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College of Agricultural Sciences

Agronomy Series

GENESIS OF PENNSYLVANIA'S LIMESTONE SOILS

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Agronomy Series Number 135

November 1995

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November 1995

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INTRODUCTION

Carbonates (calcite and dolomite) significantly influence the pathway of genesis of many soils, particularly young soils (Ciolkosz et al., 1994; 1995a). The influence of carbonates in transported material (glacial till, loess, alluvium, colluvium) will not be discussed in this presentation. Thus, the focus of this presentation will be on what has been perceived as residual soils developed from carbonate rocks. In this publication the term soil and residuum are used interchangeably, because residuum is considered soil material that has weathered from the rock by soil-forming reactions. The term limestone is frequently used to include both calcitic and dolomitic carbonate rock. A more detailed terminology restricts the use of limestone to calcitic rock and dolomite to dolomitic rock. We will use the term limestone in most cases in the general sense. There is scattered published and unpublished information on Pennsylvania's limestone soils, but there is no integrated presentation, particularly on their genesis. Thus, the objective of this publication is to present a review of the genesis of limestone soils of Pennsylvania.

DISTRIBUTION

Pennsylvania's limestone soils are found primarily in the central (Ridge and Valley) and southeastern (Triassic-Piedmont) areas of the state (Figure 1). In these areas the limestone soils are found on the valley floors in a number of large valleys such as Nittany Valley (Centre Co.) (Figure 2), Kishacoquillas Valley (Mifflin Co.), Great Valley (Franklin Co. and northeast to Northampton Co.), and Conestoga Valley (Lancaster Co.). In addition, limestone soils are also found in smaller valleys and in a few small areas of western Pennsylvania, particularly in the Southwest Plateau area.

GENESIS

With some exceptions, Pennsylvania's limestone soils can be separated into two main groups with the Hagerstown and Duffield soils being the prime members of these two groups (Tables 1 and 2). Four other groups of carbonate influenced soils are those developed from shale

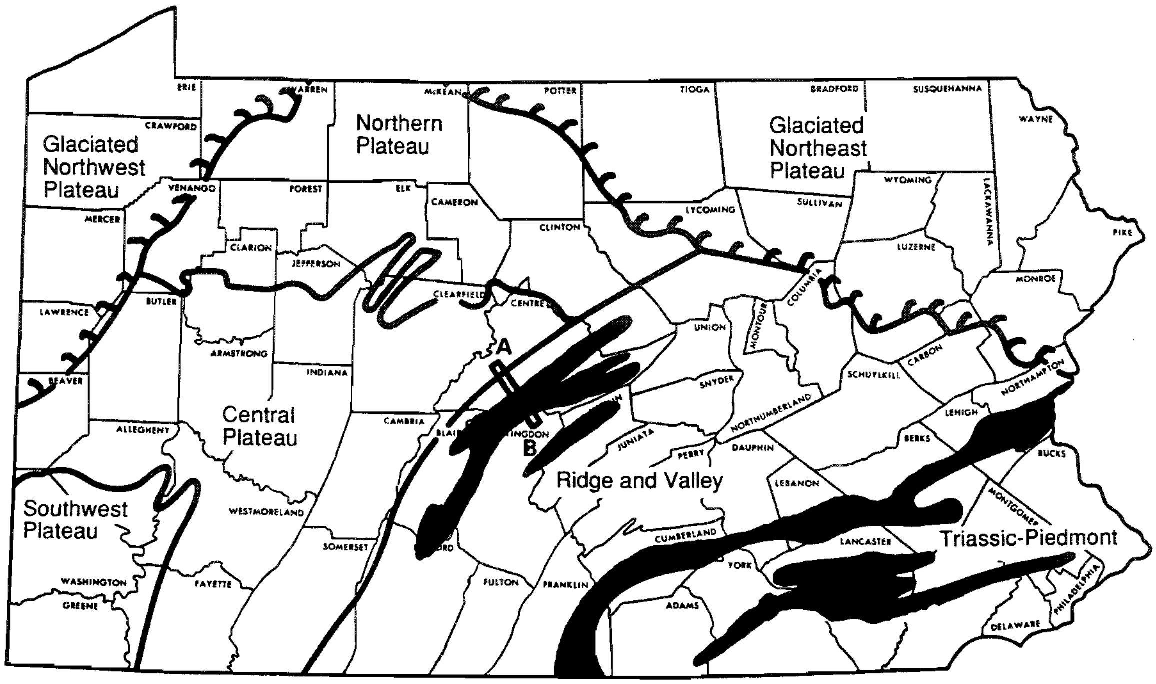

Figure 1. Limestone soil areas of Pennsylvania (shaded black). These areas are dominated by relative pure limestones. Other areas dominated by calcareous shales and calcareous shales with some interbedded limestones are not shown. The bar marked A-B in the central part of the state (Centre Co.) is the general location of the block diagram shown as Figure 2. Pennsylvania is about 300 miles east-west and 170 miles north-south.

