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Contents

INTRODUCTION

Argillic horizons are subsurface soil layers that are zones of clay (< 2μm) accumulation. This soil horizon is a part of the United States Soil Conservation Service Soil Classification System "Soil Taxonomy" (Soil Survey Staff, 1975; Soil Survey Staff, 1992), and is rigorously defined in terms of the amount of clay accumulated and its thickness. Argillic horizons are very extensive in Pennsylvania and are found in soils that cover approximately one-half of the land area of the state (Tables 1 and 2). The presence of the argillic horizon in a soil indicates a distinctive pathway of soil development and landscape stability (Smith, 1983; Brasfield, 1983). Although this is the case, very little has been published on the genesis and distribution of argillic horizons in Pennsylvania soils. Thus the intent of this publication is to focus on the distribution, properties, and genesis of argillic horizons as they are found in Pennsylvania.

DISTRIBUTION

By definition, argillic horizons are found in Alfisol and Ultisol soils (Soil Survey Staff, 1992). They also can be found in Mollisols, but they are not present in Pennsylvania Mollisols (Table 1). The reason is that most Pennsylvania Mollisols are found on floodplains, and floodplain soils are too young to have had a significant amount of clay accumulated in the subsoil (Bilzi and Ciolkosz, 1977).

In Pennsylvania, soils with argillic horizons are found extensively in all parts of the state except on the Glaciated Northeast Plateau (Table 2 and Figure 1). Although argillic horizons are recognized in the glaciated Northwest Plateau, for the most part they are very weakly developed and are marginal argillic horizons.

PROPERTIES

Soil Taxonomy (Soil Survey Staff, 1975; Soil Survey Staff, 1992) defines an argillic horizon as a zone of illuvial clay accumulation that has a clay content that is greater than the

Table 1. Order, suborder, and great group acreage data for Pennsylvania soils (from Ciolkosz and Dobos, 1989). Only Alfisol and Ultisol soils have argillic horizons.

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

eluvial horizon (zone of clay loss) above it. The horizon of accumulation (illuvial) must meet the following requirements:

1. If the eluvial horizon has 0 to 15% clay, the illuvial horizon has ≥ 3 % or more clay than the eluvial horizon (e.g., 10% vs. 13%).
2. If the eluvial horizon has 15 to 40% clay, the illuvial horizon has 1.2 times the clay content of the eluvial horizon (e.g., 20% vs. 24%).
3. If the eluvial horizon has ≥ 40% clay, the illuvial horizon has 8% or more clay than the eluvial horizon (e.g., 40% vs. 48%).

These limits were set by Guy Smith (the author of Soil Taxonomy) so that soil scientists using the "Feel Method" of soil texturing (rubbing the soil between the fingers and thumb) could consistently map soils that had argillic horizons (Brasfield, 1983). In addition, an argillic horizon must be at least 7.5 cm (3 in.) thick if loamy or clayey or at least 15 cm (6 in.) thick if sandy. These limits were set by Smith so that soils with argillic horizons would indicate a significant amount of soil formation and landscape stability and separate them from the pedologically younger (less developed) Entisol and Inceptisol soils (Soil Survey Staff, 1975). Clay films (argillans) also should be evident, although in high shrink-swell soils they may not be present (Soil Survey Staff, 1992). Generally a significant amount of the clay in argillic horizons is fine clay (< 0.2 μm). Although this is the case Isbell (1980) reports that the amount of fine clay in argillic horizons can vary widely.

Fine clay analysis is not a part of the standard characterization analyses done by the Penn State Soil Characterization Laboratory (Ciolkosz and Thurman, 1993). Thus, the only fine clay data generated in the past was a part of a limited number of special studies (Bilzi and Ciolkosz, 1977; Hoover, 1983; Carter, 1979; Levine and Ciolkosz, 1983; Levine, 1981). Thin section observation of clay films is also used to help identify argillic horizons (Soil Survey Staff, 1975; Soil Survey Staff, 1992). As with fine clay data, only a few studies have been done on Pennsylvania soils (Bilzi and Ciolkosz, 1977; Waltman, 1981; Waltman, 1985; Hoover, 1983).

Table 2. Percentage of each geographic region of Pennsylvania with various soil or land characteristics. Data from the Soil Conservation Service (SCS) Map Unit Use File (MUUF). The MUUF was obtained from Ed White (SCS-Harrisburg, PA) in 1991 and is complete for all counties of Pennsylvania. Only Alfisol and Ultisol soils have argillic horizons. The slight differences in the data between Table 1 and Table 2 are due to different sources of the data. 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
Alfisols	< 0.5	46	85	12	4	18	38	18
With Fragipans	< 0.5	39	< 0.5	4	3	3	12	7
Without Fragipans	< 0.5	7	85	8	1	15	26	11
Ultisols	2	13	< 0.5	59	43	33	33	32
With Fragipans	1	8	0	17	24	18	3	12
Without Fragipans	1	5	< 0.5	42	19	15	30	20
Inceptisols	89	31	4	19	49	41	17	40
With Fragipans	53	15	0	< 0.5	12	1	< 0.5	12
Without Fragipans	36	16	4	19	37	40	17	28
Argillic horizons	2	59	85	71	47	51	71	50
Fragipans	54	62	< 0.5	21	39	22	15	31
Aquic moisture regime*	27	54	6	11	7	7	12	16
Slope Classes								
0-3%	13	29	8	9	7	12	22	13
3-8%	33	40	11	28	29	30	46	32
8-15%	18	16	17	22	12	19	18	18
15-25%	24	9	30	21	19	20	10	19
25+%	12	6	34	20	33	19	4	18

*Somewhat poorly and poorly drained. The remainder are well or moderately well drained.

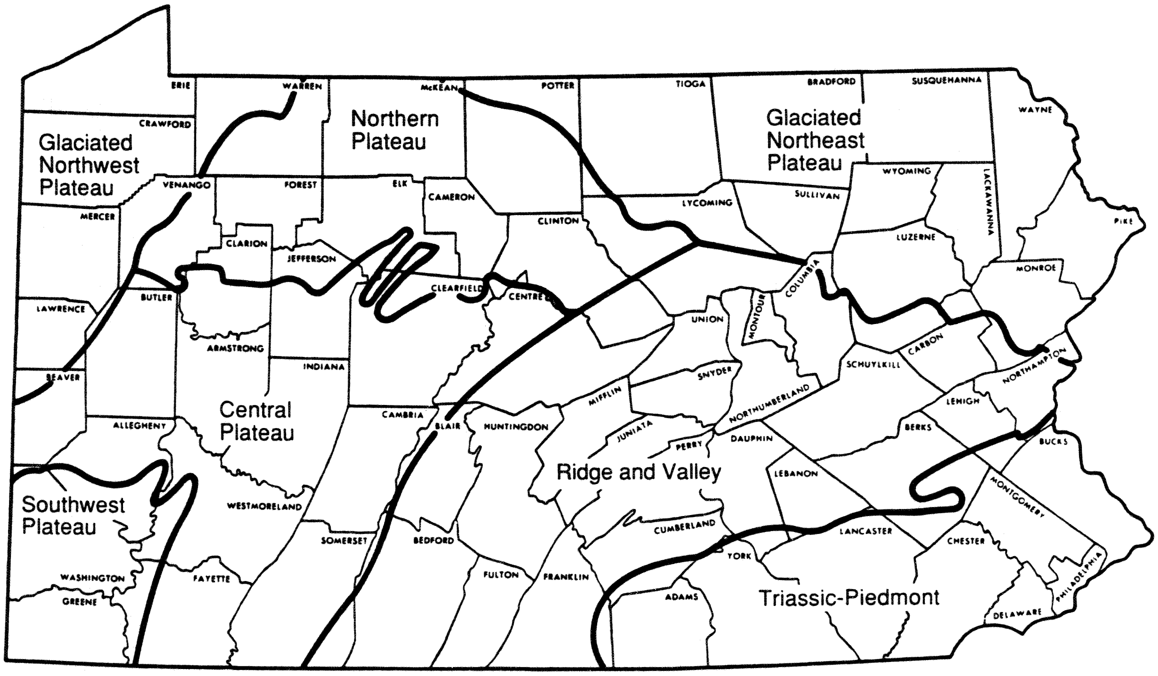

Figure 1. Generalized physiographic-parent material regions of Pennsylvania. These regions are those given in Table 2 (From Ciolkosz and Cunningham, 1987). Pennsylvania covers an area that is about 300 miles east-west and 170 miles north-south.

