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FRAGIPANS IN PENNSYLVANIA SOILS

by

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INTRODUCTION

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 by a large number of workers and three excellent reviews have been published (Grossman and Carlisle, 1969; Smalley and Davin, 1982; and Smeck and Ciolkosz, 1989). 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 Pennsylvania 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, Alfisol, Ultisol, and Spodosol soils but not in Entisol or Mollisol soils (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 1/3 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

Table 1. Order, suborder, and great group acreage data for Pennsylvania soils (from 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

studies of Petersen et al. (1970), Ranney et al. (1975), Waltman (1981), Ciolkosz et al. (1989), Ciolkosz et al. (1990), and Waltman et al. (1993) present some of the these data. These studies indicate that fragipans are found at variable depth below the surface, with or without an argillic 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 colloquially described by Ciolkosz in 1975 as fragipan-brown.

The faces of the prisms 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 iron 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 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) indicates that high chroma mottles and the iron oxides zones in fragipans are dominantly Lepidocrocite. The time required to form the gleyed

Table 2. Percentage of each geographic region of Pennsylvania with various soil or land characteristics. Data from Ciolkosz et al. (1993). See Figure 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.

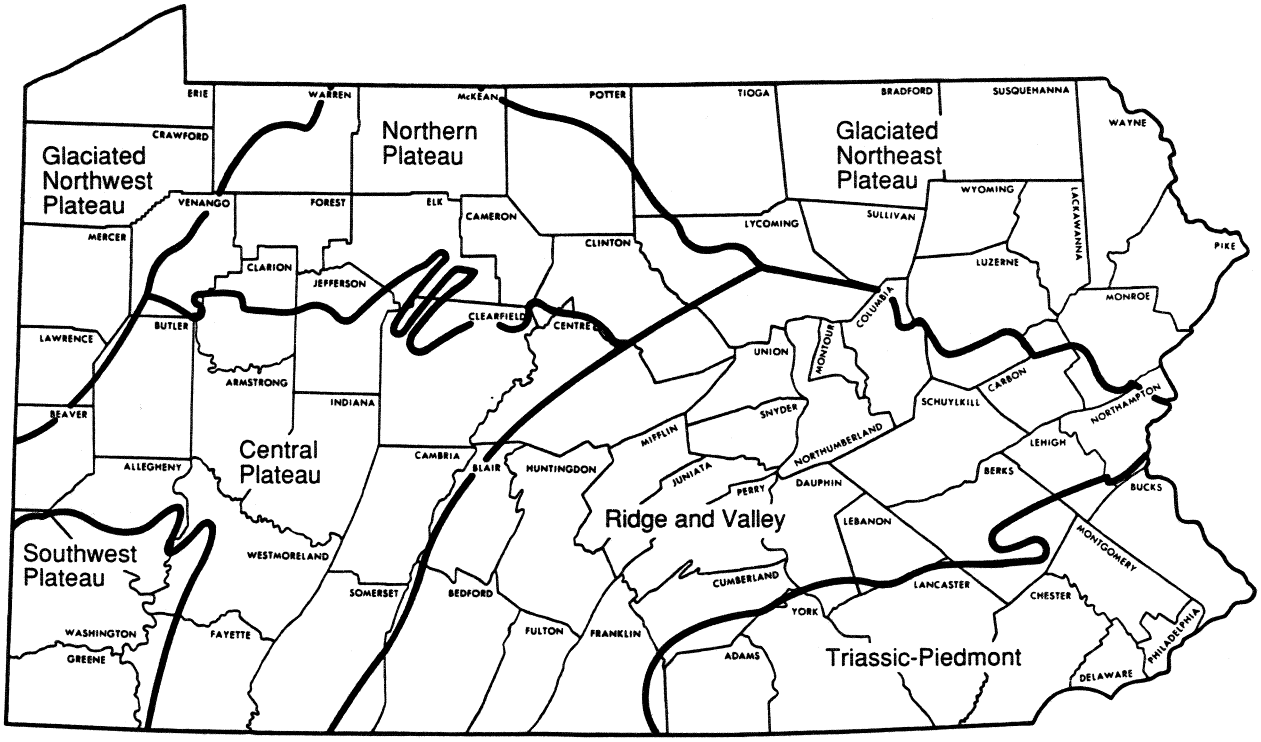

Figure 1. Physiographic-parent material regions of Pennsylvania. These regions are those given in Table 2. (From Ciolkosz and Cunningham, 1987).

