the sum of the longest diameter and the shortest diameter divided by 2 equals 10 cm or more, or 75 cm or less. See figures 2 and 3.
- b. The prisms or columns have some evidence of pedogenesis. This can be demonstrated by areas of oriented inped clay, or by clay films on faces of peds, or by uncoated silt or sand grains or by coats of albic material on faces of peds or in seams. At least a few fine faint redoximorphic concentrations are present also. See figure 4.
- c. Inped spacing of very fine or fine roots is 10 cm or more.
- d. The manner of failure class of a moderately moist or wetter specimen is brittle. The soil horizon is brittle in 60 percent or more of the volume.^{a/} See figure 5.
- e. The moist (33kPa) bulk density of the brittle part of the primary structural unit is 1.6g cm^{-3} or more if the clay content is 20 percent or more. It is 1.7 g cm^{-3} or more if the clay content is less than 20 percent or the sand content is 40 percent or more.^{b/}
- f. The clay content is 5 to 35 percent. The content of sand coarser than very fine is less than 75 percent. Where clay films are 1 mm or more thick they can be removed before particle size distribution analysis.
- g. An air dry specimen will slake when submerged in water in less than two hours. Rupture resistance class is noncemented. See figure 6.
- h. Thickness is 15 cm or more.

^{a/} A specimen is brittle if it undergoes sudden nonplastic deformation when compressed between thumb and forefinger.

^{b/} Use conventional rounding off techniques, i.e., 1.54 rounds off to 1.5; 1.65 rounds off to 1.7.

2. FRAGALBIC PANS have all of the following properties.

- a. They have all of the properties of an albic horizon, except that chroma moist can be 3 or less, with any value.
- b. Primary soil structure is moderate or strong platy. ^{c/}
- c. The plates have some evidence of pedogenesis. This can be demonstrated by areas of oriented inped clay, or by clay films on faces of peds, or by uncoated silt or sand grains or by coats of albic material on faces of peds or in seams. At least a few fine faint redoximorphic concentrations are present also.
- d. Inped spacing of very fine or fine roots is 10 cm or more.
- e. The manner of failure class of a moderately moist or wetter specimen is brittle. The soil horizon is brittle in 60 percent or more of the volume. ^{d/}
- f. The moist (33kPa) bulk density of the brittle part of the primary structural unit is 1.6 g cm^{-3} or more if the clay content is 20 percent or more. It is 1.7 g cm^{-3} or more if the clay content is less than 20 percent or the sand content is 40 percent or more. ^{e/}
- g. The clay content is 5 to 35 percent. The content of sand coarser than very fine is less than 75 percent.
- h. An air dry specimen will slake when submerged in water in less than two hours. Rupture resistance class is noncemented. See figure 6.
- i. Thickness is 10 cm or more.

^{c/} Soil horizons that have high content of rock fragments sometimes appear to be massive when not examined in detail.

^{d/} A specimen is brittle if it undergoes sudden nonplastic deformation when compressed between thumb and forefinger.

^{e/} Use conventional rounding off techniques, i.e., 1.54 rounds off to 1.5; 1.65 rounds off to 1.7.

B. DEFINITION - SOILS WITH FRAGIC PROPERTIES

Fragic soil properties of subsoil horizons are physical properties that restrict the entry of very fine and fine roots and cause water to perch. Soil horizons that have fragic soil properties have the same characteristics as do fragipans except that the fragic properties are less well expressed. They must have, with or without redoximorphic features, all of the following properties.

1. The prisms, columns or plates have some evidence of pedogenesis. This can be demonstrated by areas of oriented inped clay, or by clay films on faces of peds, or by uncoated silt or sand grains or by coats of albic material on faces of peds or in seams.
2. The moist (33kPa) bulk density of the brittle part of the primary structural unit is 1.6g cm^{-3} or more if the clay content is 20 percent or more. It is 1.7 g cm^{-3} or more if the clay content is less than 20 percent or the sand content is 40 percent or more. a/
3. An air dry specimen will slake when submerged in water in less than two hours. Rupture resistance class is noncemented. See figure 6.
4. Where the primary soil structure consists of prisms or columns, it is medium or larger. Where the primary structure is platy, chroma can be as high as 4 moist, with any value.
5. The soil is brittle in 20 percent or more of the volume of the matrix. The manner of failure class of a moderately moist or wetter specimen is brittle. b/
6. One or two fine or very fine roots can enter brittle peds at less than 10 cm intervals.

NOTE: These criteria will be used to classify soils at the subgroup level.

a/ Use conventional rounding off techniques, i.e., 1.54 rounds off to 1.5; 1.65 rounds off to 1.7.

b/ A specimen is brittle if it undergoes sudden nonplastic deformation when compressed between thumb and forefinger.

IV. SOIL CLASSIFICATION - Sample Taxonomic Keys

At his time there are approximately 375 soil series that have fragi in the taxonomic name. Examples of how the keys might work are as follows. This list is not complete.

A. Key to Great groups of Udalfs

IEE. Glossudalfs

IEF. Other Udalfs that have a fragalfic pan that has its' top within 100 cm of the mineral soil surface.

Fragalfudalfs

IEG. Other Udalfs that have a fragalbic pan that has its' top within 100 cm of the mineral soil surface.

Fragalbudalfs

B. Key to Great groups of Aquepts

JAD. Other Aquepts that have a fragalfic pan that has its' top within 100 cm of the mineral soil surface.

Fragalfaqepts

Remarks: 17 series in 3 subgroups. All appear to be Fraqalfic. 10 have fragipans over Cd dense till horizons. 3 are underlain by shale, sandstone, and siltstone.

A. Key to Great groups of Aquods

BAC. Other Aquods that have a fragalbic pan that has its' upper boundary within 100 cm of the mineral soil surface.

Fragalbaquods

Remarks: 23 series-all in cold climates. Two great groups are needed, but probably no extra subgroups. Of the seven series examined, 5 do not make any of the fragipan definitions. Reexamination will probably focus on soils with densic properties and Fragalbic horizons, to the extent that none are left without diagnostic properties.

B. Keys to subgroups of Hapludalfs

IEKN. Other Hapludalfs that have a fragipan that has it's top at 100 to 200 cm from the mineral soil surface, or have a horizon that has fragic soil properties that has it's top within 200 cm of the mineral soil surface.

Fragic Hapludalfs

Remarks: A number of subgroups with "fragic" will be needed, i.e., Fragiaquic.

V. ILLUSTRATIONS

**Figure 1.
Map Showing the Location of
Soils Mapped as Having
Fragipans in the U.S.A.**

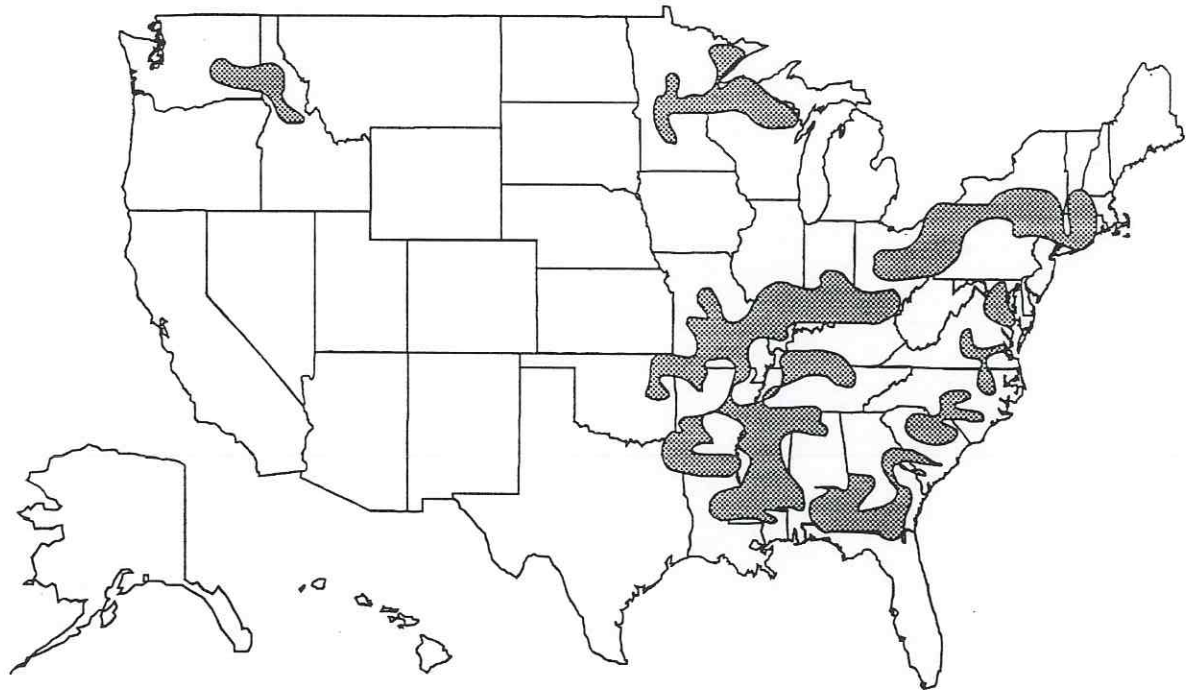


Figure 2. Macro-Structure Very Coarse Prismatic

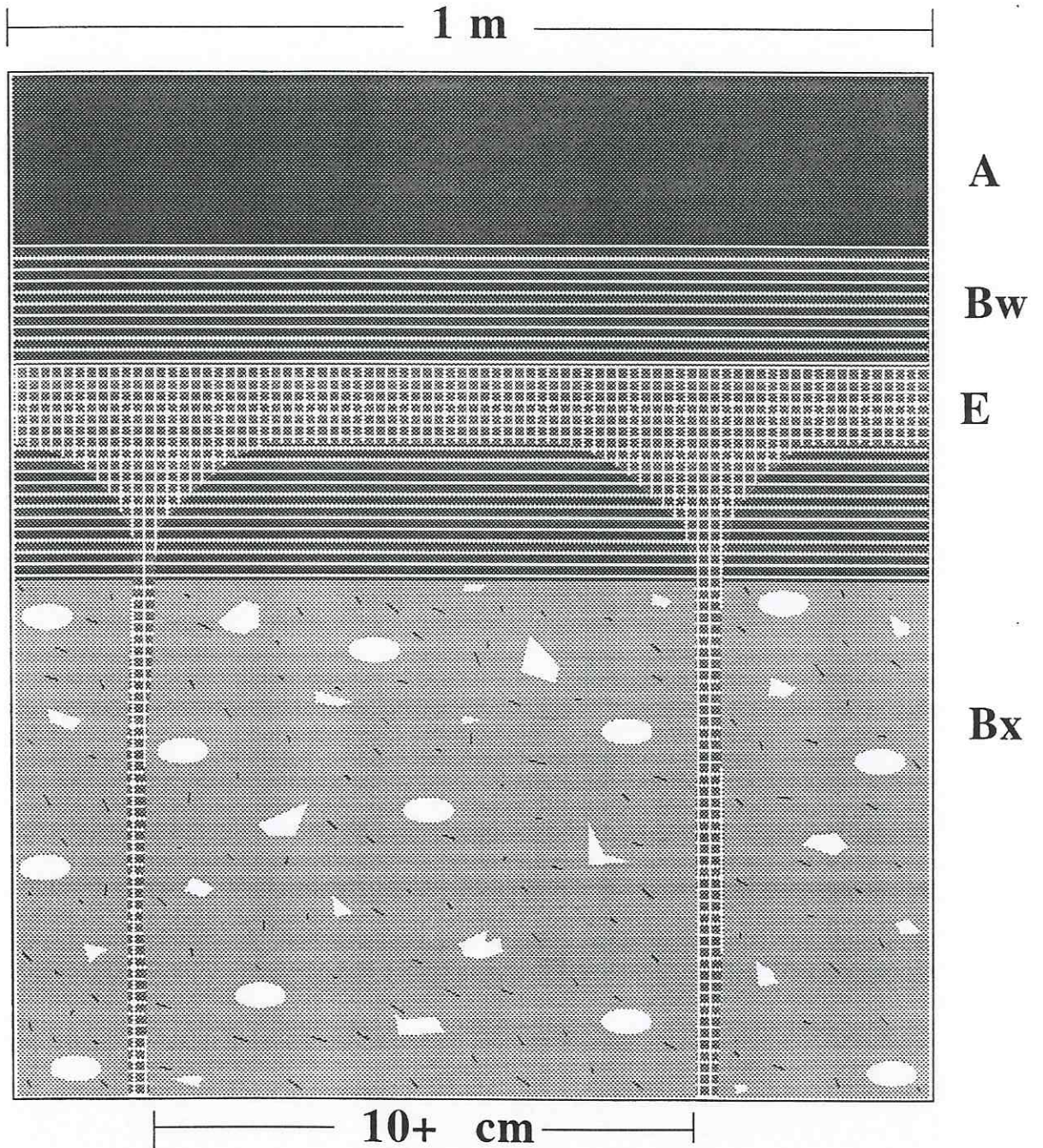
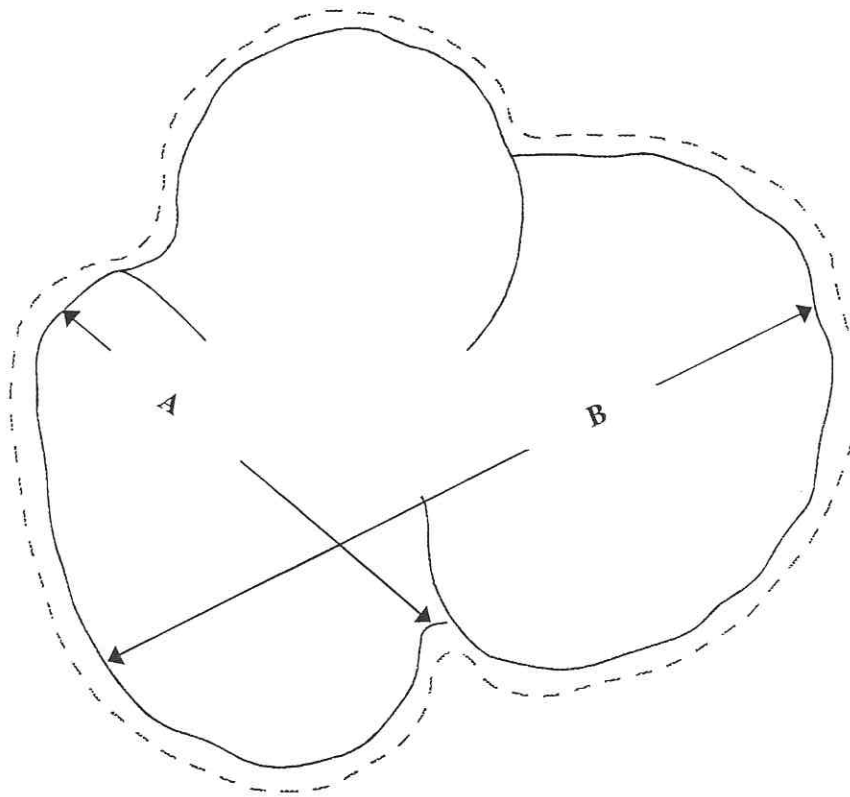


Figure 3. Measuring the Dimensions of a Ped

Horizontal view of a ped



Solid line - indicates the outline of a ped and attendant seams.

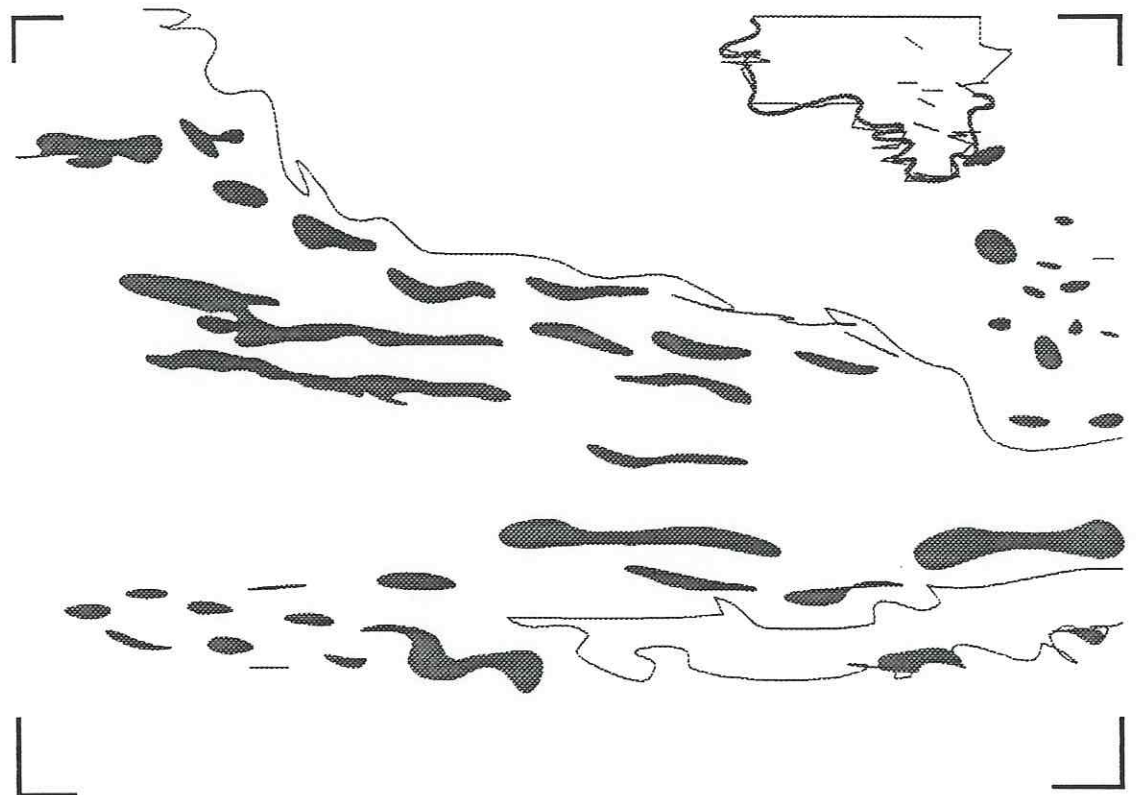
Dashed line - indicates a seam that forms a closed loop.

(A vertical view will not reveal the dimensions of a ped. The vertical seams will make the ped appear smaller than it really is.

If the ped is less than 10 cm in one dimension then the equation $\frac{A + B}{2} = >10\text{cm and } < 75\text{cm}$ can be used.

If line A is 5 cm long and line B is 71 cm long, then 5 plus 71 divided by 2 equals 38 cm. Therefore, the prism or column is very coarse.

Figure 4. Evidences of Inped Oriented Clay



Dark areas are oriented clay

Photomicrograph after Nettleton et al. (1992)

Figure 5.

Volume of Horizon Percent Brittle

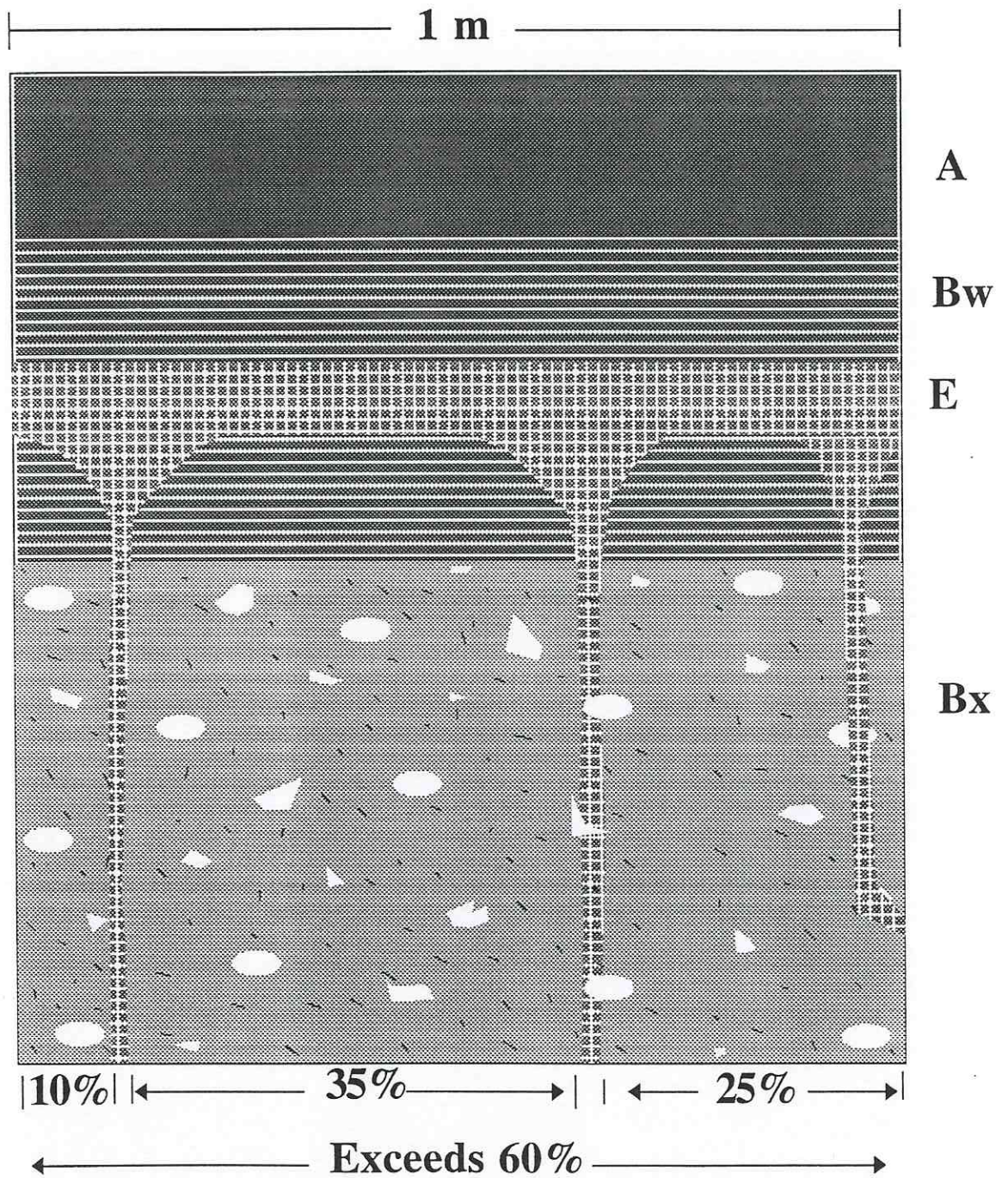
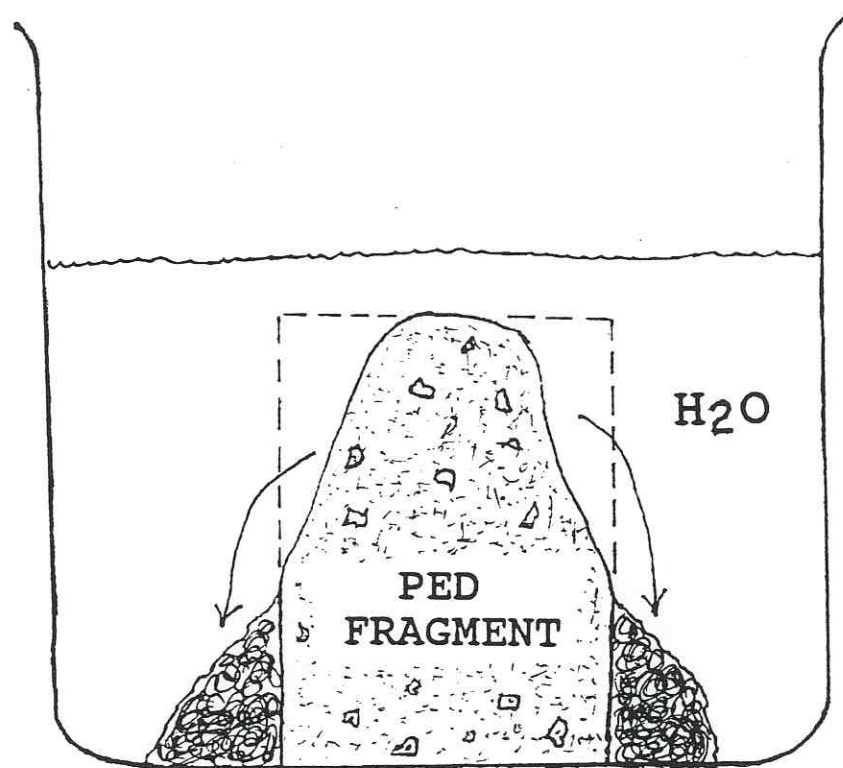
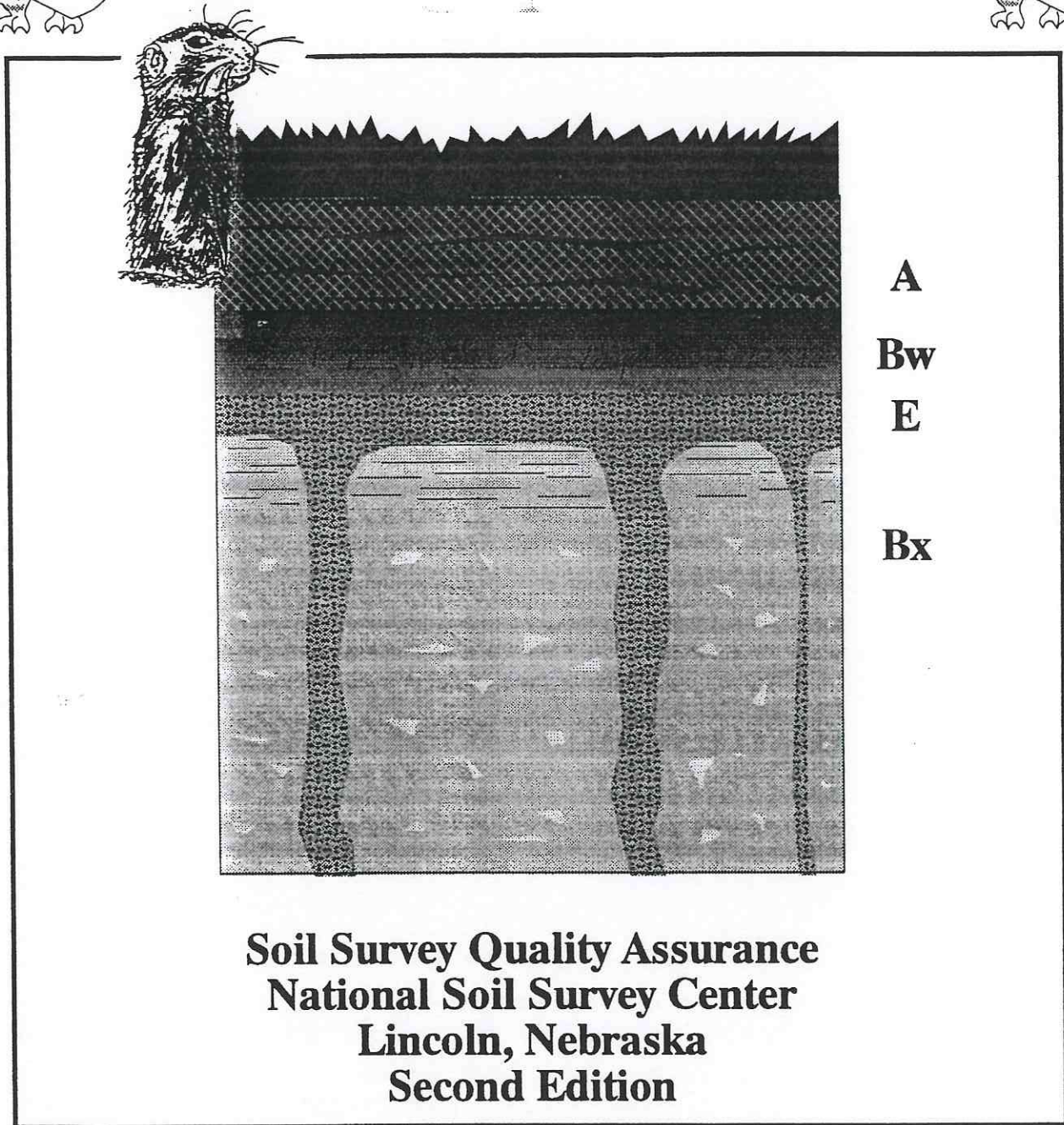


Figure 6.
Rupture Resistance
Slaking in Water





What's Up In Fragipans?