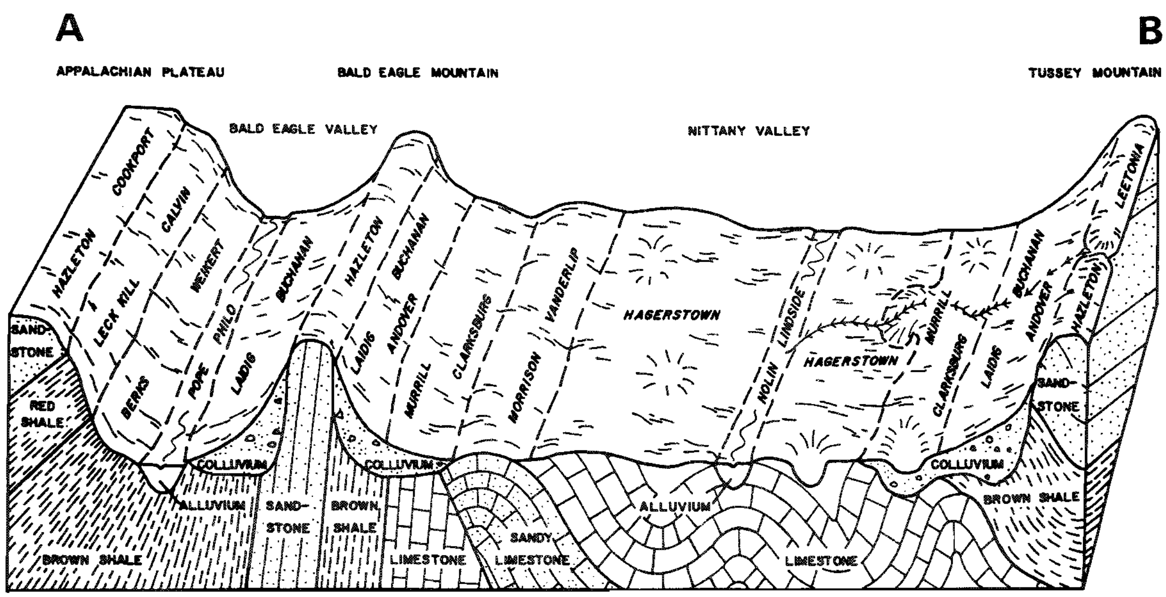

Figure 2. Generalized soil-landscape relationship (not to scale) of Nittany Valley (central Ridge and Valley area) (From Ciolkosz and Dobos, 1990b). The general location of this area is given in Figure 1 (bar marked A-B in the central part of the state).

Table 1. Distribution and parent material for Pennsylvania's major soils and Pennsylvania's limestone, shaly limestone, cherty limestone, micaceous limestone, and sandy limestone soils. The data are from the USDA Natural Resource Conservation Service (NRCS) Map Unit Use File (MUUF). The MUUF was obtained from the NRCS office in Harrisburg, PA in 1991 and is complete for all counties of Pennsylvania. See Ciolkosz et al. (1995a) for additional information on these and other soils.