In Pennsylvania, the argillic horizon can take two forms. It can be a continuous vertical accumulation or it can be made up of a series of lamellae interspersed with nonargillic material. The argillic horizon can also be a combination of both of these types of accumulations, with the lamellae being found below the main argillic zone. In Pennsylvania the only study of lamellae was done by Carter (1983). Although this is the case, some lamellae were sampled in two Vanderlip pedons (31-01 and 31-02) in Huntingdon County as a part of the Pennsylvania Soil Characterization program (Ranney et al., 1970). A third type of argillic horizon occurs in the midwestern part of the United States, but has not been as yet observed in Pennsylvania. This type of argillic is a double maxium of clay accumulation, in two-story parent material (silty or loamy over sandy calcareous material). The first maxium is in the upper material and the second is at the contact between the upper and the lower material. These types of soils have been studied by Bartelli and Odell (1960) and the clay maxium at the contact between the two materials has been named a Beta B horizon.

HORIZON NOMENCLATURE

Some confusion exists between soil horizon nomenclature and Soil Taxonomy subsurface horizons such as an argillic horizon. Soil horizon nomenclature is a qualitative field assessment of the type of pedogenesis that has taken place in a particular layer of the soil. Thus the horizon symbol Bt indicates that in the judgment of the field soil scientist this subsurface horizon shows an observable accumulation of illuvial clay as indicated by clay films (argillans) on ped faces and/or in pores. Soil Taxonomy requires a defined minimum quantitative amount of clay accumulation as discussed on page 3. Thus a horizon could be a Bt but not have enough clay accumulated to qualify as an argillic horizon. In summary it can be said that soil horizon nomenclature is a qualitative assessment while a Soil Taxonomy horizon is a quantitative assessment of the pedogenesis that has taken place in a soil layer during soil formation.

GENESIS

PROCESS

In order for a soil to form an argillic horizon, the soil's parent material must have clay or clay must be formed through weathering. Argillic horizon formation is a three step process. Step one is the dispersion of the clay. Step two is the translocation of the clay, and step three is the accumulation of the clay (Eswaran and Sys, 1979). This is an ongoing process in which clay is dispersed, translocated, and accumulated continuously through time.

In soils that have clay in their parent material, the clay is usually a part of an aggregate, and its separation from the other soil particles can occur through physical and/or chemical means. On the soil surface, rain drop impact can cause dispersion of soil aggregates (Van Wambeke, 1992). Although rain drop impact may be effective in areas with sparse vegetation, in Pennsylvania most soils probably had a vegetative cover during their development, thus rain drop impact has played a minor role in physical dispersion of clay in these soils. Barshad (1964) indicates that the upper horizons of a soil are greatly affected by surface evaporation, and can dry to an air-dry state (100,000 kPa soil moisture tension). He also indicates that the subsoil in humid regions usually only dries out to the permanent wilting point (approximately 1500 kPa soil moisture tension) because the moisture content in the subsoil is primarily drawn down by plant roots. In a dry state (soil is considered dry at moisture tension of > 1500 kPa; Soil Survey Staff, 1992) the soil has little capillary water, and when the aggregates are wetted by rainfall, they absorb water rapidly, slake, and disaggregate; also if they are wetted rapidly from various directions, the air within the aggregate may compress until the aggregate literally explodes (Baver, 1963; Thorp et al., 1959; Daniels et al., 1967). In addition Baver (1963) indicates freezing and thawing, particularly very rapid freezing, may cause soil material to disaggregate. As a result of these various physical disaggregation processes, the clay within soil aggregates disperses. Chemical dispersion can occur when the electrolyte content in the soil solution is lowered. When the electrolyte content is low, there are not enough cations in the soil to keep the negatively charged clay particles from repelling each other and dispersion occurs. Barshad (1964) lists high rainfall (leaching) and active plant growth (assimilation of salts) as processes that would lower the electrolyte content in the soil solution and induce dispersion. The Na content of the soil solution has also been mentioned as a factor in dispersion (Hallsworth, 1963), but it is uncertain if it is a factor in the dispersion of Pennsylvania soils. Thus, it appears that in the summer and early fall during precipitation events the maximum amount of clay dispersion would occur in the eluvial zone of Pennsylvania soils. At this time of the year the eluvial zone would be the driest and electrolyte content would be drawn down by plant uptake.

In soils, the clay is moved in aqueous suspension through the coarse pore (macropore) system (dominantly the cracks that form between the ped faces) until the downward movement of the water stops or the clay is flocculated. Stoppage of the downward movement of the soil suspension can occur when the water is absorbed by dryer soil or the water is absorbed by plant roots. The soil water may also stop when it encounters a hydrological barrier such as a major change in pore size or pore continunity. This may occur at major changes in soil texture due to parent material stratification or the development of the argillic horizon itself. In addition, pore size and pore continunity changes such as those found in fragipans may also stop the downward movement of the water (see Ciolkosz et al., 1992; Olson, 1985). The major flocculating condition is associated with high concentrations of Ca or Mg (electrolytes) or positively charged Al or Fe oxides. Data from evapotranspiration studies indicate that very little precipitation that falls on the surface of Pennsylvania soils during the growing season percolates through the soil profile (Ciolkosz et al., 1994b; Figures 2-5). Thus the clay that is dispersed and translocated downward during the summer and early fall is deposited in the subsoil and very little is carried downward out of the soil profile during this time of the year. Although little clay moves out of the soil during the summer and early fall, some may be eluviated out of the profile during the late fall, winter, and spring when precipitation exceeds evapotranspiration and after the profiles have been recharged with water (Figures 2-5).

The major mechanism of clay accumulation in loamy and clayey soils appears to be the deposition of the clay on the ped faces and in the pores of the subsoil. The clay is literally sieved from the suspension as the water is drawn into the fine pore system within the peds or pores by capillary forces. This conclusion is supported by many thin section studies which show layer upon layer of clay particles deposited parallel to the ped or pore face (see Brewer, 1964; Douglas, 1990; Bullock and Thompson, 1985). Flocculation can also be a significant factor in the accumulation of clays. This is particularly true when soils are developed from calcareous material. Although this may be the case, the main visual evidence of clay accumulation (clay films) may be lacking when flocculation is significant. According to Eswaran and Sys (1979), during flocculation the clay tends to form face to edge bonds and does not tend to orient face to face as it does when deposited on ped faces during drying. Thus, you get clay accumulation but few clay films. Eswaran and Sys (1979) cite studies of Beta B horizons (Bartelli and Odell, 1960) as evidence for this conclusion. After the clay has accumulated, it apparently is stabilized. The mechanism of stabilization is not known, but in well drained soils there is a very close correspondence of clay content and iron oxide content in the Bt horizon (Table 3). The clay and iron oxide may form bonds which help resist dispersion. An additional factor may be the fact that the moisture content of the argillic usually does not dry to < 1500 kPa, thus it is not likely that the soil will be easily dispersed. Argillic horizons may have a finite lifespan. Observations of degraded argillic horizons in the glaciated midwest (D. Cremeens, personal observation) and in New York (Bullock et al., 1974) indicate that argillic horizons can become unstable and degrade from the top downward. Although the degradation mechanisms are not known, one suggestion is that hydrogen and other acid producing oxides may accumulate at the top of the B horizon, producing an environment conducive to clay dispersion and/or clay destruction. Further work is needed to determine the feasibility of this mechanism of argillic horizon degradation.

In sandy soils the mode of clay accumulation is slightly different than in finer textured soils which have discreet peds. In the sandy material the clay forms bridges between the sand grains, and coatings on the sand grains. Apparently when the soil suspension stops moving downward it forms necks of suspension between the sand grains due to a combination of attraction between the water and the surface of the sand grains and cohesion between the water molecules. When the water in the suspension is removed, the clay particles are arranged as a connecting bridge between the sand grains and as coating on the sand grains. As in finer material, the downward movement of the suspension occurs when the water in the suspension is lost by evaporation, plant uptake, or is absorbed by the soil. In addition the downward movement may be stopped by a change in pore size or pore continuity due to a slight change in texture. As shown by Bond (1986) pore size change seems to be of major importance in the formation of lamellae.