USDA - Soil Conservation Service

1993

Fragipan formation in argillic brown earths (Fragiudalfs) of the Milfield Plain, north-east England. I. Evidence for a periglacial stage of development

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SUMMARY

In this first of three papers, the parent materials, morphology and field relationships of soils with fragipans, similar to those in north-eastern United States, are described and analyses of their chemical and physical properties are presented to support a periglacial stage of development. The soil materials have been affected by periglacial processes, including ice-wedge formation, the age of which has been established by reference to a buried paleosol. The fine earth bulk density of the fragipans is between 1.75 and 1.91 g cm⁻³ whereas the density of overlying Eb horizons is < 1.40 g cm⁻³. The formation of the compact lenticular structures and polygonal fissuring of fragipans is ascribed to the former presence of permafrost during the Loch Lomond Stadial 11 000 to 10 000 years B.P. The polygonal fissures, after subsequent infilling with illuvial material, have determined the position of the greyish polygonal zones which have formed by the eluviation of Fe and Mn from fissure infill and fissure walls by redox processes. Clay migration from the Eb horizon into the fragipan is well marked. Clay and silt have also been locally removed from the upper parts of the greyish zones and redeposited towards their lower parts. Similar textural degradation has affected eluvial pockets in the upper fragipan. It is concluded that periglacial processes fully explain the genesis of macrostructural features but not the distinctive consistence of the fragipan.

INTRODUCTION

Fragipans are currently recognized in both England and Wales (Avery, 1980) and the United States (Soil Survey Staff, 1975) as dense, closely packed, uncemented pan horizons which have considerable strength when dry but slake in water from an air dry fragment and are brittle when moist. They have been studied most extensively in North America but have also been widely described in British soils (Mackney & Burnham, 1966; Rudeforth, 1970; Ragg & Futty, 1977; Payton, 1980, 1988). Difficulties of identification, inadequate definition, and obscurity of genesis continue to be recorded in reviews of fragipan formation, both in North America (Grossman & Carlisle, 1969; Smeck & Ciolkosz, 1989), and elsewhere in the world (Smalley & Davin, 1982; Payton, 1988; Witty & Knox, 1989). The often synonymous use in Britain of the term indurated horizon (Glentworth, 1954; FitzPatrick, 1976; Pyatt, 1978; Bridges & Bull, 1983), which includes cemented pans (Romans, 1976), has increased confusion over fragipan characteristics and genesis. This helps to explain why many horizons described as fragipans in Britain fail to slake in water from an air dry fragment (Payton, 1988).

Ideas on fragipan formation in Britain and Europe have been strongly influenced by the permafrost hypothesis. This was first suggested by FitzPatrick (1956) to account for the lenticular structure, vesicular voids and silt cappings observed in Scottish indurated horizons. The hypothesis was later developed to include compression of the soil mass by ice lens segregation in the former

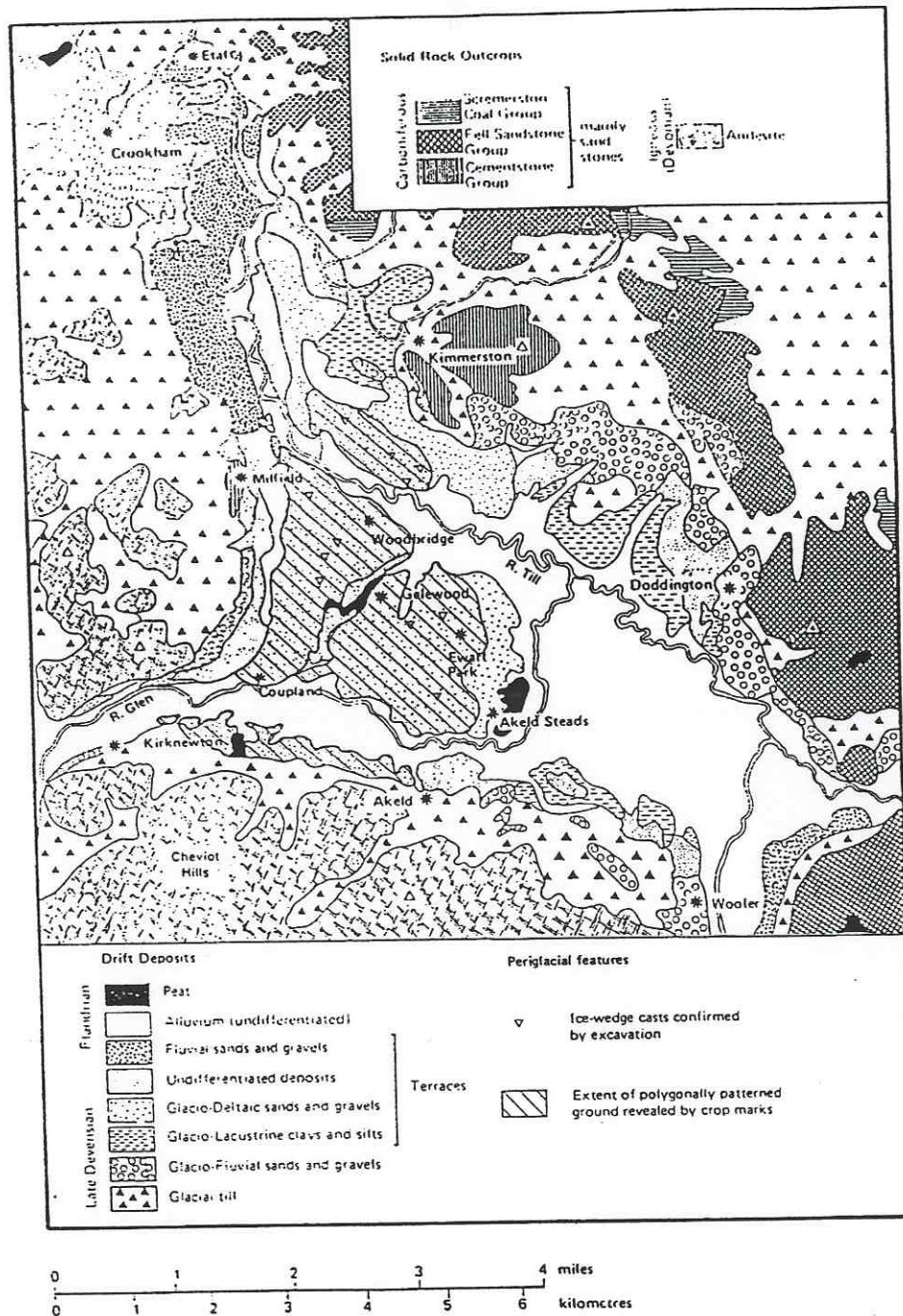


Fig. 1. A geological sketch map of the Milfield Plain showing the extent of glacio-lacustrine deposits and polygonally patterned ground related to ice-wedge casts.

soil descriptions were recorded according to methods in Hodgson (1974). Soil types were classified at subgroup level according to Avery (1980) and subdivided according to soil texture and parent material. The final soil map of the Milfield Plain was presented at 1:50 000 scale in Payton (1988).

A study was also made of the Late Devensian and Flandrian deposits which form the Milfield Plain to ascertain the age and origin of the soil parent materials and to reconstruct Late Quaternary environmental changes which have affected fragipan evolution. The sediments were examined, described and sampled from deep continuous exposures revealed in gravel pit sections, river cliffs, archaeological excavations and a gas pipeline trench which traversed the Plain. A map of the Quaternary deposits was constructed from these data and from soil survey results (Fig. 1). A peat



Plate 1. Fossil ice-wedge cast polygons as revealed by crop marks on the delta surface of the Milfield Plain, Northumberland (copyright Tim Gates).

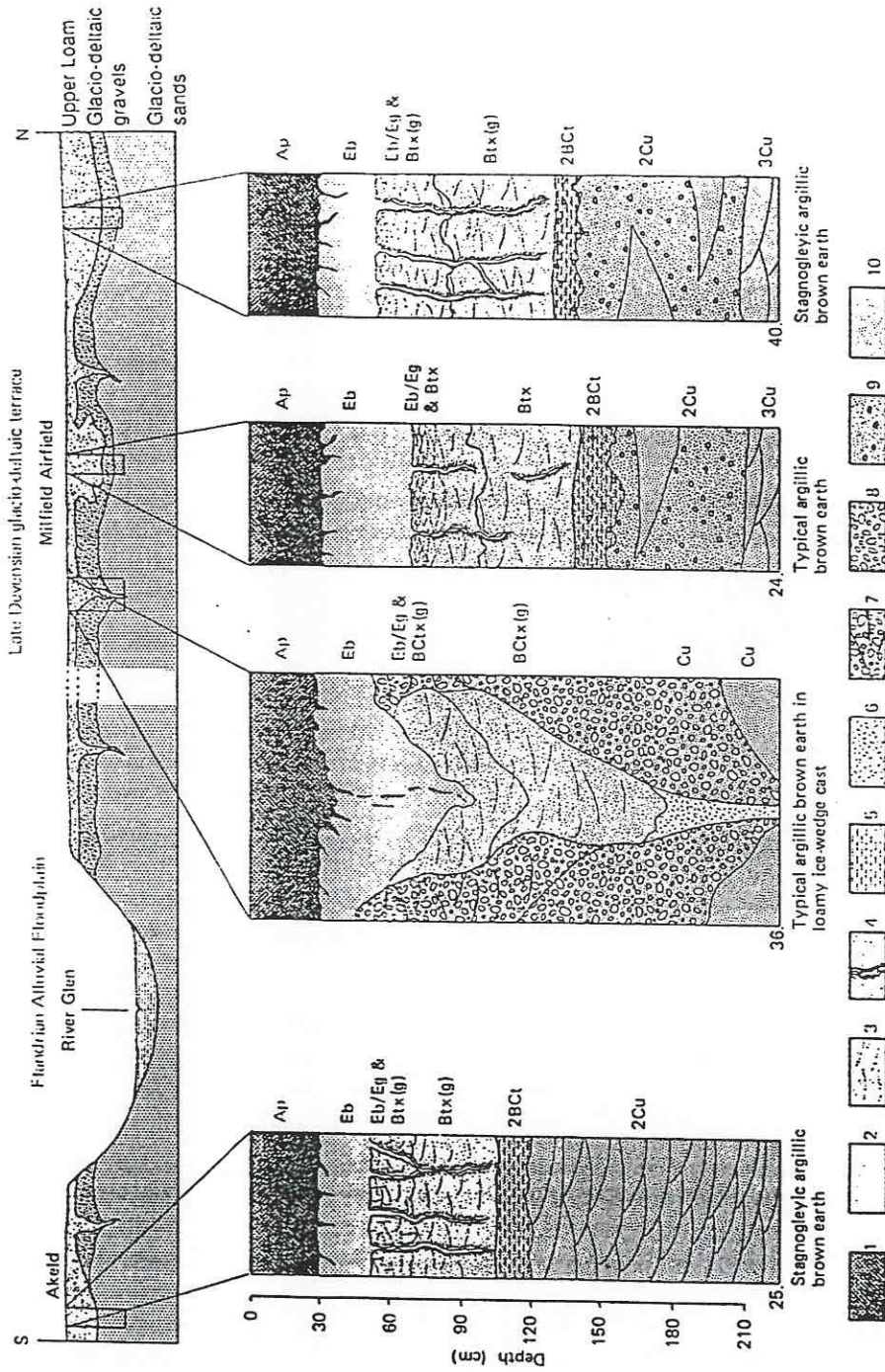
Character and age of soil parent materials

The topset beds of the delta largely represent sand and gravel bars laid down in a braided outwash plain which extended on the aggrading surface of the delta, but are interrupted by poorly-sorted loams (Upper Loam), up to 1.5 m thick, which were deposited in wide depressions or channels in the glacio-deltaic environment. These deposits form the parent materials of the soils with fragipans and represent quieter periods of localised deposition as meltwater discharge subsided. A 6-m deep section south-west of Woodbridge (Fig. 1) showed a typical deltaic sequence. Gravelly topset beds cut by Upper Loam deposits overlie deltaic forsets of crossbedded medium sands that fine downwards into cross-laminated fine sands and silts.

The deltaic sequence grades laterally into laminated glacio-lacustrine silts and clays at elevations between 37 and 43 m OD to the north of the former delta front near Kimmerston (Fig. 1). Here, the peaty horizon of the Black Burn paleosol, buried by 2 m of laminated glacio-lacustrine clays and silts, gave a radiocarbon date of $11\,460 \pm 100$ years B.P. (Payton, 1988). This corresponds to Pollen Zone II, the Allerod Interstadial of Continental stratigraphy, and the latter part of the longer Windermere interstadial in Britain (Coope & Pennington, 1977). Stratigraphic relationships between the deposits at Black Burn and those of the delta terrace demonstrate that the bulk of both the glacio-lacustrine sediments and the coarser glacio-deltaic deposits were laid down before 11 460 years B.P. (Payton, 1988). By this time lake levels had fallen to below 37 m OD and a humic gley soil had formed on the exposed clays. Lake levels subsequently rose no higher than 40 m OD and the delta surface experienced cold periglacial conditions throughout the following Loch Lomond Stadial

Evidence for the former existence of permafrost

The glacio-deltaic deposits, including the Upper Loam, have been affected extensively by periglacial processes. Evidence for this includes: (i) cryoturbation structures such as festoons of finer material and contortion of bedding within the sands and gravels; (ii) coarse lenticular structure and fine material capping stones (FitzPatrick, 1956; Corte, 1963), and (iii) a network of fossil ice wedges forming polygonally patterned ground evident as crop marks on aerial photographs taken at times of soil moisture stress (Plate 1). The polygonally patterned ground covers all the delta surface



1. Loamy topsoil; 2. Eluvial clay-depleted horizon; 3. lenticular fragipan (Upper Loam); 4. lenticular fragipan with grey polygonal zones (Upper Loam); 5. sandy argillic horizon below lithological discontinuity; 6. non-fragic loamy ice-wedge cast infill; 7. discontinuous compact weakly cemented pan in glacio-deltaic sand and gravel; 8. loose glacio-deltaic sand and gravel; 9. crossbedded glacio-deltaic sands with fine gravel; 10. crossbedded medium to fine glacio-deltaic sands

Fig. 3. Profile morphology of argillic brown earths with fragipans (Fragiudalfs) from the Millfield Plain in relation to landform and parent material.

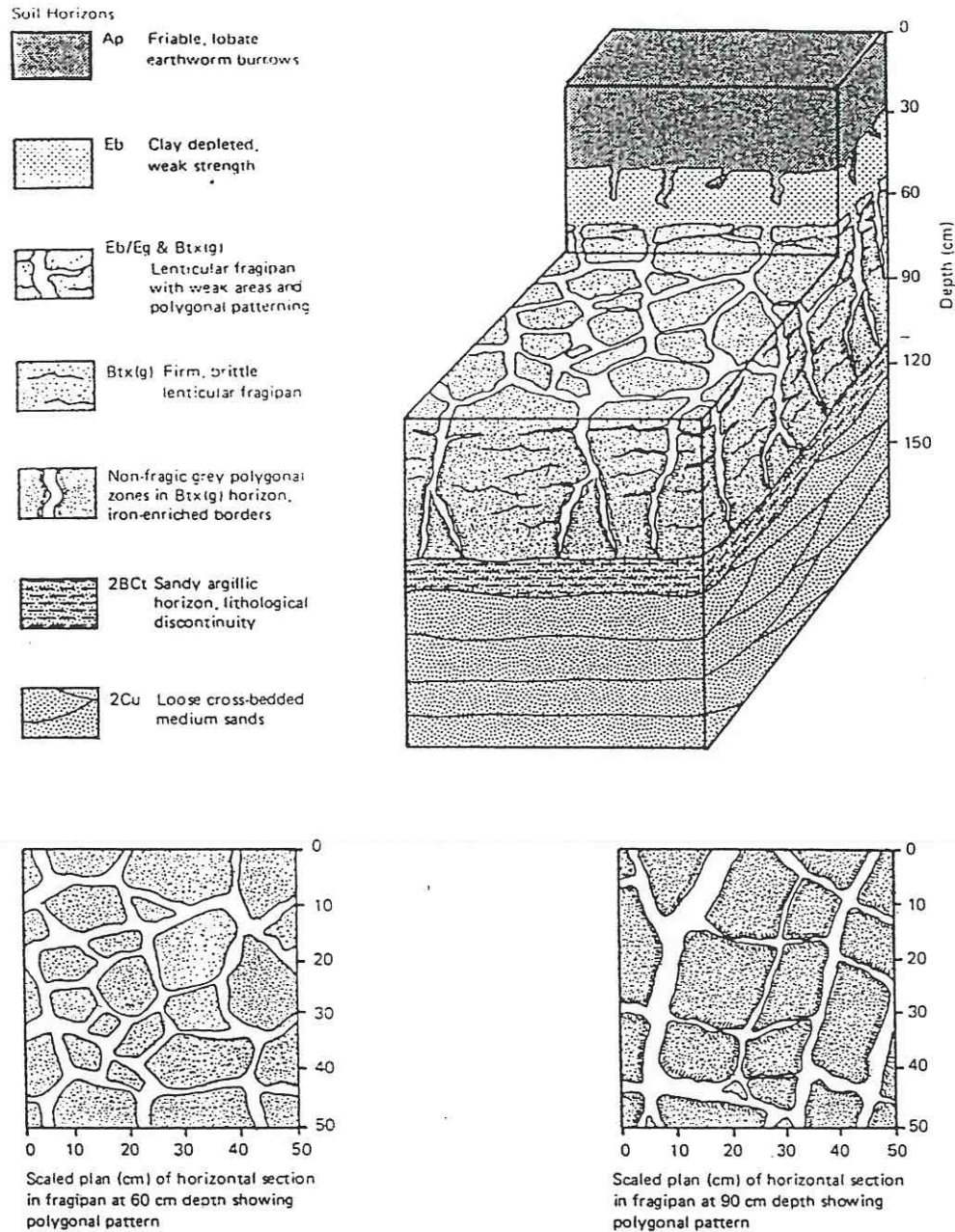


Fig. 4. Fragipan morphology showing grey polygonal patterning in a stagnogleyic argillic brown earth (Glossic Fragiudalf) from the Milfield Plain, Northumberland. (Profile 25).

detached. Up to 25% of the Btx(g) parts within this upper zone are only moderately firm or weaker when moist.

The lowermost parts of the fragipan are more massive and the greyish vertical zones between polygons are invariably more clayey. At depths of about 1 m the fragipan passes abruptly across a lithological boundary into a thin, moderately sticky, massive loamy sand. Clay illuviation within glacio-deltaic sands is confirmed by micromorphological data (Payton, 1988). This BCt horizon passes abruptly into loose cross-bedded sands of the 2C horizon below.

Particle size distribution and uniformity of soil parent materials

Cumulative frequency curves of particle size distribution (Figs 7 and 8) and ratios of fine sand to total sand calculated on a clay free basis demonstrate the lithological continuity of Upper Loam soil parent materials. They also show an abrupt discontinuity immediately below the fragipans to the

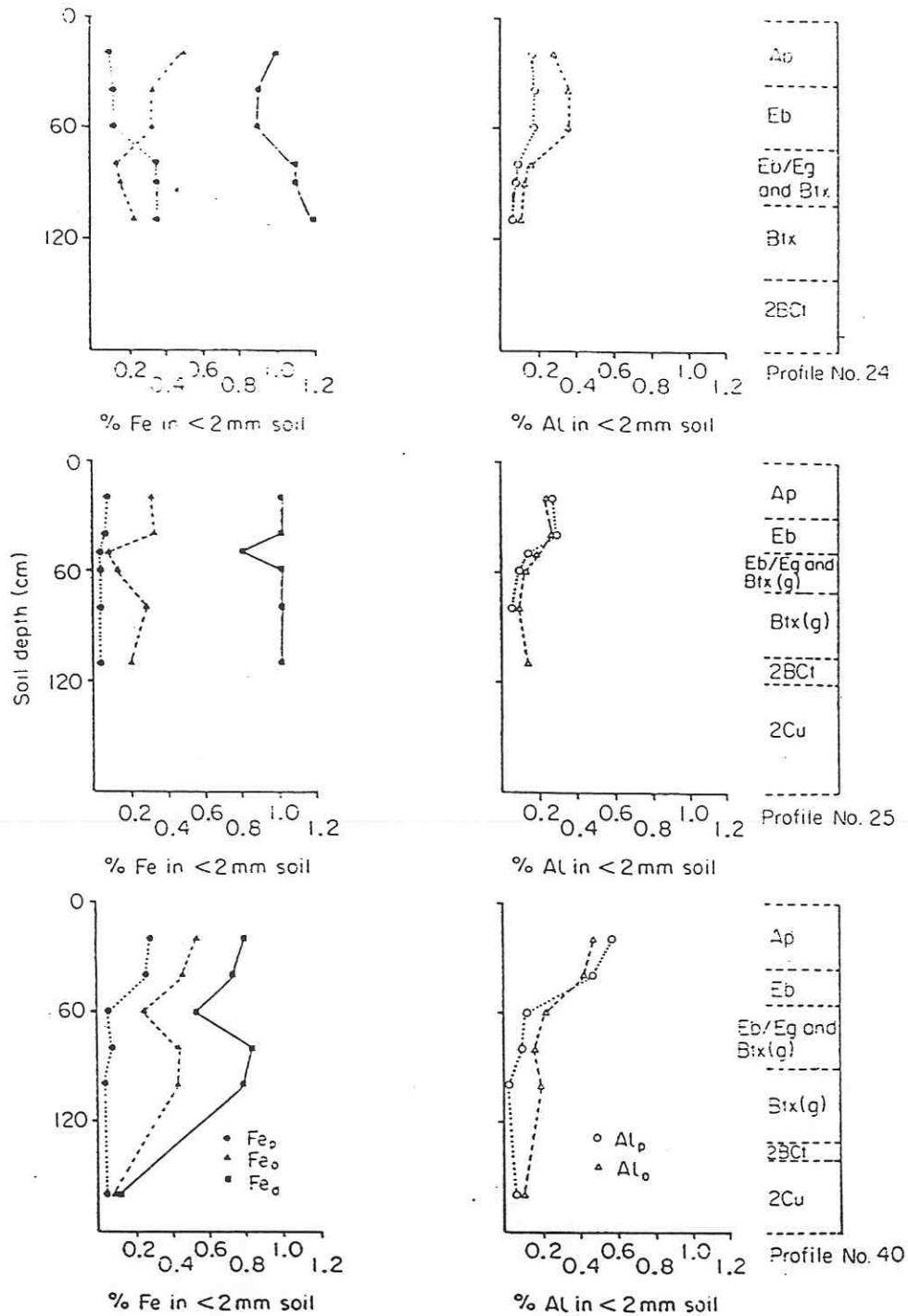


Fig. 6. Depth functions of pyrophosphate (p), oxalate (o) and dithionite (d) extractable iron and aluminium in Milfield Plain and argillic brown earths with fragipans. (Profiles 24, 25 and 40).

of particle size distribution occurs within the fragipans. Silt-deficient pockets of variable clay content occur and are well marked in Profile 25. In addition, greyish polygonal zones have particle size distributions with much greater fine silt contents and increasing clay content with depth (Table 1).

Translocation of clay and other constituents

There is a significant increase in clay of between 5 and 7% in the Btx and Btx(g) horizons relative to the overlying Eb horizons in most profiles (Fig. 5). The increase is accompanied by higher ratios of

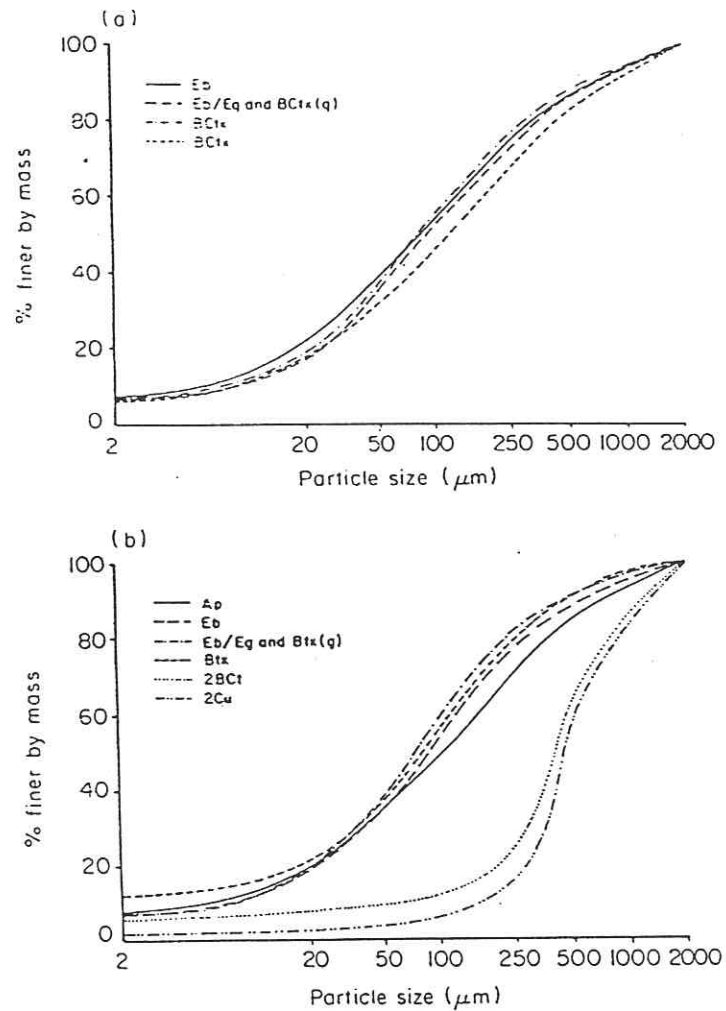


Fig. 8. Cumulative frequency curves of particle size distribution in Milfield Plain argillic brown earths with fragipans (2): (a). Profile 36 (Milfield gravel pit V); (b), Profile 40 (Milfield Airfield XII).

decrease with depth of organic complexed forms of these elements extractable with pyrophosphate, indicates that cheluviation is inactive in these soils.

