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Agronomy Series

Pennsylvania's Fragipans

by

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William J. Waltman

Agronomy Series Number 147

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INTRODUCTION

By

Edward J. Ciolkosz and William J. Waltman

Fragipans are of great interest to soil science. Particularly Pennsylvania soil science because they are found in soils that cover about 30% of Pennsylvania's land surface (Ciolkosz et al., 1999). Although very abundant, their distribution is not uniform across Pennsylvania landscapes (Figure 1).

Fragipans have been studied for decades, and a number of reviews have been published (Grossman and Carlisle, 1969; Smalley and Davin, 1982; Smeck and Ciolkosz, 1989; Glocker and Quandt, 1993; and Ciolkosz et al., 1995). The most recent of these reviews (Ciolkosz et al., 1995) is of particular interest to Pennsylvanians because it targets Pennsylvania's fragipans. In addition to this review, other information on fragipans in Pennsylvania soils has been gathered.

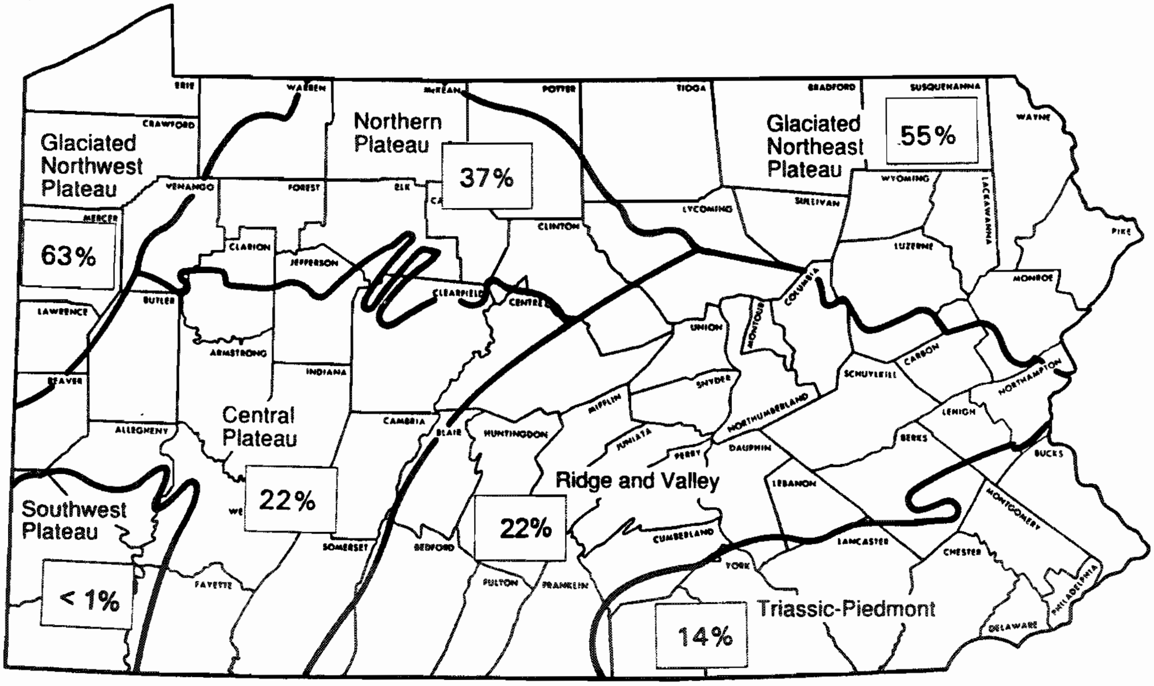

Figure 1. Percent of land area within various Pennsylvania physiographic areas that have fragipans in the soil. Previous data for the Ridge and Valley (14%) and Southwest Plateau (3%) were in error.

Much of this information has been published, but some has not been published. Although much of the published and unpublished information is available, it is in diverse locations. Thus, the intent of this publication is to bring together this information. This will be done by presenting in this introduction a brief discussion of information (primarily unpublished) under the headings fragipan genesis, fragipan hydrology, and fragipan soil climate. In addition, three of the published papers with applications to soil genesis are also presented.

Fragipan Genesis

The genesis of fragipans as viewed by the authors is given in the last reprinted paper in this publication (Ciolkosz et al., 1995). In general, fragipans are viewed as pedologically rapidly developing horizons (Bx) that, once formed, degraded with time. Early in the study of fragipans, it was debated whether a fragipan was geologic or pedologic? A part of this paradigm was rooted in the 1950's and 60's, when fragipans in Pennsylvania and elsewhere were described as having both Bx and Cx horizons. The separation in the late 1960's was made on whether the material had intraprism clay films (mainly in the pores). The very coarse prismatic structure was not considered a significant property in B vs C horizon separation. In 1973, during a field trip at Cornell University, Dr. Marlin Cline (he was retired at that time) was asked about the B vs C horizon issue, and he said that if the structure is pedogenic, it is a B horizon. That statement convincingly indicated that the term Cx was inappropriate for fragipan material that had very coarse prismatic structure. Since that time, the Bx horizon concept has gained acceptance, and the Cx horizon has been dropped from soil profile descriptions. This acceptance somewhat parallels the concept that Cca horizons (accumulation of illuvial $CaCO_3$ in soils with limited rainfall) are really Bca (now indicated as Bk horizons). These paradigm changes have acknowledged the pedogenic origin of both calcic and fragipan horizons in soils.

One aspect of Pennsylvania fragipans has been studied and deserves more attention. This is the bulk density relations of fragipans. In 1993, the USDA Natural Resources Conservation Service (NRCS) National Soil Survey Center proposed that bulk densities of 1.60 Mg m-3 (with ≥ 25% clay) to 1.65 Mg m-3 (with clay content < 25%) be used to define a fragipan (Glocker and Quandt, 1993). Work on Pennsylvania fragipans (Figure 2) indicates that loess fragipans and the upper fragipan horizons in old alluvium can have bulk densities less than 1.6 Mg m-3. Thus, many Pennsylvania fragipans would not meet this 1.6 requirement. The bulk density proposal has not been implemented as a diagnostic criteria for fragipans. The data in Figure 2 also shows that fragipan bulk density is higher in glacial till and colluvium than in loess, and it is somewhat in between these values in old alluvium (terrace deposits). In general, these data follow the conclusions given in Table 3 of Ciolkosz et al. (1995) (the last reprinted paper in this

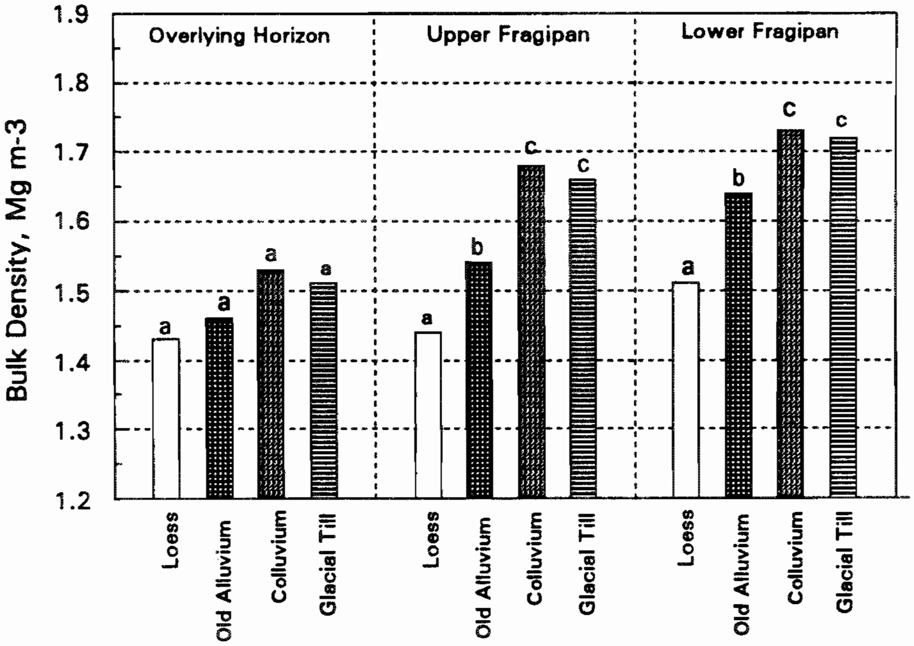

Figure 2. Mean (fine earth < 2 mm; 1/3 atmosphere moisture) bulk density of fragipan horizons (upper and lower) and overlying horizons grouped by parent material. Within each horizon, values followed by different letters are significantly different at $p = 0.05$. This data set represents 169 pedons of data from the Penn State Soil Characterization Lab (Ciolkosz, 2000).

publication), which indicate that till, and colluvial fragipans show a greater degree of development than loess fragipans. This general observation needs to be tested more rigorously, and hard data are needed to support this apparent relationship. Although more study is needed, intuitively increasing fragipan development should be accompanied by increasing bulk density. Figure 2 also indicates that the first fragipan horizon is less dense than lower fragipan horizons. This also parallels field observations that indicates that the first fragipan horizon is a less well developed fragic zone. These observations and data indicate that degradation is taking place in the upper part of the fragipan. Loess fragipan soils in the middle and lower Mississippi River Valley show a great deal of degradation in the upper part of the fragipan. This has lead the NRCS to define the fragipan as a zone that must have 60% or more of the horizon firm or very firm and brittle (Soil Survey Staff, 1999). Pennsylvania fragipans do not exhibit a large amount of none brittle volume in their degrading horizons. The difference between Pennsylvania's and the Mississippi River Valley's apparent rates of degradation is probably due to higher temperatures and higher rates of precipitation in the Mississippi River Valley area leading to a faster rate of degradation.

The next subject on fragipans to be discussed is their genesis with time. With few exceptions, there is very little discussion in the literature on what happens to fragipans with time. The conclusions and model (Figure 3) of Ciolkosz et al. (1995) indicates that if the landscape stays stable, fragipans will degrade with time. They will degrade faster in well drained soils than in poorly drained soils. The study by Waltman (1981) of somewhat poorly drained Wisconsinan and Pre-Wisconsinan glacial till fragipan soils showed a distinctive degradation of the fragipan when the young fragipans were compared to the older fragipans. Waltman (1981) presented a number of indicators of degradation (pedogenesis) which included clay mineral weathering, iron

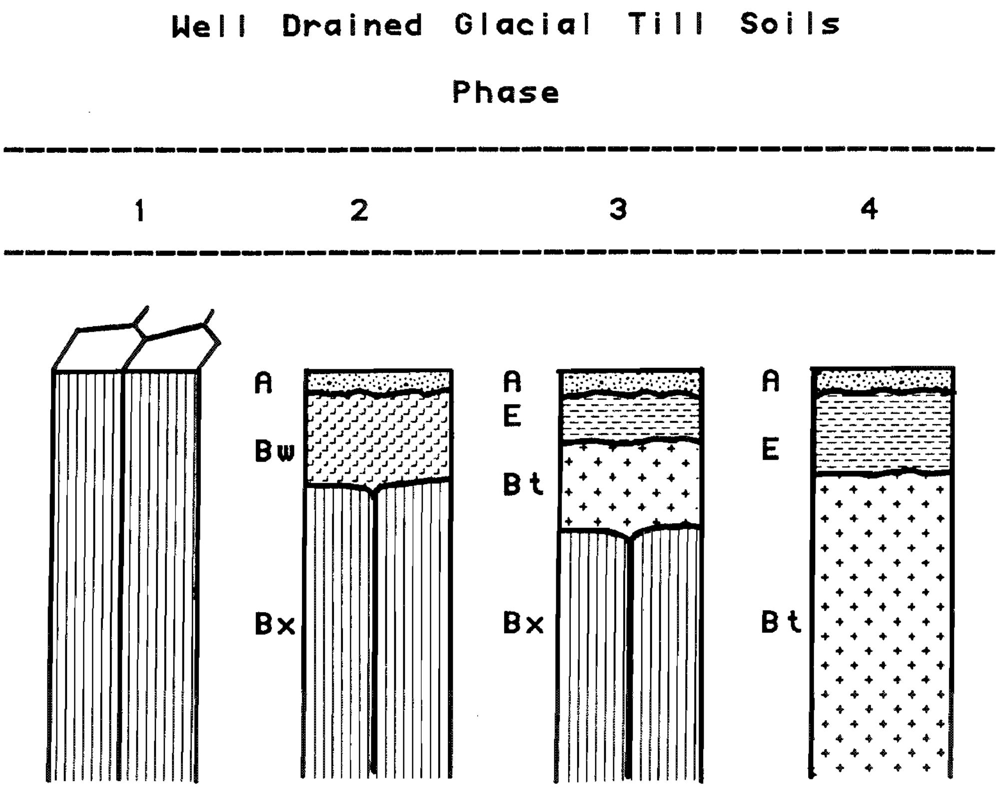

Figure 3. Sequential developmental model for well drained soils developed in glacial till in Northeastern Pennsylvania. Please see Ciolkosz et al. (1995) for a detailed discussion of phases 1-4.

oxide accumulation, clay accumulation (argillic horizon formation), and interestingly, a decrease in bulk density with increased age of the fragipan.