Rank	Soil Series	Location*	Acres in Pennsylvania**	Parent Material
1	Hazleton	Plateau and R&V	2,739,178	Acid brown sandstone
2	Gilpin	Plateau	1,613,830	Acid brown shale
3	Weikert	Plateau and R&V	928,949	Acid brown shale
4	Oquaga	Glaciated NE Plateau	924,760	Acid red till
5	Berks	R&V	817,992	Acid brown shale
6	Cookport	Plateau	815,751	Acid brown sandstone and shale
7	Ernest	Plateau	689,066	Acid shale & sandstone colluvium
8	Buchanan	R&V	617,682	Acid sandstone & shale colluvium
9	Volusia	Glaciated NE & NW Plateau	610,854	Acid brown till
10	Wellsboro	Glaciated NE Plateau	592,807	Acid red till
11	Morris	Glaciated NE Plateau	586,238	Acid red till
12	Laidig	R&V	577,694	Acid sandstone & shale colluvium
13	Wharton	Plateau	555,977	Acid brown shale
14	Lordstown	Glaciated NE Plateau	535,908	Acid brown till
15	Lackawanna	Glaciated NE Plateau	452,752	Acid red till
16	Hagerstown	R&V and Tri-Piedmont	451,669	Pure Limestone
17	Hartleton	R&V	436,078	Acid brown shale
18	Dormont	SW Plateau	429,833	Shale and limestone
19	Mardin	Glaciated NE & NW Plateau	429,712	Acid brown till
20	Leck Kill	Glaciated NE Plateau and R&V	424,398	Acid red till and acid red shale
21	Cavode	Plateau	397,337	Acid brown shale and clay
22	Culleoka	SW Plateau	352,234	Shale and limestone
38	Duffield	R&V and Tri-Piedmont	207,925	Shaly limestone
40	Guernsey	SW Plateau	191,875	Shale and limestone
53	Murrill	R&V	128,204	Limestone, shale, and sandstone colluvium
58	Edom	R&V	109,231	Shale and limestone
59	Westmoreland	SW Plateau	109,193	Calcareous shale
64	Morrison	R&V	98,134	Calcareous sandstone
65	Upshur	SW Plateau	96,890	Calcareous red shale
72	Clarksburg	R&V, Tri-Piedmont, and SW Plateau	86,195	Limestone colluvium
81	Opequon	R&V and Tri-Piedmont	73,359	Pure limestone
90	Elliber	R&V	65,770	Very cherty limestone
99	Conestoga	Tri-Piedmont	53,807	Micaceous limestone
100	Hublersburg	R&V	51,685	Cherty limestone

*See Figure 1 for general location in the state.
**Only soils with > 50,000 acres are listed.

and limestone, calcareous sandstone (most have interbedded limestone), very cherty limestone, and micaceous limestone (Tables 1 and 2). Because they are extensive in distribution (Table 1), typify a range of residual limestone soil properties, and have been studied, the Hagerstown and Duffield soils will be the main focus of this presentation. Other carbonate influenced soils will only be discussed briefly.

The Hagerstown and Duffield soils are deep (> 100 cm) to bedrock and well drained (Table 2). They differ mainly in the character of their B horizon with the Hagerstown having a red, clayey B, while Duffield has a brown, silty B. These soils occur in areas of karst topography that contain sink holes and a limited integrated surface drainage network. Most of the surface runoff of these soils does not drain directly into drainage ways and streams, but into sink holes, and then into the ground water. A typical groundwater recharge rate for these soil areas is about 1×10^6 gal/sq mile/day. The groundwater discharges via springs into streams. Therefore, the Hagerstown and Duffield soils are associated with major groundwater resources (see Parizek et al., 1971; Wood, 1980; and White, 1988 for a discussion of karst hydrology).

PARENT MATERIAL

Limestones

The major properties of the limestone soil's subsoil (B horizon) can be related directly to the type of parent material from which the soil has developed. According to Folk (1974) and Bates and Jackson (1987), limestone parent materials vary from relatively pure limestones ($\geq$ 90% limestone), to shaly limestone (90-50% limestone), to calcareous shale (50-20% limestone), to sandy limestone (90-50% limestone), to calcareous sandstone (< 50% limestone). Pennsylvania soils have developed in all of these types of parent materials, although not in equal acreages (Table 1). The parent material for the soils is the insoluble residue (IR) remaining after the calcite and/or dolomite has been dissolved by percolating water and the soluble fraction leached from the soil. The IR of a carbonate rock can be determined in the laboratory by crushing the rock and dissolving the carbonate with an acid (e.g., HCL) or an acid buffer (e.g., HOAC-NAOAC). Tables 3, 4, and 5 give data on the IR of limestones of Pennsylvania. Additional sources for IR data are Miller

Table 2. Major carbonate affected soils of Pennsylvania arranged according to parent material and drainage. All soils have mesic soil temperature regimes. They all also have mixed mineralogy except as noted.