Bulk density and porosity

All profiles show a marked increase in bulk density and corresponding decreases in porosity on passing from Eb horizons into fragipan horizons (Fig. 5). Over a range of moisture contents from near field capacity to the air-dry state the fine earth bulk density of Eb horizons is always $< 1.40 \text{ g cm}^{-3}$ (i.e. $> 0.45 \text{ m}^3 \text{ m}^{-3}$ porosity). That of the fragipans exceeds 1.75 g cm^{-3} in all profiles and attains a maximum of 1.91 g cm^{-3} in the most strongly developed parts of Profile 36, i.e. considerably greater than the mean values in Pennsylvanian Fragiudalfs (Peterson *et al.*, 1970) and similar to Fragiudalfs in till (Miller *et al.*, 1971; Wang *et al.*, 1974; Hallmark & Smeck, 1979). This represents an increase of about 0.5 g cm^{-3} relative to Eb horizons, corresponding to a 20% reduction in porosity to give fine earth porosity values of as little as $0.25 \text{ m}^3 \text{ m}^{-3}$ (Table 1). Eb/Eg parts of the upper fragipan have distinctly lower fine earth bulk densities of the order of 1.50 g cm^{-3} compared to $> 1.70 \text{ g cm}^{-3}$ in adjacent Btx or Btx(g) parts. Clearly an explanation is required to account for the compact state of the fragipan horizons and the variation in physical properties within their upper parts.

The relationship of fragipans to ice-wedge casts

At the beginning of this study, I thought that the occurrence of soils with fragipans in parent materials cut by ice-wedge casts would provide a method of dating fragipan formation relative to

PROFILE 25 (NT 936400)

Horizon	Ap	Eb	Eb/Eg ^a & Btx(g) 70	Eb/Eg ^b & Btx(g) 70	Fissure infill	Btx(g) 90	Btx(g)2 105	2BC1 120	2Cu 200	Fissure infill 105
Lower depth (cm)	30	48			70					
Particle size (% by mass)										
1-2 mm	6	5	6	5	4	6	6	3	8	5
500-1000 µm	8	7	8	6	5	7	7	30	27	5
250-500 µm	11	9	13	7	6	10	8	33	28	5
100-250 µm	16	16	26	13	12	18	15	16	21	8
50-100 µm	10	9	9	11	9	9	16	3	6	10
20-50 µm	14	17	11	20	20	11	18	1	2	19
2-20 µm	18	25	19	23	31	21	18	3	3	28
<2 µm	17	11	8	15	13	18	12	11	5	20
<0.2 µm	5	2	1	9	5	9	6	5	2	12
Bulk density (g cm ⁻³)										
total (moist)	1.34	1.47	1.56	1.69		1.79	1.88			
(air dry)		1.54	1.43	1.75		1.90	1.87	1.96		
<2 mm (moist)	1.25	1.25	1.51	1.64		1.77	1.74			
(air dry)		1.46	1.38	1.65		1.87	1.85	1.98		
Porosity (% by volume)										
total (moist)	47	46	39	34		30	27			
(air dry)		39	44	32		26	27	22		
<2 mm (moist)	50	51	41	36		31	32			
(air dry)		42	46	36		27	28	24		

^aPale weak Eb/Eg area.

^bModerately firm Btx(g) area.

Table 1b. (Continued)

PROFILE 40 (NT 934629)										
Horizon	Ap	F _b	E _b /E _g ^a B(x)(g)	E _b /E _g ^b B(x)(g)	E _b /E _g ^c B(x)(g)	B(x)(g)	B(x)(g)	2BC ₁	2C _u	Fissure infill
Lower depth (cm)	35	55	90	90	90	110	130	140	200	75 · 130
Particle size (% by mass)										
1-2 mm	7	5	5	2	3	3	5	14	16	10
500-1000 µm	8	6	4	3	6	6	7	23	25	5
250-500 µm	14	11	9	8	15	13	12	37	44	10
100-250 µm	23	25	23	23	14	22	23	14	9	21
50-100 µm	12	19	23	20	21	19	19	2	2	23
20-50 µm	17	16	18	24	17	16	14	1	1	13
2-20 µm	11	12	11	12	11	9	7	3	1	12
<2 µm	8	6	7	8	13	12	13	6	2	6
<0.2 µm	2	2	4	6	8	6	8			
Bulk density (g cm ⁻³)										
total (air dry)		1.37	1.40	1.53	1.71	1.78	1.79			
<2 mm	1.28	1.32	1.50			1.75				
Porosity (% by volume)										
total (air dry)		46	46	41	35	32	32			
<2 mm	49	49	42			33				

^aPlaty, moderately weak, degraded Eb/Eg area from upper fragipan.

^bDegraded, porous, moderately firm (dry) Eb/Eg area from upper fragipan.

^cVery firm, brown B(x)(g) area from upper fragipan.

Table 2. Extractable iron, aluminium and manganese in grey polygonal zones and the adjacent fragipan

Profile	25	25	25	25	25	25	40	40	40
Soil material	Fragipan matrix	Fe-rich* zone	Grey zone	Fragipan matrix	Fe-rich* zone	Grey zone	Fragipan matrix	Fe-rich* zone	Grey zone
Depth (cm)	50-60	50-60	50-60	80-90	80-90	80-90	55-75	55-75	55-75
Dithionite extractable									
Fe (%)	1.10	1.74	0.12	1.10	1.81	0.47	0.84	1.51	0.09
Al (%)	0.12	0.14	0.11	0.11	0.13	0.08	0.15	0.16	0.12
Mn ($\mu\text{g g}^{-1}$)	190	280	76	190	270	110	58	86	26
Oxalate extractable									
Fe (%)	0.14	0.48	0.09	0.29	0.94	0.22	0.43	0.91	0.08
Al (%)	0.11	0.12	0.09	0.08	0.11	0.08	0.16	0.17	0.10

*Ochreous zone of subsurface iron accumulation parallel to grey polygonal zones.

matrix coatings suggests either transport over short distances by water, probably as a slurry, or dry particle movements in open fissures under gravity. Such processes would require open fissures and, therefore, must date to an early stage of infilling. Turbulent flow of water which was possible in these large voids would have allowed translocation of clay, silt and fine sand to be deposited as better sorted layered fissure wall coatings. The interlayering of matrix coatings and these better sorted types indicates alternating wet and dry conditions with sudden wetting of fissure walls leading to instability and transport. The partial withdrawal of fine clay suspensions into finer air-filled voids of the dry soil matrix adjacent to the fissure walls could also explain the formation of the ferri-argillans currently engulfed by the parallel zones of subsurface iron impregnation.

The simultaneous presence on the delta terrace of a network of large scale ice-wedge casts cutting through layered deposits of Upper Loam, gravel and sand, alongside small scale polygonal fissuring restricted to the Upper Loam, is thus best accounted for by contemporaneous but contrasting thermal and desiccation processes operating in a former periglacial environment during the Late Devensian. The results of the present study substantiate the origin of polygonal fissuring in fragipans proposed by FitzPatrick (1976), and more recently by van Vliet & Langohr (1981), by providing dated evidence for the former existence of permafrost, and by showing that temperate desiccation cracking alone cannot account for the infilled fissures associated with grey polygonal patterning.

Origin of compact lenticular and platy structure

Several studies from the United States regard fragipan density as having resulted from contemporary pedogenesis, but the origin of the platy structure is not explained (Grossman & Carlisle, 1969). The platiness of eluvial horizons in soils of the Boreal zone has been related to banded microfabric and seasonal ice lens formation (Dumanski & St Arnaud, 1966). This cannot account for the scale and depth of the structures in the fragipans of the present study under a temperate climate. White (1966) observed that current pedogenetic processes leading to platy structures are uncommon in temperate climatic zones. In view of the substantial evidence for a former permafrost layer, the inheritance of the planes of separation left after the melting of ice lenses, as proposed by FitzPatrick (1956), provides the most logical explanation of lenticular structure over the depths encountered in the fragipans of this study.

The relatively closely-spaced sub-horizontal planes of weakness in the Milfield fragipans require that ice lenses were frequent and well developed within the depths of present day fragipan occurrence. Ice lenses form parallel to the freezing front which advances from the ground surface and they are fed by water held under tension which is drawn upward from saturated layers at greater depth. The continued growth of the lenses therefore depends partly on the capacity of the material to develop sufficient matric suctions to allow capillary water movement (Yong & Warkentin, 1975). The particle size distribution of the Upper Loam meets these criteria and would have been conducive to the development of both ice lenses and polygonal vein ice given the low temperatures indicated by ice-wedge casts. There would have been an adequate supply of shallow groundwater controlled by water levels in the adjacent lake.

The compact state of the lenticular structures within the fragipan horizons is attributed in a large part to the compression caused by ice lens growth, and the shrinkage of the soil material as water was withdrawn to centres of ice crystallization. Experimental evidence presented by van Vliet-Lanoë (1985) has shown that these cryogenic processes can lead to stable compact lenticular peds. However, fragipan consistence is also related to other aspects of microfabric (Payton, 1983).

CONCLUSIONS

Fragipans in the argillic brown earths of the Milfield Plain conform with those in many Fragiudalfs from the north-eastern United States and Canada. Their compact state and low porosity cause some seasonal impedance of drainage and, together with high *in situ* soil strength, restrict rooting and burrowing soil fauna. Grey polygonal patterning is explained by preferential waterlogging and resulting redistribution of iron and manganese oxides within an infilled fissure network formed by

Grossman, R.B., E.C.
 restriction prediction in a mine
 National Symposium on Prime Farmland Reclamation

Table 1. Studies of seedling root inhibition related to bulk density arranged by ascending clay percentage and silt percentage within clay percentage.

Clay pct	Suction MPa	Plant	Bulk Density at Relative Growth			Source
			1.0	0.5	0.2	
			-----Mg/m ³ -----			
5	0.02	Cotton	1.51	1.67	1.72	Bar-Yosef and Lambert (1981)
6	0.01	Cotton	1.56	---	1.75	Jones (1983) ^{a/}
7	0.02	Cotton	1.55	1.72	1.79	Taylor et al (1966)
7	0.03	Cotton	1.55	1.65	1.70	
8	0.03	Sorghum	1.25	1.58	1.72	Hemsath and Mazurak (1974)
9	0.02	Cotton	1.55	1.76	1.83	Taylor et al (1966)
9	0.03	Cotton	1.55	1.70	1.77	
10	0.02	Cotton	1.10	1.74	1.81	
10	0.03	Cotton	1.10	1.70	1.77	
10	0.03	Soybean	1.55	1.86	1.94	
10	0.03	Pea	1.29	1.50	1.62	Baligar et al (1981)
10	0.02	Cotton	1.55	1.79	1.86	Voorhees et al (1975)
11	0.007	Pea	1.10	1.63	---	Taylor and Gardner (1963)
12	0.005	Lettuce	1.25	1.50	---	Eavis (1972)
12	0.03	Pea	1.50	1.70	---	Carr and Dodds (1983)
14	0.03	Pea	1.55	1.75	1.82	Barley et al (1965)
15	0.03	Sorghum	1.00	1.64	1.75	Taylor et al (1966)
15	0.005	Sugar Cane	1.15	1.54	1.65	Hemsath and Mazurak (1974)
17	0.02	Rye Grass	1.05	1.53	---	Monteith and Banath (1965)
18	0.01	Yellow Poplar	1.25	1.48	1.54	Cornish et al (1984)
18	0.01	Sweet Gum	1.25	1.48	1.56	Simmons and Pope (1987)
19	0.02	Cotton	1.25	1.52	1.62	
19	0.03	Cotton	1.25	1.45	1.55	Taylor et al (1966)
19	0.018-0.03	Wheat	1.17	1.41	---	Masle and Passioura (1987)
22	0.03	Cotton	1.30	1.60	1.70	Tackett and Pearson (1964a)
22	0.03	Cotton	1.30	1.52	1.62	Tackett and Pearson (1964b)
24	0.03	Pea	1.35	1.50	1.57	Blanchar et al (1978)
30	0.02	Sorghum	1.00	1.55	1.73	Hemsath and Mazurak (1974)
34	0.005	Sugar Cane	1.33	1.49	1.63	Monteith and Banath (1965)
42	0.01	Corn	0.93	1.19	1.34	Phillips and Kirkham (1962)
42	0.001	Corn	0.93	1.16	1.31	
50	0.005	Sugar Cane	1.17	1.33	1.43	Monteith and Banath (1965)
53	0.003	Edible Bean	1.15	1.30	1.45	Asady et al (1985)
55	0.01	Pea	0.92	1.21	---	Voorhees et al (1975)
55	0.01	Pea	0.99	1.34	---	Cockroft et al (1969);
65	0.005	Pea	1.23	1.30	1.33	Greacen and Gardner (1982)

^{a/} Personal communication from A.T.P. Bennie in reference cited.

Table 2. Studies of seedling root inhibition related to penetration resistance arranged by ascending clay percentage and silt percentage within clay percentage.

Clay pct	Suction MPa	Plant	Penetration Resistance at Relative Growth			SOURCE
			1.0	0.5 MPa	0.2	
5	0.016	Cotton	1.8	1.3	2.6	Bar-Yosef and Lambert (1981)
7	0.02	Cotton	0.06	0.7	1.9	Taylor and Ratliff (1969)
7	0.08	Cotton	0.005	0.4	1.8	Taylor et al (1966)
7	0.05	Cotton	0.6	1.3	1.7	Taylor and Ratliff (1969)
7	0.02	Peanut	0.005	2.0	4.9	
7	0.04	Peanut	0.005	2.0	2.9	
8	0.03	Sorghum	0.2	0.8	1.0	Hemsath and Mazurak (1974)
9	0.02-0.1	Cotton	0.4	1.1	1.5	Taylor et al (1966)
10	0.02-0.07	Cotton	0.6	1.4	1.8	
10	0.03	Pea	1.0	3.3	6.4	Voorhees (1975)
10	0.1	Pea	1.0	3.4	7.3	
10	0.02	Cotton	0.5	1.4	3.3	Taylor and Gardner (1963)
10	0.03	Cotton	0.8	2.2	3.6	
10	0.05	Cotton	1.0	2.1	2.9	
12	0.03	Pea	1.5	1.7	---	Barley et al (1965)
12	0.07	Pea	1.5	3.0	3.6	Hemsath and Mazurak (1974)
15	0.02	Sorghum	0.3	0.8	---	
15	0.005	Sugar Cane	0.3	1.9	---	Monteith and Banath (1965)
17	0.02	Rye Grass	0.3	2.0	---	Cornish et al (1984)
19	0.02-0.07	Cotton	0.6	1.4	1.9	Taylor et al (1966)
19	0.02-0.1	Wheat	1.4	4.6	6.7	Masle and Passioura (1987)
19	0.03	Cotton	0.0	0.4	1.4	Pearson et al (1970)
19	0.03	Cotton	0.0	1.0	---	
19	0.03	Cotton	0.0	1.4	---	Shierlaw and Alston (1984)
21	0.02	Ann. Rye Grass	0.4	0.8	1.2	
21	0.01	Ann. Rye Grass	0.4	3.0	5.1	
21	0.02	Corn	0.4	1.0	1.5	
21	0.1	Corn	0.4	4.1	7.3	
24	0.03	Pea	---	1.2	2.2	Blanchar et al (1978)
28	0.1	Corn	1.6	1.3	---	Mirreh and Ketcheson (1973a)
30	0.015	Sorghum	0.2	0.6	1.0	Hemsath and Mazurak (1974)
30	0.03	Sorghum	0.1	0.7	1.3	
34	0.005	Sugar Cane	0.6	1.3	1.6	Monteith and Banath (1965)
50	0.005	Sugar Cane	0.4	0.6	0.7	
53	0.008	Edible Bean	0.4	3.1	4.3	Asady et al (1985)
55	0.01	Pea	0.1	1.1	---	Voorhees et al (1975)
55	0.03	Pea	0.5	2.1	---	
55	0.1	Pea	0.9	1.7	---	
65	0.005	Pea	0.6	1.4	2.0	Cockcroft et al (1969)

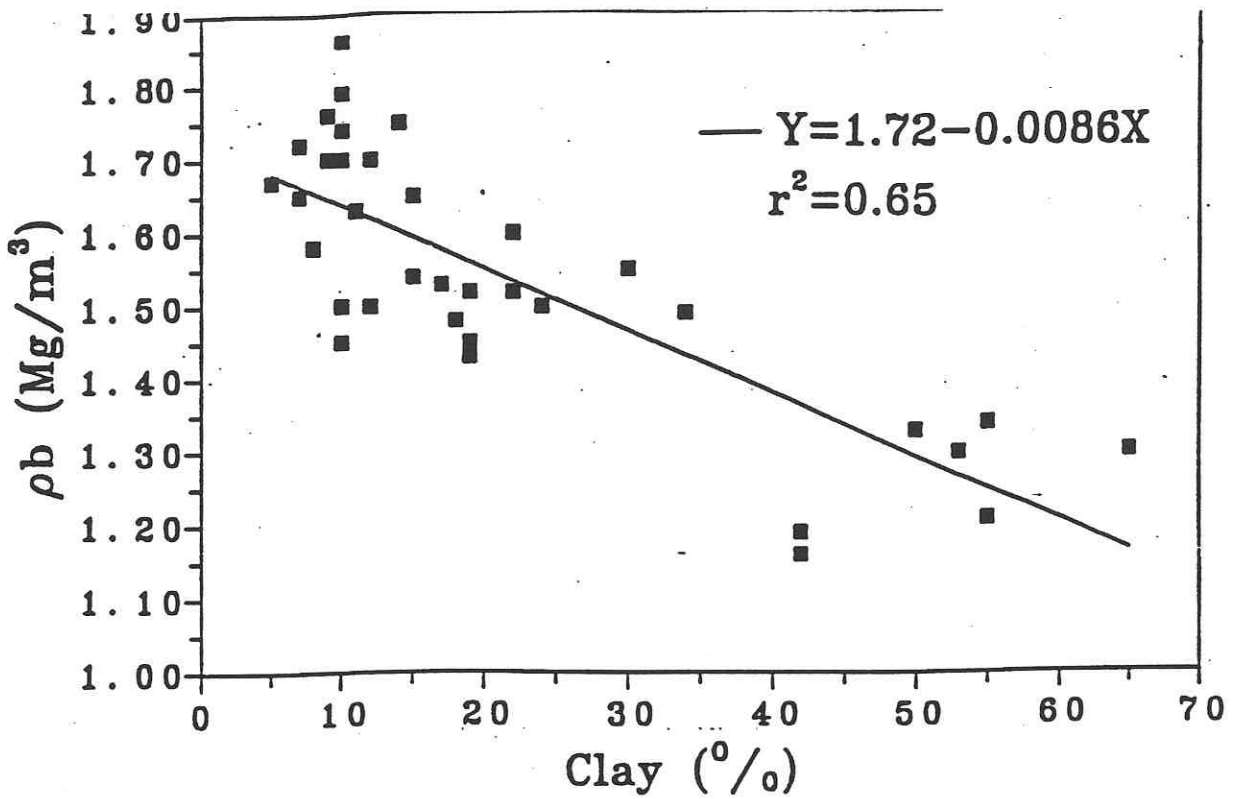


Figure 1. Relationship between clay percentage and the bulk density at 0.5 of maximum root growth for 17 laboratory studies. (Table 1)

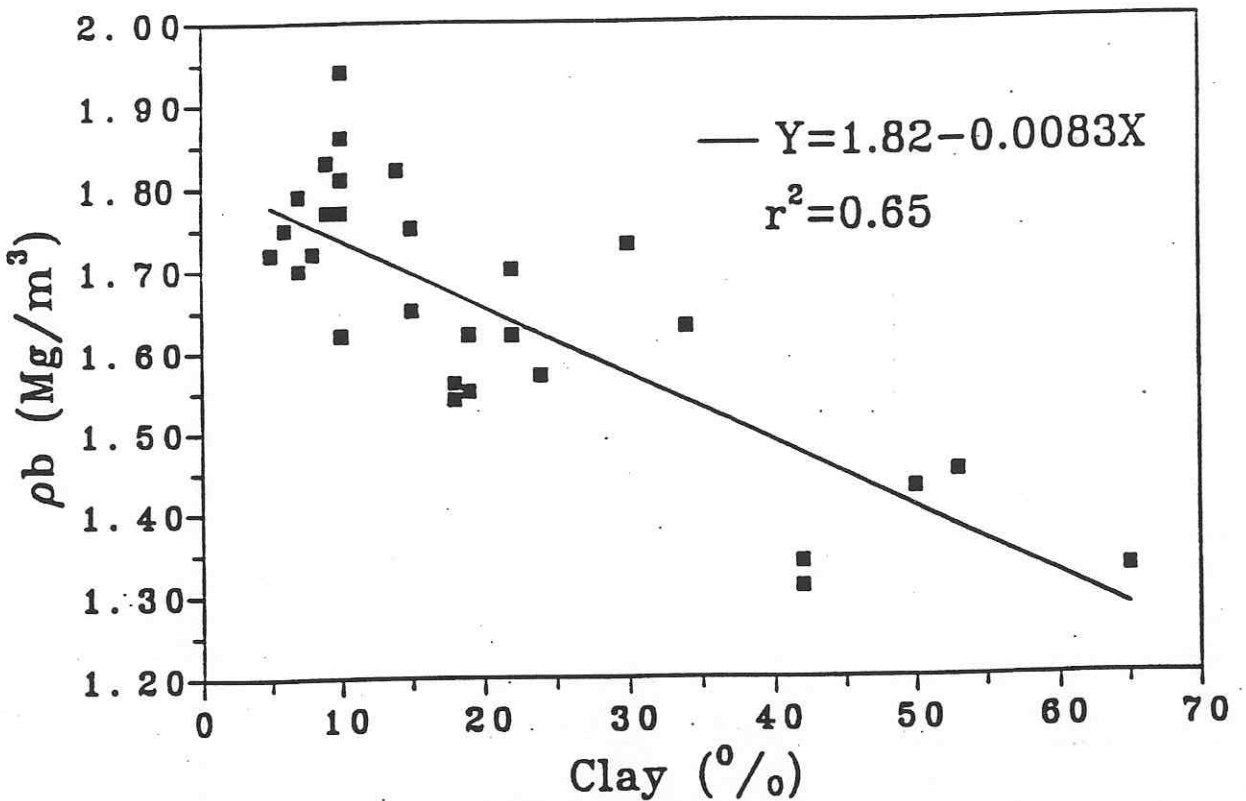


Figure 2. Relationship between clay percentage and the bulk density at 0.2 of maximum root growth for 17 laboratory studies. (Table 1)

Bulk Density at Intermediate Water Content and Related Calculations

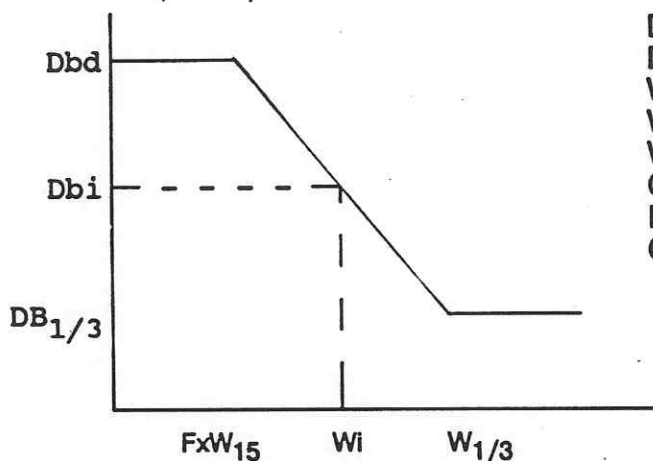
$$D_{bi} = D_{b_{1/3}} + \frac{(D_{bd} - D_{b_{1/3}})(W_{1/3} - W_i)}{W_{1/3} - (W_{15} \times F)}$$

- Where, D_{bi} = Bulk Density Intermediate Water Content
- $D_{b_{1/3}}$ = Bulk Density 1/3 (1/10) bar retention
- D_{bd} = Bulk Density dry clod
- $W_{1/3}$ = Gravimetric Water 1/3 (1/10) bar
- W_i = Gravimetric Water Intermediate
- W_{15} = Gravimetric Water 15 bar retention
- F = Factor that varies by Linear Extensibility

COLE	F
<0.06	0.6
0.06-0.09	0.5
0.09-0.12	0.4
≥0.12	0.3

From D_{bi} an intermediate coefficient of linear extensibility (COLEI) may be calculated (assume no >2 mm):

$$COLEI = \left(\frac{D_{bi}}{D_{bd}} \right)^{1/3} - 1$$



- $D_{b_{1/3}} = 1.20$
- $D_{bd} = 1.80$
- $W_{1/3} = 30.0$
- $W_{15} = 15.0$
- $W_i = 23.0$
- $COLE = 0.14$
- $D_{bi} = 1.36$
- $COLEI = 0.04$

Field water content may be estimated from hydrologic models and the associated intermediate bulk density computed to be used for prediction of root restriction. The related intermediate extensibility may be helpful in the prediction of surface-connected cracks. To evaluate if bulk density would limit root growth before suction, the equation for intermediate water content consistent with the root limiting bulk density is calculated.

$$W_{ir} = \frac{W_{1/3} - [(D_{br} - D_{b_{1/3}}) \times (W_{1/3} - FxW_{15})]}{D_{bd} - D_{b_{1/3}}}$$

where the subscript r refers to root restrictive. The value of W_{ir} is compared to W_{15} . If it is higher, root restriction by bulk density is assumed to occur before restriction by suction. The restriction considered is entry into structural units.