PARENT MATERIAL AND TIME

Northeast and Northwest Plateau

As mentioned earlier, argillic horizon formation in the soil requires the presence of clay in the parent material or it must be formed by weathering. The glacial till soils of the Northeastern Plateau do not have argillic horizons (Inceptisols) while the colluvial soils on the slopes in the Ridge and Valley do have argillic horizons (Alfisols and Ultisols; Ciolkosz et al. 1990). The parent material of these two groups of soils is very similar (acid sandstones and shales) and it is believed that they are approximately the same age (18,000 to 20,000 yrs old;

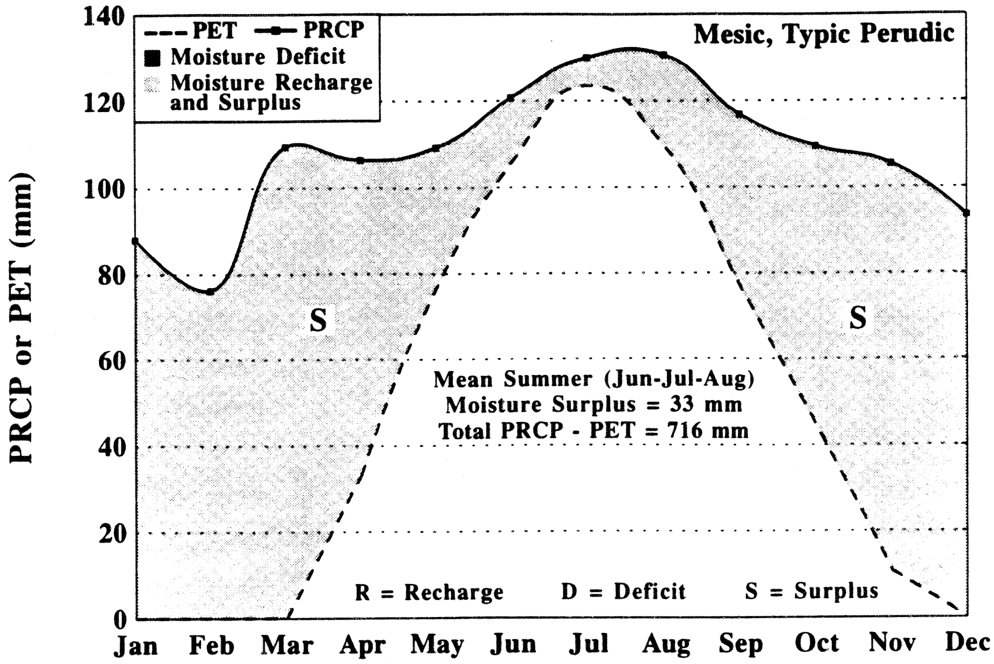

Figure 2. Moisture balance (Newhall Model; Van Wambeke et al., 1992) for Mount Pocono 2 N, PA, elevation 1920 feet. PRCP is precipitation and PET is potential-evapotranspiration. R (recharge) is the water added to bring the soil to field capacity. D (deficit) is the water lost by PET and not replaced during the growing season. S (surplus) is the water in excess of PET and storage (200 mm) that is leached from the soil.

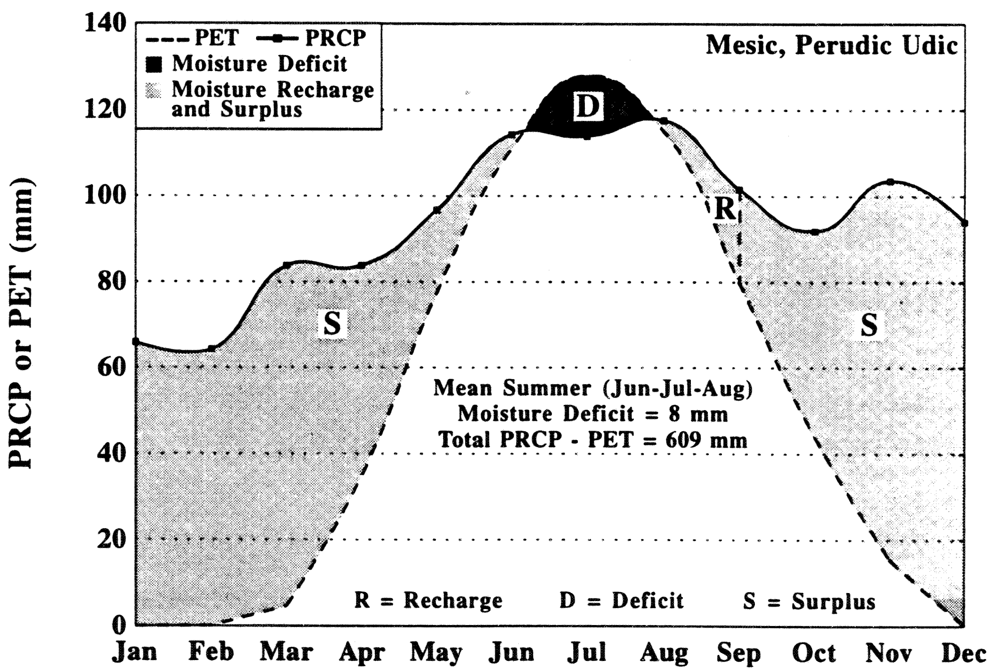

Figure 3. Moisture balance (Newhall Model; Van Wambeke et al., 1992) for Meadville 1 S, PA, elevation 1065 feet. PRCP is precipitation and PET is potential-evapotranspiration. R (recharge) is the water added to bring the soil to field capacity. D (deficit) is the water lost by PET and not replaced during the growing season. S (surplus) is the water in excess of PET and storage (200 mm) that is leached from the soil.

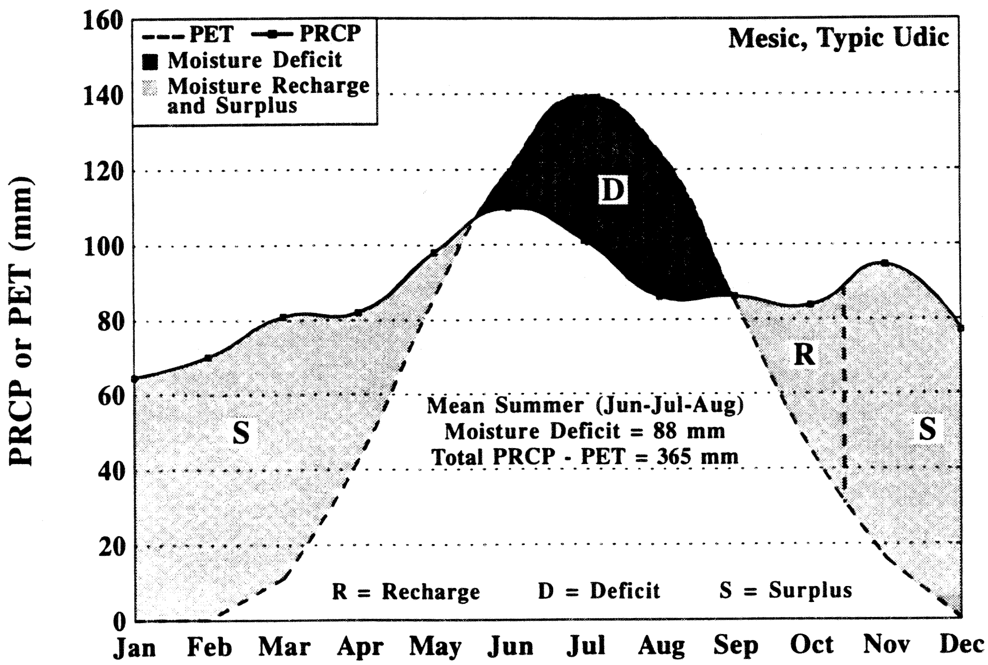

Figure 4. Moisture balance (Newhall Model; Van Wambeke et al., 1992) for Williamsport WSO Airport, PA, elevation 529 feet. PRCP is precipitation and PET is potential-evapotranspiration. R (recharge) is the water added to bring the soil to field capacity. D (deficit) is the water lost by PET and not replaced during the growing season. S (surplus) is the water in excess of PET and storage (200 mm) that is leached from the soil.