	(Shallow) < 50 cm to bedrock	(Moderately Deep) 50-100 cm to bedrock	(------------------ Deep > 100 cm to bedrock (R horizon)			--------------)
	Drainage Class and Depth to Mottling					
Parent Material	(---------------------- Well Drained (------------------------- > 100 cm		---------------------------) ---------------------------)	Moderately Well Drained (50-100 cm)	Somewhat Poorly Drained (25-50 cm)	Poorly Drained (0-25 cm; some gleying)
Residual Relatively pure limestone*	Opequon Lithic Hapludalf; clayey		Hagerstown Typic Hapludalf; fine	Clarksburg Typic Fragiudalf; fine-loamy	Penlaw Aquic Fragiudalf; fine-silty	Thorndale Typic Fragiaqualf; fine-silty
Shaly limestone*		Ryder Ultic Hapludalf; fine-loamy	Duffield Ultic Hapludalf; fine-loamy	Clarksburg Typic Fragiudalf; fine-loamy	Penlaw Aquic Fragiudalf; fine-silty	Thorndale Typic Fragiaqualf; fine-silty
Micaceous Limestone*			Conestoga Typic Hapludalf fine-loamy	Clarksburg Typic Fragiudalf; fine-loamy	Penlaw Aquic Fragiudalf; fine-silty	Thorndale Typic Fragiaqualf; fine-silty
Shale and Limestone*			Edom Typic Hapludalf; fine^{+}, illitic	Clarksburg Typic Fragiudalf; fine-loamy	Penlaw Aquic Fragiudalf; fine-silty	Thorndale Typic Fragiaqualf; fine-silty
Redbeds and weakly calcareous greenish-gray shale			Upshur Typic Hapludalf; fine	Vandergrift-------------------------) Aquic Hapludalf; fine		
Neutral to weakly calcareous shale and fine-grained sandstone	Weikert Lithic Dystrochrept; loamy-skeletal	Culleoka Ultic Hapludalf; fine-loamy	Westmoreland Ultic Hapludalf; fine-loamy	Dormont Ultic Hapludalf; fine-loamy	Library Aeric Ochraqualf; fine	
Limestone, calcareous shale, and clays	Weikert Lithic Dystrochrept; loamy-skeletal	Culleoka Ultic Hapludalf; fine-loamy	Westmoreland Ultic Hapludalf; fine-loamy	Guernsey Aquic Hapludalf; fine	Library Aeric Ochraqualf; fine	
Cherty limestone*			Hublersburg Typic Hapludalf; clayey^{+},illitic	Clarksburg Typic Fragiudalf; fine-loamy	Penlaw Aquic Fragiudalf; fine-silty	Thorndale Typic Fragiaqualf; fine-silty
Very cherty limestone*			Elliber Typic Hapludult; loamy-skeletal	Kreamer Aquic Hapludult; clayey, illitic	Evendale-----------------------------) Aeric Ochraquult; clayey	
Grayish brown sandstone (in some places a very sandy limestone)			Vanderlip Typic, Quartzipsamment; coated Morrison Ultic, Hapludalf; fine-loamy			

* Moderately well to poorly drained soils have moderate to significant colluvial influence.

$^{+}$ The fine textural class indicates 35-60% clay while clayey indicates > 35% clay.

(1934), Folk (1952), O'Neil (1964), and Parizek and White (1985). Generally the limestone IR data can be grouped into rock categories of < 10% IR and > 10% IR. The rock with < 10% IR would be classified as a pure limestone, and the data in Tables 3 and 4 indicate that this is the type of rock that weathers to form Hagerstown soils. The data in Tables 3 and 4 also indicate that limestones with greater than 10% IR are the parent rock of the Duffield soils. It has been proposed that dolomite is the parent rock for the Hagerstown soils (Carey, 1970). Limited data (Tables 3 and 4 and Cronce, 1988a) does not support this proposal. Thus, the type of carbonate (calcitic or dolomitic) is apparently not a factor in determining the difference between Hagerstown and Duffield soils. Although the type of limestone is not a factor, there does appear to be an association of rock color with IR content, and therefore with Hagerstown soils. Pennsylvania's limestones generally have low Munsell chromas, but they do vary in Munsell value. The values vary from light gray (value of 7) to black (value of 2.5 or less). The data in Tables 3 and 4 indicate that Munsell colors with values of 5 (gray) or less are associated with rock that have less than 10% IR. The work of Folk (1952) also supports the association of dark-colored limestones with low IR contents. According to Folk (1952), this variation in rock color is related to a higher amount of organic matter in the darker (low value) rocks. Cronce (1988b) supports Folk's conclusion with organic carbon data that ranges from 0.25% (for light colored rocks) to 1.75% (for dark colored rocks). Folk also notes that when these rocks weather, the weathered material is much lighter in color (higher value) due to the oxidation of the organic matter. This relationship is very obvious in many limestone road cuts throughout Pennsylvania. When these cuts are first made, the dark-colored rocks have a dark-colored surface; but after a relatively short period of time (5 to 10 years) the surface weathers and turns a light color while the unweathered rock interior remains dark in color. As a matter of fact, as the dark-colored and light-colored limestones weather, the weathered zone of each tends to become a similar color.