Another interesting note on the amount of time required for a fragipan to form is the conclusion of Cremeens et al. (1998) that a fragipan has formed in alluvium in the Lock Haven area in 4,500 years. This study site was visited while it was being investigated, and no zone was observed that was identified as a fragipan. Although no fragipan was observed at the site, there was a zone that had some features that indicated that a fragipan was forming. This site was somewhat similar to the Atkins site of Bilzi and Ciolkosz (1977) in which some fragipan character was noted in the Bw horizon of the soil that was dated at 1955 ± 80 years BP. In addition, bulk density measurements were made from samples above and in the pan-like zone at the Lock Haven site by the Penn State Soil Characterization Laboratory, and no difference was noted in bulk density between these two zones. Thus, it was concluded that the zone that was called a fragipan at the Lock Haven site would better be called a protofragipan (proto-meaning earliest phase of).

Fragipan Hydrology

The most important impacts that a fragipan has in a soil is its effect on root growth and the water regime of the soil. These impacts greatly affect the land use of fragipan soils for purposes that range from sewage drain fields to agriculture production. Following will be a brief mention of the information both published and unpublished on this general subject area for Pennsylvania fragipans.

Fragipans restrict the down growth of roots through restricted root penetration and the creation of seasonal saturated conditions. Subsoiling has been proposed to increase the effective rooting depth of fragipan soils. Stout and Ciolkosz (1974) tested this proposal in a laboratory study. In this study, broken fragipan material (untreated and treated with aggregating agents to stabilize the broken material) was subjected to wetting and drying cycles. The authors concluded that aggregating agents can increase the rooting depth, but with time, the fragipan material disperses and the material again becomes impermeable. The untreated material dispersed immediately. Thus, in the short run, in the field the aggregating agent approach may be useful, but with time, the treatments would fail, unless natural processes such as soil structure formation would stabilize the material.

Field studies on Pennsylvania fragipan hydrology have been conducted by Palkovics et al., 1975; Palkovics and Petersen, 1977; Daniels, 1992; Daniels and Fritton, 1994; Day et al., 1998; Calmon et al., 1998; and Jabro and Fritton, 1990).

The studies of Palkovics and Petersen (1975, 1977) in colluvium in the Ridge and Valley area, Calmon et al. (1998) in glacial till in the northeast area, and Latshaw and Thompson (1972; also see Simpson, 1979) in the southeast area document the seasonal trends of saturated conditions above the fragipan in leaf off (late fall, winter, and early spring) seasons in Pennsylvania. In a slightly different type of flow study, Day et al. (1998) measured the amount of lateral flow above the fragipan and between the prism faces in a Wisconsinan glacial till fragipan in Wayne County (northeastern PA near Lake Wallenpaupack). The authors concluded that 63% of the input water moved laterally above the fragipan and 10% moved laterally through the prism face area of the upper 50 cm of the fragipan. The remaining 27% moved laterally below 50 cm or vertically through the fragipan. Observations (primarily in Ridge and Valley sideslope colluvium) indicate that fragipans may not be continuous on the landscape; therefore, there may be areas (sumps) that drain water downward within a fragipan landscape. The lack of continuity (sumps) in fragipans of the Ridge and Valley was observed in colluvial parent materials in which the parent material changed rapidly, which apparently did not allow fragipan formation in some of the material. In addition to having sumps, fragipans tend to have an irregular surface. This irregularity is usually not noticeable in soil pits, but it is on lower side slopes in roads cuts (relatively fresh) in the spring as the top of a wet zone (darker color) as lateral flow discharge from the cut surface and runs down the ditch bank.

The study of Daniels and Fritton (1994) documented that a water mound can build up above a fragipan in conditions similar to septic tank drainage fields. This build up is due to the low permeability in the fragipan. The low permeability of fragipans, as pointed out by Olson (1985), may be in part due to a relatively large amount of fine low water conducting pores and a small amount of coarse high water conducting pores. With few exceptions (Jabro and Fritton, 1990; Palkovics, 1973), little data is available on the hydraulic conductivity of Pennsylvania fragipans. Although this is the case, there have been percolation tests done on over 400 Pennsylvania soils (many of which have fragipans) as a part of the soil characterization program in Pennsylvania (Ciolkosz et al., 1998). These data have been summarized by Matelski (1975), and the complete data are available in the Penn State soil characterization lab database (Ciolkosz, 2000). The leap from percolation rate to saturated hydraulic conductivity is great, and as yet, no one has attempted to distill any hydraulic conductivity information from this source.

The effect of a perched water table on surface runoff of a fragipan soil is presently being studied by Brian Needleman (Needleman, 2002). This study is being conducted in the USDA ARS Mahantango Creek watershed in eastern Pennsylvania; and in the near future, these results will be available.

Fragipan Soil Climate

To the authors' knowledge, no studies have addressed fragipan expression under varying climatic regimes. For the most part, Pennsylvania fragipans are associated with Udic or Aquic soil moisture regimes. Although this is the case, there must be impacts of differences in annual water balances, frequency of drying events in the growing season, and argillic horizon expression relative to fragipan development. In Pennsylvania, summer water balances ($PREC-PET_{june-july-august}$) vary greatly from the Ridge and Valley (Figure 4) with a pronounced water balance deficit to the Appalachian Plateau, with portions of the higher plateau having a moisture surplus (Figure 5) through the summer months (Waltman et al., 1997). Therefore, the differences in the above ground climates may play a role in the occurrence of fragipans with argillic horizons and the expression of the brittleness and possibly the firmness in the fragipan.

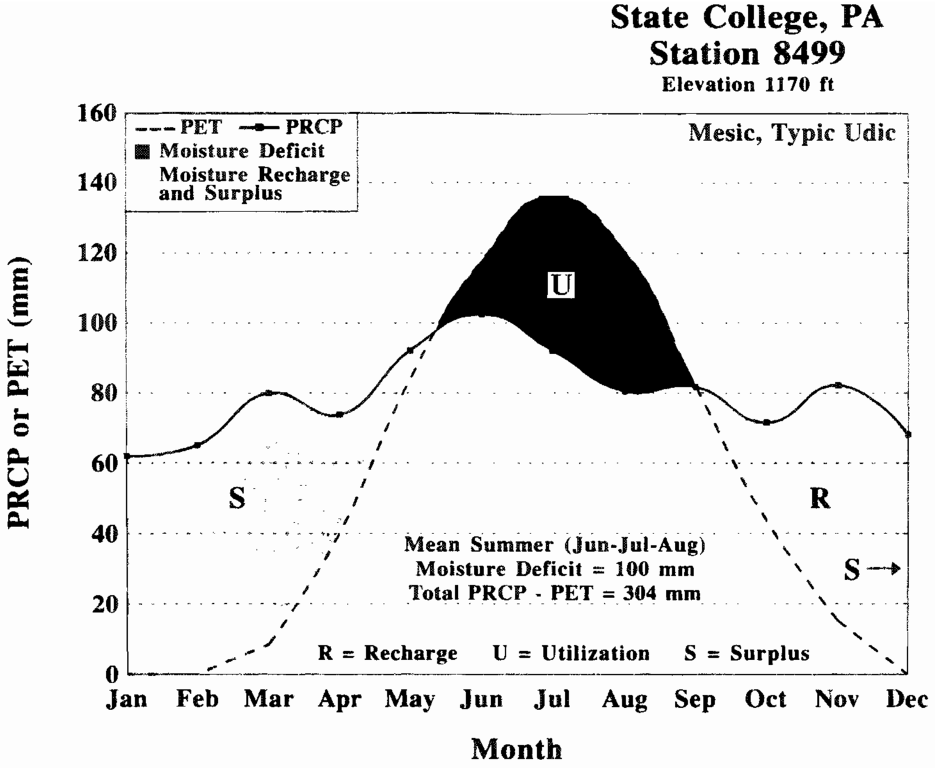

Figure 4. Moisture balance for State College, Pennsylvania, based upon a period of 1961-1990. PET calculated by the Newhall Simulation Model as modified by Van Wambeke et al. (1992) (Waltman et al., 1997).

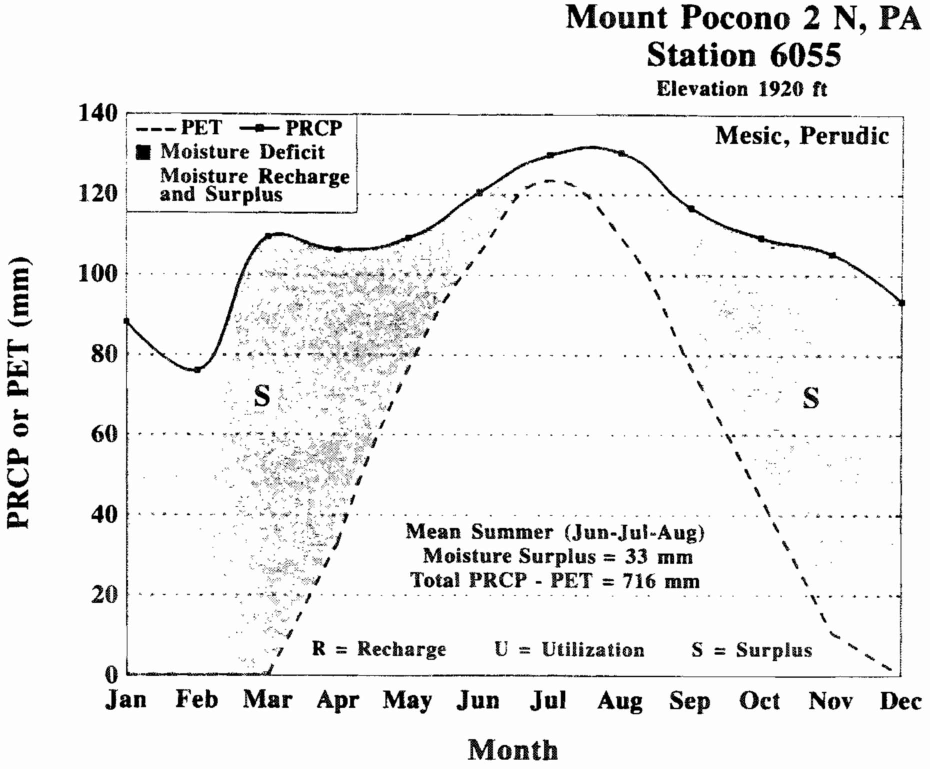

Figure 5. Moisture balance for Mount Pocono 2 N, Pennsylvania, based upon a period of 1927-1960. PET calculated by the Newhall Simulation Model as modified by Van Wambeke et al. (1992) (Waltman et al., 1997).

Although argillic horizons above the fragipan or within the fragipan have long been recognized in the Ridge and Valley Province, fragipan soils on parts of the Appalachian Plateau often lack argillic horizon development (Bath-Mardin-Volusia; Swartswood-Wurtsboro) or they have weakly expressed argillic horizon development above the fragipan (Cookport-Nolo; Ernest-Brinkerton). In the past, the presence or absence of argillic horizons has often been attributed to the age of the parent materials (i.e. Wisconsinan versus Pre-Wisconsinan) or its composition rather than the recognition of the importance of a moisture deficit in the process of argillic horizon formation and the degradation of fragipans. Additionally, under different climatic regimes, fragipans should not be expected to behave similarly with respect to various land uses. For example, given parallel landscape positions and depth to the upper surface of the fragipan, fragipan soils in Typic Udic and Perudic areas would not be expected to behave similarly with respect to leach fields or many other land uses. In future research, greater emphasis needs to be placed on relating fragipan horizonation and morphology to climate characteristics, as part of enhancing soil interpretations.