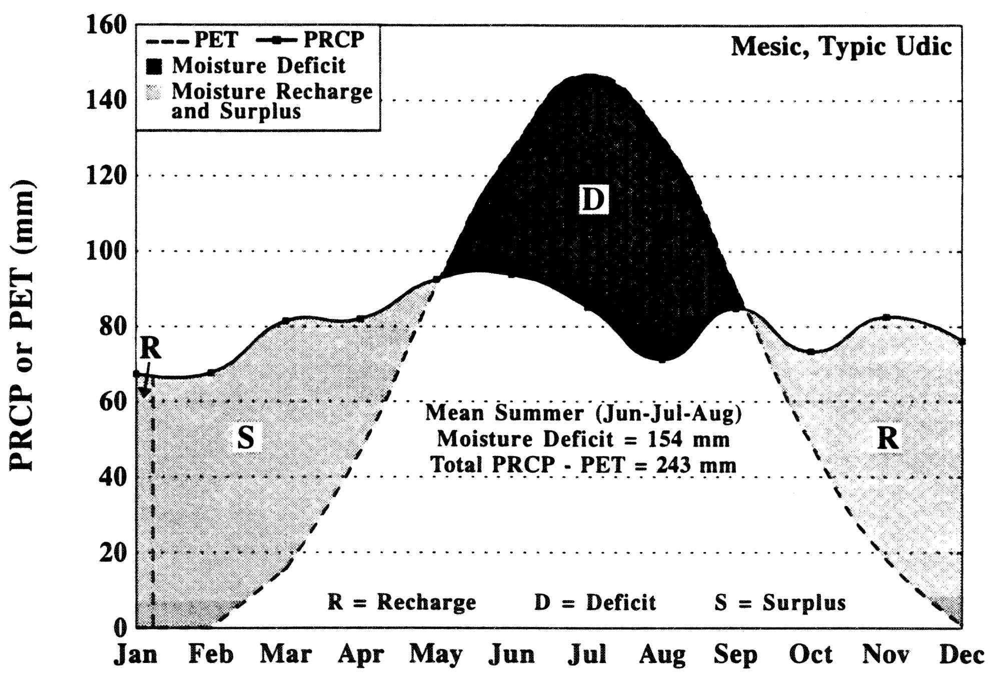

Figure 5. Moisture balance (Newhall Model; Van Wambeke et al., 1992) for Shippensburg, PA, elevation 680 feet. PRCP is precipitation and PET is potential-evapotranspiration. R (recharge) is the water added to bring the soil to field capacity. D (deficit) is the water lost by PET and not replaced during the growing season. S (surplus) is the water in excess of PET and storage (200 mm) that is leached from the soil.

Ciolkosz et al., 1990). Thus, the colluvial parent material appears to be more weathered with more clay available for movement than the less weathered glacial till. It is believed that the colluvial parent material did not weather more rapidly than the glacial till in the last 18,000 years, but rather it was weathered prior to movement and deposition as colluvium. This does not mean that the till soil will not form an argillic horizon with additional time of formation. The chronosequence shown in Figure 6 has been described by Ciolkosz (1978) and Ciolkosz et al. (1985), and indicates that as till soils get older they form argillic horizon and with time the argillic horizon (1) increases in total clay as well as fine clay content, and (2) is found deeper in the profile. The data in Figure 6 and Table 3 also indicates that some of the clay in the argillic horizons of the older soils is formed in place, and not all of it came from overlying horizons. In addition the data in Table 3 indicates that as soils get older the amount of fine clay in all horizons increases and the transitional horizon (BC) between the argillic and the underlying C horizon increases in thickness.

Although the glacial till soils of the Northeast Plateau do not have argillic horizons, glacial till soils north of this area in central New York with an age of about 12,000 yrs (Muller, 1965) do have argillic horizons. This difference is a reflection of limestone in the parent material of the New York till soils. When the limestone in the upper horizons dissolves, it releases clay that was an impurity in the limestones. Even very pure limestones have 3 to 8% acid insoluble residues (Ciolkosz and Dobos, 1990). This clay and other clay in the till moves through the leached horizons and is flocculated when it comes in contact with the calcareous zone. This mechanism is the main reason that the till soils of the Pennsylvania Northwest Plateau have argillic horizons. The parent material in this area is weakly calcareous and provides both clay and a high electrolyte concentration to flocculate the clay as it passes into the subsoil. The till soils of the Northwest Plateau have weakly developed argillic horizons. If they had high concentrations of carbonate in their parent materials, they would have well developed argillic horizons such as those found in the calcareous drift areas of the midwest (Ohio, Indiana, Michigan, Illinois, and Wisconsin). In contrast to the midwest, the till soils of New England do not have argillic horizons and very few have any clay films. These soils are basically ground igneous and metamorphic rocks and their minerals (Feldspars, etc.) have not had enough time since the deposition of the till to weather to clay.

Southwest Plateau

Like the Northwest Plateau, the Southwest Plateau has carbonates in their parent materials. These carbonates are in limestones and calcareous shales. The residual and colluvial soils in this area, like the soils in the Northwest Plateau, are Alfisols; but in general they have better developed argillic horizons than the northwest till soils. The reason for this is that the residual soils of the area are probably older although it is not known how old they are, while the colluvial soils probably have more weathered material in their parent material. These colluvial soils show a degree of development similar to the colluvial soils in the Ridge and Valley and are probably of a similar age (18,000 to 20,000 years old).

Central Plateau

The Central Plateau soils also have argillic horizons, but these soils are Ultisols not Alfisols. These Ultisols are unique in that the majority of them show weak to moderate development, high rock fragment content, and are relatively shallow to bedrock (Table 4). These soils have been called "Parent Material Ultisols" by Ciolkosz et al. (1989) because they do not fit well with the genetic Ultisols of the southeastern United States. Properties of the parent material Ultisols are related to the acid shale and sandstone parent materials of these soils. Also important in the genesis of these soils is the periglacial landscape truncation and turbation that this area and all of Pennsylvania experienced during the last major glacial advance in Pennsylvania which reached its maximum about 18,000 yrs ago (Clark and Ciolkosz, 1989). Thus, the argillic horizons in these soils are a reflection of the resistance of the parent materials to weather rapidly and form deep well developed soils, but with enough dispersion and movement of clay to form argillic horizons.

Table 3. Clay, iron oxide (as CBD-Fe) and total iron content (as Fe) in three glacial till soils from northeastern Pennsylvania. These are the same three soils that the clay content is plotted with depth in Figure 6. Data taken from Ciolkosz et al. (1993) and Levine and Ciolkosz (1983).