It has been assumed (Ciolkosz and Dobos, 1990b) that the difference in clay content between the subsoil (B horizon) of the Hagerstown and Duffield soils is due to a higher clay content of the IR of the Hagerstown soil. The data of Cronce (1988a) (Table 4) on this point is inconclusive. Additional IR clay data is needed from a wider geographic area of the state to clarify this point. If additional data supports the assumption that the Hagerstown IR has more clay than the Duffield IR, no other explanation is needed. If not, it may be possible that the silt-size IR material of the Hagerstown weathers faster than that of the Duffield, and because the Hagerstown IR has more silt than the Duffield IR, more clay would be produced from weathering of the Hagerstown IR than the Duffield in the same period of time. In addition, scanning electron micrographs of the IR show a highly porous sponge-like matrix (Cronce, 1988a). If these sponge-like particles are more abundant in the Hagerstown IR than the Duffield IR, they would probably weather more rapidly than solid particles resulting in a higher clay content in the Hagerstown soil.

The clay content of the B horizon of both the Hagerstown and Duffield soils is greater than their A horizon. This difference has been attributed to eluviation of clay from the A into the B forming an argillic Bt horizon (See Ciolkosz et al., 1994 for a discussion of argillic horizon formation). Observations of clay films in the argillic horizons indicate that clay has been translocated and has accumulated in the Bt. Although this appears to be the case, the very strong contrast in clay content between the A and Bt, particularly for the Hagerstown (A - 20%, Bt - 40 to 60%) suggests that translocation and accumulation is not the only cause of this contrast. The realization that eolian deposits are more extensive than previously envisioned (Smith et al., 1970; Reheis, 1995; Simonson, 1995) and the work in Pennsylvania of Cronce (1988a) and Carter (1983) indicate significant eolian addition to the surface of these soils. For example, Cronce (1988a) reports that between 25 and 50% of the silt in the upper part of Hagerstown profiles in Nittany Valley is of eolian origin. Thus, the strong contrast in clay content between the A and B horizons is due both to clay illuviation and a dilution of the clay content of the A by the addition of silt-size eolian material. In some pedons there appears to be more illuvial clay in the Bt than would be expected from the overlying horizons. In these cases, some of the clay may have been eluviated from soil material that has subsequently been eroded from the soil surface. This process has been used to help explain the genesis of limestone soils in Illinois by Ballaugh and Runge (1970).

Table 3. Soil and rock data for selected soils developed from limestone. Data from Ciolkosz and Dobos (1990b), Ciolkosz and Thurman (1994), and Jeffries and White (1940).

				Percent				
Horizon	Depth (cm)	Color	Limestone Type	Fe_2O_3	Insoluble Residue	Sand	Silt	Clay
				Hagerstown				
Ap	0-18	10YR 3/2		2.5		14.1	64.5	21.4
Bt	18-97	5YR 4/6		4.6		19.7	41.5	38.8
C	97-100	5YR 3/3		6.0		20.9	24.3	54.8
R	100-120	N 4/0	dolomitic	0.4	4			
Ap	0-18	10YR 2/2		2.1		11.4	64.2	24.5
Bt	18-101	5YR 4/6		3.9		7.8	39.1	53.1
R	101-150	N 5/0	dolomitic	0.5	9			
Ap	0-20	10YR 3/2		2.6		15.0	65.6	19.4
Bt	20-76	5YR 4/6		5.2		6.0	27.0	67.0
R	100-155	N 3/0	calcitic	0.2	3			
R		N 5/0	dolomitic	1.2	6			
R		N 4/0	calcitic	0.2	3			
R			dolomitic		6			
Bt3	84-117	2.5YR 4/6		5.8		8.2	31.7	60.1
Bt2	58-84	5YR 5/6		6.9		9.7	31.2	59.1
Bt3	71-79	5YR 5/4		4.4		7.6	43.6	48.7
Bt2	61-89	5YR 5/6		5.5		9.1	26.3	64.6
Bt2	79-109	5YR 4/8		4.7		2.2	36.0	61.8
Bt4	89-109	5YR 4/6		6.2		2.9	4.9	92.2
				Duffield				
Ap	0-33	10YR 3/3		2.0		5.7	73.8	20.5
Bt2	56-76	7.5YR 5/6		3.6		11.0	53.6	35.4
C1	132-170	10YR 5/6		2.4		15.8	56.1	28.2
R	203-240	N 6/0	dolomitic	1.9	14			
Bt3	79-99	7.5YR 5/6		4.4		9.3	64.2	26.5
Bt2	56-84	7.5YR 5/8				13.0	52.7	34.3
Bt3	86-117	7.5YR 5.8				16.6	52.2	31.2
Bt4	86-122	10YR 4/4		2.0		13.0	51.2	35.8
Bt2	74-100	10YR 5/6		2.3		29.6	44.8	25.6

Table 4. Selected rock and soil data for limestone soils in Nittany Valley (Centre County). Data from Cronce (1988a).