Grossman and Carlisle (1969) proposed a "dessication-crack" hypothesis in the development of fragipans. As part of the hypothesis, drying cycles would generate shrinkage cracks (i.e. prismatic structure) in the soil and soil materials from horizons above would wash into these spaces and re-expand during wetting cycles. The expansion would increase the density of the prisms and result in the higher bulk densities associated with fragipans. Given the dessication-crack hypothesis, fragipans in areas with significant drying periods or a greater frequency of cycles might be expected to have more strongly expressed fragipan horizons. However, from field observations and soil characterization work, the glacial till fragipan soils in northeastern Pennsylvania with the moister Udic to Perudic environments often have higher bulk densities than fragipan soils in the older Pre-Wisconsinan till soils or in the colluvial soils that would be associated with the more pronounced summer moisture deficits of the Ridge and Valley Province. This may point out a parent material influence or that wetting and drying and the resultant expansion and contraction is a packing mechanism in early fragipan formation and in later fragipan pedogenesis a degrading mechanism. This may also indicate that expansion and contraction and argillic horizon formation in the Ridge and Valley are working at a more rapid rate to degrade fragipans than in the more Perudic northeast plateau area.

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Fragipans in Pennsylvania Soils: A Statistical Study of Laboratory Data[1]

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ABSTRACT

Soils sampled for laboratory characterization in Pennsylvania were separated into those profiles with fragipans and those without fragipans to determine statistically the soil properties consistently related to fragipan occurrence. Fragipans occurred in the following five parent material groups: aeolium, fluvium, lacustrine deposits, glacial till, and colluvium. Comparisons were made with horizons from comparable depths from nonfragic soils in these same parent material groups, except for colluvial soils, which in every case contained fragipans. Data were analyzed from 773 samples from 254 soil profiles. Fragipan bulk densities of the < 2-mm material were significantly higher at the 1% level than nonfragipan horizons within till and fluvial parent materials, but were not significantly different within aeolian and lacustrine deposits. Multiple regression analyses using 16 soil variables indicated no relationships between these variables and bulk density. Plots of soil textures showed clustering of fragipan samples in loam and silt loam textural classes, whereas nonfragipan samples were more widely spread over other textural classes. Fragipans had significantly lower organic carbon, lower Ca:Mg ratios, and higher mean base saturations with less alteration of illite to vermiculite than nonfragipan horizons. Chemical and mineralogical data indicate that fragipans are less leached and less weathered than comparable nonfragipan horizons.

Additional Key Words for Indexing: **parent material, bulk density, texture, chemical and mineralogical properties.**

FRAGIPANS, a common subsurface horizon in Pennsylvania soils, are dense and relatively impermeable to water and roots, and usually occur within 30 to 90 cm of the surface and may extend beyond 150 cm. They are hard to extremely hard when dry and firm to very firm when moist. When pressure is exerted on portions of the displaced fragipan, the soil shatters showing brittleness. Fragipans generally have very coarse prismatic structure with prisms delineated by lighter colored soil material. These prisms range from 20 to 75 cm in diameter. Morphologically, some fragipans appear similar to those described in New York (2) with insufficient clay accumulation for an argillic horizon, while others are considered part of an argillic horizon like those described in Illinois (3). These fragipans occur below A'2 or cambic horizons and below or are part of argillic horizons.

This study was initiated to determine statistically the soil properties consistently related to fragipan occurrence in Pennsylvania in an effort to characterize them more precisely.

MATERIALS AND METHODS

Data from 773 samples from 254 soil profiles were used in this study. These samples were collected over the last 10 years during the progress of Pennsylvania's Soil Characterization Program. Prior to sampling each soil profile was described in detail by personnel from the Agronomy Department and Soil Conservation Service. Horizon designations were assigned that included subdivision of the fragipans. Using these descriptions, soil profiles were placed into one of two groups—those with fragipans and those without fragipans. Profiles with fragipans were separated into parent material classes and these same parent material classes were used to group the nonfragipan soils. All fragipan horizons were contrasted with all nonfragipan horizons from comparable depths in other profiles within the same parent material classes.

Bulk density was determined with saran-coated clods (1) or 2.5 by 5 cm (1 by 2 inch) core samples (13). Bulk density of the <2-mm material was calculated after subtracting the weight and volume of coarse fragments in each clod or core from the total weight and volume. Coefficient of linear extensibility (COLE) was calculated from moist and dry clod bulk density (4).

Coarse fragment percentages were determined by sieving bulk samples. Particle-size analysis was done by the pipette method (7).

Ca, Mg, and K were extracted with neutral NH_4OAc solution. Ca and Mg were determined by precipitation methods (11) or atomic absorption. K was determined by flame emission. Exchange acidity was determined by the $BaCl_2$-triethanolamine method (8) and cation exchange capacity was calculated by summing the cations. Aluminum was extracted with unbuffered KCl solution and determined by aluminon. Reaction was measured with a pH meter and glass electrode using a 1:1 mixture of water and air dried soil. Organic carbon was determined with a Fisher high-frequency induction furnace (15).

Clay minerals were identified by x-ray diffraction following treatment with sodium dithionite-citrate-bicarbonate (9) or oxalic acid (6) for removal of iron oxides. X-ray patterns were made with Mg saturation with and without ethylene glycol solvation, and with K saturation at room temperature, 300C and 500C. Mineral percentages were estimated (to the nearest 5 or 10%) by relative peak heights based on known mineral mixtures (L. J. Johnson, *unpublished data, Dept. of Agronomy, Pennsylvania State Univ., University Park, Pa. 16802*).

Statistical analyses were performed on the IBM 360 using single classification analysis of variance (12, p. 101–106) to determine means and Duncan's multiple range test (12, p. 107–109) for means comparisons.

RESULTS AND DISCUSSION

Parent Material

Fragipans occurred in profiles developed from the following unconsolidated, transported parent materials: aeolium, colluvium, fluvium, lacustrine deposits, and till.

Morphologically, fragipans are not as strongly expressed

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Table 1—Means of soil properties within fragipan and nonfragipan horizons by parent material groups and by drainage class within till

			Sands										Clay minerals							Extractable cations							
Parent material	n	Coarse fragments	Very coarse	Coarse	Medium	Fine	Very fine	Total sand	Total silt	Total clay	Organic carbon	Iron oxide	Kaol	Ill	Verm	Mt	Chl	Int	pH	Ca	Mg	K	Total bases	Acidity	CEC (sum)	Al	Base sat.
		% by weight																		meq/100 g of < 2-mm material							%
									Fragipan horizons																		
Aeolium	25	7.2	0.6	1.9	1.8	1.5	3.3	9.2	74.4	16.4	0.10	2.8	21	40	15	19	1	4	5.6	3.0	3.7	0.1	7.1	8.0	15.1	0.9	47.2
Colluvium	48	25.7	4.1	4.6	7.5	8.2	9.8	34.2	42.0	23.8	0.34	2.3	29	49	10	3	1	8	5.1	2.8	2.0	0.2	5.2	9.1	14.3	2.7	33.9
Fluvium	23	6.1	0.5	1.1	2.9	5.1	7.5	17.1	61.4	21.6	0.14	2.7	22	34	12	12	0	20	5.0	3.0	2.4	0.1	5.6	9.8	15.5	2.7	36.1
Lacustrine deposits	10	7.6	1.3	1.6	2.2	4.9	13.9	23.9	59.0	17.1	0.19	2.4	8	55	14	0	19	4	5.3	2.2	2.0	0.1	4.5	7.5	12.0	0.8	36.5
Till	281	38.0	0.1	5.5	6.9	9.9	10.9	38.4	43.4	18.3	0.13	2.1	8	63	7	3	9	10	5.5	2.6	1.4	0.1	4.2	6.2	10.4	1.2	38.4
Well	61	42.6	6.3	6.9	9.5	13.1	11.6	47.3	36.9	15.9	0.09	2.3	6	64	7	1	16	5	5.1	0.7	0.5	0.1	1.4	6.1	7.5	1.2	20.2
Moderately well	84	40.0	5.8	5.8	6.9	11.0	11.6	41.1	42.2	16.8	0.12	2.0	5	66	5	2	12	10	5.2	1.7	1.1	0.1	3.0	6.6	9.6	1.3	31.7
Somewhat poorly	88	33.3	4.2	4.3	5.7	8.3	10.6	33.0	45.9	21.1	0.13	2.0	12	56	9	5	3	13	5.4	3.5	1.8	0.1	5.6	7.3	12.9	1.5	42.5
Poorly	29	34.8	4.2	4.8	5.3	7.2	8.8	30.4	47.7	21.8	0.12	2.0	12	65	6	5	6	6	6.5	5.8	2.5	0.1	8.5	3.8	12.3	0.4	65.6
Very poorly	19	40.8	5.8	5.7	6.0	6.9	9.5	33.9	51.2	14.8	0.38	1.8	3	62	12	3	4	14	6.2	3.6	1.9	0.1	5.7	3.4	9.1	0.1	65.4
Total fragipan	387	32.0	4.5	4.8	6.3	8.8	10.1	34.5	46.5	18.9	0.16	2.2	12	59	8	5	7	9	5.4	2.6	1.7	0.1	4.6	6.9	11.6	1.3	38.1
									Non-fragipan horizons																		
Aeolium	28	2.6	0.5	1.1	1.9	3.1	8.2	14.8	68.0	17.2	0.23	2.6	18	40	24	2	9	7	5.6	2.8	1.2	0.1	4.3	5.9	10.2	0.6	42.6
Fluvium	229	20.1	4.1	5.6	11.6	17.6	14.4	52.2	32.9	13.9	0.40	2.1	14	43	21	5	6	10	5.7	3.8	1.0	0.1	5.1	6.2	11.3	1.3	41.8
Lacustrine deposits	16	4.9	0.9	1.6	3.1	4.5	8.6	18.9	52.9	28.4	0.36	2.7	35	39	9	6	2	10	4.8	3.4	3.2	0.2	7.0	11.2	18.2	-	39.4
Till	113	45.9	6.6	8.2	7.3	7.9	7.7	37.7	40.1	22.1	0.33	2.6	10	51	18	2	10	9	5.5	2.5	0.8	0.1	3.5	7.3	10.8	2.2	33.5
Total non-fragipan	386	25.7	4.4	5.9	9.2	13.2	11.7	44.5	38.4	17.1	0.36	2.2	16	44	20	4	6	10	5.6	3.3	1.0	0.1	4.6	6.7	11.4	1.4	39.2

Table 2—Bulk densities of the < 2-mm fraction of fragipan and nonfragipan horizons by parent material groups

Parent material	n	< 2-mm bulk density, g/cc	Stat.* sig.
Till	27	1.36	a
Aeolium	22	1.46	ab
Aeolium (x)†	21	1.48	bc
Fluvium	130	1.48	bcd
Lacustrine (x) deposits	10	1.52	bcde
Lacustrine deposits	12	1.57	bcdef
Fluvium (x)	23	1.61	ef
Colluvium (x)	20	1.66	ef
Till (x)	232	1.67	f

* Duncan's multiple range at 1% level. Classes without a common letter are significantly different.

† (x) indicates fragipan horizon.

in soil profiles developed in aeolian and lacustrine parent materials and this is exemplified by the similarity in soil properties between fragipan and nonfragipan horizons from profiles developed in these two materials (Tables 1 and 2).

Within the fluvial parent material group, fragipans only occurred in silt loam and loam materials in high terrace positions. No floodplain soils contained fragipans. This may indicate that fragipan development in fluvial materials requires medium textures and considerable time or that the environment no longer favors fragipan formation in recently deposited fluvial materials.

Fragipans are rare in residual soils in Pennsylvania and consequently few fragipans in soils derived from residuum have been sampled. Therefore residuum was not considered as a parent material group for the study of fragipan characteristics.

Bulk Density

Bulk densities of the < 2-mm material from fragipan and nonfragipan horizons were averaged within each parent material group (Table 2). Fragipan bulk densities were significantly higher, at the 1% level, than nonfragipan horizons within till and fluvial parent materials, but were not significantly different within aeolian and lacustrine deposits. All the colluvial soils sampled contained fragipans. The mean bulk density of all fragipan horizons was 1.65 and for all nonfragipan horizons from comparable depths it was 1.47.

Multiple correlation and regression analyses were used to determine if some selected soil variables were importantly related to soil bulk density within fragipans. The following soil variables were included in the analyses: percentages of very coarse, coarse, medium, fine, and very fine sands; 50–5μ, 20–2μ and 5–2μ silts; total sand, silt, and clay; coarse fragments and organic carbon; COLE values; and median depth of subhorizon. No consistent relationships were found within the parent material groups and usually the multiple correlation coefficient (R) was not significant. When using partial correlations, median depth and coarse fragment content were always positively correlated with bulk density, and organic carbon negatively correlated, although not always significant. None of the other variables showed any consistent trends.