Soil Name and Drainage	Soil and Horizon Number	Depth in cm	Horizon	pH	Percent: Sand+	Silt+	Total Clay+	Fine Clay+	Percent: CBD Fe	Total Fe	Ratios: $\frac{Fe_d}{Fe_t}$	$\frac{(Fe_d-Fe_o)}{Fe_t}$*
			Late Wisconsinan Till Soil									
Lackawanna	45-80-01	0-18	Ap	5.3	42.3	45.6	12.1	1.9	0.98	2.96	33.1	29.4
Well	45-80-02	18-36	Bw1	5.5	44.8	42.4	12.8	2.2	0.77	3.35	23.0	20.6
drained	45-80-03	36-51	Bw2	5.7	44.4	43.9	11.7	1.9	0.77	3.25	23.7	20.3
	45-80-04	51-71	Bw3	5.8	47.0	40.9	12.1	1.9	0.70	3.20	21.9	18.7
	45-80-05	71-109	Bx1	5.6	51.7	37.6	10.7	1.7	0.91	3.36	27.1	25.0
	45-80-06	109-135	Bx2	5.3	49.8	38.5	11.7	1.9	0.84	3.63	23.1	19.0
	45-80-07	135-163	Bx3	5.1	53.0	36.5	10.5	1.9	0.91	3.36	27.1	24.4
	45-80-08	163-175	C	5.1	66.9	24.0	9.1	0.2	0.84	3.56	23.6	21.6
	45-80-09	175-201	R	.	.	.	.	.	.	.	.	.
			Early Wisconsinan Till Soil									
Leck Kill	41-39-01	0-23	Ap	6.1	31.2	56.2	12.6	2.0	1.12	2.48	45.1	37.1
Well	41-39-02	23-30	E	6.0	21.5	56.4	22.1	2.9	1.12	3.48	32.2	28.7
drained	41-39-03	30-41	BE	6.0	23.7	52.4	23.9	5.0	1.26	3.90	32.3	29.2
	41-39-04	41-66	Bt1	5.2	27.9	42.3	29.8	6.7	2.24	4.25	52.7	50.1
	41-39-05	66-84	Bt2	4.7	33.9	38.8	27.3	5.8	1.96	4.40	44.5	40.9
	41-39-06	84-104	BC1	4.7	38.9	39.9	21.2	4.8	1.19	3.87	30.7	27.9
	41-39-07	104-124	BC2	4.6	44.7	38.6	16.7	3.3	1.12	3.19	35.1	31.3
	41-39-08	124-160	C1	4.6	42.1	39.9	18.0	2.8	1.26	3.56	35.4	32.3
	41-39-09	160-206	C2	4.5	45.7	41.9	12.4	2.3	1.47	3.27	44.9	41.5
	41-39-10	206-254	C3	4.6	44.8	40.6	14.6	2.5	1.47	3.34	44.0	40.7
			Pre-Wisconsinan Till Soil									
Allenwood	41-42-01	0-23	Ap	5.4	24.3	56.3	19.4	8.3	1.75	2.98	58.7	52.0
Well	41-42-02	23-30	E	5.9	21.0	54.6	24.4	11.4	2.38	3.88	61.3	58.4
drained	41-42-03	30-43	BE	6.9	21.3	46.6	32.1	15.1	2.73	4.81	56.7	54.8
	41-42-04	43-66	Bt1	6.3	18.0	41.6	40.4	19.8	2.94	5.78	50.8	48.9
	41-42-05	66-89	Bt2	5.6	12.7	37.0	50.3	24.6	2.94	5.94	49.4	46.9
	41-42-06	89-114	Bt3	5.2	15.6	34.8	49.6	24.3	2.94	6.08	48.3	46.0
	41-42-07	114-135	Bt4	5.1	19.3	39.9	40.8	19.6	2.87	5.94	48.3	46.2
	41-42-08	135-157	BC1	5.1	22.2	39.7	38.1	18.3	2.80	5.72	48.9	46.5
	41-42-09	157-188	BC2	5.2	19.9	41.1	39.0	18.7	2.80	5.81	48.1	45.6
	41-42-10	188-221	BC3	5.2	27.6	38.5	33.9	15.9	2.66	5.18	51.3	48.0
	41-42-11	221-274	C1	5.1	25.9	41.9	32.2	15.1	2.24	5.16	43.4	39.7
	41-42-12	274-312	C2	5.1	28.3	40.7	31.0	14.6	2.73	5.50	49.6	45.8
	41-42-13	312-356	C3	5.2	27.4	41.7	30.9	14.3	2.45	5.49	44.6	39.5

*d = Citrate-Dithionite-Bicarbonate (CBD); t = total, o = oxalate

+sand = 2 mm-50 µm, silt = 50 µm-2 µm, total clay = < 2 µm, fine clay = < 0.2 µm

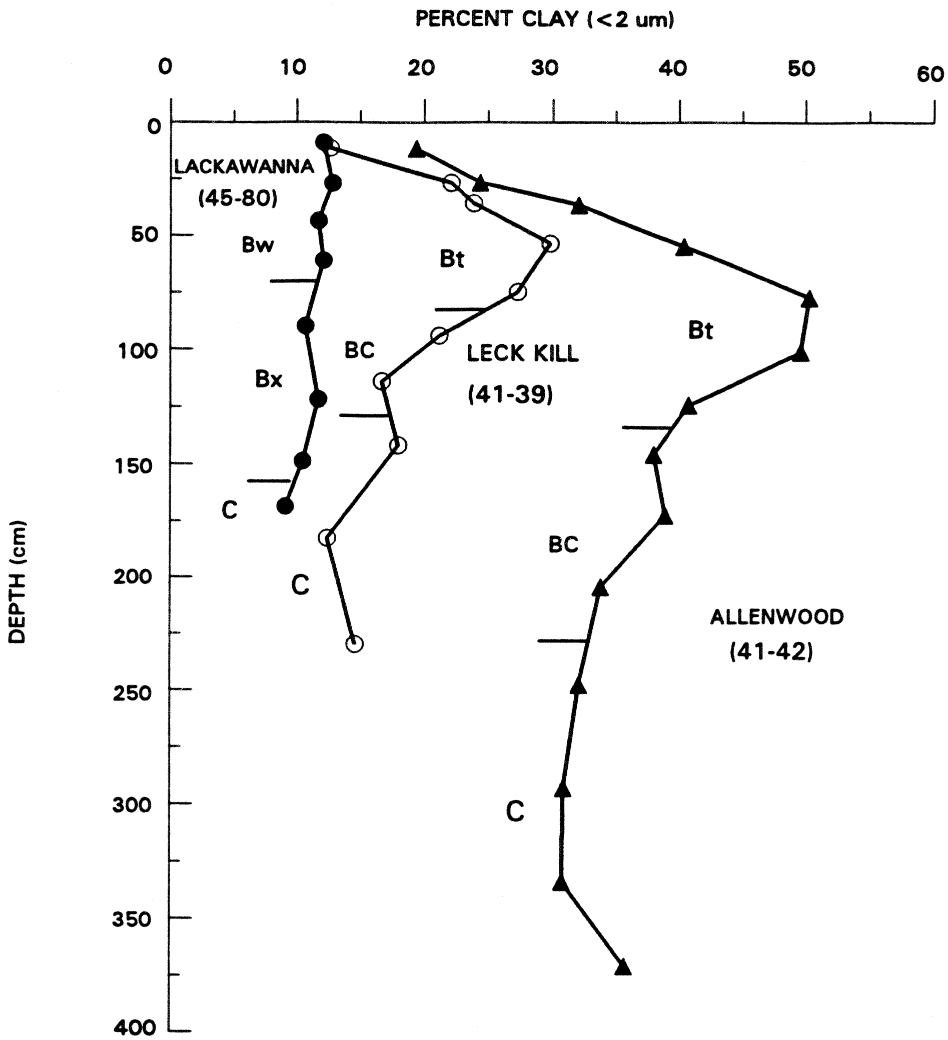

Figure 6. Clay content with depth of the Lackawanna (late Wisconsinan Age), Leck Kill (early Wisconsinan Age), and Allenwood (Pre-Wisconsinan Age) soils in Northeastern Pennsylvania. These soils have developed from similar glacial till parent material. Modified from Ciolkosz (1978).

Ridge and Valley

Within the Ridge and Valley region argillic horizons are found in the lower sideslope colluvial soils and the soils developed from limestone on the valley floors. The limestone soils have been studied by Cronce (1988) and the colluvial soils by Hoover (1983) and Ciolkosz et al. (1979). These and additional studies have been summarized by Ciolkosz et al. (1990). The parent material of limestone soils is believed to be primarily the acid insoluble residues from the

Table 4. Characterization data for a typical Central Plateau Parent Material Ultisol (Gilpin soil pedon S65 PA 2-8(1-6). Data from Ciolkosz and Thurman (1993).

Horizon	Depth	Color	pH	Percent Rock Fragments*	Sand+	Silt+	Clay+	Base Sat.
	cm							
Ap	0-18	10 YR 4/3	4.4	16	21.6	64.8	13.6	10
Bt1	18-25	10 YR 5/4	4.8	31	23.4	56.6	20.0	18
Bt2	25-53	10 YR 5/5	5.1	15	34.4	42.7	22.9	24
BC	53-69	10 YR 5/4	5.3	61	46.5	36.5	17.0	26
C	69-74	10 YR 5/5	5.3	66	52.1	31.7	16.2	19
R	74-90	10 YR 4/3 and 5/3 shale						

*On a weight basis, > 2 mm in size.
+sand = 2 mm-50 μm, silt = 50 μm-2 μm, clay = < 2 μm

weathering of the limestones. These soils (e.g., Hagerstown) have argillic horizons that have high clay contents (40 to 50%). They also have low clay contents (20%) in their eluvial horizons. The work of Cronce (1988) indicates that this very strong contrast in clay content is not just due to the eluviation and deposition of the clay in the soil but a significant amount of the contrast is due to the addition of aeolian silts to the surface of these soils during their development. This is reasonable because many of these limestone soils are 1.5 to 3 meters to bedrock and are 500,000 to a million years old (Table 5). In addition Cronce's study indicates that there is a strong correlation between the top of the argillic horizon and a value of 40% or higher base saturation. This may mean that this concentration of bases (Ca and Mg) on the exchange complex may initiate flocculation of clays in these argillic horizon as the clay moves downward in soil suspension. Most of these soils classify as Alfisols, although the deeper, older profiles (over 2.5 meters from the surface to bedrock) are leached more extensively and classify as Ultisols (Paleudults). Cronce (1988) also noted that these limestone soils have very little sand in the parent rock and the sand found in the soil was concretions and aggregates of iron cemented material. This pedogenetic sand seemed to be most abundant in the argillic horizon.