Horizon	Depth (cm)	Color	Limestone Type	Percent Fe_2O_3	Percent Insoluble Residue	Percent Sand	Percent Silt	Percent Clay
				Hagerstown (14-66)				
A	0-8	10YR 3/2		1.5		4.7	77.2	18.1
Bt	76-97	5YR 5/8		4.7		3.2	34.6	62.2
R*	112-178	10YR 5/2	dolomitic	0.3	4	2.0	86.3	11.7
				Hagerstown (14-75)				
A	0-10	10YR 3/2		1.2		10.3	73.2	16.6
Bt2	61-86	5YR 5/6		4.1		3.8	38.4	57.8
R*	160-180	10YR 4/1	calcitic	0.2	3	2.1	81.4	16.5
				Duffield (14-73)				
A	0-8	10YR 3/1		1.2		9.8	73.8	16.3
Bt2	61-86	7.5YR 5/8		2.9		10.4	48.3	41.3
R*	189-200	10YR 6/2	dolomitic	0.4	17	23.8	69.2	7.0
				Duffield (14-74)				
A	0-18	10YR 3/2		1.2		6.8	75.9	17.3
Bt2	71-94	7.5YR 5/8		3.3		3.5	57.2	39.3
R*	330-340	2.5YR 7/3	dolomitic	0.4	39	7.5	78.2	14.3

*Mean of multiple samples (3 to 6).

The rock fragment content of the Hagerstown and Duffield soils is usually low (< 10%). The Hagerstown rock fragments are mainly chert while those in the Duffield are dominantly shale. An exception for both soils occurs in the Triassic-Piedmont area where many of the rock fragments are vein quartz. Apparently sometime in the geologic past fluids were injected into these rocks and quartz crystallized out of these fluids. Since quartz is very resistant to weathering, it remains as a residual product after the carbonate of the limestone has solublized and has been leached away.

Calcareous Sandstones

Soils formed from calcareous sandstone and interbedded limestone and sandstone form a unique type of soil and are dominantly the Vanderlip and Morrison soils (Tables 1 and 2). These sandy soils have developed in the upper part of a thick accumulation of residual material that has weathered from the underlying bedrock. Parizek and White (1985) indicate that in Nittany Valley, these residual materials can be up to 30 to 60 meters thick. The Vanderlip is classified as a Psamment while the Morrison is classified as a Udalf. The bulk of these soils are found in Centre and Blair counties and have formed from the Gatesburg formation (Table 5). As the bedrock weathered, the dolomite beds dissolved leaving the insoluble materials as layers of fine textured material in a very thick, sandy regolith. Although the sandy material is most evident, Butts and Moore (1936) state that the sandstone probably makes up only about 20% of the bedrock formation. Butts and Moore (1936) also state that some of the sandstone beds are as much as

Table 5. Iron (Fe_2O_3) and insoluble residue (IR) data for Gatesburg and Stonehenge Formations in Nittany Valley. Data from Rose (1995). The iron data was obtained by analysis of the solution after the carbonates were dissolved and does not include any iron that was retained in the IR material.

	Sample Number									
	1	2	3	4	5	6	7	8	9	10
Fe_2O_3 (%)	0.74	1.11	0.72	1.72	0.57	0.57	0.72	0.52	1.49	0.63
IR (%)	14	10	55	42	11	7	12	60	40	7
Formation*	LSdol	LSdol	LSss	LSsh	OHdol	USdol	USdol	USss	USsh	STls

*LS = lower sandy member, Gatesburg Fm.; OH = orehill member, Gatesburg Fm.; US = upper sandy member, Gatesburg Fm.; ST = Stonehenge Fm.; dol = dolomite, ls = limestone, sh = shale, and ss = sandstone.

3 meters thick. Where the thicker sandstone residuum intercepts the surface because of sloping topography or dipping sandstone beds, the Vanderlip soils are found. Apparently in this situation the sandstone residuum did not have enough clay in it (Vanderlip soils have 4-8% clay) to form an argillic horizon by illuviation, but where the sandstone residuum was thinner, some of the finer material from the limestone residuum has accumulated as an argillic horizon. In these places, Morrison soils are found (see Ciolkosz et al., 1994, for a more complete discussion of argillic horizon formation).