Texture

Field observations have indicated that fragipans are generally medium textured. Winters and Simonson (14) and Grossman and Carlisle (5) have also reported that fragipans tend to be medium textured. To test this premise, sand, silt, and clay percentages from fragipan horizons and nonfragipan horizons were plotted on textural triangles for each parent material group. Within each parent material group, most textures of the fragipan horizons plotted in the loam and silt loam portions of the textural triangle, whereas the nonfragipan horizon textures were more dispersed throughout the triangle. These differences in dispersion are very evident when comparing plots of fragipan and nonfragipan horizons from profiles formed in glacial till (Fig. 1). Within the fragipan horizons 80% of the horizons in the till parent material group plotted as silt loams or loams, 100% of the lacustrine, 92% of the aeolian, 91% of the fluvial, and 59% of the colluvial. The

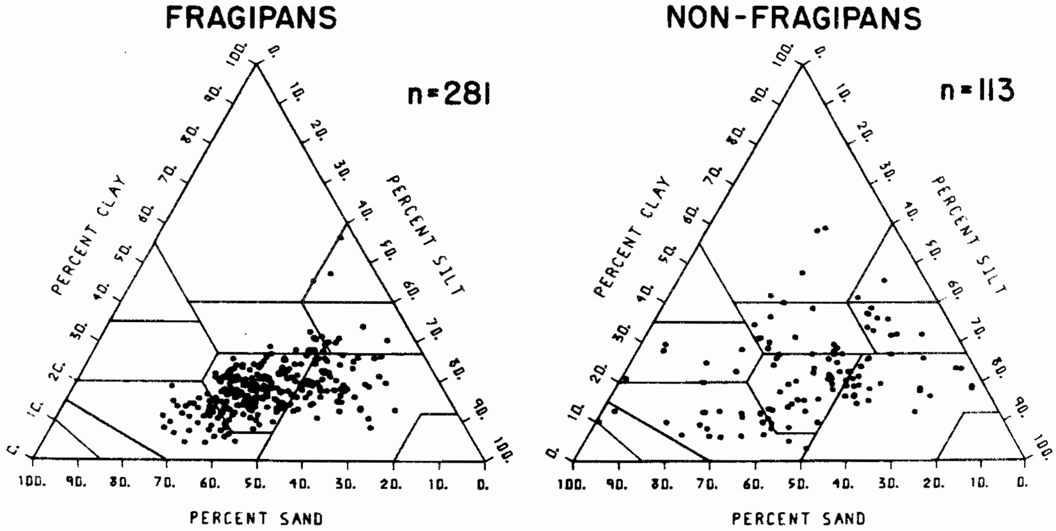

Fig. 1—Textural distribution of fragipan and nonfragipan horizons from soils developed within glacial till.

nonfragipan horizons were more dispersed with 48% of the tills plotting as silt loams or loams, 44% of the lacustrine, 92% of the aeolian, and 31% of the fluvial.

Average sand, silt, and clay percentages and their standard deviations were computed for all the fragipan horizons as well as for all the nonfragipan horizons to indicate the relative dispersions of textures within each group. The average texture of the fragipans plot as loams near the silt loam boundary, whereas the nonfragipans plot near the center of the loam textural class. Standard deviations for particle size percentages were as follows: fragipans—sand-15.5, silt- 13.3, clay-6.7; nonfragipans—sand-25.4, silt-19.1, clay-10.6. Standard deviations were greater for each of the sand, silt, and clay percentages for the nonfragipan horizons than the fragipan horizons, indicating more textural dispersion of the nonfragipan horizons. The differences in their dispersion can be shown by adding the standard deviations for sand, silt, and clay percentages for the fragipan horizons and for the nonfragipan horizons to determine their "total deviation." The "total deviation" of the nonfragipan horizons is almost twice that of the fragipan horizons.

Because of this clustering of textures for fragipan horizons, a fragipan textural class was determined. This was done by plotting the mean fragipan texture and taking two standard deviations on each side for the mean sand, silt, and clay percentages and using these limits to form the sides of a polygon (Fig. 2). This polygon would then include most of the textures of the fragipan samples. A confidence probability cannot be assigned to this polygon as the sand, silt, and clay percentages are not independent, but are strongly dependent.

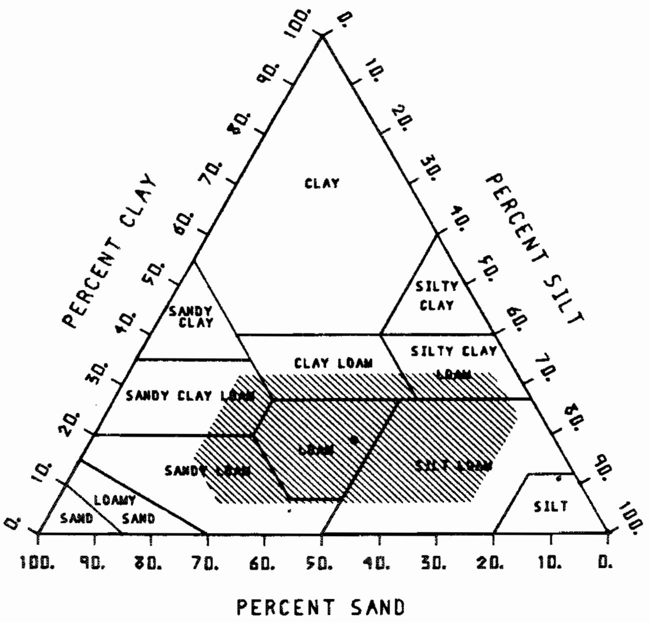

Fig. 2—Fragipan textural class.

Chemical and Mineralogical Properties

Statistically, fragipans had significantly lower organic carbon content and Ca/Mg ratios than nonfragipan horizons (Table 1). Mean base saturations were generally higher in fragipans than in nonfragipan horizons indicating that fragipans are less leached and less weathered. The nonfragipan horizons formed in fluvial materials, however, were higher in base saturation than the fragipan horizons presumably because many of these soils are more recent and less weathered than the fluvial soils with fragipans. Base saturations were similar within lacustrine soils for both fragipans and nonfragipan horizons. These soils tend to have high base saturation because of their fine textures and the presence or absence of a fragipan would not greatly affect the leaching of these profiles.

The clays of all parent material groups were predominantly illite, which weathers to vermiculite during soil profile development. In soil profiles with fragipans, the portions of the profiles above the fragipan typically show considerable weathering of illite to vermiculite. However, at the upper boundary of the fragipan the clay mineralogy

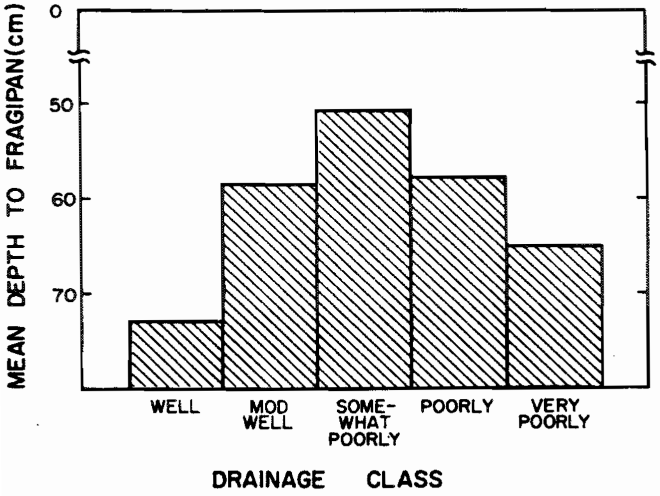

Fig. 3—Relationships of mean depth to fragipan and drainage class of soils developed from glacial till.

changes markedly as the fragipans are high in illite and low in vermiculite. Fragipans show less alteration of illite to vermiculite than nonfragipan horizons (Table 1) indicating retardation of clay mineral alterations and chemical weathering within fragipans.

Drainage Class

To determine if fragipan development differed with changes in soil drainage, soils developed in till were separated into five groups according to drainage class. The mean depth to fragipan varied as shown in Fig. 3. Fragipans tend to be closer to the surface in somewhat poorly drained soils and also tend to be most strongly expressed within soils of this drainage class. Similar relationships were also observed in North Carolina coastal plain sediments (10). The drainage of the moderately well and somewhat poorly drained soils may be controlled by the presence of fragipans whereas the drainage of the poorly and very poorly drained soils may be controlled more by depressional topographic position.

Bulk densities progressively increased from well to poorly drained soils (Table 3). The well and moderately well drained classes have bulk densities significantly lower, at the 5% level, than the somewhat poorly, poorly, and very poorly drained classes. Soil textures also became progressively finer from well drained to poorly drained soils (Table 1) as silt increased at the expense of fine and very fine sand. The pH, total bases, and base saturation also progressively increased from well drained to poorly drained soils (Table 1) and indicates less leaching with poor drainage. Clay mineralogy, however, is similar for all five drainage classes (Table 1) and appears to be related to the presence of fragipans regardless of drainage. This indicates that fragipans have been altered chemically, particularly in better drained soils, but evidently weathering has been insufficient to alter them mineralogically.

Table 3—Bulk densities of the < 2-mm fraction of fragipan horizons developed in till by drainage class

Drainage class	n	< 2-mm bulk density, g/cc	Stat.* sig.
Well	53	1.64	a
Moderately well	65	1.65	a
Somewhat poorly	69	1.70	b
Very poorly	17	1.70	b
Poorly	28	1.71	b

* Duncan's multiple range at 5% level. Classes without a common letter are significantly different.

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Fragipans in Pennsylvania Soils: Properties of Bleached Prism Face Materials[1]

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ABSTRACT

Bleached prism faces are a common feature of soil fragipan horizons. Particle size and chemical and clay mineralogy data indicate these zones are areas of accumulation of material from horizons above. The data also indicates that two processes are active in the movement of material into the prism face area. These processes result in bimodal distribution of particle sizes in the prism face areas. The exact nature of the processes is unclear and may involve both deposition and some stripping.

Additional Index Words: **fragipans, bimodal sorting, prism face materials.**

FRAGIPANS are generally considered to be an important feature in many soils, but a clear definition of these horizons and an explanation of their genesis are still being sought (Grossman and Carlisle, 1969). Very coarse prismatic structure with bleached prism face material is being treated as an important diagnostic feature of fragipans (Soil Survey Staff, 1975).

The pattern of bleached prism faces was vividly described by Nikiforoff (1955) for soils derived from coastal plain sediments in Maryland and by Carlisle[3] who investigated these features in soils derived from glacial till materials in New York. Others contributing information about fragipan prism face material include Gile (1958); Grossman, Fehrenbacher, and Beavers (1959); Jha and Cline (1963); Miller, Wilding, and Holowaychuk (1971); and Lozet and Herbillon (1971).

The Soil Survey Staff (1975) has endorsed a theory expressed by Carlisle[3] that the bleached interprism zones contain material washed from above into desiccation cracks. In *Soil Taxonomy* the authors (Soil Survey Staff, 1975) emphasize the importance of this process. The present study was conducted to confirm or deny the above theory for a number of Pennsylvania fragipan soils found in a variety of settings and developed from a number of different parent materials.

METHODS AND MATERIALS

Over a period of several years, pedons with fragipans and representing a wide range of parent materials were exposed for characterization or other purposes. Many of these fragipan soils have been characterized (Petersen et al., 1970), but the pedons chosen for this study were those with the strongest expression of the pattern of very coarse prismatic structure and bleached prism faces (Table 1).

Several pieces of prism from each fragipan were removed with prism faces intact and brought to the laboratory for dissection. For each clod or piece, the prism-face material (usually 5 to 10 mm thick) was removed with care to include only bleached material. The bright reddish or yellowish brown zone (of similar thickness to the bleached face but more irregular) of iron oxide accumulation was then sampled, and lastly, a sample of the interior of the prism similar in size to the other two samples was obtained. Care was taken to insure that the prism interior was sampled at the same profile depth as the other samples. Thus, for each soil three samples of approximately 50 g each were obtained.