The bulk density of the in place <2 mm fabric at intermediate water content is assumed to encompass the vertical desiccation cracks. This bulk density, D_{bis} , is calculated as follows:

$$\begin{aligned} D_{bis} &= D_{b_{1/3}} \times \left(\frac{D_{bi}}{D_{b_{1/3}}} \right)^{1/3} \\ &= 1.20 \times \left(\frac{1.36}{1.20} \right)^{1/3} = 1.25 \text{ g/cc} \end{aligned}$$

Appendix 4 S-6—SOIL AND WATER MANAGEMENT AND CONSERVATION

Effect of Soil Texture on Critical Bulk Densities for Root Growth¹

C. ALLAN JONES²

ABSTRACT

Published and unpublished data from 10 studies were analyzed to determine the effects of soil texture on critical bulk densities for rooting at near-optimum soil water contents. Highly significant negative relationships were found between percentage clay or silt + clay and the bulk density at which rooting was at a maximum or the bulk density at which rooting was 0.2 of that maximum. Similar relationships were also found between percentage clay or silt + clay and (i) the bulk densities of soil layers classified as fragipans and (ii) the maximum bulk densities at which "many" roots are reported in U.S. Soil Conservation Service pedon descriptions. Thus, soil texture can be used to estimate bulk densities of fragipans and critical bulk densities at which root growth is severely affected at near-optimal soil water contents.

Additional Index Words: soil-strength, clay, fragipan.

Jones, C.A. 1983. Effect of soil texture on critical bulk densities for root growth. *Soil Sci. Soc. Am. J.* 47:1208-1211.

NUMEROUS STUDIES have shown that crop root growth is affected by soil strength. In developing crop growth simulation models, we should consider these effects in soils with fragipans or traffic pans. However, in most agricultural soils, soil strength has not been measured for all layers of the profile, and no general model is available to estimate soil strength in a wide range of soils.

Two important determinants of soil strength are bulk density and soil water content. The U.S. Soil Conservation Service (SCS), National Soil Survey Laboratory (NSSL), routinely measures bulk density at -33 kPa in all soil layers in soil pedon descriptions. These data are available for many soils from the USA and other parts of the world. However, the relationship between bulk density at -33 kPa and root growth is not clear. Several studies (Gerard et al., 1982; Monteith and Banath, 1965; Taylor et al., 1966) suggest that the bulk density at which root growth stops varies with soil texture as well as with soil water content. This study examines the combined effects of bulk density and soil

texture on crop rooting behavior at near-optimum soil water contents. The results can be used in crop growth simulation models to estimate the effects of these factors on root growth under near-optimum water contents.

Three sources of data are used in this study: (i) empirical data from 10 published and unpublished studies relating soil texture to critical bulk densities at which root growth is either not reduced by soil strength or is reduced to 0.2 of its maximum; (ii), measurements of soil texture and bulk density determined at -33 kPa in soil layers described as fragipans; and (iii), semiquantitative estimates of root abundance and measurements of bulk density at -33 kPa and soil texture for 213 layers of the B and C horizons of 79 soil pedons.

METHODS

Experimental Data

Published experimental data were taken from Bar-Yosef and Lambert (1981), Cockcroft et al. (1969), Gerard et al. (1982), Greacen and Gardner (1982), Grimes et al. (1975), Meredith and Patrick (1961), Monteith and Banath (1965), Tackett and Pearson (1964), Taylor and Gardner (1963), and Taylor et al. (1966). Unpublished data were furnished by A. T. P. Bennie (personal communication). Data were restricted to measurements of rooting behavior at soil water potentials (Ψ) between -5 and -33 kPa. When rooting behavior was measured at $> 1 \Psi$ within this range, data from the Ψ with the greatest root growth were used. In some cases, gravimetric or volumetric soil water (θ) content was reported instead of Ψ . In the cases of Gerard et al. (1982) and Meredith and Patrick (1961), the soil water contents were estimated to have been at or above -33 kPa during most of the period of root growth from unpublished data of the relationship between θ and Ψ in soils of the same texture. The data of Grimes et al. (1975) are from an irrigated field experiment, and I assumed that θ in the 30- to 61-cm zone from which data were obtained was at or above -33 kPa during most of the period of study.

In most cases, percentages of silt and clay were reported. When they were not reported, they were estimated from soil texture classes.

The critical bulk densities reported are those at which rooting activity was at its maximum at the soil water content selected ($D_{1.0}$) and at which rooting activity was 0.2 of that maximum ($D_{0.2}$). The value of $D_{0.2}$ was estimated graphically.

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Table 1—Critical bulk densities, soil texture, soil water potential, crop, and method of evaluating rooting in 10 studies.

Source	Crop	Root observation	Soil water potential	Texture		Bulk density	
				Clay	Silt	Maximum	0.2 Maximum
			MPa	%		g/cm ³	
Bar-Yosef and Lambert (1981)	Cotton	Elongation	0.016	5	16	1.50	1.68
A. T. P. Bennie (personal communication)	4 Crops	Elongation	0.010	6	8	1.56	1.75
Cockroft et al. (1969) and Greacen and Gardner (1982)	Pea	Elongation	0.005	65	17	1.26	1.43
Gerard et al. (1982)	Cotton	Elongation	fc†	14	13	1.36	1.63
				27	15	1.25	1.52
				29	26	1.42	1.56
				27	28	1.42	1.57
				30	25	1.33	1.49
Grimes et al. (1975)	Corn	Density (30-61 cm)	fc	14	26	1.32	1.67
Meredith and Patrick (1961)	Sudangrass	Weight	fc	(13)†	(35)	1.43	1.60
				(13)	(35)	1.49	1.72
Monteith and Banath (1965)	Sugarcane	Weight	0.005	(18)	(40)	1.35	1.65
				(35)	(35)	1.33	1.62
				(50)	(45)	1.17	1.43
Tackett and Pearson (1964)	Cotton	Elongation	0.033	22	10	1.30	1.62
Taylor and Gardner (1963)	Cotton	Percent penetration	0.02	(10)	(30)	1.55	1.87
Taylor et al. (1966)	Cotton	Percent penetration	0.02	19	37	1.25	1.55
				9	8	1.55	1.83
				10	21	1.55	1.78
				7	27	1.55	1.77

† Approximately field capacity or above during much of the period of root growth.

‡ Values in parentheses estimated from soil texture classes.

cally or by interpolation or extrapolation. Extrapolation was used only if the lowest value of rooting activity was < 0.3 of $D_{1.0}$.

Pedon Descriptions

Silt and clay contents, bulk density at -33 kPa, and observations of root density were taken from the B and C horizons of 43 pedons described in *Soil Taxonomy* (Soil Survey Staff, 1975). Identical data were obtained from 36 other pedon descriptions provided by the SCS National Soil Survey Laboratory. The presence of fragipans was also noted. The Soil Survey Staff (1975) describes three categories of root abundance: few, common, and many. If < 10 fine or very fine roots occur per square decimeter, root abundance is described as few. Ten to 100 fine or very fine roots constitute common roots. Many roots are described as > 100 fine or very fine roots. The pedon descriptions examined also included the terms abundant, very few, and no roots. For the purpose of this study, layers having many, abundant, and common roots were assigned to the class of "many" roots. Few and very few roots were considered "few" roots. Layers were assigned to the class of "no" roots when (i) the description specified that no roots occurred in the layer or when (ii) roots were not mentioned in a layer directly below a layer having roots.

RESULTS

Soil water potentials, silt and clay contents, and the bulk densities at which rooting behavior was at the maximum and 0.2 of that maximum are shown in Table 1. Examination of the table reveals that soils with high clay or silt + clay percentages usually have lower critical bulk densities than soils with low clay or silt + clay percentages. The relationships between bulk density and clay or silt + clay at the critical bulk densities at which (i) rooting is not reduced and at which (ii) rooting is reduced to 0.2 of the maximum are shown in Fig. 1 and 2. Thus, in 10 studies repre-

sented 20 soils with a wide range in percentage clay and silt + clay, the two critical bulk densities for root growth decrease as soil clay or silt + clay percentage increases.

A fragipan is a loamy or rarely sandy subsurface horizon that has high bulk density relative to the horizons above it, is hard or very hard when dry, is brittle when wet, is slowly or very slowly permeable to water, and is virtually free of roots except along vertical ped faces (Soil Survey Staff, 1975). In a survey of 222 NSSL pedon descriptions, 24 layers in the B and C horizons were described as fragipans. The relationships between percentage clay or silt + clay and bulk density at -33 kPa in these layers are shown in Fig. 3 and 4. All fragipans in this study had clay percentages < 32%. Thus, high silt + clay percentages shown in Fig. 4 are due to high silt as well as clay. The bulk density of fragipans decreases as the percentage of clay or silt + clay increases. This suggests that the fragipan characteristics of hardness, brittleness, low permeability to water, and high resistance to root growth occur at lower bulk densities as soil clay or silt + clay percentage increases.

Rooting density in the field can vary for a number of reasons, including crop species, stage of development, soil water content, nutrient availability, and soil strength. From Fig. 1 through 4, it is reasonable to suspect that above a critical bulk density root growth in the field is reduced due to soil strength and that the critical bulk density is a function of the percentage of clay and silt + clay. The relationships between bulk density at -33 kPa and the percentages of clay and silt + clay for 106 soil layers having "many" roots and 107 soil layers having "no" roots are shown in Fig. 5 and 6. The lower line in each figure represents a line above which only 10% of the layers with "many" roots are found. The upper line in each figure is a line

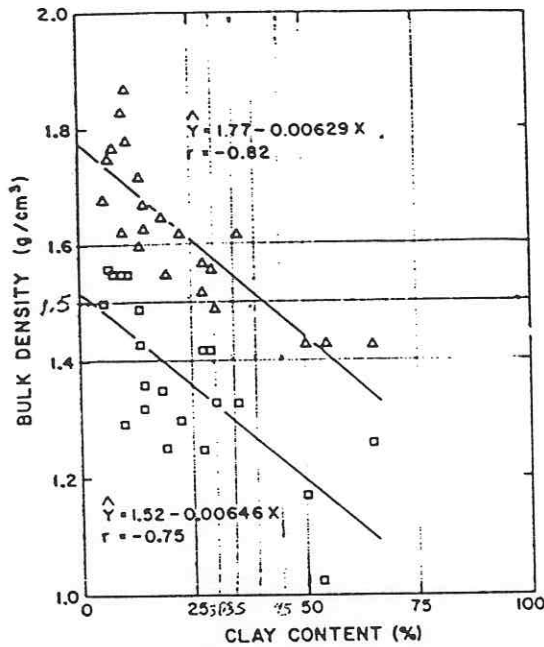


Fig. 1—Relationship between percentage clay and bulk density in 22 soils from 11 studies: optimum root behavior (□); 0.2 of optimum (Δ).

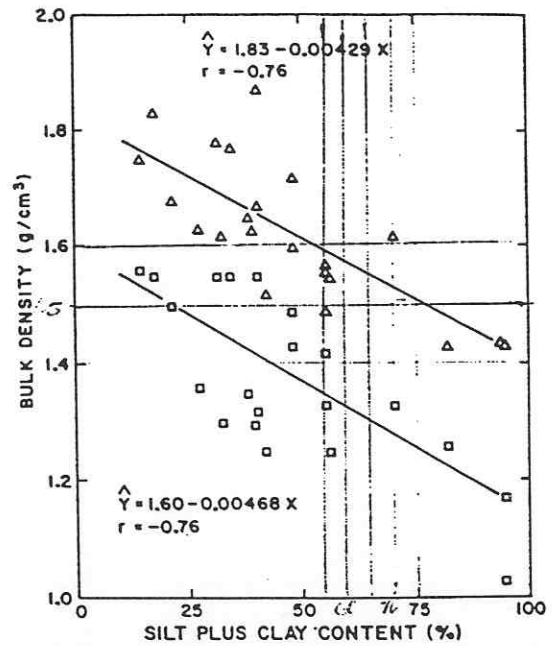


Fig. 2—Relationship between percentage silt + clay and bulk density in 22 soils from 11 studies: optimum rooting behavior (□); 0.2 of optimum (Δ).

above which 10% of the layers with “no” roots occur. These lines were fitted subjectively, but their similarity to the regression lines in Fig. 1 through 4 suggests that they have physical meaning. The lower line in each figure represents a critical combination of bulk density and clay or silt + clay percentage above which “many” roots are rarely found. The upper line represents the critical bulk density above which soils of the B and C horizons rarely occur in the field.

DISCUSSION

Analyses by three independent methods show that critical bulk densities for crop rooting and fragipan formation are inversely related to soil clay and silt + clay percentages. The correlation coefficients for the

regression equations in Fig. 1 and 3 are similar to those in Fig. 2 and 4, suggesting that either clay or silt + clay percentages can be used to predict rooting behavior and the bulk density of fragipans. However, the slopes of the relationships shown in Fig. 2, 4, and 6 are similar while the slopes of those in Fig. 1, 3, and 5 vary by a factor > 3. Thus, when silt + clay percentage is used as the independent variable, its effect on the rate of change of the relationship is similar for all three methods of determining root-restricting bulk densities. That is not the case when clay percentage is the independent variable. This suggests that percentage silt + clay is a better index of critical bulk density than is percentage clay.

At all percentages of silt + clay, the calculated crit-

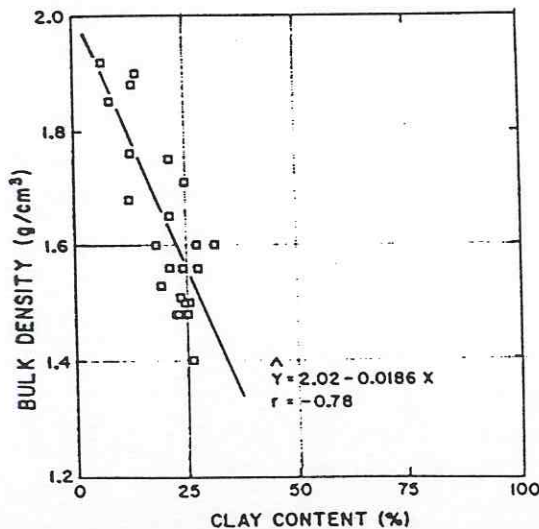


Fig. 3—Relationship between percentage clay and bulk density at -33 kPa in 24 horizons defined as fragipans.

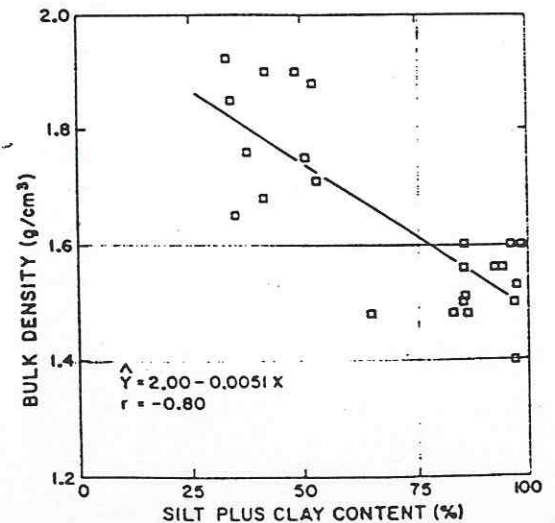


Fig. 4—Relationship between percentage silt + clay and bulk density at -33 kPa in 24 horizons defined as fragipans.

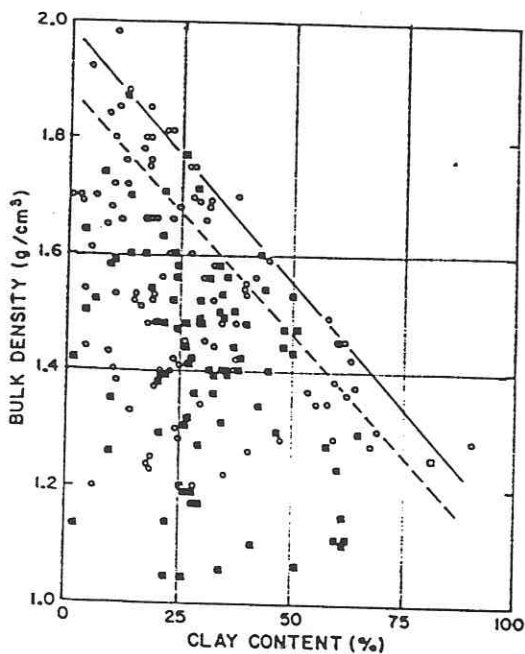


Fig. 5—Relationship between percentage clay and bulk density at -33 kPa in 106 horizons described as having “many” roots (■) and 107 horizons described as having “no” roots (○). Ten percent of the horizons having “no” roots fall above the solid line, and 10% of the horizons having “many” roots fall above the dashed line.

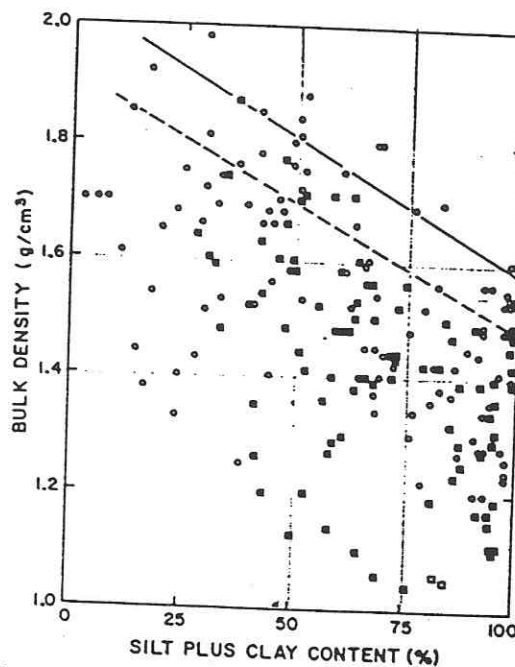


Fig. 6—Relationship between percentage silt + clay and bulk density at -33 kPa in 106 horizons described as having “many” roots (■) and 107 horizons described as having “no” roots (○). Ten percent of the horizons having “no” roots fall above the solid line, and 10% of the horizons having “many” roots fall above the dashed line.

ical bulk density at which rooting is 0.2 of maximum (Fig. 2) is lower than that at which fragipans occur (Fig. 4) and “many” roots are observed (Fig. 6). This may be due to the fact that the natural ped structure of most soils in Fig. 2 was disrupted by the compaction treatment, while natural planes of soil weakness were not disturbed in the data shown in Fig. 4 and 6. This suggests that different relationships between bulk density and rooting behavior should be used to estimate the effects of bulk density on root growth in soil layers in which ped structure has been destroyed by tillage compared with those in which ped structure has not been destroyed.

The results also suggest (Fig. 6) that in undisturbed soils with silt + clay percentages near 100%, “many” roots may be found at bulk densities approaching 1.6, the highest bulk densities observed in these soils. This may result from the high shrink-swell potential of some clay soils in which roots freely develop in zones of weakness between peds.

The relationships developed in this study can be used in crop growth simulation models to estimate the effects of soil texture and bulk density on root growth at near-optimum soil water contents. Many other factors, including crop genotype, depth to the layer, soil aeration, soil water content, chemical factors such as aluminum and manganese toxicity or calcium deficiency, lithic or paralithic contacts, soil structure, and soil consistence can also affect crop rooting. Grossman and Berdanier (1982) have recently discussed these

effects, and they should be considered in any comprehensive crop root growth model.

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Differentiation of an Eluvial Fragipan from Dense Glacial Till in Northern Minnesota

M. B. Miller,* T. H. Cooper, and R. H. Rust

ABSTRACT

Over the past two decades there has been considerable discussion among soil scientists in glaciated regions of North America regarding the differentiation of a fragipan horizon from dense glacial till. This study was conducted to determine if the Nashwauk soil series (fine-loamy, mixed Typic Glossoboralf) has a horizon that meets the criteria for a fragipan. Standard soil survey methods were used for sampling and measurement of physical and chemical soil properties. Micromorphology was investigated using thin sections and the scanning electron microscope. Results from this study indicate that the fragipan is of pedogenic origin. Presently, soil taxonomy does not allow for recognition of the fragipan in the Nashwauk soil series since it occurs above the argillic horizon. The eluvial fragipan (Ex) has many morphological, physical, and chemical characteristics that are significantly different from the underlying, comparatively unaltered, dense loamy glacial till in the lower horizons. There was not sufficient morphologic or particle size evidence, however, to indicate a lithologic discontinuity. Micromorphological observations reveal that close packing of soil particles within the Ex horizon are the likely cause of high soil bulk density, root restriction, and very slow permeability. Citrate-bicarbonate-dithionite (CBD)-extractable silica was lowest in the Bw and Ex horizons. It appears that physical processes rather than chemical processes are primarily responsible for the properties of the fragipan in this soil. Horizons above the Ex are especially susceptible to compaction when wet.

FRAGIPANS are pedogenic, root-restrictive, very slowly permeable, naturally occurring, dense subsurface soil horizons that have important practical significance. A fragipan that occurs in an eluvial horizon is an *eluvial fragipan* and is identified by the Ex symbol. Eluvial fragipans commonly occur in the lower eluvial horizon of some bisqual soils (Yassoglou and Whiteside, 1960; Pedon 26 in Soil Survey Staff, 1975; De Kimpe et al., 1972).

A key diagnostic feature of a fragipan is its brittleness when moist. This brittleness is defined as the tendency of a ped to suddenly rupture, compared with slow plastic deformation, when force is applied (Soil Survey Staff, 1990). Brittleness and high bulk density have been attributed to close packing and interlocking of soil particles and clay bridging between silt and sand grains (Payton, 1981; Bryant, 1989). Staple (1975) mixed various proportions of different-sized glass beads to obtain different bulk densities. When a mixture of 50% coarse sand, medium sand, and fine sand was mixed with 50% very fine sand and coarse silt, it resulted in a bulk density of 1.87 g/cm³. Fragipans typically have a relatively high concentration of medium to very fine sands and silts (Grossman and Carlisle, 1969).

Secondary accumulations of silica in fragipans of

soils formed in humid regions are also thought to cause brittleness (Franzmeier et al., 1989). In Indiana, researchers have found elevated amounts of CBD-extractable silica when compared with most other horizons (Harlan et al., 1977; Steinhardt and Franzmeier, 1979; Steinhardt et al., 1982). Others have found low amounts of extractable silica in fragipans labeled as Ex, Bx, or Btx horizons (Yassoglou and Whiteside, 1960; De Kimpe et al., 1972, 1983; Marsan and Torrent, 1989). There appear to be at least two distinct modes of fragipan formation: one where silica may play a role, and one where silica does not.

Fragipans in some areas have been shown to occur in soils with a lithologic discontinuity (Smeck et al., 1989; Habecker et al., 1990). Sometimes the lithologic discontinuity is not evident from morphological features such as change in glacial deposit type (e.g., till vs. outwash), coloration indicating different provenance, and lithology or abundance of coarse fragments. In this case, other chemical or physical means can be used to detect a lithological discontinuity. Smeck et al. (1989) used differences in K/Ti or Ca/Zr ratios with depth to detect lithologic and weathering discontinuities. In loessial soils with < 10% sand, Rutledge et al. (1975) found lithologic discontinuities by examining the silt-size fractions on a clay-free basis in order to reduce pedogenic effects such as translocation of clays on the particle-size distribution throughout the profile. Mausbach et al. (1983) also suggested particle-size data on a clay-free basis be examined to find lithologic discontinuities. They used a ratio of the finer sand fractions to locate discontinuities, but may have declared a statistically significant lithologic discontinuity where one does not exist (Soil Survey Staff, 1975, Pedon 26; Miller, 1991).

Dense till is commonly formed where outwash occurs below the glacial till, sometimes at great depths. Pore water within the till may be forced out of the till by the pressure of the ice overburden. This would lead to densification and strengthening of the till (Menzie's, 1979). A study on fragipans in Minnesota by Antoine (1970) concluded that fragic properties (such as brittleness and high bulk density) occurred on, but not off, drumlin landforms, which are typically composed of dense glacial till. A follow-up study by Gamble and Mausbach (1984) examined the bulk density profile in the solum and parent material and found that the moist bulk density was higher in the parent material than in the B horizon of soils thought to have fragipans. This led to the conclusion that the high bulk density in the parent material was an inherited property attributable to geogenic rather than pedogenic forces. Subsequently, the origin of many fragipans described in glaciated areas was called into question,

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Abbreviations: CBD, citrate-bicarbonate-dithionite; ICP-AES, inductively coupled plasma-atomic emission spectrophotometer; CEC, cation-exchange capacity; ANOVA, analysis of variance; COLE, coefficient of linear extensibility; K_{sat} , saturated hydraulic conductivity.

creating a controversy that has been mentioned by others (Pickering and Veneman, 1984; Lindbo and Veneman, 1989).

This study examines the Nashwauk soil series in northern Minnesota, which formed in loamy dense glacial till. Assessment of properties of these soils during soil mapping by field soil scientists led them to conclude that this series also has a fragipan. From a practical standpoint, occurrence of a fragipan or dense till located near the soil surface has several important implications for the use and management of the Nashwauk soil. Our field observations indicate that this soil has severe limitations for equipment when wet, since ponding and rutting will occur. Compaction of the soil horizons above the fragipan causes an anaerobic condition when water is not removed by surface runoff or infiltration, and this may have a significant effect on future production (Bates et al., 1990). Standing water on the surface of the Nashwauk soil was not observed in undisturbed areas. Where vegetation and the surface layer are removed (such as along unimproved roads), this soil is readily eroded by water and wind (Nyberg, 1987; Miller, 1991). Species that concentrate Ca and Mg in the tree (such as aspen, *Populus* spp.), may in time cause the shallow rooting zone to become depleted in these nutrients as trees are harvested (Alban, 1982), resulting in a possible decrease in future productivity (Shields and Bockheim, 1981). This should be of particular concern on lower-carbonate parent materials.

Our study was designed to determine if a fragipan does exist. Specific objectives of this study were to: (i) determine if a lithologic discontinuity exists in the soil profile; (ii) evaluate if the fragipan is pedogenic; and (iii) evaluate if the brittleness of the fragipan is caused by accumulation of secondary silica.

MATERIALS AND METHODS

The Nashwauk soil series is presently classified as a fine-loamy, mixed Typic Glossoboralf due to restrictions in classification of Alfisols that do not permit fragipans to occur above the argillic horizon (Soil Survey Staff, 1990, p. 71). This soil formed in dense, loamy low-carbonate glacial till that is thought to include lacustrine sediments from the Rainy lobe of the Wisconsinan glaciation (Hobbs and Goebel, 1982). The Nashwauk till is underlain by outwash at depths commonly ranging from 2 to > 10 m based on exposures at gravel pits and well-boring records. The Nashwauk moraine occupies a portion of eastern Itasca County and western St. Louis County in northeastern Minnesota (Fig. 1). Itasca County has recorded 65 000 ha of the Nashwauk series (Nyberg, 1987). Soil mapping is currently in progress in St. Louis County and has an estimated 40 000 ha of the Nashwauk series.