Table 5. Accumulation of residual soil during weathering from a limestone with 6% acid insoluble residues, assuming varying rates of dissolution over time. A bulk density of 2.85 (g/cc) for the rock and 1.65 for the soil is used in the calculations. A dissolution rate of 30 mm/1,000 yrs appears to be a reasonable rate for Pennsylvania soils. Using this number, it will take 1,000,000 yrs to accumulate a soil 300 cm (3 m) deep. Data from Ciolkosz and Dobos (1990).

Dissolution rate	Time (years)			
mm/1,000 yrs.	10,000	100,000	1,000,000	2,000,000
	----------cm of residuum----------			
10	1	10	100	200
30	3	30	300	600
100	10	100	1,000	2,000

The soils developed from shales in the Ridge and Valley are generally Inceptisols. An exception is many of the red shale soils. The red shale parent rock of these soils weathers and disaggregates more rapidly than the gray and brown shales that are on the same type of landscape, and produce deeper, lower rock fragment content soils (Table 6). In addition the red rock soils also tend to have argillic horizons, although the argillics tend to be weakly developed. Many of the red rock soils may have inherited some of their character from lithified paleosols that are common in these redbed Paleozoic rocks (Driese, 1993).

Table 6. Relative percentage of shallow (< 50 cm) moderately deep (50 to 100 cm) and deep (> 100 cm) to bedrock soils on red and grayish brown siltstones and shales in four Pennsylvania counties that encompass the Allegheny Front (Clark, 1992).

County	Red Rock Soils			Grayish-Brown Rock Soils		
	Shallow	Mod. Deep	Deep	Shallow	Mod. Deep	Deep
Lycoming	23*	0	87	66*	34*	0
Clinton	5*	0	95	8*	89*	3
Centre	0	16*	84	25*	74*	1
Blair	0	0	100	37*	63*	0

*These soils are also skeletal (have > 35 percent rock fragments).

Triassic-Piedmont

The Triassic-Piedmont region has two different parent materials. The Triassic area is dominantly redbed shales and siltstones and has soils with weakly developed argillic horizons. What has been concluded for the Ridge and Valley redbed soils also appears to apply to the Triassic redbed soils. The Piedmont region on the other hand has schist as its parent rock. The Piedmont region has recently been undergoing a rebirth of research interest and significant complexity has been uncovered (Pollack, 1992; Pazzaglia, 1993). A part of this complexity is associated with the landscape areas located near major drainages. These areas have undergone significant downslope mass movement during the last glacial ice advance (Woodfordian - 18,000 yrs ago). Because of these processes, many of the soils show stratification and turbation which complicates the identification of argillic horizons. Although the total picture is still unclear, the soils on broad upland surfaces with low slope gradients in the Piedmont probably have well developed argillic horizons while the soils on sloping landscapes with greater relief near major drainages may or may not have argillic horizons. A more complete assessment of Piedmont-argillic horizon relations requires additional work in this very complex region of Pennsylvania.

Lamellae

Very sandy materials form a unique parent material for argillic horizon formation. Probably the most common form is a series of lamellae below a cambic horizon (Bw); although the lamellae also can be found below argillic horizons. Lamellae are widely distributed and are found in soils from Pennsylvania (Carter, 1983) to South Carolina (Foss and Segovia, 1984) to Oklahoma, Wisconsin, Michigan (Schaetzl, 1992), and New York (E. Ciolkosz, personal observation). The genesis of lamellae has been investigated and a number of papers have been published on the subject (see Schaetzl, 1992). Soil Taxonomy (Soil Survey Staff, 1992) indicates that in order for lamellae to qualify as an argillic horizon, the lamellae must have an aggregate thickness of at least 15 cm (6 in) and an increase in clay content of at least 3% (e.g., 3 vs. 6%). The only data available on lamellae and inter-lamellae material in Pennsylvania soils is given in Table 7. These data indicate an increase of 4 to 5 times clay and 2 times the iron oxide content between the E horizons and the Bt. The increase in iron oxide gives a distinctive darker

Table 7. Characterization data for lamellae (Bt) and inter-lamellae (E) horizons of two Vanderlip pedons from Huntingdon County. Data from Ranney et al. (1974).

Soil Number	Horizon	Depth cm	Color	Percent Fe_2O_3	Sand+	Silt+	Clay+	Textural Class
31-1-11	E	71-91	10YR 6/4	0.6	90.8	7.0	2.2	fs
31-1-12	Bt	71-91	10YR 4/4	1.2	83.3	7.0	9.6	fsl
31-2-13	E	66-97	7.5YR 5/6	0.8	94.5	2.4	3.1	s
31-2-14	Bt	66-97	7.5YR 4/4	1.6	78.6	6.6	14.9	ls

+sand = 2 mm-50 µm, silt = 50 µm-2 µm, clay = < 2 µm

and frequently redder color to the Bt when compared to the E. The horizonation of these soils has been debated, and in the opinion of the authors a sequence of E, Bt, E, Bt, E, Bt horizons best describes the genetic process. Foss and Segovia (1984) and Bond (1986) show that a number of lamellae form simultaneously, thus the interlamellae zones are being eluviated and the lamellae are being illuviated with clay and iron. Although the E, Bt sequence may be thought by some to be unconventional, it is the most logical from a genetic view point. Lamellae can apparently form relatively rapidly. Foss and Segovia (1984) indicate that in South Carolina significant lamellae formation has taken place in 3,000 to 6,000 years. Ciolkosz (personal observation) has viewed significant lamellae formation in the leached zone of calcareous dune sands that are believed to be 10,000 year old on the shore of Lake Ontario near Rochester, New York. Hinkel (1993) shows an interesting photograph of lamellae developed in leached tongues of late Wisconsinan calcareous outwash in Indiana. These photos show the very strong influence of calcareous material on argillic horizon formation.

Some studies have concluded that lamellae in soils are geologic in origin. That is, that the lamellae accumulated as a part of the parent material and not as illuvial accumulations. This contention has not been rigorously tested in Pennsylvania. Although this is the case, the observation that the lamellae studied by Carter (1983) in ridge top sandstone soils wraps around the rock fragments indicates accumulation after the bedrock had been broken-up by soil forming processes. In addition, the observations that the clay in lamellae forms discreet bridges between the sand grains and coats the sand grains indicates a pedologic and not a geologic origin for the lamellae observed by the authors in Pennsylvania soils.

Clay Accumulation Index

Levine and Ciolkosz (1983) attempted to relate the amount of clay accumulated in the B horizon to soil age in Northeastern Pennsylvania. From this study Levine and Ciolkosz (1983) concluded that soils thought to be Altonian (early Wisconsinan) in age were 40,000 years old and had well developed argillic horizons. They also attempted to project the age of Pre-Wisconsinan till soils, but their results were not reasonable. They explained these anomalous results by the fact that the C horizon material which is used in the index was weathered and thus did not give an accurate base-line of comparison. It is believed that if a deep sampling of Pre-Wisconsinan till soil could be obtained, the method would give reasonable results. This conclusion is based in part on a recent study by McCahon and Munn (1991) who used this approach to successfully predict the age of Pre-Wisconsinan till soils in the Medicine Bow Mountains of Wyoming.