Table 1—Classification and parent materials of pedons used in this study

Parent material	Soil series	Classification	Remarks
Colluvium	Andover	Typic Fragiaquult	Sandstone and shale materials on lower slopes of a ridge.
	Ernest	Aquic Fragiudult	Shale and sandstone materials.
	Evendale (taxadjunct)	Aeric Fragiaquult	Materials weathered from chert and limestone. Evendale series is an Aeric Ochraquult.
	Kreamer (taxadjunct)	Aquic Fragiudult	Materials weathered from chert and limestone.
	Shelmadine	Typic Fragiaqualf	Shale from Martinsburg formation.
Residuum	Cookport[*] (taxadjunct)	Aquic Fragiudalf	Sandstone and shale materials. Some colluvial activity probable. Cookport series is an Aquic Fragiudult.
Loess	Doylestown[†]	Typic Fragiudalf	Thin (69 cm) silt cap over Triassic shales.
Glacial till	Gresham[‡]	Aeric Fragiaqualf	Early Wisconsinan Age.
Terrace deposits	Rainsboro[§] (taxadjunct)	Typic Fragiudalf	Weak argillic development.

[*] Pedon 62-6 (Ciolkosz et al., 1970).
[†] Pedon 9-11 (Peterson et al., 1972).
[‡] Pedon 10-1 (Cunningham et al., 1971).
[§] Pedon 3-11 (Cunningham et al., 1971).

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[2] Assistant Professor, Associate Professors, and Professor of Soil Genesis and Morphology, respectively, Department of Agronomy, The Pennsylvania State Univ. The senior author is now deceased.

[3] F. J. Carlisle. 1954. Charcteristics of Soils with Fragipans in a Podzol Region. Ph.D. thesis. Cornell University, Ithaca, NY.

Table 2—Particle-size distribution of subsamples from dissected fragipans

Horizon	Gravel or shale, >2mm†	Very coarse sand, 2-1mm	Coarse sand, 1-0.5mm	Medium sand, 0.5-0.25mm	Fine sand, 0.25-0.1mm	Very fine sand, 0.1-0.05mm	Coarse silt, 0.05-0.02mm	Fine silt, 0.02-0.002mm	Clay, <0.002 mm	Ratio coarse silt/fine silt
	%	% of <2-mm fraction								
Andover Bx2, 76-97 cm										
Prism face	7.0	2.4	2.5	5.0	7.1	7.9	10.4	33.0	31.6	0.32
Iron oxide zone	18.2	8.1	6.6	8.4	9.1	8.1	15.3	26.2	18.2	0.58
Prism interior	19.9	9.4	5.9	7.7	8.9	7.1	8.4	26.1	26.4	0.32
Andover Bx3, 97-114 cm										
Prism face	11.6	1.1	2.4	6.6	9.1	8.8	11.3	31.9	28.8	0.35
Iron oxide zone	19.3	8.3	7.4	6.8	8.0	7.7	10.0	26.9	24.9	0.37
Prism interior	32.7	9.4	7.8	8.1	7.7	6.7	9.9	26.2	24.3	0.38
Ernest Bx1, 51-89 cm										
Prism face	5.2	0.0	0.6	1.0	8.8	21.4	17.2	29.3	21.8	0.59
Iron oxide zone	21.0	9.0	6.7	4.3	8.3	15.9	10.4	25.4	20.0	0.41
Prism interior	31.0	9.9	9.3	5.2	8.4	15.2	11.9	24.2	15.9	0.49
Evendale taxadjunct Bx2, 127-147 cm										
Prism face	4.0	0.3	0.7	0.7	1.1	3.3	18.9	30.4	44.6	0.62
Thick clay films	other particle-sizes not determined								85.8*	--
Iron oxide zone	6.9	3.0	2.0	1.9	2.1	2.9	16.4	32.1	39.8	0.51
Prism interior	8.5	1.1	1.7	1.4	1.6	2.4	14.7	34.6	42.6	0.44
Kreamer taxadjunct Bx1, 125-140 cm										
Prism face	6.3	1.4	1.9	4.3	9.4	6.9	20.3	34.9	20.9	0.58
Iron oxide zone	14.3	4.2	6.4	6.3	8.7	6.5	14.6	34.3	18.9	0.43
Prism interior	13.3	2.4	3.5	5.8	9.6	7.0	16.1	32.5	23.0	0.49
Shelmadine Bx5, 165-198 cm										
Prism face	n.d.	1.2	2.2	1.4	9.0	8.5	13.8	31.0	32.7	0.45
Prism interior	n.d.	3.6	6.9	4.7	18.5	7.3	6.2	16.4	36.4	0.38
Cookport taxadjunct, Bx1, 58-69 cm										
Prism face	n.d.	0.2	0.5	1.2	1.7	4.4	26.0	41.8	24.2	0.62
Prism interior	n.d.	2.5	2.8	2.1	1.0	5.5	22.2	41.4	22.5	0.54
Doylestown Bx2, 46-69 cm										
Prism face	n.d.	0.1	0.2	0.6	0.7	2.7	36.4	28.4	30.9	1.28
Prism interior	n.d.	1.5	2.2	1.6	1.5	3.5	42.8	32.3	14.7	1.32
Gresham Bx1, 53-76 cm										
Prism face	n.d.	0.5	0.5	2.0	3.6	6.0	29.4	30.9	27.1	0.95
Iron oxide zone	n.d.	1.4	0.9	2.6	4.6	6.3	30.7	29.6	23.9	1.03
Prism interior	n.d.	3.3	0.7	2.1	3.9	7.0	30.7	32.2	20.1	0.95
Gresham Bx2, 76-99 cm										
Prism face	n.d.	1.2	1.9	3.4	7.4	8.4	28.0	28.9	20.8	0.97
Iron oxide zone	n.d.	4.4	2.1	4.5	7.8	9.3	23.7	29.6	18.7	0.80
Prism interior	n.d.	3.5	2.5	5.2	8.3	8.1	25.0	31.0	16.4	0.81
Rainsboro taxadjunct Bx1, 71-102 cm										
Prism face	n.d.	0.0	0.6	1.9	2.7	6.3	35.1	33.9	19.6	1.03
Prism interior	n.d.	0.0	1.1	2.6	3.3	6.9	30.2	37.8	18.0	0.80

* Thick clay films manually separated from the prism face. n.d., not determined.
† Percent by weight on total soil basis.

The samples were carefully crushed and passed through a 2-mm sieve. Unfortunately coarse fragment percentages were not recorded for the first samples obtained. Particle size analysis was done by the pipette method (Kilmer and Alexander, 1949). Organic carbon was determined with a Fisher high-frequency induction furnace (Young and Lindbeck, 1964). Clay minerals in the <0.002-mm size separate were identified by X-ray diffraction following treatment with sodium dithionate-citrate-bicarbonate (Mehra and Jackson, 1960) for removal of iron oxides. Iron was determined in this extract using ortho-phenanthroline. X-ray diffraction patterns were made of the soil clay with Mg saturation with and without ethylene glycol solvation and with K saturation at room temperature, and after 2-hour heat treatments at 300C and 500C. Mineral percentages were estimated to the nearest 5 or 10% by relative peak heights based on known mineral mixtures (L. J. Johnson, unpublished data).

RESULTS AND DISCUSSION

Field observation generally indicated textural similarity between prism faces and interiors except in some cases where plentiful clay films made higher clay content in prism faces evident. Particle size analysis data, however, indicated there are differences between prism faces and interiors which, though small in some instances, are consistent (Table 2). Particles larger than fine sand (> 0.25 mm) are in every case less plentiful in the prism face material than in the interior. This trend is also evident when particle size distribution is calculated on a clay-free basis. Carlisle[3] reported the same kind of results for soils developed from glacial till in New York and the particle size data presented by Jha and Cline (1963) and by Miller et al. (1971) also show less of the coarser sands in the prism faces than in the interiors. With such consistent differences it is evident that something has happened to the prism faces other than clay illuviation or eluviation and removal of iron oxides (Table 3) since these processes could not remove coarse particles.

Data in Table 2 are consistent with Carlisle's[3] hypothesis that the formation of the prisms resulted from desiccation cracking and that the prism faces have been influenced by addition of material from above. Jha and Cline (1963) thought that formation of desiccation cracks was likely in the pedon they studied but attributed the differentiation of the prism face material to weathering of the prism face zone and removal of clays and perhaps fine silt. There is little evidence of intense weathering in the prism face material of the Pennsylvania soils. The clay mineralogy data in Table 3 indicates a slightly higher percentage of vermiculite and less illite in the prism face material than in the prism interiors. This could be a result of illite weathering to vermiculite, which is the most common mineralogical conversion in the upper horizons of Pennsylvania soils (Ciolkosz et al., 1975), or to the addition of clay size material from above. The latter is the most feasible explanation when it is noted that the clay films of the Evendale prism faces have a very high percentage of vermiculite. Although Jha and Cline (1963) attribute prism face material differentiation

Table 3—Chemical and clay mineralogical data from samples of dissected fragipans

Horizon and subsample	Organic C	Free iron oxides (Fe_2O_3)	Kaolinite	Illite	Vermiculite	Montmorillonite	Interstratified
	%	%	% of <0.002-mm fraction				
Andover B×2, 76-97 cm							
Prism face	0.18	0.7	15	55	30	--	--
Iron oxide zone	0.10	2.7	n. d.				
Prism interior	0.11	2.0	15	60	20	--	5 verm-chl
Andover B×3, 97-114 cm							
Prism face	0.11	0.7	20	55	25	--	--
Iron oxide zone	0.16	2.5	n. d.				
Prism interior	0.02	2.1	20	60	20	--	--
Ernest B×1, 51-89 cm							
Prism face	0.04	0.5	30	35	30	--	5 verm-chl
Iron oxide zone	0.11	4.6	30	45	20	--	5 verm-chl
Prism interior	0.06	2.8	30	45	20	--	5 verm-chl
Evendale taxadjunct B×2, 127-147 cm							
Prism face	0.13	0.4	15	55	25	5	--
Iron oxide zone	0.14	6.0	20	65	15	--	--
Prism interior	0.10	3.8	15	65	20	--	--
Thick clay films	1.07	0.1	10	25	45	20	--
Kreamer taxadjunct B×1, 125-140 cm							
Prism face	0.04	0.3	15	65	20	--	--
Iron oxide zone	0.14	4.1	n. d.				
Prism interior	0.10	3.2	15	70	15	--	--
Cookport taxadjunct B×1, 58-69 cm							
Prism face	0.32*	0.5	30	45	25	--	--
Iron oxide zone	0.23*	4.4	30	50	20	--	--
Prism interior	0.37*	2.8	30	50	20	--	--
Doylestown B×2, 46-69 cm							
Prism face	0.25	0.4	15	35	20	30	--
Iron oxide zone	0.10	4.7	n. d.				
Prism interior	0.09	3.0	20	30	30	20	--
Gresham B×1, 53-76 cm							
Prism face	0.17	0.4	15	35	20	30	--
Iron oxide zone	n. d.	4.8	15	35	20	30	--
Prism interior	0.13	2.7	20	40	15	25	--
Gresham B×2, 76-99 cm							
Prism face	0.08	0.2	25	35	15	25	--
Iron oxide zone	n. d.	3.2	25	40	30	5	--
Prism interior	0.09	2.2	25	40	30	5	--
Rainsboro taxadjunct, B×1, 71-102 cm							
Prism face	0.14	0.8	15	35	30	20	--
Iron oxide zone	n. d.	4.4	n. d.				
Prism interior	0.15	2.3	15	35	30	20	--

* Probably influenced by traces of coal. n. d., not determined.

to weathering they established that there was very little weathering of the quartz-rich silt and sand fractions of their soil. Weathering alone, then, is not a likely cause for differences in sand and silt-size distribution between prism faces and interiors.

The hypothesis of prism formation advanced by Carlisle[3] and the Soil Survey Staff (1975) states that at the end of a relatively dry period, when desiccation cracks are open, the first percolating waters would wash some soil material into the cracks. This material was assumed to be silty and lower in coarse particles because that was the composition of the horizons above. For all the soils listed in Table 2 except the Andover and Ernest, particle size data for overlying horizons are available (Pennsylvania State University, Soil Characterization Laboratory, unpublished data; Ciolkosz et al., 1970; Petersen et al., 1972; Cunningham et al., 1971, 1972). These data show for each soil at least one overlying subhorizon has more > 0.25-mm material than the prism face material. In the Evendale and Cookport pedons every subhorizon above has more > 0.25-mm material than the prism face. Thus, some type of sorting must have occurred during the movement of the material into the cracks or after its deposition.

The evidence of sorting suggests a movement of particles in water suspension with the coarser particles being left behind. We assume from the presence of clay films that clay moved into the prism face zones, and perhaps the silts and even very fine sands were deposited similarly when water flow in the cracks was strong enough.