Prior to logging in the late 1800s, upland forest types on the Nashwauk moraine were categorized as having nearly pure stands of white pine (*Pinus strobus* L.) and Norway pine (*P. resinosa* Ait.) with scattered amounts of jack pine (*P. banksiana* Lamb.) barrens, aspen, birch (*Betula* spp.), and beaked hazel (*Corylus cornuta* Marsh) (Marschner, 1974). Present vegetation is a mixture of aspen, birch, balsam fir (*Abies balsamea* (L.) Mill.) and jack pine, with grasses (*Gramineae* spp.) and beaked hazel. The area has very cold winters, short but fairly warm summers, an annual precipitation of 700 mm with 400 mm of precipitation falling during the growing seasons (May–September), and an average annual snowfall of ≈ 1.4 m. The mean annual air temperature is 3 °C (Nyberg, 1987).

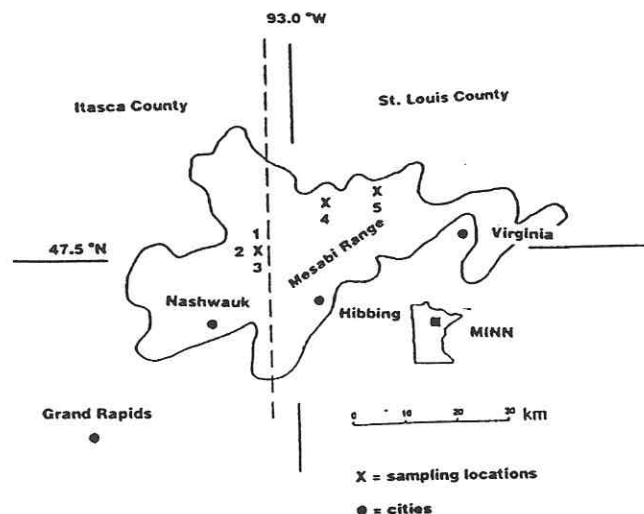


Fig. 1. Outline of Nashwauk moraine and location of the pedons in northern Minnesota (based on Hobbs and Goebel, 1982).

Soil pits were dug by backhoe or by hand and typically measured 1 m wide, 2 m long and 1.7 m deep. Three pits of the Nashwauk series were described in Itasca County in the same general location as the typical pedon of the Nashwauk series (no. 1765) (Nyberg, 1987). These pedons represent the summit, backslope, and intermediate footslope landscape positions (identified as Pedons 1, 2, and 3, respectively). Two pits of the same series were described in St. Louis County, and represent a broad summit and an intermediate footslope landscape position (Pedons 4 and 5) (Fig. 1). Additional pedons were sampled for bulk density determinations.

Soils from the pits were described, sampled, and analyzed for chemical and physical properties according to standard soil survey procedures (Soil Survey Staff, 1951, 1975, 1984), except where noted. Horizon depth measurements were taken at five positions over the pit face (at 25-cm intervals) and averaged.

Bulk density was measured by an excavation method (Bradford and Grossman, 1982) for the A, E, and Bw horizons from seven pits. For horizons below the Bw, bulk density was measured by the saran clod method at a soil water pressure of -33 kPa for six pits. Bulk density values are the mean of two replicates per horizon. Saturated hydraulic conductivity was measured in the Bw, Ex, and Btd1 horizons using a Guelph permeameter¹ (Soil Moisture Equipment Corp., Santa Barbara, CA) (Reynolds and Elrick, 1985). Consistence was determined by the rupture resistance test of Grossman (1988). Particle-size distribution was determined by standard pipette and sieve analysis, after organic matter had been removed by additions of H_2O_2 . Fine clays ($<0.2 \mu m$) were determined by centrifugation and pipette analysis. The normalized sand method (Miller, 1991) was used to identify lithological discontinuities within the soil profiles. Thin sections were prepared at the Soil Science Department of the University of Wisconsin, Madison, using standard procedures (Innes and Pluth, 1970). Freshly fractured ped faces were coated with C and Ni for observation under the scanning electron microscope.

Soil pH was measured in 1:1 soil/distilled water (w/w). Organic C was determined using a LECO CR-12 C furnace (LECO Corp., St. Joseph, MI) where sample mass was doubled in all horizons below the E/A horizon to increase precision. Exchangeable basic cations (Ca, Mg, K, and Na) were extracted with 1.0 M NH_4OAc buffered at pH 7.0. They were measured

¹The use of trade names in this publication does not imply endorsement by the Minnesota Agricultural Experiment station of the products named or criticism of similar ones not mentioned.

simultaneously by an ICP-AES (Dahlquist and Knoll, 1978). Aluminum was extracted by 1.0 M KCl and measured by ICP-AES for calculation of the effective CEC. Titratable acidity was extracted by a BaCl₂ triethanolamine solution adjusted to pH 8.2 and used for total CEC and base saturation calculations. Oxides of Si, Fe, Al, and Mn were extracted by the CBD extraction method as modified by Franzmeier et al. (1977) and measured by ICP-AES for four pedons.

Chemical and physical analyses are reported on a <2-mm basis. Data in tables are means representing five pedons per horizon unless otherwise noted. Analysis of variance was used to test means among horizons and among pedons. Where ANOVA *P* values were <0.05, the conservative Scheffe's statistic was used to test for differences among means.

RESULTS

Morphology

All five of the pedons described in this study have the following sequence of horizons in the upper 1 m: A, E/A, Bw, Ex, Btd/Ex, Btd1, Btd2. The pedon with the most-developed fragipan (based on thickness, consistence, and other morphological properties) is Pedon 3, which occurs on the intermediate footslope landscape position (Table 1). Of the five pedons, Pedon 3 has the highest pH, free CaCO₃, and clay skins in the lowest horizon, and so is designated a Cd/Bt. Other pedons have the lowest horizon designated as a Btd3 since no free carbonates were detected at the depths described. The Btd3 and the Cd/Bt horizons are the deepest soil horizons reported, since deeper samples did not reveal significant differences, and thus should be considered as a close approximation of the parent material. Most of the horizons in the Nashwauk soil have a loam texture. Horizons above the Btd have a mean clay content of 11%, whereas the Btd horizons have a mean clay content of 26%.

Earthworms (*Lumbricidae* spp.) were noted at each soil pit. None of the pedons described had an O horizon, presumably due to the worms pulling leafy material down into the soil profile. They cause considerable biopedoturbation as evidenced by numerous channels and castings, and are thought to be responsible for the mixing that creates the E/A horizon. Earthworm burrows were observed in tongues below the fragipan in the argillic horizon in some pedons.

Roots are abundant above the fragipan. In and below the fragipan, finer roots are confined to vertical faces between prismatic peds, and occur with clay skins. Occasionally a larger root (>1 cm) was seen to have penetrated through the fragipan into the dense till. These larger roots are contorted and flattened, branched at right angles, and are also confined to the vertical faces. These characteristics are indicative of root restriction (Trowse, 1978). Soil horizons exhibiting these characteristics are given the subordinate horizon designation *d* (Soil Survey Staff, 1990) and need to be identified for proper use and management of this soil.

Key morphological properties of the fragipans (Ex horizons) exhibited in most pedons are the absence of clay skins, dry soil colors of high value (>6) and low chroma (<3) indicating strong eluviation, either high or low chroma mottles suggesting restricted drainage, platy parting to angular blocky soil structure, hard or very hard dry consistence, very firm moist consistence, brittleness in 80 to 90% of the horizon, absence of roots within the brittle areas, and vesicular pores.

Table 1. Description of Nashwauk Pedon 3.

Horizon	Depth	Description (moist color unless otherwise noted)
	cm	
A	0-12	Very dark gray (10YR 3/1) loam, light grayish brown (2.5Y 6/2) dry; moderate fine granular structure; friable; many roots; many worm casts on surface; very strongly acid (4.9); abrupt smooth boundary.
E/A	12-21	(E) pale brown (10YR 6/3) loam, light grayish brown (2.5Y 6/2) dry; few fine faint brown (10YR 5/3) mottles; moderate fine subangular blocky structure; friable; common roots; common very dark gray (10YR 3/1) worm casts in channels (A); very strongly acid (5.0); abrupt smooth boundary.
Bw	21-29	Brown (10YR 5/3) loam, light gray (10YR 7/2) dry; many medium distinct yellowish brown (10YR 5/4) mottles; moderate fine subangular blocky structure; friable; common to few roots; strongly acid (5.1); abrupt smooth boundary.
Ex	29-38	Pale olive (5Y 6/3) loam, white (2.5Y 8/2) dry; many fine distinct gray (5Y 6/1) mottles; moderate medium platy parting to angular blocky structure; very firm, brittle; few very fine roots concentrated only on vertical planes; common yellowish brown (10YR 5/6) concentrations in internal planes; many fine vesicular pores; sands of same size concentrated on horizontal planes; strongly acid (5.4); clear smooth boundary.
Btd/Ex	38-50	(Bt) yellowish brown (10YR 5/4) loam, very pale brown (10YR 7/4) dry, and (Ex) pale olive (5Y 6/3), white (2.5Y 8/2) dry; moderate coarse subangular blocky structure; very hard, firm; common very fine roots concentrated only along vertical planes; common dark grayish brown (10YR 4/2) and gray (5Y 5/1) clay skins on ped exteriors; common grayish brown (2.5Y 5/2) silt coatings on ped exteriors; common black (N 2/0) manganese coatings on internal planes; medium acid (5.8); gradual smooth boundary.
Btd1	50-70	yellowish brown (10YR 5/4) loam; moderate coarse sub-angular blocky structure; very hard, firm; many very fine roots concentrated only along some vertical clay skins and tongues; common gray (5Y 5/1) clay skins on ped exteriors; common grayish brown (2.5Y 5/2) silt coatings on ped exteriors; common black (N 2/0) manganese coatings on internal planes; slightly acid (6.4); gradual smooth boundary.
Btd2	70-106	yellowish brown (10YR 5/4) loam; few fine prominent reddish brown (5YR 4/4) mottles; moderate coarse platy parting to strong fine subangular blocky structure; very hard, firm; many very fine roots concentrated only along some vertical clay skins and tongues; common gray (5Y 5/1) and very dark gray (5Y 3/1) clay skins on ped exteriors; common grayish brown (2.5Y 5/2) silt coatings on ped exteriors; common black (N 2/0) manganese coatings on internal planes; neutral (7.4); gradual smooth boundary.
Cd/Bt	106-120+	(Cd) brown (10YR 5/3) and (Bt) light olive gray (5Y 6/2) loam; weak medium platy parting to moderate medium subangular blocky structure; very hard, firm; many very fine roots concentrated dominantly along some vertical clay skins; common very dark gray (5Y 3/1) clay skins on ped exteriors; common black (N 2/0) manganese coatings on internal planes; slight effervescence; mildly alkaline (7.8).

Soil morphology suggests that the Btd/Ex horizon is a zone of Btd degradation. Tongues of Ex or E' material begin in this horizon and extend through portions of the lower Btd horizons as tonguing and interfingering (e.g., gray streaks). The argillic horizon (Btd1, Btd2) occurs in the dense till underneath the fragipan and is generally characterized by high chroma mottles, prismatic parting to platy parting to angular blocky structure, hard to extremely hard dry consistence, firm to very firm moist consistence, an absence of brittleness, silt coatings and clay skins with chroma <3, and Fe-Mn coatings on internal planes.

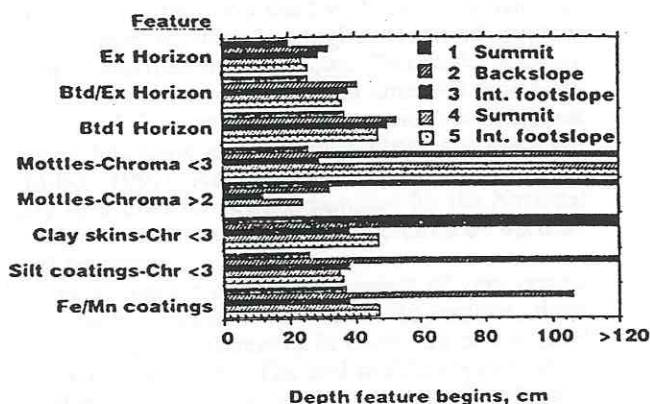


Fig. 2. Depth from the soil surface to selected features in five pedons of the Nashwauk soil series.

Landscape position had an effect on the type and depth of morphological features observed in the soil profile (Fig. 2; Pedons 1, 2, and 3). The top of the Ex and Btd1 horizons are closest to the surface on the summit landscape position (Pedon 1), possibly due to less lateral throughflow with time. Drainage mottles of chroma <3 occur in the upper 25 cm of the argillic horizon or Pedon 1, indicating this soil should be classified in the aquic subgroup (Soil Survey Staff, 1990). Depth to Fe-Mn coatings was greatest on the backslope position (Pedon 2). Coupled with the absence of low chroma mottles, and other low chroma coatings, this pedon has the best drainage of the pedons observed at this site. Although low chroma mottles occur at a depth of 29 cm in the Ex horizon of Pedon 3, they do not occur in the upper 25 cm of the argillic horizon. Therefore, this pedon would be classified in the typic subgroup in spite of high chroma mottles occurring at the 12-cm depth, and the presence of clay skins and silt coatings with chroma <3 in the

upper 25 cm of the argillic horizon (Btd/Ex and Btd horizons) (Soil Survey Staff, 1990). Pedons 4 and 5 would both be classified in the typic subgroup since they have no mottles of chroma <3 in the upper 25 cm of the argillic horizon. They do have other indications of wetness within the upper 25 cm of the argillic horizon (high chroma mottles, clay skins and silt coats of chroma <3, and Fe-Mn coatings), but these features are not diagnostic for the aquic subgroup of Fragiboralfs (Soil Survey Staff, 1990). Perhaps low chroma clay skins or Fe-Mn coatings could be allowed as a substitute in the definition of the aquic subgroup where low chroma mottles are not present.

Physical and Chemical Analyses

Particle-size analyses of the five Nashwauk pedons indicate that medium to very fine sands dominate the sand-size fractions (Table 2). Silts comprise >40% of most horizons, with the fine-silt fraction (2–20 μm) being two to three times greater than the coarse-silt fraction (20–50 μm). Clay contents are low in the upper solum, intermediate in the Btd/Ex transitional horizon, and are typically slightly higher in the uppermost Btd horizon. Differences in clay content throughout the profile are assumed to be due to both vertical and lateral translocation of clays.

It is possible that the Nashwauk soil formed in two parent materials, the upper consisting of the A, E/A, Bw, and Ex horizons, and the lower comprised of the Btd/Ex and Btd horizons. To establish the number of parent materials, the sand-size fraction was normalized to 100% and presented on a clay- and silt-free basis since horizons examined had an average of >25% sand. Clays and fine silts were removed since there was evidence that both were subject to illuviation (Table 1) and sand was thought to be the most stable of the <2-mm material. Although the results for the sand-size fraction were unchanged when

Table 2. Physical properties of the Nashwauk soil series; data are means of five pedons.

Horizon	Depth cm	Sand						Silt				Clay		Moist bulk density†	Saturated hydraulic conductivity
		>2 mm	Very coarse (2–1 mm)	coarse (1–0.5 mm)	medium (0.5– 0.25 mm)	fine (0.25– 0.1 mm)	very fine (0.1– 0.05 mm)	total (2–0.05 mm)	coarse (50–20 μm)	fine (20–2 μm)	total (50–2 μm)	total (<2 μm)	fine (<0.2 μm)		
A	0–10	6.2	1.3	6.1	11.8	13.5	10.3	42.9	15.9	29.7	45.6	11.5	2.8	0.99	—
E/A	10–17	8.2	4.3	7.2	11.3	12.8	10.1	45.7	15.6	29.5	45.0	9.2	1.8	1.43	—
Bw	17–26	6.8	4.0	7.2	11.6	13.3	10.8	47.1	14.5	28.0	42.5	10.4	1.8	1.54	–4.74
Ex	26–35	7.2	3.8	6.9	11.2	12.8	9.5	44.3	11.9	32.2	44.2	11.6	1.4	1.91	–6.41
Btd/Ex	35–47	6.4	3.3	5.8	9.3	10.7	8.4	37.6	9.4	30.2	39.6	22.8	4.8	1.78	—
Btd1	47–71	4.5	2.4	4.6	7.4	8.7	6.6	29.6	9.1	32.0	41.1	29.2	6.4	1.78	–7.08
Btd2	71–96	3.6	2.7	4.9	7.5	8.9	6.7	30.7	9.3	33.2	42.5	26.8	5.4	1.79	—
Btd3 or Cd/Bt	96–120	5.1	2.7	4.5	7.4	8.9	6.5	30.1	7.8	35.4	43.2	26.7	4.7	1.76	—
Horizon effect															
$P > F$		0.6697	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0127	0.0158	0.0001	0.0001	0.0001	
LSD(0.05)		NS‡	1.9	2.1	3.1	4.7	2.9	13.3	4.3	7.7	6.5	8.6	2.0	0.06	
Location effect															
$P > F$		0.0445	0.0072	0.0001	0.0001	0.0001	0.0001	0.0001	0.0004	0.0001	0.0001	0.0006	0.0412	0.0001	
LSD(0.05)		6.7	1.2	1.4	2.0	3.0	1.9	8.5	2.7	4.9	4.2	5.5	1.3	0.07	

† Seven pedons had bulk density measurements for the A, E/A, and Bw horizons and six pedons for the other horizons. Least significant difference (LSD) values for bulk density pertain to the lower five horizons. (LSD[0.05] is 0.26 g/cm³ for horizon effect and 0.48 g/cm³ for location effect for the A, E/A, and Bw horizons).

‡ NS = not significant at 0.05 probability level.

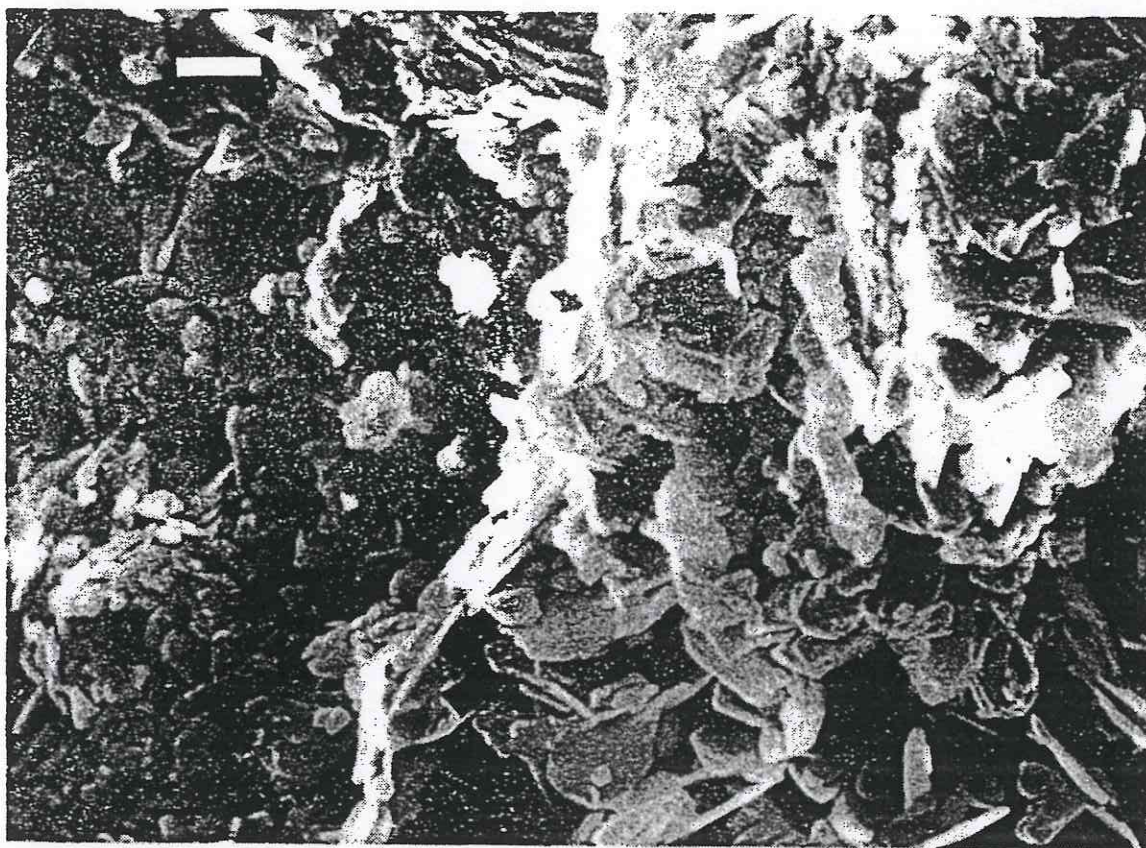


Fig. 4. Scanning electron micrograph of an air-dry fragment of the Ex horizon of the Nashwauk soil series. Note the absence of coatings. Bar is 2 μm long.

were not saturated. When the fragipan is saturated, its low soil strength may be overlooked by someone searching for high-strength layers. When the fragipan is unsaturated, it is sufficiently rigid that fabric rearrangement cannot take place under confined or unconfined conditions and it exhibits its characteristic brittleness. The recognition of the Ex horizon is important since it is the first limiting horizon with respect to bulk density and K_{sat} to be encountered by either water or biota (roots and earthworms) from above. The saturation and subsequent reduction in the Ex horizon are hypothesized to be responsible for the creation of eluviation features and low oxide contents observed.

Chemical composition of the Nashwauk series offers further evidence that the upper profile (including the Ex) has undergone substantial pedogenesis. Concentrations of exchangeable basic cations, total CEC, and effective CEC are all lower in the E/A, Bw, and Ex horizons than in the Btd or A horizons (Table 3). If the Ex horizon had not been influenced by pedogenic forces with time, then the fragipan should be more like the lower soil profile in chemical as well as physical characteristics.

Means of CBD-extractable Fe, Al, and Mn oxides tend to be lower in the fragipan than in most other horizons in the soil profile. These mean values were not always significantly different as determined by the conservative Scheffe's statistic (Table 3). Lowest concentrations of CBD-extractable silica are in the Bw and Ex horizons and highest concentrations occur in the A and Btd horizons. One would expect that, if extractable oxides were causing the brittleness in the eluvial fragipan,

they would be in higher concentration in the fragipan than in other nonbrittle horizons.

Elevated amounts of extractable silica near the surface appear to be related to organic C and clay content. Opal phytoliths from grasses and tree leaves may be influencing the extractable silica content in the A and E/A horizons (Wilding et al., 1977). Exclusion of clay and CBD-extractable silica values from the surface two horizons (A and E/A) in this study resulted in r^2 values for individual pedons that varied from 0.92 to 0.99 with probabilities of 0.0027 to 0.0001 (six horizons per pedon). Thus, in the Nashwauk Bw and lower horizons there is a strong relationship between the amounts of clay and silica extracted by the CBD method. This indicates that secondary silica is probably not the cementing agent within the Nashwauk fragipan and that silica extracted by the CBD method may be attributable to biogenic silica, to slight dissolution of clays during extraction, or to amorphous silica complexes held on the surfaces of clays.

Correlation of clay with CBD-silica data from other studies of fragipans bears out that this is not a phenomenon limited to the Nashwauk series. In Wisconsin, exclusion of data from the upper two horizons (an A and an E horizon) improved correlation to an r^2 value of 0.85 with a 0.0031 probability (Habecker, 1988 Pedon G-5). Using data from Indiana (Steinhardt and Franzmeier, 1979), correlation of clay with CBD-silica using nine horizons of the Clermont pedon (S71IND40-4) yielded an r^2 value of 0.79, with $P = 0.0014$.

The Si/Fe ratios in the Bw and Ex horizons are lower than other horizons in the profile (Table 3). The Si/Fe

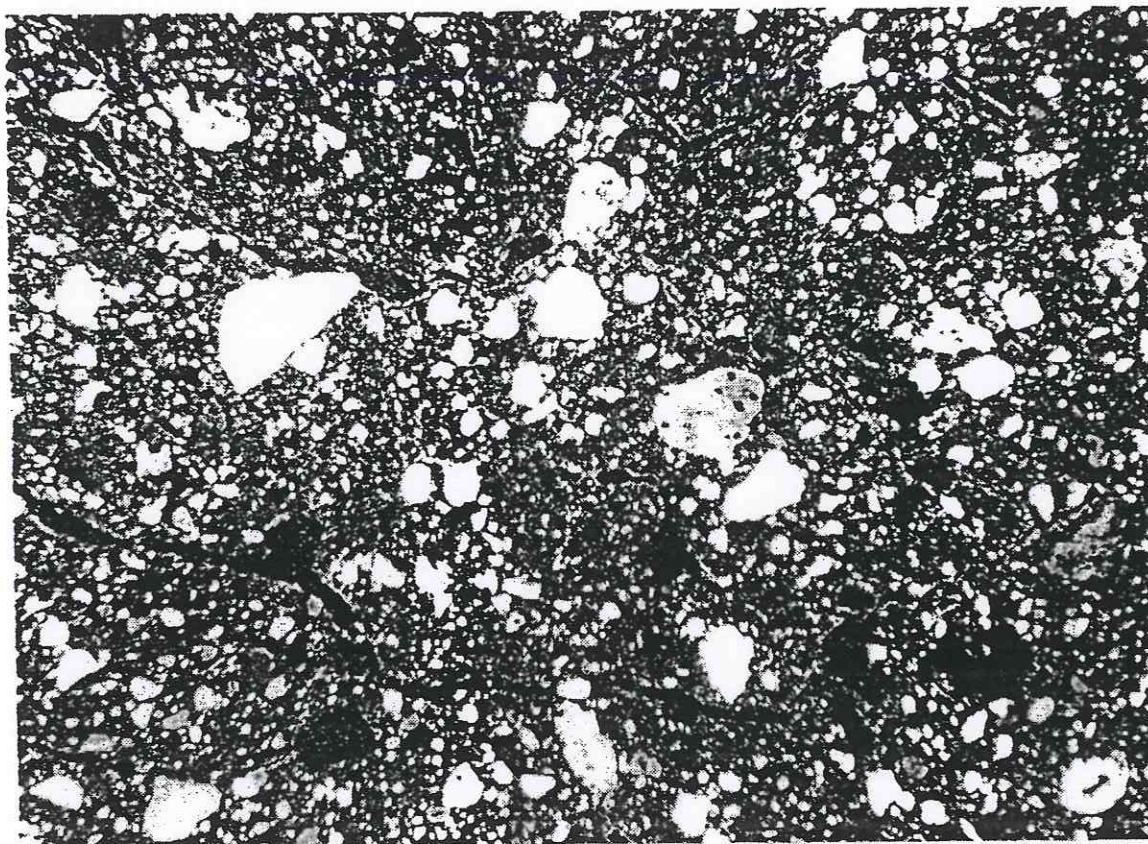


Fig. 5. Relatively homogenous fabric of the Btd2 horizon of the Nashwauk soil series. Cross-polarized light. Frame width is 7 mm.

values measured by Marsan and Torrent (1989) ranged from 30 to 41 with the highest amount occurring in the fragipan. The Si/Fe ratio for the Nashwauk series ranges from 113 to 388 with one of the lowest ratios occurring in the fragipan. Brittleness is not associated with higher Si/Fe values in the Nashwauk soil.