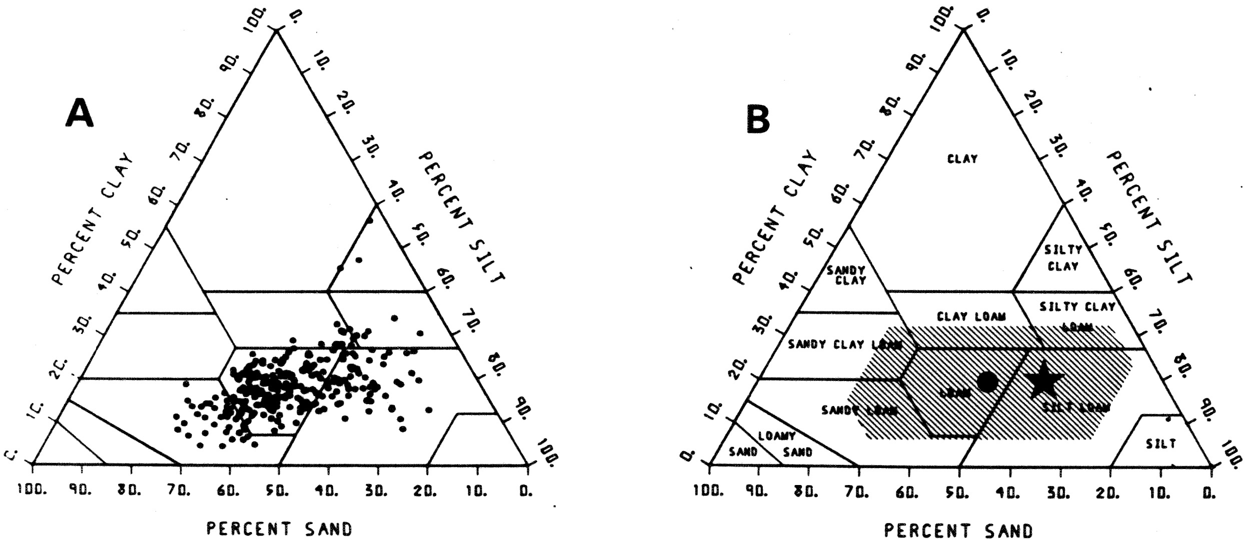

Figure 2. (A) Texture of 281 fragipan horizons developed in glacial till. (B) Fragipan textural class (the dot in the loam class represents the mean and the shaded area equals one standard deviation). The star in the silt loam class indicates the maximum expression of brittleness. (From Petersen et al., 1970).

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 are also 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 a 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 inches) to very large (> 2 feet). 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,

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 2 Moderate	Mardin 2.5 Moderate to strong	Volusia 3 Strong	Chippewa 2.5 Moderate to strong
Pre-Wisconsinan Acid Sandstone and Shale Glacial Till	Allenwood 0 None	Watson 1.5 Moderate to weak	Alvira 2 Moderate	Shelmadine 2 Moderate
Brown Wisconsinan Acid Sandstone and Shale Colluvium	Laidig 1.5 Weak to moderate	Buchanan 2 Moderate	Buchanan 2.5 Moderate to strong	Andover 2 Moderate
Brown Wisconsinan Acid Shale Colluvium	Shelocta 0 None	Ernest 1 Weak	Ernest 2 Moderate	Brinkerton 2 Moderate
Brown Wisconsinan Limestone, Shale and Sandstone Colluvium	Murrill 0 None	Clarksburg 0.5 Very weak	Penlaw 1 Weak	Thorndale 1 Weak
Brown Wisconsinan Loess	Duncannon 0 None	Lawrenceville 1.5 Weak to moderate	Chalfont 2 Moderate	Doylestown 2 Moderate

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 strengths of the total soil material and to the over-all toughness of the fragipan. 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 are also 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 (Figure 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 (Figure 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 brittleness. With increasing clay content, fragipan material tends to show similar firmness. With increasing sand content from silt loam to loam, fragipan firmness is also 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., 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 is also 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 is also 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 would also 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 inches 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 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 (Figure 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

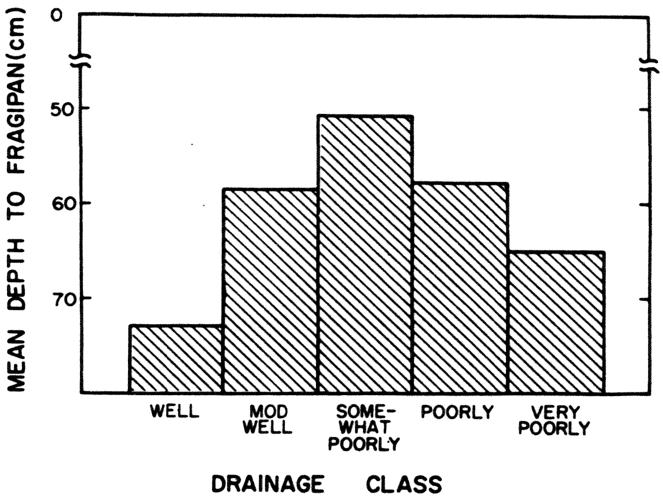

Figure 3. Relationships of mean depth to fragipan and drainage class of soils developed from glacial till. The mean depth of 0 marks the top of the soil profile. (From Petersen et al., 1970).