If the deposition between the prisms were simply a movement in water suspension, one would expect the finer silt particles to be preferentially moved in relation to coarse silt. Consequently, it would seem reasonable to expect a larger proportion of fine silt in the prism face zones particularly where the percentage of clay is higher. However, coarse-to-fine silt ratios given in Table 2 show that prism faces in no instance have a much higher proportion of fine silt and in most cases have a higher proportion of coarse silt than prism interiors. Moreover, the percentage of very fine sand in the majority of cases is higher in the prism face material than in the interiors. In the Kreamer, Shelmadine, Gresham, and Rainsboro soils the prism face material had a higher coarse-to-fine silt ratio than any subhorizon above. In the other soils the tendency is the same with some subhorizons as exceptions. Thus, there is evidence of a bimodal distribution with one peak in the clay size and the other in the coarse silt to very fine sand size material.

Two modes of deposition are probably responsible for the tendency toward bimodal sorting. Deposition of clay films is attributed to movement of clay-size particles in water suspension. The second mode of deposition would be one that favors coarse particles, perhaps because of their easier detachability. The specific nature of this process is unclear. It may possibly be dry movement of individual particles. Particles > 0.25 mm could be excluded from this second process simply by the limited width of the cracks and pores. The second mode could also be a deposition of fine sand, silt, and clay in a suspension when the prism faces are open their maximum width, and a subsequent selective stripping of some clay and fine silt. An alternate mechanism to explain the coarse silt to very fine sand maximum, is physical weathering of the coarse fragments and coarse sands to coarse silt and very fine sand. One of the strongest objections to this mechanism and additional support for the theory of two modes of deposition is presented by the micromorphological observations of Carlisle[3] and Miller et al. (1971). These authors describe layers of clay alternating in many instances with layers of silty material containing little clay in the prism face material. These observations strongly indicate, as Miller et al. (1971) pointed out, that the silty material and the clay were moved at different times under different conditions.

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Fragipans in Pennsylvania Soils[1]

Edward J. Ciolkosz, William J. Waltman, and Nelson C. Thurman[2]

Abstract

Fragipans are a common feature in Pennsylvania, occurring in 30% of Pennsylvania's soils. These fragipans resist root penetration and are characterized by very coarse prismatic structure, firm to very firm brittle consistence, low permeability, bulk densities that are higher than overlying horizons, loamy textures, and a low organic matter content. An index of fragipan expression (weak, moderate, and strong), based on firmness, brittleness, permeability, resistance to root penetration, and strength, is proposed. Fragipans form in transported parent materials: glacial till, colluvium, loess, old alluvium, and, less commonly, in lacustrine and turbated residual materials. Fragipan formation is favored in climates that promote a leaching environment under forest vegetation. Topographic effects on fragipan formation are suggested by the relationship between fragipan expression and depth and drainage. The degree of fragipan expression follows the trend: somewhat poorly drained > moderately well drained > well drained, while the depth to the top of the fragipan follows the opposite trend. Studies suggest that a weakly developed fragipan requires 6000 yr to form, while a strong fragipan requires 18000 yr. A four-phase fragipan formation model is proposed for Pennsylvania fragipans. In Phase 1, transported parent material dries from the surface downward, forming prisms and the prism material is packed slightly. In Phase 2, clay and amorphous aluminosilicates are added to the prisms plugging some pores and creating brittleness by forming grain-to-grain contacts. Maximum fragipan expression occurs during this phase. The upper part of the prism begins to degrade during Phase 3 as more illuvial clay accumulates resulting in increased expansion and contraction during wetting and drying. The prisms are physically broken up and become a part of an overlying argillic horizon. The amorphous materials that formed the grain-to-grain bridges are leached from the upper part of the prism. By Phase 4, these processes have completely destroyed the fragipan.

Fragipans are subsurface, mineral, genetic soil horizons which restrict the downward movement of water and roots (Grossman and Carlisle, 1969; Soil Survey Staff, 1975). According to Grossman and Carlisle (1969) the term fragipan was coined by Guy D. Smith in 1946. Prior to 1946, fragipans had been studied under various names such as silica hardpans (Winters, 1942), siltpans (Smith and Browning, 1946), and just hardpans (see literature cited by Smalley and Davin, 1982; Nikiforoff, 1955). Fragipans have been studied in many works and four excellent reviews have been published (Grossman and Carlisle, 1969; Smalley and Davin, 1982; Smeck and Ciolkosz, 1989; and Glocker and Quandt, 1993). The intent of this presentation is not to review the vast amount of literature on fragipans but to focus on their distribution, properties, and genesis in Pennsylva-

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nia soils. The genetic presentation will be centered on the soil forming factors parent material, vegetation, climate, topography, and time. In addition, a model of fragipan formation and degradation will be presented.

Distribution

In Pennsylvania, fragipans occur in Inceptisol, Alfisols, Ultisols, and Spodosols but not in Entisols or Mollisols (Table 1). The data in Table 1 and Table 2 indicate that 30% of Pennsylvania's landscapes are covered by soils with fragipans. Although almost one-third of Pennsylvania soil has a fragipan, fragipans are not equally distributed across the state. Figure 1 and the data in Table 2 indicate that the largest extent of fragipan soils is found in the glaciated regions of Pennsylvania and the smallest extent is found in the southwest corner of the state, where the soils are dominantly residual.

Properties

Pennsylvania's fragipans have properties that are similar to those found in fragipans in other areas. A large amount of data (201 pedons) has been gathered on fragipan soils through the Pennsylvania State University Soil Characterization Program (Ciolkosz and Thurman, 1992). The studies of Petersen et al. (1970), Ranney et al. (1975), Waltman (1981), Ciolkosz et al. (1989), Ciolkosz et al. (1990), and Waltman et al. (1995), present some of these data. These studies indicate that fragipans are found at variable depth below the surface, with or without an agrillic horizon above it, and they generally have the following properties:

1. Low organic matter content.
2. Loamy texture (without high clay or sand content).
3. Very coarse prismatic structure which may have massive interiors or which may part to platy or subangular blocky structure.
4. Firm or very firm, brittle consistence (moist state).
5. High bulk density (higher than the horizons above it).
6. Low permeability.

In addition except in red parent materials, fragipans commonly have a distinctive dark brown color that contrasts with the color of the cambic or argillic horizon above it. This dark brown color has been coloquially described by Ciolkosz in 1975 as fragipan-brown.

The faces of the prisims are usually friable and gray in color (gleyed) with a bright yellowish brown zone just inside the gray gleyed zone. The gray and yellowish brown zones are each usually 5 to 15 mm thick. The yellowish brown zones are accumulations of iron oxides. The study of Ranney et al. (1975) indicates that the yellowish brown zones contain about two times the iron oxide content of the prism matrix (e.g., 4.5 vs. 2.5%), while the gley zone usually contains less than 0.5%. The iron oxide zone is an accumulation of Fe that was reduced either in the gray prism face area or elsewhere in the soil, moved, and then oxidized and immobilized. This zone is equivalent to the high chroma mottled areas found in wet soils. The difference in fragipans is that the iron oxides form a

Table 1. Order, suborder, and great group acreage data for Pennsylvania soils (Ciolkosz and Dobos, 1989).

Order	Acres	%	Suborder	Acres	%	Great Group	Acres	%
Alfisols	5 652 900	19.68	Aqualfs	1 524 800	5.31	Fragiaqualfs	1 444 200	5.03
						Ochraqualfs	80 600	0.28
			Udalfs	4 128 100	14.37	Fragiudalfs	790 300	2.75
						Hapludalfs	3 337 800	11.62
Entisols	1 218 300	4.24	Aquents	714 700	2.49	Fluvaquents	714 700	2.49
			Arents	2 800	0.01	Arents	2 800	0.01
			Fluvents	69 100	0.24	Udifluvents	69 100	0.24
			Orthents	410 200	1.43	Udorthents	410 200	1.43
			Psamments	21 500	0.07	Quartzipsamments	12 100	0.04
						Udipsamments	9 400	0.03
Histosols	18 400	0.06	Saprists	18 400	0.06	Medisaprists	18 400	0.06
Inceptisols	12 106 200	42.15	Aquepts	1 557 300	5.42	Fragiaquepts	1 390 300	4.84
						Haplaquepts	140 700	0.49
						Humaquepts	26 300	0.09
			Ochrepts	10 548 900	36.73	Dystrochrepts	8 443 600	29.37
						Eutrochrepts	146 900	0.51
						Fragiochrepts	1 968 400	6.85
Mollisols	40 800	0.14	Aquolls	16 700	0.06	Haplaquolls	16 700	0.06
			Udolls	24 100	0.08	Hapludolls	24 100	0.08
Spodosols	109 200	0.38	Orthods	109 200	0.38	Fragiorthods	9 800	0.03
						Haplorthods	99 400	0.35
Ultisols	9 581 900	33.35	Aquults	934 400	3.25	Fragiaquults	408 100	1.42
						Ochraquults	526 300	1.83
			Udults	8 647 500	30.10	Fragiudults	3 392 700	11.81
						Hapludults	5 254 800	18.29
Total							28 727 700	100.00

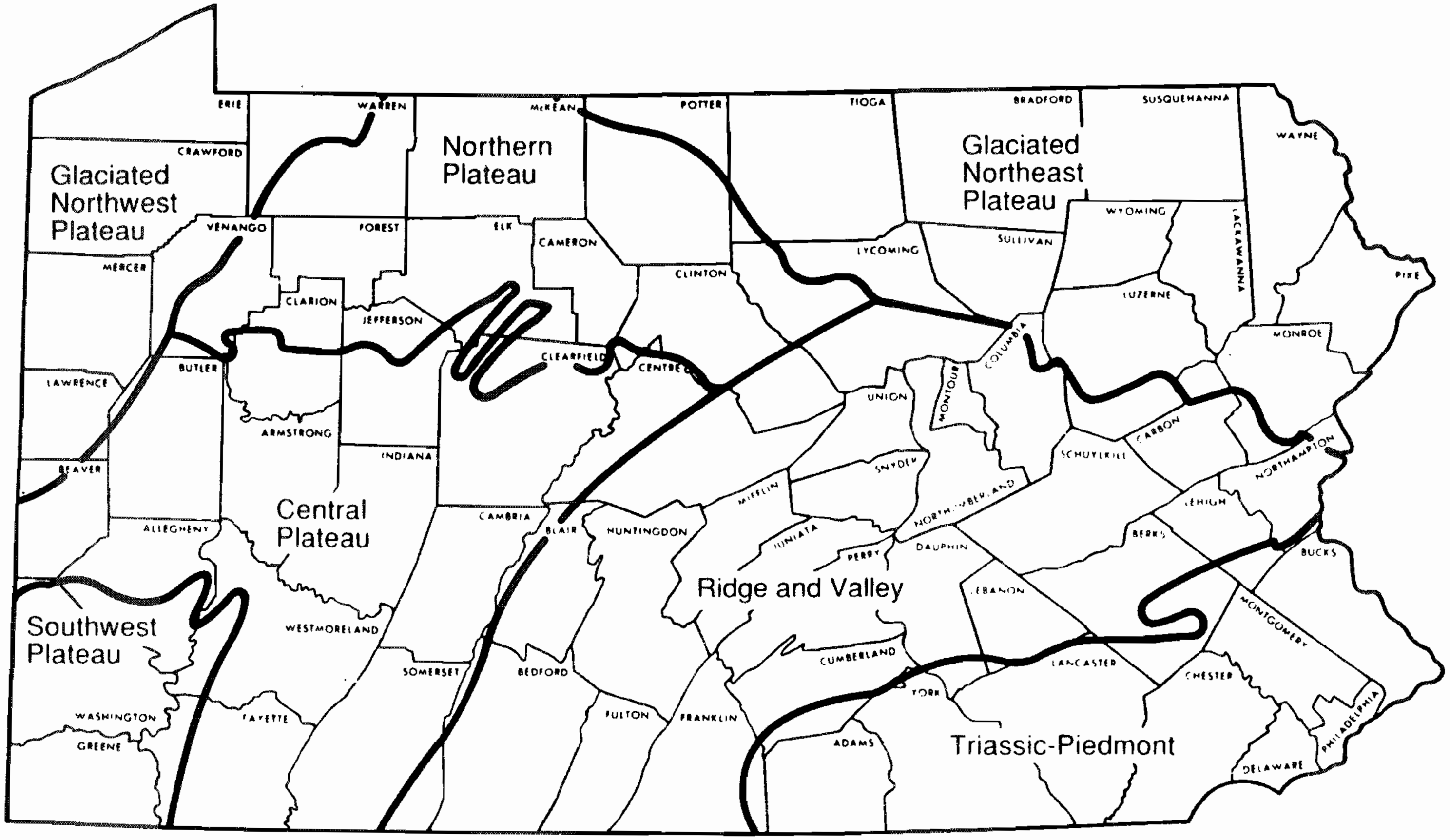

Fig. 1. Physiographic-parent material regions of Pennsylvania. These regions are those given in Table 2 (from Ciolkosz and Cunningham, 1987).