Micromorphology

Grain contact points were examined to see if coatings of secondary silica were cementing grains within the fragipan. A freshly fractured ped face of an Ex horizon examined at $3750\times$ magnification did not have any such coatings, but did show interlocking of soil particles (Fig. 4). Energy dispersive x-ray analyses did not show recognizable differences in Si across the sample.

Larger particles within the fabric of the Btd2 horizon appear to be evenly distributed (Fig. 5). By comparison, fabric of the Ex horizon has been rearranged (Fig. 6) such that soil particles are closely packed and particles of similar size are grouped together in horizontal bands. This phenomenon is also evident in the fragipan studied by Habecker et al. (1990, Fig. 1). The banding of soil particles in the fragipan is also observable on a macroscale where sands of the same size are concentrated along horizontal planes (Table 1), and has been noted in other pedon descriptions (Soil Survey Staff, 1975, Pedon 26, IIA'2x horizon). Darker bands in Fig. 6 are weakly birefringent under cross-polarized light, indicating they may be related to clay deposition by water coming from above.

Ferruginous nodules within the Ex horizon were noted in some thin sections not presented here.

At the base of the Ex horizon, there is evidence of current Btd horizon degradation (Fig. 7). The upper portion of the micrograph is Ex material, whereas the lower portion is Btd horizon material. Clay films in the Btd material occur on a slight angle from lower left to middle right of Fig. 7. The large crack running vertically through the Btd material was possibly initiated by the freezing of water in the small crevice at the upper surface. In the crack, about half-way down, soil material directly adjacent to the crack is becoming bleached due to removal of Fe and soil clays. It appears that the fragipan is thickening at the expense of the Btd horizon. A crack due to desiccation of the sample would have accommodating surfaces and would not have the translocation feature in it.

Thin sections of the Ex horizon show a variety of features (vesicular pores, destruction of clay skins, close-packing of particles, and ferruginous nodules) that are characteristic of many fragipans, but especially of those fragipans that could be classed as eluvial fragipans (Yasoglou and Whiteside, 1960; Grossman and Carlisle, 1969). All thin sections of the Ex horizon of the Nashwauk series have close packing of soil particles, which will contribute to its strength and brittleness (Bryant, 1989). When the Ex horizon is saturated, the packing is probably enhanced by the high proportion of soil particles in the finer sand and silt fractions that can fill in the interstices, and by the absence of the finer swelling clays

and oxides. The lack of fine clays and oxides are hypothesized to allow easier fabric rearrangement of the material in the fragipan. Compared with the Ex horizon, the lower moist bulk density of the Bw is possibly due to greater freezing and thawing disturbance, a higher concentration of organic matter and Al and Fe oxides, and a slightly higher fine clay content (Tables 2 and 3).

DISCUSSION

Vesicular Pore Formation

Vesicular pores are commonly found in fragipans (FitzPatrick, 1956; Yassoglou and Whiteside, 1960; Habecker et al., 1990) and can be formed by frost (FitzPatrick, 1956; Van Vliet-Lanoe, 1985) or as a consequence of irrigation (McSweeney et al., 1988). They form in material that behaves as a liquid at some time. Some have suggested that vesicular pores in fragipans are permafrost remnants (FitzPatrick, 1956; Van Vliet-Lanoe, 1985). It seems unlikely that these pores would escape the forces of pedogenesis for thousands of years.

The vesicular pores that occur in fragipans (especially those that are within 0.5 m of the surface) are probably of a transitory nature. We hypothesize that when the upper solum becomes saturated after high-intensity rainfall, air that had previously occupied interpedal spaces and tongues of coarser material in the argillic horizon must be evacuated as soil water percolates into the argillic horizon. As the Ex horizon dries, it may entrap some of the rising air, forming preserved vesicular pores (Fig. 6).

Source of Brittleness

The source of brittleness in the Ex horizon of the Nashwauk soil series is primarily attributed to interlocking of soil particles as evidenced in Fig. 4.

The following points tend to rule out the necessity of silica being a cause of the apparent cementation and brittleness in the Nashwauk eluvial fragipan: (i) coatings of oxides visible under high magnification are absent; (ii) silica appears to be a function of the biocycling of opaline-Si and clay in the upper two horizons; (iii) CBD-extractable silica is very highly correlated with soil clays in most horizons; (iv) horizons with high levels of CBD-extractable silica are not brittle; and (v) other studies have found a low concentration of silica in fragipans (Yassoglou and Whiteside, 1960; De Kimpe et al., 1972, 1983; Habecker, 1988; Marsan and Torrent, 1989).

Packing of Soil Particles in the Fragipan

It is hypothesized that packing of soil particles in the Nashwauk eluvial fragipan: (i) occurs during drying after the soil has been saturated; and (ii) is enhanced by a particle-size distribution that is (a) low in clay, especially fine clay, and (b) high in medium to very fine sands as well as silt.

Fragipan Formation

Based upon a review of studies of fragipans in the literature, and results of this study, we hypothesize that the following conditions and processes are necessary for development of an eluvial fragipan: (i) a parent material

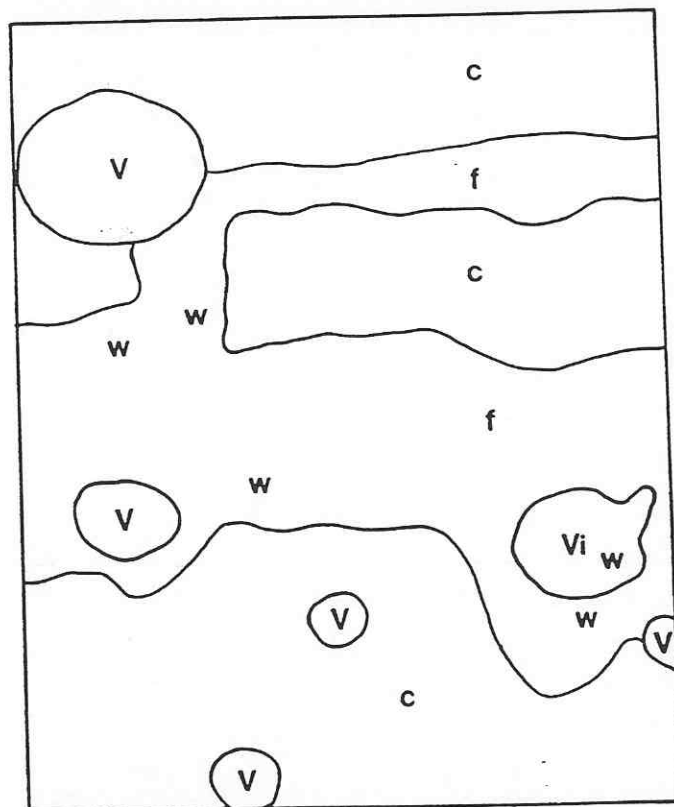
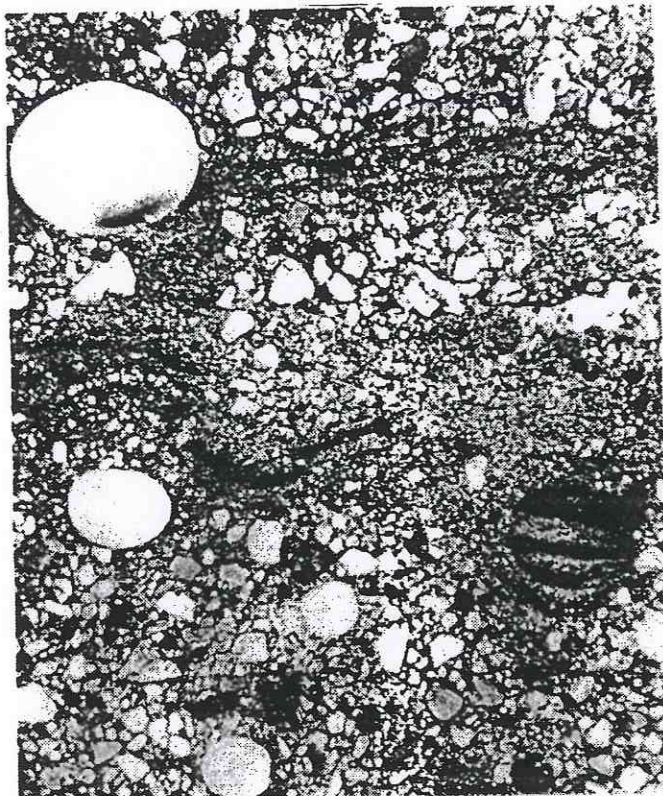


Fig. 6. Rearranged fabric of the Ex horizon of the Nashwauk soil series with accommodated packing and horizontal bands of similar-sized particles. V = vesicular pore, Vi = infilled vesicular pore, c = coarser Ex material, f = fine Ex material, w = weakly birefringent illuvial clay bands. Plane-polarized light. Frame height is 7 mm.

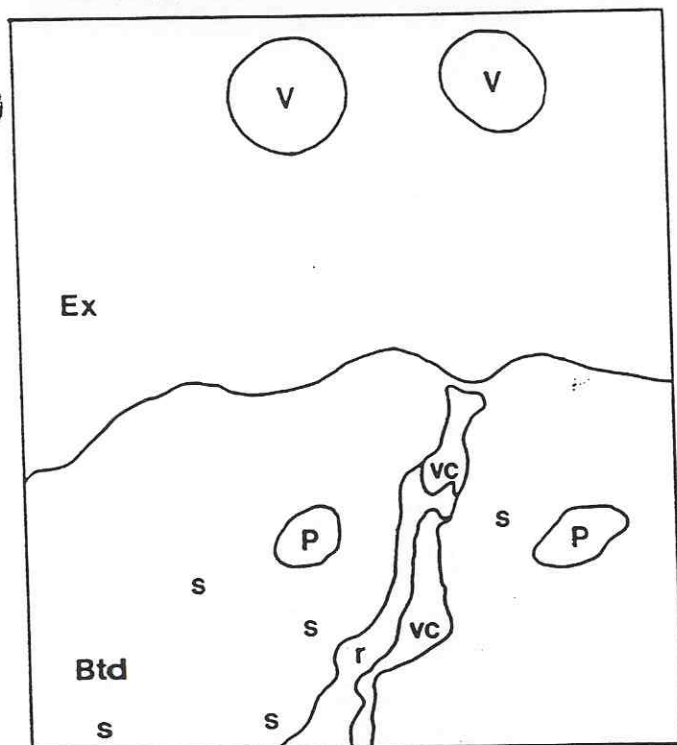
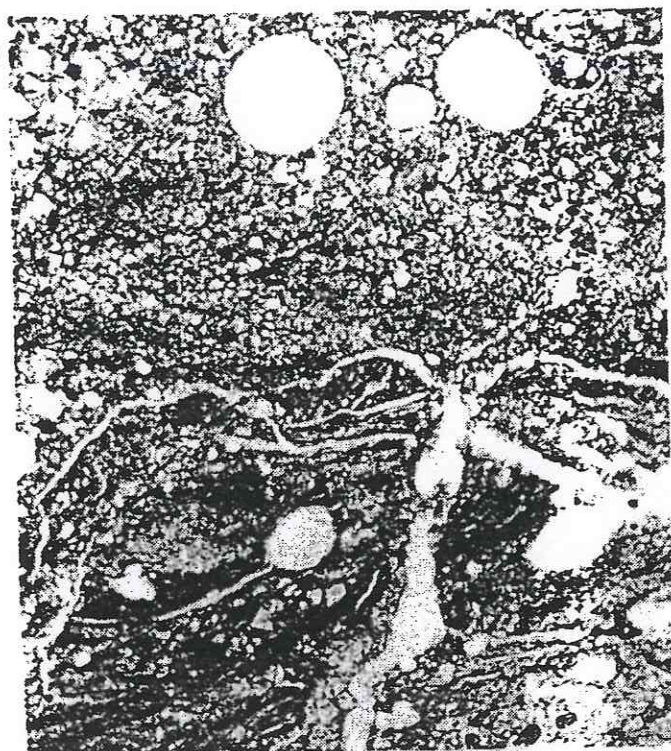


Fig. 7. Interface of the Ex and Btd horizons. The Btd horizon material (lower half of photo) appears to be undergoing degradation along the vertical crack (vc) where some material has been removed (r). V = vesicular pore, P = pore, s = strongly birefringent clay skins. Cross-polarized light. Frame height is 3.5 mm.

low in CaCO_3 , that allows for clay translocation and thus formation of the Bt horizon; (ii) a particle-size distribution that favors dense packing of soil particles; (iii)

presence of a hydrologic or a lithologic discontinuity and slope conditions where saturation is favored, which may be encountered: (a) in dense parent material, (b) in soil profiles with finer over coarser parent materials, or (c) in soils with Bt horizons where vertical permeability is limited by clay accumulation; (iv) a humid climate with high-intensity rainfall that promotes translocation of oxides and fine clays and saturation of the horizon to allow for fabric rearrangement and entrapment of air to form vesicular pores; and (v) no dependence on the concentration of CBD-extractable silica.

Recognition of the Fragipan in Soil Taxonomy

Currently, fragipans are allowed within the Alfisol soil order only where the fragipan: (a) is in or underlies an argillic or kandic horizon; or (b) meets all requirements of an argillic or kandic horizon; or (c) has clay skins more than 1 mm thick in some part (Soil Survey Staff, 1990, p. 71).

Clearly this presents problems for classification of a soil such as the Nashwauk series that has an eluvial fragipan above an argillic horizon, and does not have clay skins >1 mm in thickness. Perhaps item (a) should be revised to include fragipans above the argillic horizon as well. Eluvial fragipans occur above argillic horizons and below spodic horizons in Alfic Fragiorthods.

CONCLUSIONS

Based on our examination of the physical, chemical, and micromorphologic characteristics of this soil, we conclude that the Nashwauk soil series has a pedogenic, eluvial fragipan located in the lower sequum. Soil taxonomy does not presently allow recognition of the fragipan in the classification of this soil series. Particle-size analyses suggest that the soil formed in a single parent material. Eluvial characteristics of the Ex horizon are thought to be due to saturation and reduction. There appears to be no evidence indicating that CBD-extractable silica is a cementing agent in the fragipan. Brittleness in the eluvial fragipan is likely due to the interlocking effects of soil particles rearranged and packed when the Ex is saturated. Further study might show that the brittleness may also be due to remaining coarser soil clays bridging larger soil particles. The Ex and Btd1 are very slowly permeable. Our field observations indicate that the shallow rooting zone of this soil is susceptible to compaction when wet, and erosion when deforested.

ACKNOWLEDGMENTS

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Table 1. General characteristics of the study sites.

Site	Erosion class	Landscape position	Slope		Depth to fragipan			Cropping history
			Shape	Gradient	Range	Mean	SD	
			%		cm			
Crockett County, Tennessee	Virgin, uneroded	Backslope, middle	Linear	7	90-112	100	7.9	None
Holly Springs, MS	Slight	Backslope, lower one-third	Linear	3	50-74	59	5.2	Corn silage
Holly Springs, MS	Moderate-1	Backslope, lower one-third	Linear	2	23-60	44	7.8	Corn silage
Holly Springs, MS	Moderate-2	Backslope, middle	Linear	3	30-62	42	6.2	Corn silage
Holly Springs, MS	Severe	Backslope, lower one-third	Linear	6	15-30	19	3.6	Corn silage

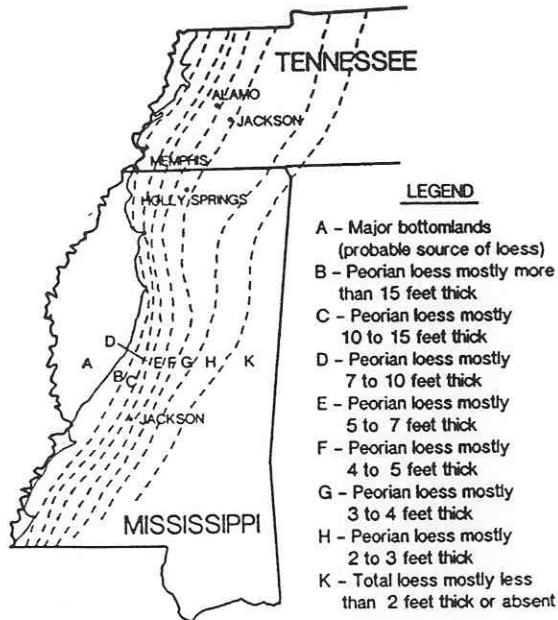


Fig. 1. Thickness of loess in the lower Mississippi Valley (from Wascher et al., 1948).

cultivation and erosion were located on Grenada silt loam at the North Mississippi Agricultural Experiment Station near Holly Springs (HS). Relative degrees of erosion were assigned to these sites on the basis of depth to fragipan. Two of the sites were considered to be moderately eroded, and the other sites represented slight and severely eroded phases. Due to a predominance of gentle slopes, these soils had been intensively cultivated; therefore, virgin sites were nonexistent in most areas. However, a virgin site was located approximately 105 km northeast of HS near Alamo in Crockett County, Tennessee (Fig. 1). All members of the Memphis catena were represented at this site, which was situated in a 35-ha mixed hardwood forest. Tree age, which ranged to 300 yr, was used to verify virgin conditions. The relative positions of the HS and Alamo sites in the loess thinning pattern are shown in Fig. 1. Although the sites did not occur in the exact same zone, we believe that the distances from the source area are so similar, considering the depth ranges in the two zones, that the original depth of loess between the two sites probably did not differ enough to prevent comparisons. All general characteristics associated with the sites appear in Table 1.

The study areas at HS consisted of experimental field plots that were installed to measure the effects of erosion on soil productivity. The plots were arranged within the sampling area so that variability in depth to fragipan was minimized. Depth to fragipan was measured at 60 randomly selected points within each 557-m² area using a hand-operated bucket auger; however, only samples from 30 of these points were characterized in the laboratory. This gave 30 samples per sampling depth. The surface horizon (A or Ap) was sam-

Table 2. Characteristics of depth-to-fragipan groups used to determine the relationship between soil properties and degree of erosion.

Group	n†	Depth of fragipan		
		Range	Mean	SD
cm				
1	20	15.0-19.0	15.8	1.4
2	11	20.0-30.0	23.5	3.5
3	20	33.0-40.0	36.7	2.4
4	31	41.0-50.0	46.0	2.6
5	24	51.0-60.0	55.7	3.3
6	14	61.0-74.0	64.7	3.4
7	4	90.0-97.0	92.3	3.1
8	6	100.0-112.0	105.7	4.3

† n equals the number of sampling points within each group.

pled in two 7.5-cm increments, with additional samples being obtained every 15 cm down to the fragipan surface. At the virgin site, depth to fragipan surface and samples were obtained at 10 randomly selected points within an area of 372 m². The sampling scheme with depth was identical to the one used at the eroded sites. The lower number of sampling points relative to the eroded sites was justified on the basis of assumed greater site uniformity, since the area had not been exposed to accelerated erosion. In addition to the random sampling in prescribed increments, pits were dug near the center of each HS site and immediately adjacent to the virgin site for profile description and characterization.

All soil samples were air dried in the laboratory, ground, and sieved to <2 mm. Soil organic matter contents were determined by the Walkley-Black wet oxidation method (Soil Survey Staff, 1984). Exchangeable cations were measured by atomic absorption spectroscopy (AAS) following extraction with 1 M NH₄OAc, and 1 M KCl exchangeable acidity was determined using titrimetric methods (Thomas, 1982). Extractable Fe and Mn were determined by AAS after double-acid extraction (Gambrell and Patrick, 1982). Soil pH was measured in a 1:1 soil/water suspension (McLean, 1982) and cation exchange capacity was by summation. Particle size distribution was determined by the pipette method (Day, 1965). Bulk density (D_b) was estimated by the saran-coated clod procedure (Soil Survey Staff, 1984) using only samples collected from the 0- to 7.5-cm depth at 12 points within each eroded site prior to seedbed preparation. Only three D_b samples were collected from the same depth at the virgin site because surface conditions were uniform and the soil was so friable that it was difficult to obtain clods of adequate size. Pressure plate extraction (Richards, 1965) was used for determining soil water retention on previously dried and sieved samples, and available water content (AWC) was calculated as the water released between 0.03 and 1.50 MPa. Modulus of rupture (MR) and percent aggregation were measured on sieved samples from the 0- to 7.5-cm depth using the procedures of Richards (1953) and Kemper (1965), respectively. Soil color at the experimental plots was measured quantitatively by the Agronomy De-

Table 3. Selected physical and chemical properties of the virgin and eroded pedons.

Horizon	Depth cm	Color† (moist)	Sand	Silt	Clay	Bulk density Mg m ⁻³	pH (H ₂ O)	Exchangeable						Effective CEC‡	Base satura- tion %	Extractable		Organic matter g kg ⁻¹	
								Ca	Mg	K	Na	Acidity	Al			H	Fe		Mn
Virgin																			
A1	0-10	10YR 3/2	0.5	82.1	17.4	1.08	6.5	8.4	3.1	0.5	0.02	0.1	0.1	0.0	12.1	99	2.8	287.0	49.8
A2	10-20	10YR 3/3	0.4	82.7	16.9	1.08	5.3	1.3	1.6	0.3	0.01	1.4	1.2	0.2	4.6	70	37.0	259.0	13.7
BA	20-36	10YR 4/4	2.6	79.3	18.1	1.28	5.1	1.4	2.4	0.3	0.02	1.6	1.4	0.2	57	72	58.4	191.0	7.3
BW	36-48	10YR 5/6	3.1	78.0	18.9	1.44	5.0	1.6	3.3	0.3	0.02	2.6	2.3	0.3	7.8	67	60.9	146.0	4.4
Bt1	48-64	10YR 5/6	3.6	75.8	20.6	1.51	4.7	1.2	3.1	0.2	0.04	4.7	4.3	0.4	9.2	49	66.4	51.9	2.7
E/Btx	64-74	10YR 6/2	3.5	74.8	21.7	1.54	4.6	1.2	3.7	0.2	0.06	6.2	5.6	0.6	11.4	46	63.5	34.8	2.1
Btx1	74-127	7.5YR 4/4	2.7	71.1	26.2	1.58	4.4	1.9	5.6	0.2	0.18	7.4	6.7	0.7	15.3	52	92.0	47.2	1.5
Btx2	127†	7.5YR 4/4	1.2	77.9	20.9	1.60	4.7	3.2	7.5	0.2	0.62	2.3	1.6	0.7	13.8	83	60.2	34.6	1.0
Slightly eroded																			
Ap	0-15	10YR 4/4	3.9	78.4	17.7	1.48	6.6	5.7	0.8	0.3	0.04	0.1	0.0	0.1	6.9	99	30.4	213.0	14.5
BA	15-28	10YR 5/6	1.5	71.7	26.8	1.46	5.8	4.3	1.8	0.2	0.07	0.7	0.6	0.1	7.1	90	54.7	78.8	4.1
Bt1	28-43	10YR 5/6	1.8	73.1	25.1	1.37	5.1	2.9	2.6	0.2	0.08	1.8	1.6	0.2	7.6	76	74.4	99.0	2.8
Bt2	43-61	10YR 5/4	2.2	76.4	21.4	1.41	4.9	1.5	2.3	0.2	0.09	3.0	2.7	0.3	7.1	58	76.7	79.5	2.0
E/Bx	61-74	10YR 6/2	2.1	80.5	17.4	1.49	4.9	0.8	2.2	0.2	0.11	3.3	2.9	0.4	6.6	50	67.7	22.9	1.0
Btx1	74-88	7.5YR 4/4	2.3	73.8	23.9	1.52	5.1	1.1	4.5	0.2	0.32	4.0	3.3	0.7	10.0	61	77.9	16.2	0.8
Btx2	88-100+	7.5YR 4/4	4.2	74.6	21.2	1.60	5.2	0.7	4.7	0.2	0.60	3.7	3.4	0.3	9.9	63	66.7	11.7	0.7
Moderately eroded-1																			
Ap	0-11	10YR 4/4	3.1	78.2	18.7	1.43	6.4	5.8	0.8	0.4	0.03	0.0	0.0	0.0	7.0	100	34.2	205.0	12.4
BW1	11-23	10YR 5/6	2.5	75.7	21.8	1.46	4.9	3.3	1.3	0.2	0.05	2.5	2.1	0.4	7.4	64	74.4	100.0	2.7
BW2	23-37	10YR 6/4	2.3	78.0	19.7	1.41	4.7	1.9	1.8	0.2	0.09	3.4	3.0	0.4	7.4	54	81.3	86.1	1.6
E/Bx	37-47	10YR 6/3	2.4	81.0	16.6	1.51	4.8	1.1	2.4	0.1	0.10	3.3	2.9	0.4	7.0	53	62.6	23.6	0.9
Btx1	47-75	7.5YR 4/4	2.5	73.2	24.3	1.55	4.9	1.2	4.4	0.2	0.31	4.6	3.9	0.7	10.7	57	73.1	12.5	0.8
Btx2	75-100+	7.5YR 4/4	4.8	73.6	21.6	1.58	5.3	1.4	4.9	0.1	0.53	2.4	1.8	0.6	9.3	74	59.8	31.7	0.1
Moderately eroded-2																			
Ap	0-7	10YR 4/4	2.1	78.0	19.9	—	6.5	8.7	1.4	0.2	0.05	0.0	0.0	0.0	10.0	100	54.1	157.0	12.3
Bw1	7-16	10YR 5/4	1.8	75.6	22.6	—	5.0	6.9	1.6	0.2	0.07	1.5	1.3	0.2	10.1	85	75.6	178.0	7.2
Bw2	16-32	10YR 5/6	1.8	74.7	23.5	—	5.0	2.3	2.3	0.2	0.08	3.0	2.7	0.3	7.7	61	62.0	99.7	2.0
E/Bx	32-41	10YR 6/3	2.4	79.2	18.4	—	5.0	1.1	2.7	0.2	0.10	3.9	3.6	0.3	7.7	53	65.2	64.3	1.2
Btx1	41-70	7.5YR 4/4	2.6	76.6	20.8	—	5.0	1.3	4.8	0.2	0.24	4.1	3.3	0.8	10.5	61	74.7	30.1	0.9
Btx2	70+	7.5YR 4/4	6.9	72.6	20.5	—	5.4	1.8	5.9	0.1	0.58	2.2	1.4	0.8	10.6	79	52.5	9.8	0.6
Severely eroded																			
Ap	0-10	10YR 5/6	4.7	74.4	20.9	1.44	5.4	3.9	2.8	0.2	0.07	0.4	0.2	0.1	7.4	95	61.8	128.0	10.1
Bx1	10-43	7.5YR 4/4	2.0	74.3	23.7	1.54	4.9	1.9	5.2	0.2	0.26	2.9	2.4	0.5	10.5	72	74.3	23.5	1.1
Bx2	43-84+	7.5YR 4/4	5.6	74.1	20.4	1.58	5.0	1.9	7.1	0.2	0.54	2.9	2.3	0.6	12.6	77	48.2	6.4	1.4

† 7.5 YR 4/4 = dark brown; 10YR 3/2 = very dark grayish brown; 10YR 3/3 = dark brown; 10YR 4/4 = dark yellowish brown; 10YR 5/4 = yellowish brown; 10YR 5/6 = yellowish brown; 10YR 6/2 = light brownish gray; 10YR 6/3 = pale brown; 10YR 6/4 = light yellowish brown.