CLIMATE AND VEGETATION

Precipitation and Temperature

Soil Taxonomy (Soil Survey Staff, 1975) indicates that for argillic horizons to form the soil must have a season in which there is a greater amount of evaportranspiration than precipitation (e.g., udic moisture regime; Figures 4 and 5) and that argillic horizons are not found in soils with a perudic moisture regimes (Figure 2). In perudic moisture regimes precipitation exceeds evapotranspiration throughout the year, which means that any clay that was dispersed will be moved right through the soil unless it is flocculated. In Pennsylvania only two high elevation areas, the Pocono Plateau (NE PA) and the Laurel Highlands (SW PA) have low enough temperatures and get enough precipitation (≥ 125 cm, 50 in) to be slightly perudic (Ciolkosz et al., 1994b). The remainder of the state has a udic moisture regime. Although most of the state has a udic moisture regime the higher elevations areas, particularly on the Appalachian plateau in the northwest and central parts of the state, have a tendency to grade toward a perudic moisture regime and a frigid soil temperature regime. Although it has not been done, it would be interesting to study argillic horizon formation in a transect from the lower moisture surplus areas in the southeastern and western parts of the state to the areas that have higher moisture surpluses and are trending toward a perudic moisture regime (Figure 7). This type of study may show a distinctive trend of decreasing argillic horizon development with increasing perudic character of the soil moisture regime (see Figures 2-5) and may show a correlation with the proposed moisture classes given in Table 8. A similar approach was

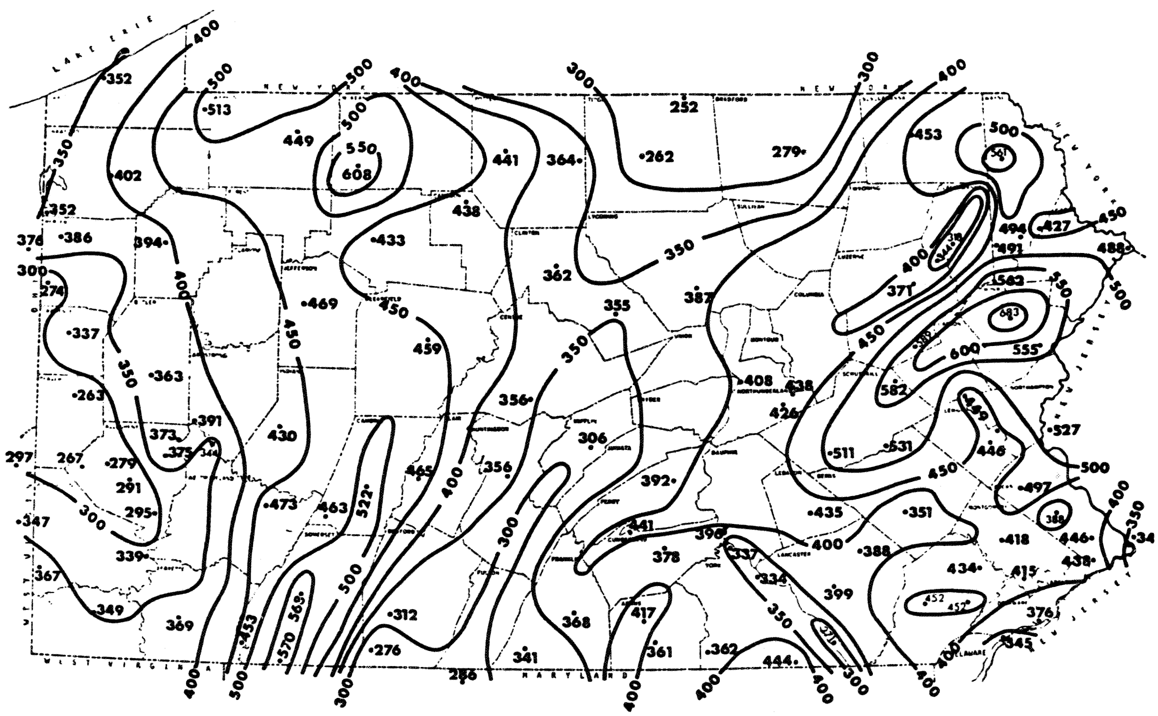

Figure 7. Moisture surplus (Thornwaite and Mather, 1957) in millimeters at specific weather stations in Pennsylvania generalized by isograms. Moisture surplus equals the total amount of precipitation minus the total amount of evapotranspiration, and is an estimate of the amount of water that leaches through the soil and into the groundwater (From Ranney et al., 1974). Pennsylvania covers an area that is about 300 miles east-west and 170 miles north-south.

Table 8. Proposed subdivisions of udic and perudic moisture regimes. These proposed subdivisions are partly based upon the resolution of the Newhall simulation model and surplus or deficit classes outlined in the Canadian System of Soil Classification (Clayton et al., 1977). Given the assumptions of the Newhall simulation model (Van Wambeke et al., 1992), a moisture surplus or deficit of 25 mm (1 inch) and 100 mm (4 inches) should be a recognizable minimum difference to support subdivisions in the perudic moisture regime. In comparison with the Canadian System of Soil Classification, the moist udic class would approximate the criteria of the perhumid subclass, with no significant moisture deficits (< 2.5 cm) during the growing season and the climatic moisture index (CMI > 84).

Subdivision	Mean Summer Surplus or Deficit	Mean Annual PRCP	Mean Annual Moisture Surplus	PRCP > PET
	(mm)	(mm)	(mm)	
Strongly Perudic	> 100	> 2000	> 1000	Yes, exceeds in all summer months
Typic Perudic	25-100	1700-2000	725-1000	Yes, exceeds in all summer months
Weakly Perudic	0- +25	1270-1700	650-725	Yes, exceeds in all summer months
Perudic Udic	0- +25	1143-1270	575-650	Fails, in 1 or 2 summer months
Moist Udic	0- -25	1016-1143	500-575	Fails, in 1 or 2 summer months
Typic Udic	-170-25	575-1143	< 500	Fails, in all 3 summer months

*Based upon 1961-1990 monthly precipitation (PRCP) normals and potential evapotranspiration (PET) calculated by the Newhall simulation model (Van Wambeke et al., 1992). Surplus or deficit = monthly PRCP normal-PET for June-July-August.

developed by Scrivner et al. (1973). These workers developed a model for converting long-time daily records of temperature and precipitation into daily depths of moistening and drying of the soil. When applied to Missouri soils their model indicates that the depth that had a frequency of one completed moist-dry cycle per year coincided with the depth of the solum (base of B horizon), while the upper boundary of the Bt horizon was determined by the average depth of penetration of summer rains. It is uncertain what effect temperature may have on argillic horizon formation. Higher temperatures may have the effect of increasing the weathering rate of soil minerals, thus increasing the rate of clay formation in the eluvial as well as the illuvial horizons. Higher temperatures may also contribute to argillic horizon formation by increasing the amount of evapotranspiration which would lead to a greater amount of summer moisture loss. This in turn would lead to a moisture regime tending toward ustic, which Eswaran and Sys (1979) indicate is the moisture regimes in which argillic horizons are expressed to the greatest extent.

Spodic Horizons

An interesting interaction of climate, vegetation, and parent material occurs when these conditions combine to form a spodic horizon (Bhs + Bs) in Pennsylvania soils. Under these conditions if there is clay in the parent material, it will move with the Fe, Al, and humus and accumulate in the spodic horizon (Table 9). This feature of Pennsylvania spodic horizons caused many problems in the early development of spodic classification criteria. These early criteria used an oxide to clay ratio to determine the spodic horizon, and in doing so many of Pennsylvania's best morphological Spodosols did not qualify as Spodosols (Stanley and Ciolkosz, 1981). This error in classification criteria has subsequently been corrected (Soil Survey Staff, 1992).

Table 9. Clay (< 2 μm) content of a selected number of soils with Spodosol morphology in Pennsylvania (from Stanley, 1979).

Horizon	% Clay	Horizon	% Clay	Horizon	% Clay	Horizon	% Clay	Horizon	% Clay
11-01*		14-01*		53-07*		54-05*		54-06*	
A	3.5	E	4.8	E	5.7	E	2.3	E	4.7
E	3.3	Bhs	11.1	Bhs	18.0	Bh	15.6	Bh	14.5
Bhs	13.2	Bs	9.6	Bs	15.8	Bs	20.1	Bs	19.1
Bs1	13.6	Bw	9.0	BC	11.1	Bw	13.2	Bw1	20.2
Bs2	11.6	BC	10.2	C	3.6	BC	7.3	Bw2	6.8
Bw1	10.8	C1	5.6			C	7.3	C	3.1
Bw2	11.6	C2	6.6						
BC	6.2								
C	3.8								

*Penn State Soil Characterization Lab Number.