Table 2. Percentage of each geographic region of Pennsylvania with various soil or land characteristics (data from Ciolkosz et al., 1995; see Fig. 1 for the location of the geographic regions).

Soil or land character	Glaciated Northeast plateau	Glaciated Northwest plateau	Southwest plateau	Central plateau	Northern plateau	Ridge and valley	Triassic-Piedmont	Pennsylvania
Fragipan	55	63	3	22	37	14	14	30
Argillic horizon	2	66	83	72	42	52	74	51
Aquic moisture regime[†]	29	51	6	11	9	8	12	16
Slope								
0–3%	8	28	7	7	7	10	24	11
3–8%	37	43	12	29	32	32	42	33
8–15%	17	15	17	21	12	16	20	17
15–25%	24	8	30	25	20	22	10	21
25+%	14	6	34	18	32	20	4	18

[†] Somewhat poorly and poorly drained, the remainder is well or moderately well drained.

sheath in the prisms instead of individual spot concentrations. Schwertman (1988) indicates that high chroma mottles are composed primarily of the mineral lepidocrocite (γFeOOH). Data from a Cookport and Nolo soil in northcentral Pennsylvania (Waltman, 1985) indicate that high chroma mottles and the iron oxides zones in fragipans are dominantly lepidocrocite. The time required to form the gleyed prism faces and the iron oxide zone is unknown. Although unknown, the initial formation of these features probably does not take very long when the proper conditions are present (Dobos et al., 1990; Ciolkosz and Dobos, 1990). Although these features form rapidly, they undoubtedly continue to develop with time.

The prisms terminate at depth, although in many past studies the soil pits were not excavated to a sufficient depth to encounter the prism terminations. The interior of the upper part of the prisms may be mottled (high and low chroma drainage mottles). If the upper part of the fragipan is mottled, the mottles fade and usually disappear with depth within the prisms. In contrast to mottling, the grayest (gleyed) prism faces in many fragipans are found well below the top of the fragipan. Clay films are frequently found in pores in the upper part of the prisms. They, like the mottles, also tend to disappear with depth. Clay films also are frequently found on the prism faces. In past studies where clay films were observed in the upper part of the fragipan prisms, the zone was designated a Bx horizon and where clay films were not found at depth, the zone was designated as Cx horizon. Today, regardless of whether the fragipan has clay films or not, it is designated a Bx horizon. This is based on the contention that the prisms are pedogenetic structure, and that the fragipan is a pedologic and not a geologic zone.

The prisms may have massive interiors or they may part to subangular blocky or platy structure. Commonly when the fragipan is developed in a layered deposit (old alluvium, loess and till), the secondary structure is platy. The size of the prisms can vary from small (6 in.) to very large (>2 ft). Presently there are no studies which have investigated the factors affecting the development of the various prism sizes. Although unknown, it is reasonable to assume that the texture and the number and intensity of wetting and drying cycles must determine the prism size. Future studies are needed to determine the importance of these factors.

Not all fragipans show an equal degree of expression (Table 3). Generally they can be described as having weak, moderate, or strong expression. Fragipans are field-identified soil horizons and presently there are no laboratory measurements to confirm or deny their presence. Thus, the degree of expression classes listed in Table 3 are impressions based on firmness, brittleness, apparent permeability as indicated by mottling, resistance to root penetration, and toughness or strength (resistance to digging or penetration). Although seldom mentioned, the toughness or strength of a fragipan noted in the field is significantly affected by rock fragments. The rock fragments contribute reinforcement to the fine earth (<2 mm) material much like steel reinforcing rods add strength to concrete. As a fragipan is probed with a knife or dug with a shovel or backhoe, rock fragments are encountered and must be displaced. Thus the mass of the rock and its attachment to other rock fragments and fine earth contribute to the compressive and shear strength of the total soil material and to the overall toughness of the fragipan.

Table 3. Fragipan expression in six Pennsylvania soil catenas. Descriptive and numeric terms are given (1 = weak, 2 = moderate, and 3 = strong).

	Soil series and degree of fragipan development			
Parent material	Well drained	Moderately well drained	Somewhat poorly drained	Poorly drained
Brown Wisconsinan acid sandstone and shale glacial till	Bath	Mardin	Volusia	Chippewa
	2	2.5	3	2.5
	Moderate	Moderate-strong	Strong	Moderate-strong
Pre-Wisconsinan acid sandstone and shale glacial till	Allenwood	Watson	Alvira	Shelmadine
	0	1.5	2	2
	None	Moderate-weak	Moderate	Moderate
Brown Wisconsinan acid sandstone and shale colluvium	Laidig	Buchanan	Buchanan	Andover
	1.5	2	2.5	2
	Weak-moderate	Moderate	Moderate-strong	Moderate
Brown Wisconsinan acid shale colluvium	Shelocta	Ernest	Ernest	Brinkerton
	0	1	2	2
	None	Weak	Moderate	Moderate
Brown Wisconsinan limestone, shale, and sandstone colluvium	Murrill	Clarksburg	Penlaw	Thorndale
	0	0.5	1	1
	None	Very weak	Weak	Weak
Brown Wisconsinan loess	Duncannon	Lawrenceville	Chalfont	Doylestown
	0	1.5	2	2
	None	Weak-moderate	Moderate	Moderate

Generally the larger the rock fragments, the greater its contribution to the toughness of the fragipan.

Genesis

Parent Material

Fragipans are formed in glacial till, lacustrine deposits, colluvium, loess, and old alluvium (on terraces), but not in recent alluvium (on floodplains). They also are found in parent materials that have in the past been perceived as residuum. These "residual" parent materials are now believed to have moved downslope somewhat or have been turbated in place. Thus it appears that movement or transportation of the parent material is a factor in predisposing the material to fragipan formation.

The texture (<2 mm) of a parent material affects fragipan formation. If the material is too sandy or too clayey, fragipans do not form. Petersen et al. (1970) showed that Pennsylvania fragipans typically have an average texture that is at the boundary between the loam and silt loam textural classes (Fig. 2B). The data presented by Petersen et al. (1970) may give a false impression that soils with high silt-contents (silt textural class) do not form fragipans. This is not correct. The reason no fragipans are found in silt-textured deposits is that this type of parent material is very uncommon in Pennsylvania as well as elsewhere.

In the field the impression of brittleness also appears to be affected by texture. The maximum brittleness appears to be centered in the central part of the silt loam textural class (Fig. 2B). From this point, brittleness decreases with increasing sand and clay content. With increasing clay content, as a soil sample is squeezed, it tends to deform plastically and not with an abrupt brittle rupture. With high clay contents shrinking and swelling as the material wets and dries may prevent brittle consistence from developing. The firmness of the fragipan does not show a trend parallel to brittlenesss. With increasing clay content, fragipan material tends to show similar firmness. With increasing sand content from silt loam to loam, fragipan firmness also is similar, while from loam to sandy loam, the firmness decreases. The data in Table 3 also indicates that soils high in silt content (Shelocta, Murrill, and Duncannon catenas) tend to show less fragipan expression than soils with lower silt contents. Rock fragments (>2 mm material) are a part of the soil, but they apparently do not affect the development of the fragipan. A possible exception may be when the rock fragment content gets very high. Although rock fragments do not affect fragipan development, they do contribute to the toughness of the fragipan.

Calcareousness of the parent material is frequently cited (Ciolkosz et al., 1989), as a factor in fragipan formation. Fragipans do not form in calcareous materials until the carbonate has been leached from the material; and if the carbonate content is very high, argillic horizons form in preference to fragipans as the carbonate is leached. The effect of the carbonate is not known, although it may keep clay and amorphous aluminosilicate material stabilized and resistant to eluviation. An additional factor may be that as Bruckert and Bekkary (1992) claim, fragipans do not form in material that overlies permeable rock such as limestone.

Fragipans found in the loess of the Mississippi River Valley are frequently said to form in an underlying paleosol or preweathered surface (Buntley et al.,

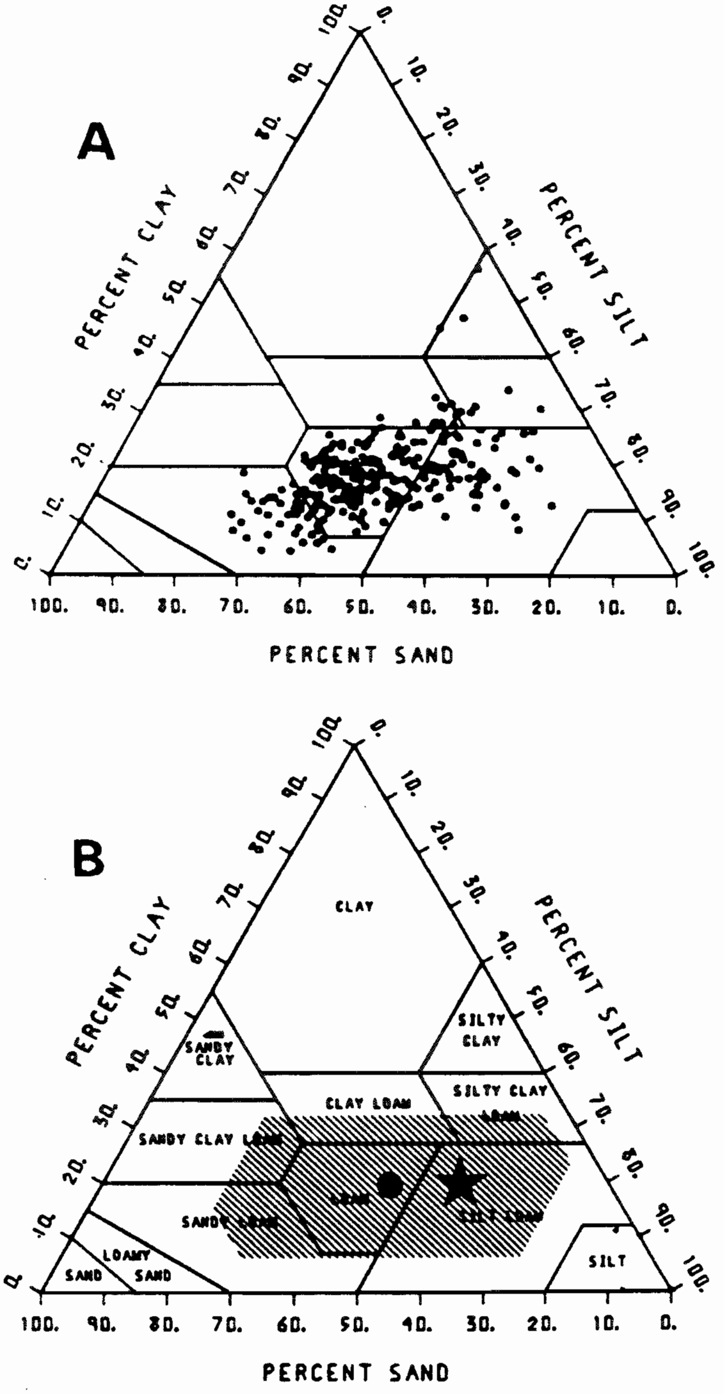

Fig. 2. (*A*) **Texture of 281 fragipan horizons developed in glacial till.** (*B*) **Fragipan textural class (the dot in the loam class represents the mean and the shaded area equals one standard deviation). The star in the silt loam indicates the maximum expression of brittleness (from Petersen et al., 1970; published with permission of the Soil Science Society of America).**

1977). In Pennsylvania the work of Hoover (1983) indicates that fragipans form in brown Wisconsinan Age colluvium but they do not pass from the overlying brown colluvium into a red Pre-Wisconsinan paleosol below, which also is developed in colluvium. An exception to this observation occurs where the red paleosol material was remobilized during the deposition of the brown colluvium.

Fragipans do bridge Wisconsinan Age loess-glacial till boundaries. Thus, weathering and soil formation appears to restrict subsequent fragipan formation.

It also is frequently stated that fragipans form at lithologic discontinuities in parent materials (Smeck et al., 1989). This may be the case in some instances, but it does not seem to be a general rule. The evidence usually used to indicate a lithologic discontinuity is a finer texture above the fragipan than in the fragipan. Weathering is much more rigorous in the zone above the fragipan than in the fragipan (Ciolkosz et al., 1979). Thus, the textural difference can be explained by weathering above the fragipan, in particular, the breakdown of shale rock fragments or sand-size shale material into clay. In addition, most soils also have received some aeolian additions which also would help explain the textural differences (Cronce, 1988; Ciolkosz et al., 1990).