‡ CEC = cation-exchange capacity.

partment, Purdue University (Fernandez and Schulze, 1987) using only 0- to 7.5-cm samples. Pedon colors were obtained from a Munsell soil color chart.

Laboratory data from the 130 sampling points were grouped according to similarities in depth to fragipan rather than erosion class (Table 2). This gave eight groups that, in some cases, comprised samples from different sites. Regression equations were derived using the REG procedure (SAS Institute, 1985) and average-soil-property and depth-to-fragipan values within a group as the dependent and independent variables, respectively.

RESULTS AND DISCUSSION

Pedon Characteristics

The physical and chemical properties of the virgin and eroded pedons are shown in Table 3. Virgin-pedon characteristics of this study were comparable with other Grenada pedons that had no history of erosion caused by cultivation (Seatz, 1959). There are several differences in the physical properties among the pedons that are consistent with changes expected for soils that have been eroded to different depths. Most of the changes in chemical parameters cannot be ac-

curately compared between virgin and eroded sites because the eroded phases have been amended.

The primary physical properties that show evidence of profile modification due to accelerated erosion include: a decrease in thickness of the A horizon, a progressive increase in the amount of yellow color at the surface, a substantial increase in the D_b of the plow layer compared with the virgin A horizon, and a gradual increase in sand and clay accompanied by a decrease in silt. In most instances, values recorded for these properties in the eroded pedons are found in virgin pedon samples only from well within the B horizon. This strongly suggests that the properties observed in the Ap horizons of the eroded pedons are the direct result of topsoil removal by erosion. The large decrease in organic-matter content at the surface among these sites provides additional support for this contention. Finally, values for the properties of the Bt×1 and Bt×2 horizons were averaged and compared (Table 4) to determine if differences in the previously mentioned properties may have resulted from differential loess deposition. Based on these data, the fragipan horizons from all four sites appear to be re-

Identification and Properties of Fragipan Soils in the Piemonte Region of Italy

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ABSTRACT

The presence of a fragipan horizon in the soil profile restricts plant growth and limits nonagricultural uses. This is of special concern in the Piemonte region, in northwestern Italy, where the soil of numerous areas is reported to have a fragipan. Four sites were selected for this study with the aim of ascertaining the presence in the profile of a horizon that meets the criteria for a fragipan. In addition to standard morphological observations and physical analyses, Hg intrusion porosimetry and image analysis of thin sections were used to help in fragipan characterization. The pan of all four sites showed a suite of characteristics such as coarse prismatic primary structure, prominent vertical mottling, extremely hard dry consistence, brittleness, and absence of roots that indicated the presence of a fragipan. Other pedogenic features, e.g. clay films, mangans, ferrans, and concretions, were observed in the field. Although some of the Bx horizons had a clay content slightly higher than prescribed, in general textures were within the range prescribed for fragipans, as were bulk densities. Mercury intrusion showed a decrease in total porosity with depth, residual pores becoming dominant over storage and transmission pores in the fragipans. Image analysis of thin sections revealed a decrease of elongated pores and the presence of vesicles and compound packing voids. Also, oriented clay coatings within the pores and mangans and ferrans were observed in the fragipan. Pore-size distribution and pore shape appeared to be useful in characterizing the fragipan.

FRAGIPAN is a dense subsoil horizon that can constitute a severe limitation to plant growth and land use. In the absence of a standard laboratory procedure and of a single distinctive property, its identification is based on a combination of seven field clues (Soil Survey Staff, 1990). These include a very coarse prismatic or polyhedral structure separated by bleached vertical streaks that form a roughly polygonal pattern on a horizontal plane; a very firm, dry consistence of the matrix between the streaks that becomes brittle when moist; absence of roots

except in the bleached streaks; and a texture finer than fine sand with <35% clay. Also, an air-dry fragment of the fragipan should slake or fracture when immersed in water. To promote a more consistent identification, a revision of this definition has been proposed (Witty and Knox, 1989) that adds evidence of pedogenesis (mottles, clay films, or vertical streaks) and, for most pans, a slow or very slow permeability and high bulk density relative to the overlying horizons. Reported values for bulk density range from 1.50 to 2.00 Mg/m³ (Petersen et al., 1970; Van Vliet-Lanoë and Langohr, 1981; Olson, 1985; Smith and Callahan, 1987; Habecker et al., 1990; Rhoton and Tyler, 1990; Lindbo and Veneman, 1993).

Olson (1985) proposed pore-size distribution in addition to bulk density as a useful tool for fragipan identification. He found that fragipans have lower pore volumes and higher amounts of residual pores than adjacent horizons. According to the classification of Greenland (1977), residual pores (<0.5- μ m equivalent diameter) retain water with a potential that makes it unavailable for roots and not subject to drainage. Storage pores (0.5–50 μ m) hold the water necessary for growth of plants and microorganisms and transmission pores (50–500 μ m) regulate transmission of water and exchange of gases and allow root development. An additional insight into the natural complexity of pore-size distribution, pore shape, and the relative position of pores and aggregates can be obtained by the electrooptical image analysis of thin sections (Jongierius et al., 1972; Pagliai et al., 1983).

Fragipans are reported to occur in midlatitudes in various parts of the world. In Europe, fragipan or fragipan-like horizons have been described in Scotland (Fitz-Patrick, 1956; Romans, 1962), Belgium (Van Vliet-Lanoë and Langohr, 1981), the Netherlands (Sevink and Vink, 1969), France (Duchafour, 1976), and Spain (Guitian Ojea and Macias Vazquez, 1976). In Italy, recent studies have reported fragipan soils to be confined to the central and western Po river valley on glacial and fluvio-glacial terraces (Arduino et al., 1982; Casati et al., 1987; Ajmone-Marsan and Torrent, 1989; Persicani, 1989; Ente Regionale di Sviluppo Agricolo Lombardia, 1990).

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Table 1. Soil descriptions.

Horizon	Depth cm	Description (dry colors)
<u>Site 1: fine-loamy, mixed, mesic Aquic Fragiudalf</u>		
Ap	0-30	Very pale brown (10YR 7/4) loam; dry; moderate fine and medium granular structure; slightly hard, friable; common fine pores; common medium and few fine roots; clear smooth boundary.
BE	30-60	Pale yellow (2.5Y 8/4) loam; slightly moist; weak fine granular structure; hard, firm; common medium distinct very pale brown (10YR 7/4) mottles; few black (N 2/0) concretions; common medium pores; few fine roots; abrupt smooth boundary.
Btx	60-80	Dark brown (7.5YR 4/4) and yellow (10YR 7/8) loam; slightly moist; moderate medium prismatic and angular blocky structure; extremely hard, brittle; common coarse prominent pinkish gray (7.5YR 7/2) mottles; few very dark gray (2.5YR 3/0) concretions and black (N 2/0) stainings; common fine and medium vesicular pores; clayskins up to 1 mm thick in pores; few fine roots; clear smooth boundary.
Bx1	80-100	Yellow (10YR 7/6) and red (2.5YR 4/6) loam; moist; strong very coarse prismatic and weak medium platy structure; extremely hard, brittle; many coarse prominent white (2.5Y 8/2) mottles; many black (N 2/0) concretions and stainings on plates faces; common medium vesicular pores; clayskins in pores and on some plates faces.
Bx2	100-120	As layer above.
Bx3	120-140	As layer above; diffuse smooth boundary.
Bg	140-230	Yellow (10YR 8/8) clay; moist; weak medium angular blocky structure; very hard, firm; abundant medium faint pinkish gray (7.5YR 6/2) mottles, horizontal in places; few very dark grayish brown (10YR 3/2) concretions; few fine pores; gradual smooth boundary.
BC	230-275 +	Brownish yellow (10YR 6/8) sandy clay loam with few weathered pebbles and cobbles; moist; weak fine granular structure; slightly hard, friable; common coarse distinct light gray (N 7/0) mottles; many very dark grayish brown (10YR 3/2) concretions.
<u>Site 2: fine-loamy, mixed, mesic Aquic Fragiudalf</u>		
A	0-30	Very pale brown (10YR 7/4) silty clay loam; dry; moderate fine granular structure; slightly hard, friable; common fine pores; common fine and very fine roots; clear smooth boundary.
AB	30-70	Very pale brown (10YR 7/4) loam; dry; moderate fine granular structure; slightly hard, friable; common fine and medium pores; common fine roots; abrupt smooth boundary.
Btx	70-200	Brownish yellow (10YR 6/8) clay loam; dry; very coarse weak angular blocky structure; very hard, brittle; many black (N 2/0) concretions and stainings; common vesicular round and elongated fine and medium pores mostly coated with clay; diffuse smooth boundary.
Bx	200-235	Yellow (10YR 7/8) clay loam; slightly moist; strong very coarse prismatic and angular blocky structure; extremely hard, brittle; many medium prominent gray (10YR 5/1) mottles; many black (N 2/0) concretions and stainings on ped faces; common vesicular medium pores; clayskins up to 0.5 mm thick in pores and on some ped faces; diffuse smooth boundary.
BCx	235-265	Brownish yellow (10YR 6/8) sandy clay loam; slightly moist; moderate very coarse prismatic structure; very hard, brittle; few faint gray (10YR 5/1) mottles; few fine vesicular pores; diffuse smooth boundary.
C1	265-275	Brownish yellow (10YR 6/8) gravelly sandy clay loam; slightly moist; soft, very friable; diffuse smooth boundary.
C2	275-295 +	Brownish yellow (10YR 6/8) gravelly and cobbly sandy clay loam; slightly moist; soft, very friable; many fine faint light gray (10YR 7/2) mottles.
<u>Site 3: fine-loamy, mixed, mesic Typic Fragiudalf</u>		
Ap	0-50	Reddish yellow (7.5YR 6/6) sandy clay loam; dry; moderate fine granular structure; slightly hard, friable; common fine roots; abrupt smooth boundary.
Btx	50-100	Strong brown (7.5YR 5/6) sandy clay loam; dry; weak medium prismatic and angular blocky structure; very hard, brittle; few fine faint pinkish white (7.5YR 8/2) mottles; few black (2.5Y 2/0) concretions; few fine vesicular pores; clayskins up to 0.5 mm thick in pores; clear smooth boundary.
Bx1	100-150	Dark red (10R 3/6) and yellowish red (5YR 5/6) sandy clay loam; slightly moist; moderate very coarse prismatic and moderate medium platy structure; very hard, brittle; many coarse prominent very pale brown (10YR 7/3) mottles; common vesicular fine and medium pores; clayskins in pores; few black (N 2/0) concretions and stainings.
Bx2	150-200	As layer above.
Bx3	200-300	As layer above; gradual smooth boundary.
Bg	300-350	Yellowish red (5YR 5/8) and brownish yellow (10YR 6/8) sandy clay loam with some very weathered fine gravel; slightly moist; massive and weak coarse angular blocky structure; slightly hard, friable; many coarse faint very pale brown (10YR 7/3) vertical and horizontal mottles; few black (N 2/0) concretions; few fine pores; gradual smooth boundary.
CB	350-400 +	Yellowish red (5YR 5/6) sandy clay loam with weathered cobbles and pebbles; moist; massive and weak coarse angular blocky structure; slightly hard, friable; many distinct gray (N 6/0) mottles.
<u>Site 4: fine, mixed, mesic Typic Fragiudalf</u>		
Ap	0-25	Light yellowish brown (10YR 6/4) clay loam; dry; weak fine and medium granular structure; slightly hard, friable; common medium faint light gray (10YR 7/2) mottles; common fine roots, abrupt smooth boundary.
Btx	25-90	Reddish yellow (7.5YR 6/8) and red (2.5YR 5/8) clay loam; dry; moderate medium angular blocky structure; hard, brittle; common fine and coarse prominent pinkish gray (7.5YR 6/2) mottles; many very dark brown (10YR 2/2) concretions; few vesicular medium pores; some clayskins up to 1.5 mm thick in pores and on ped faces; gradual smooth boundary.
Bx1	90-140	Red (2.5YR 5/6) clay loam; slightly moist; moderate very coarse prismatic and angular blocky structure; very hard, brittle; many coarse prominent light gray (10YR 7/2) and white (2.5Y 8/2) mottles; many black (N 2/0) concretions and stainings along ped faces; common fine and medium vesicular pores; clayskins up to 1mm thick in pores.
Bx2	140-200	As layer above; gradual smooth boundary.
Bg1	200-300	Red (2.5YR 5/6) clay; moist; moderate coarse angular blocky structure; hard, firm; many medium distinct white (2.5Y 8/2) horizontal mottles; common black (10YR 2/1) concretions; few fine pores; diffuse smooth boundary.
Bg2	300-400	Brownish yellow (10YR 6/8) and red (2.5YR 4/8) clay loam with some fine pebbles; moist; massive and weak coarse angular blocky and granular structure; hard, firm; common medium distinct white (2.5Y 8/2) mottles; common black (10YR 2/1) concretions; few fine pores; clear smooth boundary.
C	400-600 +	Pale yellow (2.5Y 8/4) gravelly sandy clay loam; moist; weak fine granular structure; soft, very friable.

High bulk density relative to the overlying horizons is one of the distinctive properties of the fragipan. In all profiles there is an increase in bulk density with depth, with the maximum occurring within the fragipan although in Sites 1 and 4 high values were observed

below as well (Table 2). This can be in part attributed to the higher particle density of these layers. On the other hand, studies of fragipans formed in glacial till (Habecker et al., 1990) have shown that high bulk density can partially be inherited from the parent material.

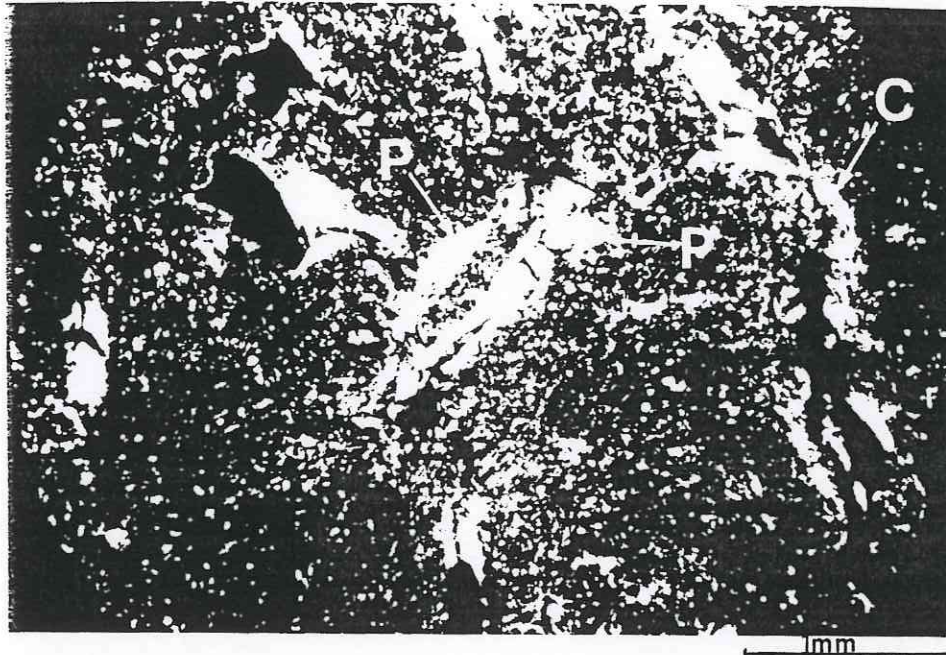


Fig. 7. Closely packed Bx horizon (Site 1, Bx2) strongly oriented papules (P) and clay infilling (C) pores; crossed nicols.

also be ascribed to the strongly oriented clay coatings that filled pores or reduced their size (Fig. 4). The laminated fabric of the clay coatings indicates that they are produced by clay translocation from overlying horizons. Microscopic examination of thin sections of Bx and Bt horizons revealed that planar pores are commonly coated with strongly parallel-oriented red (2.5YR 5/8) and yellow (10YR 7/6) clay films (Fig. 5) and mangans (Fig. 6). Cross-sectional area occupied by oriented clay was found, by point count, to be about 2.5% in the argillic horizon and 3.1% in the fragipan, which thus appears to have argillic characteristics. In some cases, vughs and planes were completely filled with oriented clay. Papules were common, as were ferruginous nodules, some of which were also manganiferous. Most of the plasma appeared to be separated as argillans, papules, and ferruginous nodules and the matrix was composed mainly of closely packed sand and silt grains (Fig. 7).

CONCLUSIONS

The observation in the field of most of the features listed by the Soil Survey Staff (1990) indicates the presence of a fragipan horizon in the soils studied. Prominent gray vertical streaks separate a very firm oxidized matrix that becomes brittle when moist. If not eroded, the polygonal pattern of streaks appears abruptly at 60 to 70 cm from the surface. Clods of the brittle matrix of the fragipan horizons slake in water. Texture is within the prescribed limits although some of the horizons show a slightly high clay content. Bulk density increases with depth and in some soils is maximum in the fragipan. Clay illuviation was observed in the field in the form of argillans and was confirmed by particle-size distributions and microscopic analysis of thin sections. Other features related to pedogenesis, such as mangans and ferrans,

were observed in the field and in thin sections. Slow permeability of the pan is indicated by its very low porosity. Pore-size distributions and pore shape characterization showed the abundance of residual pores, the lack of continuous pores, and the presence of vesicular porosity in the fragipan. Also, a matrix of closely packed sand and silt grains was observed, in accordance with the high bulk density of the horizon. Mercury intrusion and image analysis proved to be useful tools in characterizing fragipans, since pore shape and pore-size distribution appear more appropriate than total porosity or bulk density alone.

ACKNOWLEDGMENTS

The authors wish to thank Mr. G. Lucamante and Mr. M. La Marca for thin section preparation and image analysis, respectively. This research was funded by M.U.R.S.T. 40% and by the C.N.R. (90.00741.CT06 and 91.01623.CT06)

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VI. PEDON DATA

Pedon: Reggear

NSSL Pedon Number: 84P0107

Soil Survey Number: S83-ID-035-002

Location: Clearwater County, Idaho

N of Weippe 732 m W and 366 m N of SE corner Sec. 3 T36N R4E.

Physiography: Summit of Hills

Slope: 3% convex northwest facing

Elevation: 955 m MSL

Water Table Depth: 74 cm, perched

Land Use: Pasture land and native
pasture

Drainage: Well drained

Parent Material: eolian from ejecta-ash material
over alluvium from mixed material

Classification: Fine-silty, mixed, Typic Fragiboralf

Sample Date: 09/83

Described By: Peterson and Logan

0 -- 13 to 0 cm;

Not sampled. Leaves, twigs and needles; some partially decomposed litter.

A -- 0 to 15 cm; brown (7.5YR 5/4) silt loam, dry, and dark brown (7.5YR 3/4) moist; moderate fine subangular blocky structure parting to strong fine granular; slightly hard, friable, sticky, slightly plastic; many coarse and very fine roots; many very fine tubular pores; neutral (pH=6.5); clear smooth boundary.

B -- 15 to 28 cm; brown (7.5YR 5/4) silt loam, dry, and brown (7.5YR 4/4) moist; moderate medium subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; many coarse and very fine roots; common very fine tubular pores; many prominent clay films; neutral (pH=6.8); abrupt wavy boundary.

2E -- 28 to 51 cm; light gray (10YR 7/2) silt loam, dry, and yellowish brown (10YR 5/4) moist; weak fine and medium prismatic structure parting to moderate medium subangular blocky; slightly hard, friable, slightly sticky, slightly plastic; common medium and many fine roots; many very fine tubular pores; slightly acid (pH=6.4); on faces of peds, some clay coats; 95% E material; some 4n clay films on vertical surfaces; streaks of clay; clear wavy boundary.

2BE -- 51 to 74 cm; light yellowish brown (10YR 6/4) and light gray (10YR 7/2) silty clay loam, dry, and dark yellowish brown (10YR 4/4) and yellowish brown (10YR 5/4) moist; moderate medium prismatic structure parting to moderate medium subangular blocky; hard, firm, sticky, plastic; common fine, roots; common very fine tubular pores; continuous clay films in root channels and pores; many thick continuous clay films on faces of peds; medium acid (pH=5.8); E material coats 60% of faces of peds; Fe stains on faces of peds; abrupt wavy boundary.

2Btx1 -- 74 to 99 cm; very pale brown (10YR 7/4) silty clay loam, dry, and dark yellowish brown (10YR 4/4) moist; weak very coarse prismatic structure parting to moderate medium angular blocky; very hard, very firm, brittle, sticky, plastic; prominent clay films in root channels and pores, and many prominent clay films on faces of peds; strongly acid (pH=5.0); roots all flattened and following faces of peds; few fine dark root stains on faces of peds; tongues of E material 1/8 to 3/4 thick; b/w prisms; Fe- stains on faces of peds; b/w E and B material; E material coats prism faces; clear smooth boundary.

2Btx2 -- 99 to 147 cm; light yellowish brown (10YR 6/4) silt loam, dry, and dark yellowish brown (10YR 4/4) moist; weak coarse prismatic structure parting to weak coarse subangular blocky; extremely hard, extremely firm, brittle, slightly sticky, slightly plastic; many very fine vesicular and tubular pores; many prominent clay films in root channels and pores; prominent clay films on faces of peds; very strongly acid (pH=4.5); few fine dark root stains on ped faces; clear smooth boundary.

3Btx --147 to 213 cm; light yellowish brown (10YR 6/4) interior silty clay loam, dry, and dark yellowish brown (10YR 4/4) moist; weak coarse prismatic structure; extremely hard, extremely firm, sticky, plastic; many very fine tubular pores; prominent clay films in root channels and pores; very thin coating of E material.

PRIMARY CHARACTERIZATION DATA
(CLEARWATER COUNTY, IDAHO)

S83ID-035-002

SAMPLED AS: REGGEAR;
REVISED TO:

FINE-SILTY, MIXED, MESIC TYPIC FRAGIBORALF

NSSL - PROJECT 84P 19, CLEARWATER-LATAH CO

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
NATIONAL SOIL SURVEY LABORATORY
LINCOLN, NEBRASKA 68508-3866

DEPTH (CM)	HORIZON	(- -TOTAL - -)			(>2MM)	ORGN	(- BULK DENSITY -)			COLE
		CLAY LT	SILT .002	SAND .05	WT PCT OF	C	FIELD MOIST	1/3 BAR	OVEN DRY	WHOLE SOIL
		.002	-.05	-2	WHOLE SOIL	6A1c PCT	4A3a	4A1d	4A1h	4D1
		<- - - PCT - - ->					<- - - - - G/CC - - - >			CM/CM
0 -15	A	14.4	71.1	14.5	1	1.51		1.09	1.14	0.015
15 -28	B	13.9	72.9	13.2	1	0.83		1.35	1.39	0.010
28 -51	2E	18.9	71.0	10.1	TR	0.43		1.55	1.60	0.011
51 -74	2BE	22.2	68.5	9.3	TR	0.27		1.51	1.58	0.015
74 -99	2BTX1	25.4	65.1	9.5	TR	0.20		1.61	1.69	0.016
99 -147	2BTX2	25.2	65.8	9.0	TR	0.13		1.69	1.75	0.012
147 -213	3BTX	26.8	64.2	9.0	TR	0.13		1.67	1.72	0.010
74 -99	2BTX1	26.0	64.3	9.7	3					
74 -99	2BTX1	20.7	66.3	13.0	2					

SOIL SERIES: HAUBSTADT

COUNTY: ROSS

STATE: OHIO

SITE: RO-99

PEDON CLASSIFICATION: FINE-SILTY, MIXED, MESIC AQUIC FRAGIUDALF

LOCATION: 1.1 MI NW OF INTERSECTION OF S.R.41 AND BRIER RD. - 500 FT. NE OF BRIER RD.
SEC. T. R.

PHYSIOGRAPHY: TERRACE

TOPOGRAPHY: GENTLY SLOPING

SLOPE: 3 SLOPE ASPECT: E

DRAINAGE: MODERATELY WELL DRAINED

VEGETATION: PASTURE

COLLECTORS: GILMORE/LUCHT/HAMILTON

DATE: 11/21/90

PARENT MATERIALS: LOESS, ILLINOIAN LACUSTRINE

HORIZON DEPTH

- Ap 0-23 cm; dark yellowish brown (10YR 4/4) silt loam; weak medium subangular blocky structure parting to moderate medium granular; friable; many fine roots; pH 5.8; abrupt smooth boundary.
- Bt1 23-43 cm; yellowish brown (10YR 5/6) silt loam; few medium distinct brown (10YR 5/3) and few fine distinct strong brown (7.5YR 5/8) redox accumulations; moderate medium and fine subangular blocky structure; friable; common fine roots; common prominent brown (7.5YR 5/4) argillans on faces of peds; pH 5.4; clear wavy boundary.
- Bt2 43-58 cm; strong brown (7.5YR 5/6) silty clay loam; many coarse prominent gray (10YR 6/1) redox depletions; weak coarse subangular blocky structure parting to moderate medium subangular blocky; firm; common fine roots; medium patchy pale brown (10YR 6/3) and common distinct yellowish brown (10YR 5/6) argillans on faces of peds; pH 5.4; 2% coarse fragments; clear wavy boundary.
- Bt3 58-74 cm; strong brown (7.5YR 5/6) silty clay loam; common medium prominent light brownish gray (10YR 6/2) and common medium distinct brownish yellow (10YR 6/8) redox features; weak coarse prismatic structure parting to strong coarse subangular blocky; very firm; few fine roots; common prominent gray (10YR 5/1) argillans on vertical faces of peds; pH 5.0; 5% coarse fragments; abrupt wavy boundary.
- Btx1 74-117 cm; yellowish brown (10YR 5/4) silt loam; few medium distinct light brownish gray (10YR 6/2) redox depletions; strong very coarse prismatic structure; extremely firm; brittle; very few fine roots; few prominent gray (10YR 5/1) argillans on vertical faces of peds; few black (10YR 2/1) concretions on faces of peds; pH 5.0; 5% coarse fragments; clear smooth boundary.
- Btx2 117-152 cm; yellowish brown (10YR 5/4) silt loam; weak very coarse prismatic structure parting to strong medium subangular blocky; very firm; brittle; few prominent gray (10YR 5/1) and light brownish gray (10YR 6/2) argillans on vertical faces of peds; few black (10YR 2/1) concretions on faces of peds; pH 5.4; 5% coarse fragments; clear wavy boundary.
- 2Bt 152-203 cm; yellowish brown (10YR 5/6) silty clay loam; weak medium prismatic parting to moderate medium subangular blocky structure; firm; few distinct dark gray (10YR 4/1) and yellowish brown (10YR 5/4) argillans on faces of peds; few black (10YR 2/1) concretions on faces of peds; pH 6.0.