Treethrow

Treethrow is another interesting subject in relation to argillic horizon development. When trees are blown over, their root systems are ripped from the soil and protrude above the ground surface. With time the soil that adhered to the roots falls back to the soil surface and frequently forms pit and mound microtopography. Denny and Goodlett (Denny, 1956) indicate that in Potter County (Northcentral area adjacent to New York) most soils have been disturbed by treethrow in the last 300 to 500 years. The treethrows in this area are also presently being studied by Small et al. (1990). Denny and Goodlett (Denny, 1956) and Goodman (1953) ascribe the youthfulness of the Potter County soils to the treethrow process. There certainly are treethrows with pit and mount microtopography in the area of Potter County and in other areas of Pennsylvania, but there are also many areas in that state that do not show this type of surface microtopography. In the author's experience, treethrow seems to be associated with a shallow rooting depth which is caused by a high water table, a fragipan, or bedrock. In addition, a branching tree root system (as opposed to a tap root system) also contributes to treethrow. In support of this conclusion is the fact that 51% of Pennsylvania soils have argillic horizons (indicators of stable surfaces) and the absence of argillic horizons in various areas can be explained by parent material and/or age considerations and not to soil mixing due to treethrow. In addition wind patterns and landscape position may also influence treethrow (Cremeans and Kalisz, 1988).

Paleoclimate

The affect of paleoclimate on soil formation is a subject of great interest. Of particular interest are the changes from glacial to interglacial climates and its effect on temperature, precipitation, and vegetation interactions. Unfortunately soil science has not adequately addressed the role of changing climate over time and its effect on soil genesis.

TOPOGRAPHY

The effect of topography on argillic horizon formation has not been rigorously investigated. Although this is the case, studies from the glaciated midwest where parent material is more constant across drainage sequences indicate as soils become more poorly drained the top of the argillic horizon is found nearer the soil surface and the amount of clay increase is greater between the eluvial and illuvial horizon (Ciolkosz, 1967). These trends have been attributed to a less effective leaching regime in wet soils than in their better drained equivalents. This trend may also be operational in Pennsylvania for Ranney et al. (1974) reported that in Pennsylvania the poorly drained soils are not as leached as the well drained soils. A cursory evaluation of data for cherty limestone (Ciolkosz et al., 1974) and colluvial and loess soils (Ciolkosz and Thurman (1993) shows the above general trend but with many exceptions. A parallel trend of increasing proximity to the surface with increasingly poorer drainage is also noted for Pennsylvania fragipans (Ciolkosz et al., 1992). The fragipan trend may in some cases be affected by the argillic horizon, but more likely the reverse is the case, because many of the soils in Pennsylvania that have argillic horizons also have fragipans and the fragipan formed before the argillic horizon (Ciolkosz et al., 1992). Another trend in argillic horizon development in a catenal sequence has been reported by Ciolkosz (1967) and Cremeens and Mokma (1986). These authors report a greater total amount of argillic horizon development in the well drained than in the more poorly drained members of the catena. This trend is most likely related to a larger number of wet-dry cycles (more dispersion) and weathering in the well drained than in the poorly drained soils. A similar trend may also exist in Pennsylvania soils but as yet no study has been done to explore this topic.

An additional effect of topography on argillic horizon formation is the effect of aspect (the direction the slope points, e.g., north, south, northeast, etc.) on clay movement and deposition. From a study on a ridge in central Pennsylvania, Carter and Ciolkosz (1991) concluded that soils on southern aspects had more clay accumulated than on northern aspects. Carter attributed this trend to warmer and dryer conditions on the southern aspect than on the northern aspect. Carter (1983) also concluded that this trend seems to occur only when the slopes exceeded about 15 percent. The value of 15 percent slope for midlatitude areas seems to be a significant value for Schmidlin et al. (1983) in Nevada indicate that soil temperature at the same elevation only vary by aspect (North vs South) when the slope is greater than 15 percent. Franzmeier et al. (1969) noted a trend similar to that reported by Carter and Ciolkosz (1991) for argillic horizon development in soils of the southern Appalachians.

SUMMARY

Argillic horizons are subsurface zones of illuvial clay accumulation that have a greater clay content than the overlying eluvial horizon. These horizons are pedogenic B horizons and indicate a distinctive pathway of soil development and landscape stability. By definition, argillic horizons occur in Alfisol and Ultisol soils. They may also be found in Mollisols, but not in the Mollisols found in Pennsylvania. Field identification of clay accumulation in the soil is noted by an increase in clay content from the eluvial to the illuvial horizon; and, usually, by clay films (argillans) on ped faces and pores or clay bridges across sand grains. Such illuvial horizons are designated as Bt ("t" signifies an accumulation of silicate clay) horizons. Not all horizons of clay accumulation meet the quantitative criteria of an argillic horizon as defined in Soil Taxonomy. To be an argillic horizon, the illuvial zone must meet a minimum increase in clay content over the eluvial horizon, be of a certain thickness, and contain evidence of oriented clay films (argillans) or bridges between soil particles.

The formation of an argillic horizon is a three step process: (1) clay present in the parent material or formed by weathering is dispersed; (2) the dispersed clay is carried by water downward through the profile; and (3) the translocated clay accumulates in the subsurface by deposition and/or flocculation. The major mechanism of clay accumulation in loamy and clayey soils is deposition of clay on ped faces and in pores. In sandy soils, the clay accumulates as bridges between sand grains and as coatings on the grains.

Argillic horizons occur in soils that cover approximately one-half of the land area of Pennsylvania. Their distribution is not uniform across the state. For example, argillic horizons occur in 85 percent of the area of the Southwest Plateau but in only 2 percent of the area of the Glaciated Northeast Plateau. These differences in distribution can be explained by differences in the impact of the various soil-forming factors on the soils of these areas.

Parent material and time are important in argillic horizon formation. The parent material must either contain clay or clay must be formed by weathering. For example, soils forming in acid sandstone and shale colluvium have argillic horizons while soils forming in glacial till of similar age and parent material do not. The colluvial parent materials are more weathered and have more clay available for movement. Soils forming in limestone parent materials develop argillic horizons because clay is released as an impurity when limestone dissolves. The released clay moves through the leached upper horizons and flocculates when it comes in contact with the calcareous or high base saturation zone. This mechanism also explains why argillic horizons occur in soils forming in calcareous till parent materials but not in similarly-aged acidic till materials.

A comparison of argillic horizon development in progressively-older glacial till parent materials indicates that as soils get older, argillic horizons increase in both total and fine clay content, become thicker, and occur deeper in the profile. This comparison also indicates that as soils get older, a significant amount of the clay in the argillic horizon originates from in-place weathering. In contrast, argillic horizons in Ultisols forming in acid shale and sandstone parent materials in the Central Plateau reflect the resistance of the parent material to rapid weathering. These soils are relatively shallow, have a high rock fragment content, and show weak to moderate development. In these soils, the clays are inherited from the parent material. The clay in argillic horizons of red shale soils in the Ridge and Valley may also have been inherited from lithified paleosols rather than formed by weathering.

Climate has an important role in the translocation and deposition of clay. While the climate must provide sufficient water for leaching and translocation of clays, a season in which evapotranspiration exceeds precipitation is also critical. For this reason, argillic horizons are found in udic moisture regimes but not in perudic regimes. In perudic moisture regimes, precipitation exceeds evaporation throughout the year and translocated clay will be moved through the soils unless it is flocculated.

A few studies suggest that argillic horizons occur closer to the surface as soils become more poorly drained and that the total amount of argillic horizon development is greater in better-drained soils. This may be due to less effective leaching in wetter soils or to more complete wetting and drying cycles in better-drained soils.

While much is known about argillic horizon formation in Pennsylvania, more study is needed in certain areas. For example, what effect does a changing climate over time have on soil genesis and argillic horizon formation? The effects of moisture surplus on argillic horizon formation could also be evaluated. This could be done with a study of a transect of argillic horizon development across Pennsylvania, from low moisture surplus areas to high moisture surpluses (i.e., from udic to perudic moisture regime areas).

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