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 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 18,000 years. 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 6,500 years. 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). 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 6,000 years to form a weak fragipan and 18,000 years to form a strong fragipan. Thus, one may speculate that it might take 10,000 to 12,000 years 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 18,000 years and from 18,000 years to a few hundred thousand years. This topic will be explored in the following section on Formation Model.

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.

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 have also been used to explain

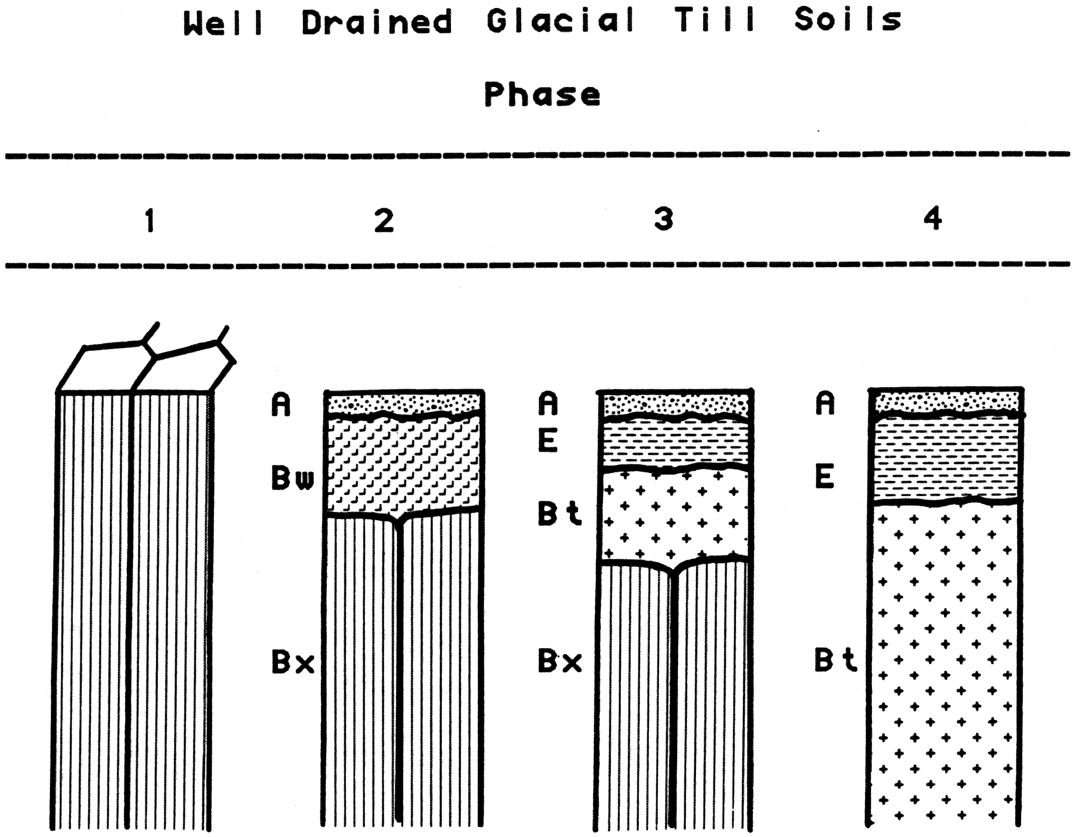

Figure 4. Sequential developmental model for well drained soils developed in glacial till in Northeastern Pennsylvania.

fragipan formation, particularly the prism formation process (Van Vliet and Langohr, 1981). In the United States this explanation does not seem reasonable because fragipans are found from areas that did have periglacial conditions 18,000 years ago (Pennsylvania and New Jersey; Clark and Ciolkosz, 1988) to areas that did not (Louisiana and Mississippi). In addition, observation of fragipan 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 is also deposited in the prism face area 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 is also eluviated into the prisms. Some of the aluminosilicate may also 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 (18,000 years 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 is also eluviated into the top of the prisms. As more and more clay is added to the prism tops, expansion and contraction upon 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 120,000 years. 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., 1993, 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.

SUMMARY

Fragipans are a common feature in Pennsylvania, occurring in 30 percent 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 impacts 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 6,000 years to form, while a strong fragipan requires 18,000 years.

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.

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