SOIL SERIES: Haubstadt COUNTY: Ross
 SITE: RO-99 DATE: 11/21/90 OSU LAB NOS.: 26256-26262

DEPTH (CM)	HORIZON	(- TOTAL -)			(>2MM)	(- BULK DENSITY -)		
		CLAY LT	SILT .002 -05	SAND .05 -2	WT PCT WHOLE SOIL	FIELD MOIST 4A3a	1/3 BAR 4A1d	OVEN DRY 4A1h
		< - - - PCT - - - >			< - - - - G/CC - - - >			
0 -23	Ap	21.2	74.2	4.6	0.3	1.56	1.59	
23 -43	Bt1	31.1	66.3	2.6	0.4	1.49	1.56	
43 -58	Bt2	31.5	65.2	3.3	0.3	1.38	1.49	
58 -74	Bt3	30.0	63.3	6.7	0.8	1.52	1.56	
74 -117	Btx1	28.2	63.5	8.3	0.6	1.73	1.74	
117 -152	Btx2	31.7	60.5	7.8	0.4	1.75	1.79	
152 -203	2Bt	38.5	54.0	7.5	0.5	1.64	1.71	

SERIES: KEENO NEWTON COUNTY, MISSOURI

DATE: 7/81

PEDON NO: S80MO-145-007

CLASSIFICATION: LOAMY-SKELETAL, SILICEOUS, MESIC MOLLIC FRAGALBUDALF

LATITUDE: N37 DEG. 00 MIN. LONGITUDE: W094 DEG. 22 MIN.

LOCATION: NEWTON CO. 548 M. N & 380M E OF THE SW CORNER, SEC. 36, T.27N., R.32W.

PHYSIOGRAPHY: SUMMIT OF HILLS IN LEVEL TO UNDULATING UPLANDS

GEOMORPHIC POSITION: ON UPPER THIRD INTERFLUVE SUMMIT

SLOPE AND ASPECT: 7 PCT CONVEX ELEVATION: 364 M M.S.L.

MICRORELIEF: NONE

AIR TEMP. 14 C SUMMER: 24 C WINTER: -3 C

PRECIPITATION: 107 CM UDIC MOISTURE REGIME

WATER TABLE: 0 CM NOT OBSERVED

DRAINAGE: SOMEWHAT POORLY DRAINED PERMEABILITY: SLOW

PARENT MATERIAL: STRONGLY WEATHERED LOCAL COLUVIUM FROM ACIDIC ROCKS OVER

STRONGLY WEATHERED RESIDUAL MATERIAL

SAMP NOS. 80P1906 1913

HORIZON DEPTH

- A11 0 to 11 cm; black (10YR 2/1) gravelly silt loam; weak very fine granular structure; very friable, soft; common very fine roots; strongly acid; clear smooth boundary.
- A12 11 to 31 cm; very dark grayish brown (10YR 3/2) and dark brown (10YR 3/3) very gravelly silt loam; weak very fine granular structure parting to weak fine granular; very friable, soft; common very fine roots; very strongly acid; clear smooth boundary.
- Bt 31 to 45 cm; brown (10YR 4/3) gravelly silty clay loam; moderate fine subangular blocky structure parting to moderate very fine subangular blocky; friable, slightly hard; common very fine roots; very strongly acid; clear smooth boundary.
- Ex1 45 to 57 cm; grayish brown (10YR 5/2) very gravelly silty clay; very few fine prominent dark red (2.5YR 3/6) redox accumulations; weak thin platy structure parting to weak very fine subangular blocky; friable, slightly hard, slightly brittle; a few very fine roots; 50 percent cherty gravel; 5 percent cobble; clear smooth boundary.
- Ex2 57 to 80 cm; grayish brown (10YR 5/2) and red (2.5YR 4/6) extremely gravelly clay loam; moderate thick platy structure; very firm; continuous silt coats on faces of peds; many distinct organo-clay coats on faces of peds; brittle; 20 percent gravel; 20 percent cobble; a few iron and manganese masses; very strongly acid; clear wavy boundary.
- 2Bt1 80 to 100 cm; grayish brown (10YR 5/2) and red (2.5YR 4/6) extremely gravelly clay; moderate fine angular blocky structure; extremely firm; common distinct clay films on faces of peds; rock fragments are predominantly chert; 20 percent gravel; 10 percent cobble; a few iron and manganese masses; very strongly acid; clear smooth boundary.
- 2Bt2 100 to 170 cm; gray (10YR 5/1) extremely cobbly silty clay; moderate very fine angular blocky structure; very firm; about 50 percent gravel and 35 percent cobble; common distinct clay films on faces of peds and on surfaces of rock fragments; very strongly acid; clear smooth boundary.
- 2Bt3 170 to 230 cm; red (2.5YR 4/6) and light gray (10YR 6/1) extremely cobbly clay; weak very fine angular blocky structure; very firm; about 30 percent gravel and 35 percent cobble; common distinct clay films on faces of peds and on surfaces of rock fragments; few fine irregular iron masses; very strongly acid.

PRIMARY CHARACTERIZATION DATA
(NEWTON COUNTY, MISSOURI)

S80MO-145-007

SAMPLES AS: KEENO
REVISED TO: KEENO

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
NATIONAL SOIL SURVEY LABORATORY
LINCOLN, NEBRASKA 68508-3866

DEPTH (CM)	HORIZON	(- -TOTAL - -)			(> 2MM)	(- BULK DENSITY -)			COLE WHOLE SOIL 4D1 CM/CM
		CLAY LT	SILT .002 - .05 PCT	SAND .05 -2	WT PCT WHOLE SOIL	FIELD MOIST 4A3a	1/3 BAR 4A1d	OVEN DRY 4A1h	
0 -11	A1	21.6	65.3	13.1	33V	1.10	1.21	0.026	
11 -31	A2	20.3	63.1	16.6	49V	1.10			
31 -45	Bt	32.1	48.4	19.5	75V	1.30			
45 -57	Ex1	40.6	43.2	16.2	76V	1.30			
57 -80	Ex2	29.2	43.0	27.8	58V	1.82	1.83	0.001	
80 -100	Bt1	52.6	37.9	9.5	46V	1.38	1.42	0.007	
100-170	Bt2	41.5	44.0	14.5	96V	1.40			
170-230	Bt3	70.0	24.7	5.3	79	1.44	1.64	0.014	

ONTUSIA SERIES

Sample No.: S86NY025-1-(1,2,3,4,5,6,7)

Location: Delaware Co., N.Y., Town of Sidney, 2000' northeast on Co. Rd. 35 from intersection with Roof Rd., then 1100' east of Co. Rd. 35; 42 degrees 16' 4" N., 75 degrees 17' 7" W.

Classification: Fine-loamy, mixed, mesic Aeric Fragalfaquepts

Vegetation: Hayfield - mixed grasses, sedges and rushes

Parent Material: Glacial till derived from sandstone, siltstone and shale

Physiography: Glaciated upland

Slope: 4%

Elevation: 1900 feet

Permeability: Moderate to 16"; slow or very slow in Bx and C

Drainage: Somewhat poorly drained

Groundwater: None encountered

Soil Profile

- AP
S86NY025-1-1 (0 to 20 cm) dark grayish brown (10YR 4/2) channery silt loam; moderate medium and coarse subangular blocky structure parting to moderate fine and medium granular; very friable; many fine roots; 15 percent rock fragments, 2 percent > 3 inches; moderately acid; abrupt smooth boundary.
- Bw
S86NY025-1-2 (20 to 29 cm) dark yellowish brown (10YR 4/6) silt loam; few medium distinct brown and grayish brown (10YR 5/3 & 5/2) clay depletions; weak medium subangular blocky structure; very friable; common fine roots; many very fine and medium tubular pores; 10 percent rock fragments, 2 percent > 3 inches, moderately acid; clear smooth boundary.
- Eg
S86NY025-1-3 (29 to 42 cm) grayish brown (2.5Y 5/2) silt loam; many (40%) medium distinct brown and strong brown (7.5YR 4/4 & 5/6) masses of iron accumulations and few medium faint light brownish gray (2.5Y 6/2) clay depletions; moderate medium platy structure; friable; few fine roots; common fine and few medium tubular pores; 10 percent rock fragments; moderately acid; clear wavy boundary
- Bx1
S86NY025-1-4 (42 to 65 cm) brown (10YR 4/3) channery silt loam; common fine and medium faint brown (7.5YR 4/4) masses of iron accumulations and common fine distinct gray (10YR 6/1) iron depletions; strong coarse and very coarse prismatic structure parting to weak coarse subangular blocky structure; firm and slightly brittle; prism faces of light olive gray (5Y 6/2) 1/4 to 1/2 inch wide with strong brown (7.5YR 5/6) rinds (iron accumulations) 1/16 to 1/4 inch wide; few fine roots along prism faces; common fine tubular and vesicular pores; common distinct continuous clay flows within pores; 20 percent rock fragments, 2 percent > 3 inches; strongly acid; gradual wavy boundary.
- Bx2
S86NY025-1-5 (65 to 90 cm) grayish brown (10YR 5/3 & 5/4) very channery silt loam; common coarse distinct brown and strong brown (7.5YR 5/4 & 5/6) masses of iron accumulations and dark reddish brown (5YR 3/2) iron and manganese stains; strong very coarse prismatic structure; very firm and brittle; prism faces are greenish gray (5GY 6/1); common fine and few medium tubular pores; thin patchy dark grayish brown (2.5Y 4/2) clay coatings in pores and on rock fragments; 25 percent rock fragments, 2 percent > 3 inches; strongly acid; clear wavy boundary.

Bx3 90 to 145 cm) grayish brown and yellowing brown (10YR 5/2 & 5/4) channery
 S86NY025-1-6 loam; common medium distinct strong brown (7.5 YR 5/6) and grayish brown distinct
 strong brown (7.5YR 3/6) masses of iron accumulations and grayish brown
 (2.5Y 5/2) iron depletions; moderate very coarse prismatic structure parting to weak
 medium platy structure; firm; prism faces are pale olive (5Y 6/4) with dark reddish
 brown (5YR 3/2) iron stains; few fine and medium vesicular pores; 25 percent rock
 fragments, 5 percent > 6 inches long; strongly acid; gradual wavy boundary.

CB (145 to 170 cm) brown and yellowish brown (10YR 5/3 & 5/4) very channery
 S86NY025-1-7 loam; common fine faint yellowish brown (10YR 5/6) masses of iron accumulations;
 weak very coarse prismatic structure parting to weak medium platy structure; firm;
 prism faces are gray (5Y 6/1) with dark brown (7.5YR 3/2) iron stains; few fine
 vesicular pores; 35 percent rock fragments, 10 percent > 6 inches long; moderately
 acid.

PEDON NUMBER: S86NY025-1-7 SERIES: ONTUSIA

DEPTH (CM)	HORIZON	(- - -TOTAL - - -)			PERCENT ROCK FRAGMENTS MM BASIS	(< - BULK DENSITY ->)		COLE CM/CM	
		SAND 2-.05 < - - - PCT - - ->	SILT .05- .002 MM	CLAY <.002		1/3 BAR VOLUME < - - - - (G/CC) - - - ->	OVEN DRIED (EST)		
1	0-20	Ap	21.6	55.4	23.0	17	-	-	0.010
2	20-29	Bw	23.5	54.9	21.6	27	1.47	1.50	0.000
3	29-42	Eg	30.9	52.0	17.1	25	1.78	1.79	0.010
4	42-65	Bx1	28.1	52.1	19.8	32	1.84	1.89	0.010
5	65-90	Bx2	29.9	49.1	21.0	32	1.87	1.91	0.010
6	90-145	Bx3	29.3	47.7	23.0	26	1.81	1.88	0.000
7	145-170	CB	31.3	47.3	21.4	32	1.89	1.90	

USDA-SOIL CONSERVATION SERVICE
PEDON NARRATIVE DESCRIPTION
SEPTEMBER 10, 1992

SOILS SERIES: AVONBURG
SOIL SURVEY NO.: S92-IN-077-001
DESCRIPTION TYPE: FULL PEDON DESCRIPTION
PEDON TYPE: MODAL PEDON FOR SERIES
PHYSIOGRAPHY: GROUND MORaine IN GLACIATED UPLAND
GEOMORPHIC POSITION: SUMMIT OF AN INTERFLUVE
SLOPE CHARACTERISTICS: .5 PERCENT CONVEX
MLRA: 114
DRAINAGE CLASS: SOMEWHAT POORLY DRAINED
LAND USE: ABANDONED CROPLAND
STONINESS: 0
PARTICLE SIZE CONTROL SECTION: 15 TO 30 INCHES
PARENT MATERIAL: EOLIAN FROM MIXED MATERIAL OVER GLACIAL DRIFT FROM MIXED
CALCAREOUS MATERIAL
DIAGNOSTIC HORIZONS: 0 TO 23 CM OCHRIC, 55 TO 287 CM ARGILLIC,
149 TO 187 CM FRAGIPAN
DESCRIBED BY: A. NICKEL, B. NAGEL, D. ROBERTS
DATE: 05/92
CLASSIFICATION: FINE-SILTY, MIXED, MESIC AERIC FRAGIC EPIAQUALF
NOTES: PEDON IS MODAL FOR SERIES AS MAPPED IN INDIANA BUT SILTS TOO THICK FOR
CURRENT SERIES CONCEPT.

HORIZON DEPTH

Ap	0 to 23 cm; brown to dark brown (10YR 4/3) silt loam; weak fine subangular blocky structure parting to weak fine granular; friable; many medium roots throughout; pH 6.8; abrupt smooth boundary.
BE	23 to 38 cm; yellowish brown (10YR 5/6) silt loam; common medium distinct light brownish gray (10YR 6/2) redox depletions; moderate medium subangular blocky structure; friable; many medium roots, and common very fine and fine roots; pH 5.3; clear smooth boundary.
Bt1	38 to 56 cm; yellowish brown (10YR 5/4) silt loam; many medium distinct light brownish gray (10YR 6/2) redox depletions; moderate medium subangular blocky structure; friable; common faint (10YR 5/2) patchy clay films on faces of peds; many very fine and fine roots throughout; pH 4.8; clear smooth boundary.
Bt2	56 to 76 cm; light brownish gray (10YR 6/2) silty clay loam; many medium distinct yellowish brown (10YR 5/4), and common yellowish brown (10YR 5/8) redox accumulations; weak medium prismatic structure parting to weak medium subangular blocky; firm; common very fine roots between peds; common fine and medium tubular pores; common faint grayish brown (10YR 5/2) discontinuous clay films (cutans) on faces of peds, and few distinct black (10YR 2/1) patchy manganese or iron-manganese stains; pH 4.8; clear smooth boundary.

Btx1 76 to 89 cm; gray (10YR 5/1) silt loam; many medium prominent yellowish brown (10YR 5/8) redox accumulations; moderate coarse prismatic structure; firm; common very fine roots between peds; common fine and medium tubular pores; few prominent gray (10YR 5/1) discontinuous clay films on faces of peds; pH 4.5; 30 percent brittle (10YR 5/8 material); gradual wavy boundary.

The 89 to 147 cm layer has two main parts. These parts are defined vertically rather than horizontally. These two parts are divided approximately 50/50 and are designated 2Bt3 and 2Btx2.

The 2Bt3 portion is 30 to 50 cm wide at the top and tapers to 1 to 3 inches at the bottom. The 2Btx portion is 2 to 3 inches wide at the top and widens to 10 to 20 cm at the bottom. The bottom 15 cm of the 2Bt horizons is 10YR 5/2 silty clay loam. This material is more clayey and gray than the upper portion of the cone.

- 2Bt3 89 to 147 cm; brown (10YR 5/3) silt loam; many medium distinct gray (10YR 6/1), and common fine strong brown (7.5YR 5/6) redox features; weak coarse subangular blocky structure; firm; common very fine roots between peds; common fine tubular pores; few faint grayish brown (10YR 5/2) discontinuous clay films in root channels and/or pores; pH 4; gradual wavy boundary.
- 2Btx2 89 to 147 cm; yellowish brown (10YR 5/6) silt loam; common coarse prominent gray (10YR 5/1) redox depletions; strong coarse prismatic structure; very firm, brittle, few very fine roots between peds; few fine tubular pores; few distinct grayish brown (10YR 5/2) discontinuous clay films in root channels and pores, and few faint dark grayish brown (10YR 4/2); discontinuous clay films on faces of peds; pH 4.4; 2 percent gravel; gradual wavy boundary.
- 2Btx3 147 to 191 cm; yellowish brown (10YR 5/6) silt loam; many coarse prominent gray (10YR 5/1) redox depletions; strong very coarse prismatic structure parting to weak coarse subangular blocky; very firm, brittle; common very fine roots between peds; common fine tubular pores; few distinct gray (10YR 5/1) discontinuous clay films on faces of peds; brownish material is more sandy than gray material; pH 4.4; 1 percent gravel; gradual wavy boundary.
- 2Btx4 191 to 211 cm; gray (10YR 5/1) silt loam; common medium prominent yellowish brown (10YR 5/8), and many faint gray (10YR 6/1) redox features; moderate medium prismatic structure parting to weak coarse subangular blocky; firm, brittle; few very fine roots between peds; common fine tubular pores; common faint light gray to gray (10YR 6/1) discontinuous clay films on faces of peds; pH 5.5; 1 percent gravel; clear wavy boundary.
- 3Btx5 211 to 244 cm; yellowish brown (10YR 5/4) clay loam; many coarse prominent gray (10YR 6/1) redox depletions; moderate medium prismatic structure parting to weak coarse subangular blocky; firm; few very fine roots between peds; common prominent light gray to gray (10YR 6/1) continuous clay films on faces of peds; many coarse irregular masses of iron-manganese; 8 percent gravel; pH 6.1; clear wavy boundary.
- 3Btb 244 to 292 cm; strong brown (7.5YR 5/8) clay loam; many coarse prominent light brownish gray (10YR 6/2) redox depletions; moderate medium subangular blocky structure parting to coarse; firm; common prominent light gray to gray (10YR 6/1) continuous clay films on faces of peds; common medium irregular masses of iron and manganese; 13 percent gravel; pH 6.4.

PRIMARY CHARACTERIZATION DATA
(JEFFERSON COUNTY, INDIANA)

S92IN-077-001

SAMPLES AS: AVONBURG

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
NATIONAL SOIL SURVEY LABORATORY
LINCOLN, NEBRASKA 68508-3866

DEPTH (CM)	HORIZON	(- -TOTAL - -)			(>2MM)	(- BULK DENSITY -)			COLE
		CLAY LT	SILT .002 -05 PCT	SAND .05 -2 PCT	WT PCT OF WHOLE	FIELD MOIST 4A3a SOIL	1/3 BAR 4A1d G/CC	OVEN DRY 4A1h	WHOLE SOIL 4D1 CM/CM
0 -23	Ap	11.9	66.8	21.3	TR	1.47	1.52	0.011	
23 -38	BE1	14.4	65.6	20.0	1	1.58	1.62	0.008	
38 -56	BE2	17.2	63.7	19.1	2	1.56	1.64	0.017	
56 -76	BT	31.6	56.3	12.1	1	1.47	1.61	0.031	
76 -89	BTX1	25.4	56.4	18.2	TR	1.63	1.74	0.022	
89 -147	2BTX2	18.0	56.7	25.3	5	1.73	1.82	0.017	
147-191	2BTX3	18.4	57.7	23.9	2	1.76	1.79	0.006	
191-211	2BTX4	24.3	50.8	24.9	2	1.73	1.76	0.006	
211-244	2BTX5	28.9	40.8	30.3	13	1.59	1.87	0.051	
244-292	3BTB	32.8	31.6	35.6	17	1.48	1.74	0.049	

3. *Some Important Properties of Soils Thought to Have Fragipans* in Southeastern and Southcentral United States

Soil Series	Indentification Number	Structure of Horizon	Bulk Density			Depth	
			Field Moisture	33kPa	Oven Dry		
Bude	S61MISS-70-3	CO ABK	-	1.60		29-44 in	
				1.64		44-57 in	
	S61MISS-70-4 S61MISS-58-2	CO ABK		1.80		28-46 in	
			1.64	1.58		45-57 in	
Byler (OSD)		CO & VCO PR		1.73		43-55 in	
Byram (OSD)		CO PR					
Calloway (OSD)	S52MISS-54-1	CO PR					
		CO ABK		1.58		16-29 in	
				1.61		39-50 in	
	S59MISS-54-2	CO ABK		1.50		20-30 in	
	S60KY-38-2	O-SBK		1.58		15-21 in	
	S60KY-38-1	CO PR		1.49		21-29 in	
	S60KY-75-2			1.6	1.68	53-74 cm	
	S63LA-83-2			1.54	1.62	64-79 cm	
	S59MS-107-1			1.61(dry)	1.61	127-152 cm	
	S59MS-107-2				1.57	51-76 cm	
	S59TN-047-2			1.63	1.65	38-74 cm	
S59TN-47-5			1.67	1.67	94-132 cm		
Cart (OSD)		VCO PR					
Crelton (OSD)		PL-horizon below = 0					
	S71MO-109-2			1.57	1.69	61-74 cm	
	S80MO-145-3			1.63	1.68	90-111 cm	
	S91MO-167-53			1.56	1.68	51-64 cm	
	S91MO-167-54			1.56	1.99	99-119 cm	
	S91MO-167-54			1.80	2.18	119-150 cm	
	S91MO-167-55			1.68	1.79	66-86	
	S91MO-167-56			1.52	1.58	71-91 ^{1/}	
	Dulac (OSD)		VCO PR				
	Erno (OSD)		x is SBK to 51" CO PR below				
Freeland (OSD)		VCO PR					

^{1/} Not an x horizon

***Some Important Properties of Soils Thought to Have Fragipans
(Continued)***

Soil Series	Identification Number	Structure of Horizon	Bulk Density		Depth
			Field Moisture	33kPa Oven Dry	
Gigger (OSD)		VCO PR			
Grenada (OSD)		B/E = VCO PR to 50"			
	S81MS-107-15	VCO PR		1.60	53-66 cm
	S81MS-049-2	MED PL to SBK		1.40	61-69 cm
	S87MS-107-10D	MED PR		1.52	58-86 cm
	S59TN-47-1		1.64		79-109 cm
			1.76		140-165 cm
	S88MS-107-10B			1.47	50-117 cm
				1.56	117-150 cm
	S88MS-107-10C	MED PR		1.53	32-56 cm
	S81MS-107-007	CO PR		1.60	86-142 cm
	S81TN-157-2	-		1.53	74-124 cm
	S59TN-047-4	-	1.55		66-102 cm
	S87MS-107-10	CO PR		1.51	46-70 cm
	S88MS-107-10A	-		1.56	24-40 cm
	S62LA-42-3			1.58	22-27 in
	S63LA-83-3	-		1.58	56-69 in
	S80MS-33-1	CO PR		1.55	46.61 cm
	S60MS-49-3	-	1.58		74-112 cm
	S80KY-35-1	CO PL		1.75	107-140 cm
			(all others .07 less than oven dry)		
	S63LA-83-1	-		1.50	71-84 cm
	S92KY-83-4			1.69	66-72 cm
	S60MISS-25-3	CO SBK		1.58	24-44 in
	S59TN-24-1				
Hatchie (OSD)		VCO PR			
Henry (OSD)		VCO PR			
	S59TN-47-6		1.67		33-46 cm
	S59TN-47-6		1.53		46-81 cm
	S59TN-24-6 and 7			1.50	80-107 in
	S59TN-47-7		1.54		46-81 cm
Hobson					
	S59MO-33-4			1.96	20-32 in
Jasco (OSD) SE TX	CHAS. BATTE M.S.	CO PR CO PR		< 1.60 1.75	in bx 115 + cm
Jay (OSD)		CO PR			
Libuse (OSD)		VCO PR			

***Some Important Properties of Soils Thought to Have Fragipans
(Continued)***

Soil Series	Indentification Number	Structure of Horizon	Bulk Density			Depth
			Field Moisture	33kPa	Oven Dry	
Loring (OSD)		VCO PR				
	S61LA-33-3		1.48		1.58	33-58 cm
	S61LA-17-2			1.51		49-60 in
	S61LA-33-2		1.48		1.60	33-58 cm ^{2/}
	S61LA-17-3			1.46		23-35 in
	S59KY-111-4			1.58		112-140 cm
	S82KY-55-5	VCO PR	no bulk densities			
	S92KY-83-2		1.70			13-31 cm
	S92KY-83-2		1.57			51-72 cm
	S60MS-49-4		1.56		1.59	91-132 cm
	S82MS-107-1	VCO PR		1.53	1.61	97-116 cm
	S81TN-157-1			1.39-1.49		15-156 cm
	S81MS-49-1	PL to SBK		1.40	1.52	36-69 cm
	S81MS-49-1			1.45	1.48	84-99 cm
	S59KY-56-3	CO PR		1.60		37-48 in
	S59KY-24-5	VCO PR		1.62		37-52 in
	S59KY-56-4	CO ABK		1.58		44-55 in
Necessity (OSD)		VCO PR				
Olivier (OSD)		VCO PR				
	S61LA-17-1	MED & CO PR		1.52		32-44 in
	S61LA-17-6	MED PR		1.52		44-60 in
Pheba						
	S63MISS-18-2			1.74		16-21 in ^{3/}
	S63MISS-18-3			1.62		18-24 in ^{4/}
				1.68		39-49 in ^{5/}
Prentiss (OSD)		VCO PR				
	S61MISS-12-1	PL to SBK		1.85		26-36 in
	Lowndes Co. MI	CO PR 6% clay, 63% sand				
	S61MISS-12-2			1.71		35-41 in ^{6/}
Providence (OSD)		VCO PR				
	S59MISS-43-2	CO PR		1.90		38-53 in ^{7/}

^{2/} Not in Bx
^{3/} Blocky A'2gx
^{4/} A'2gx
^{5/} B'tx
^{6/} Sand 54% clay 22%
^{7/} 2Btx 5YR