Climate and Vegetation

The climate in which fragipans form is a leaching environment. In Pennsylvania, they form in udic and slightly perudic moisture regime areas, but it is unclear if they also form in strongly perudic climates. Perudic climates in Pennsylvania are equivalent to greater than 50 in. of precipitation, and there are only small areas that receive enough precipitation to be classified as slightly perudic. These areas are located at the higher elevations of the Laural (southwest) and Pocono (east central) Mountain regions. Fragipans apparently form in all temperature regimes with the possible exception of the pergelic and hyperthermic. In Pennsylvania, they are found both in the mesic and frigid areas. Fragipans form under forest vegetation. This may be just a reflection of a udic (humid) climate or, as Franzmeier et al. (1989) indicate, that prairie grasses which are associated with dry udic and ustic climates may deter the formation of fragipans by their ability to take up large quantities of silica into their biomass. This point will be discussed further in the section on Formation Model.

Topography

The effect of topography is uncertain, although a general relationship exists with drainage class, slope and fragipan development. In general, fragipan expression follows the sequence somewhat poorly drained > moderately well drained > well drained (Table 3), and this sequence generally parallels increasing slope gradient. Also, the fragipan is generally found progressively closer to the surface from the well drained to the somewhat poorly drained soils (Fig. 3). The effect of slope gradient on the depth to the top of the fragipan and its degree of expression is uncertain although it is logical to assume that on steeper slopes more of the precipitation would be lost by runoff and less would enter the soil. This may create a situation where the better drained soils on steeper slopes would go through fewer wetting and drying cycles. Such cycles are believed to be important in the development of the fragipan (see section on Formation Model).

Time

The time required to form a fragipan is an interesting topic. As previously indicated, fragipans are not generally found in floodplain soils, but they are found in terrace soils topographically above floodplains. Floodplains in Pennsylvania

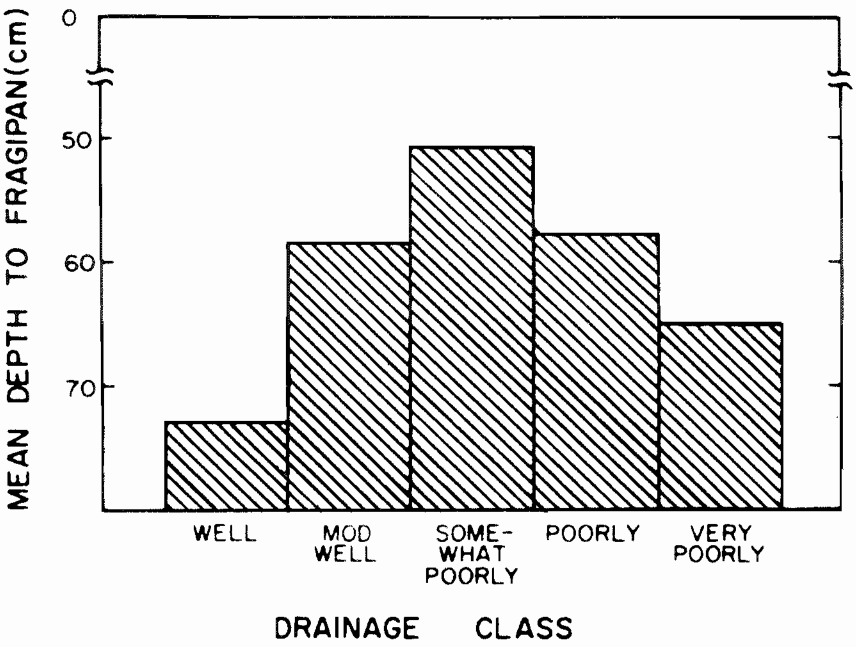

Fig. 3. Relationships of mean depth to fragipan and drainage class of soils developed from glacial till. The mean depth of 0 marks the top of the soil profile (from Petersen et al., 1970; published with permission of the Soil Science Society of America).

are a few hundred to a few thousand years old (Bilzi and Ciolkosz, 1977). Well-developed fragipans are found in Wisconsinan Age glacial till (Table 3). Thus, fragipans can form in 18000 yr. The only other data in the northeast to help date fragipan formation is that given by Foss and Collins (1987) for an alluvial-colluvial archaeological site in Virginia dated at 6500 yr. The authors describe the fragipan as moderately developed. In the classification given in Table 3, this site would show weak to moderate fragipan development (Foss, 1992, personal communication). In addition, Foss and Collins (1987) do not describe the thickness of the fragipan. These studies and the presently available data do not allow a strong extrapolation of the rate of development with regards to either thickness or the degree of expression. Although this is the case, the data indicates that it takes about 6000 yr to form a weak fragipan and 18000 yr to form a strong fragipan. Thus, one may speculate that it might take 10000 to 12000 yr to develop a moderate degree of fragipan expression.

An additional question about time as a soil forming factor with respect to fragipans is what is the mode of formation from initiation to 18000 yr and from 18000 yr to a few hundred thousand years. This topic will be explored in the following section.

Formation Model

Figure 4 gives a four-phase sequential developmental model for fragipan development in glacial till in northeastern Pennsylvania. The phases given in this model are proposed to be operational in fragipan development throughout Pennsylvania.

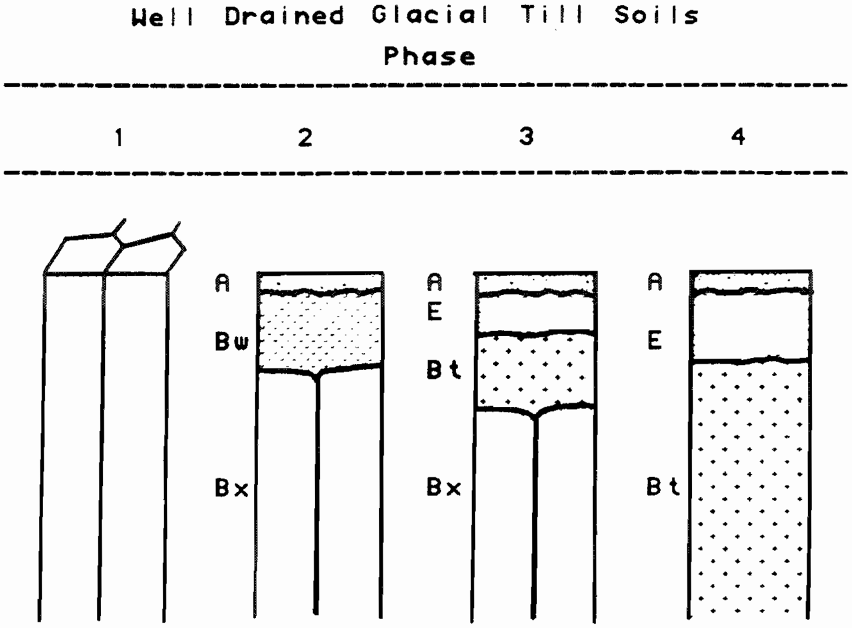

Fig. 4. Sequential developmental model for well drained soils developed in glacial till in Northeastern Pennsylvania.

Phase 1

Moist to wet transported material (e.g., loess or glacial till) dries from the surface downward forming polygonial cracks which when generated downward form prisms. Some material may fall into the cracks. Some packing of the prisms occurs through a series of wetting and drying cycles, but probably not a great deal. Possibly an increase of 0.2 to 0.3 Mg/m^3 may occur. The packing need only increase the bulk density to about 1.6 Mg/m^3 because at this density the penetration of medium textured material by roots is restricted (Zimmerman and Kardos, 1961; Thompson et al., 1987). The wetting and drying of the prisms is a continuous process. Thus, the thickness of the fragipan (top to bottom of prisms) is a function of the number of wetting and drying cycles and, in particular, the frequency of very dry periods which would allow the desiccation cracks to penetrate deeply into the material. Thus, with each significant dry weather cycle, fragipans probably increase their thickness. Most past soil investigations did not dig deep enough soil pits, thus, the bottom of the fragipan has not been observed in most studies. Generally, the fragipan is much thicker than the 200 cm maximum given in *Soil Taxonomy* (Soil Survey Staff, 1975). Periglacial frost processes also have been used to explain fragipan formation , particularly the prism formation process (Van Vliet and Langohr, 1981; Payton, 1992). In the USA this explanation does not seem reasonable because fragipans are found from areas that did have periglacial conditions 18000 yr ago (Pennsylvania and New Jersey; Clark and Ciolkosz, 1988) to areas that did not (Louisiana and Mississippi). In addition, observation of fraigpan prisms in the spring and late summer indicate that space present between the prisms during a dry summer is not there during the moist to wet spring. This indicates that the prisms are the result of past and present pedogenetic processes (wetting and drying) and are not a fossil form generated by periglacial processes during the Pleistocene

Phase 2

As the prisms develop from the surface downward, the top of the prisms undergo eluviation and mechanical disruption. The disruption is caused by animals and roots wedging their way into the top of the prisms as well as by expansion and contraction of the material due to wetting and drying. These processes break up the dense prism interiors and, with time, an A and Bw horizon are formed in what was the top of the prisms. As the A and B horizons develop, clay and probably some Fe oxide is eluviated downward and enters the prisms of the Bx horizon from the top as well as from the prism face areas. This would account for the clay films noted in the pores of the fragipan and the decrease in their abundance with depth in the Bx. Some of the clay also is deposited in the prism face as is well illustrated by the study of Miller et al. (1971) and many field observations. The initial deposition of the clay undoubtedly adds some to the increase in bulk density, but more importantly it helps close up some of the pore pathways in the prisms creating many greatly restricted or dead-end pore pathways. The clay also contributes to the brittle consistence of the fragipan by creating bonding linkages between coarse grains in the soil material (Lindbo and Veneman, 1989). In addition to the clay, amorphous aluminosilicate material also is eluviated into the prisms. Some of the aluminosilicate also may form within the prisms. This material forms grain to grain linkages (Bridges and Bull,1983; Franzmeier et al., 1989; Karathanasis, 1989), which contribute to the brittleness, higher bulk density, and reduced permeability of the fragipan. Thus, the denseness of the fragipan is a result of the packing of the mineral grains that results from movement of the original parent material and some slight additional packing as the prisms formed. Further slight increases in bulk density probably occur with the addition of some clay and amorphous aluminosilicate material. The clay and amorphous material form some grain to grain contacts which, when the material is stressed, resist deformation until the grain-to-grain bridges start to rupture. At this point the bridges break rapidly giving the brittle rupture characteristic of fragipans. The number of grain to grain contacts is probably not extensive otherwise the soil would be cemented. A Bath soil which is developed in Wisconsinan Age glacial till (18000 yr old) is a good representative of a Phase 2 soil (Table 3). The processes given in Phase 1 and 2 overlap and at about Phase 1.5 is the point at which a material could be called a fragipan.

Phase 3

With increasing time, more eluviation occurs and an argillic horizon forms above the fragipan. More clay also is eluviated into the top of the prisms. As more and more clay is added to the prism tops, expansion and contraction after wetting and drying increases and the prisms are physically broken up. This zone then becomes a part of the argillic horizon that originally started to form above the fragipans. In addition, with time, the upper part of the prism is leached of the amorphous material that acts as some of the grain-to-grain bonding material. Oxidation and other weathering reactions also add to the degradation of the top of the prisms. The observation that the first fragipan horizon (Bx1) is not as well expressed as the second one (Bx2) attests to this process. Additional indications of the degradation of fragipans comes from the studies of Bartelli (1973) and Steele et al. (1969).

Phase 4

With additional time in well-drained glacial till soils, the fragipan is completely destroyed by the processes outlined in Phase 3. The time required to do this is apparently at least 120000 yr. This conclusion is based on the fact that Pre-Wisconsinan Allenwood soils, which are developed in the same type of glacial till (acid sandstone and shale) as Wisconsinan Age Bath soils, are highly oxidized, highly leached, and have an argillic horizon but not a fragipan (Table 3). This conclusion holds for well-drained soils, but not for the wetter members of the Allenwood catena which still have fragipans (Table 3). In the wetter soils of this catena, apparently the degradational process is much slower, although Waltman et al. (1995), indicates that it is progressing. With enough time and landscape stability, it is proposed that even in the wetter soils of the Allenwood catena the fragipan will be destroyed.

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