Shale and Limestone

Although soils formed from shale and limestone (including calcareous shale) occupy larger acreage (Table 1) than limestone soils, they have not been studied as extensively (Ciolkosz et al., 1976). These soils are found mainly in the Southwest Plateau area, although some, particularly the Edom soil, are found in the Ridge and Valley area. Of these soils, the Guernsey, Upshur, and Vandergrift have high expansion and contraction properties upon wetting and drying and are unstable and prone to downslope movement (Ciolkosz et al., 1979). These properties appear to be inherited from their parent materials. The soils formed from calcareous shale (without interbedded limestone) logically should be deeper than soils formed from only limestone. The logic is that in order to form soil in calcareous shale, only the relatively small amount of calcareous cement holding the clastic particles together needs be leached from the rock for the rock to disaggregate. Although logical, no studies in Pennsylvania have pursued this topic. Although this is the case, support for this assumption comes from Alexander (1985) who states that calcareous clastic rocks weather at a rate that is an order of magnitude greater than limestones.

Cherty Limestones

The Hublersburg soil has a minor amount of chert while the Elliber and associated soils have large quantities of chert rock fragments (Ciolkosz et al., 1974). The Elliber soils form secondary ridges on the valley floor in the central Ridge and Valley area. The soils associated with the Elliber (Table 2) are found on the side slopes of these ridges, and most of them have had colluvial material added to them or have been turbated by downslope movement of the soil material.

Micaceous Limestone

The Conestoga soil is another unique type of soil. It has formed from micaceous limestone, and to a limited extent, calcareous schist. This soil is found primarily in the Triassic-Piedmont area where the limestones locally have been slightly metamorphosed, and apparently some of the detrital clay material in the limestone has been converted to mica. These soils are very similar to the Duffield in characteristics, except they have a relatively high mica content. The mica is very evident in the soil because the mica particles (sand and silt size) reflect light from their flat surfaces readily, particularly when the soil material is rubbed between the fingers.

COLOR

The color of well drained soil subsurface horizons is determined by the iron oxide mineral type (Ciolkosz and Dobos, 1990a; Schwertmann, 1993). Red soils are dominated by hematite (Fe_2O_3) and brown soils by goethite (FeOOH). Once formed, both hematite and goethite are stable in oxidizing soil environments (well drained soils), and according to Schwertmann (1993) there is no indication of a solid-state transformation of goethite to hematite by simple dehydration in soils. Schwertmann (1993) also indicates that the factors that promote the formation of hematite over goethite as iron is released from primary minerals by weathering are (1) high temperature, (2) low water activity (dryness), (3) neutral pH, (4) high iron content in the parent material and rapid release of the iron during weathering (high iron concentration in the weathering solution), and (5) a rapid turnover of biomass (rapid oxidation of the organic matter added to the soil). In addition, Schwertmann (1988, 1993) indicates that hematite has a much greater pigmenting power than goethite, and that an addition of 1% of hematite to a soil with 3% goethite can markedly redden a soil from 2.5Y (yellowish brown) to 5YR (reddish brown).

Pennsylvania data indicate, with a few exceptions, the range of free iron oxide content in B horizons is 4 to 7% for Hagerstown and 2 to 4% for Duffield soils (Tables 3 and 4). From these data it might be assumed that the higher the iron oxide content, the redder the soil. As previously indicated, however, the yellowness or redness of the soil is determined by the amount of goethite vs. hematite in the soil and that an increase in redness of a soil is related to an increase in hematite content. This conclusion is supported by observations of Pennsylvania and New York soils (Ciolkosz et al., 1993; MacFie, 1991) and data in the literature (Schwertmann, 1993).

No data are available on the iron oxide mineralogy of the Hagerstown or Duffield soils. Although no data are available for these soils, Schwertmann (1993) indicates that soils with yellow hues (7.5YR to 10YR) have little or no hematite. Thus, the color of the Duffield soil is apparently due to goethite, and the color of the Hagerstown is due primarily to hematite (hues of 2.5YR probably indicate that 50-75% of the iron oxide content is hematite). This raises an interesting question. If the iron oxide mineralogy between these soils is different, why is it different? The application of the factors given by Schwertmann (1993) (see list given above) to the Hagerstown-Duffield soil color question is not clear-cut. These soils are found on the same landscape position, thus temperature and dryness do not seem to be major factors in determining the iron oxide mineralogy. However, this assumption may not be totally correct because the silty Duffield soils hold more available moisture, and they may be slightly moister than the clayey Hagerstown. This difference may contribute to the preferential crystallization of hematite over goethite. The higher content of iron oxides in the Hagerstown than in the Duffield may also indicate a higher content of iron in the weathering solution which would also favor hematite formation over goethite, and may help explain the color difference between these two soils. Although this may be the case, there does not seem to be a major difference in the iron content of the dark- or light-colored limestones (Tables 3 and 4). An additional factor may be the pyrite (iron sulfide) content of the rock. Folk (1952) reports that pyrite is a major iron mineral in the dark-colored, pure limestones in Nittany Valley, and it weathers to hematite, while lighter colored shaly limestones have less pyrite, and in these rocks the iron weathers to goethite. Glazoskaya and Parfenova (1974) also report that limestones containing higher amounts of iron sulfide minerals favor the formation of red, hematitic soils. They state that the oxidation of iron and sulfur by oxidizing bacteria in the weathering rinds of the rock is a major factor affecting the color development of these soils. Data of Cronce (1988b) shows a sulfur concentration of 0.04% (light colored) to 0.20% (dark colored) for limestone in Nittany Valley. The data also indicate that the sulfur content of the weathered rinds of the rock regardless of the sulfur content of the rock decreases to about 0.02% within several centimeters of the unweathered rock. These data support the assumption that the parent rock of the Hagerstown releases some of its iron more rapidly than the parent rock of the Duffield. This would result in a higher concentration of iron in the weathering solution which in turn would favor hematite formation. In addition, the oxidation of the pyrite to H_2SO_4 would accelerate solublization of the rock and also increase the rate of release of iron to the weathering solution.

The Hagerstown soil will continue to redden with time because about one-third of its total iron is not in the oxide form (Ciolkosz et al., 1993). Another reason it will continue to redden is that soils do not become saturated with redness until 10-15% of the total soil material is hematite (Schwertmann, 1993). With this very high concentration of hematite, the color of the soil would probably be very red (10R to 5R).

Red soils are common in Pennsylvania, but many of them have developed from redbed parent materials such as the Catskill, Bloomsburg, Mauch Chunk formations and several Triassic age rock units. These inherited lithochromic colors generally have a 2.5YR hue and 4/4 value and chroma. Soils with pedogenic hues of 2.5YR generally have higher values and chromas (e.g., 5/6 to 6/8). Hematite is the dominant iron oxide mineral in redbeds (Blodgett et al., 1993) and in Pennsylvania's bedreds it may be the only iron oxide mineral (Elless and Rabenhorst, 1994). Thus, the main difference between lithogenetic and pedogenetic color is the value and chroma. These properties appear to be related to the size of the hematite crystals. This conclusion is supported by the statement of Blodgett et al. (1993) that redbeds get darker in color (lower chroma) with increasing hematite crystal size and by the color plates and data of Schwertmann (1993).

AGE

Another interesting question about the limestone soils concerns the time required for development of the soil material. If all the material is of residual origin, then it would take about 50 meters of bedrock to give about 5 meters of soil (6% insoluble residue by weight equals about 10% by volume). The time required to accumulate these residual materials is also an interesting question. Studies of limestone tombstone weathering give limestone dissolution rates of 10 to 100 mm/1,000 yrs (Colman, 1981; Meierding, 1981, 1993). Trudgill (1976, 1985) gives limestone dissolution rates of 1,000 to 5,000 mm/1,000 yrs for limestone under calcareous brown earth soils. These rates are a little higher than those given by Saunders and Young (1983) of 20 to 100 mm/1000 yrs, by Jennings (1983, 1985) of 5 to 30 mm/1,000 yrs, and by Goudie (1995) of 16 to 102 mm/1000 yrs. Additional data are given in Ollier (1984). Parizek and White (1985) give a rate of 30 mm/1,000 yrs for Nittany Valley. It is interesting to note that over 100 years ago, Ewing (1885) published a limestone dissolution rate of 27 mm/1,000 yrs for Nittany Valley. Dissolution rates and insoluble residue data can be used to compute some general accumulation rates for residual limestone soils (Table 6). In Pennsylvania, residual material on stable landscape surfaces varies from 2 to 8 meters in thickness, although greater thicknesses also occur. The 2 to 8 meter thickness would give an age of about 1 to 3 million years for these soils using Parizek and White's (1985) dissolution rate of 30 mm/1,000 yrs. Thus, an age of 1 to 3 million years for the deep limestone soils of Pennsylvania seems reasonable. A slightly different estimate of 2.5 to 5 million yrs for 5 meters of limestone residual soil accumulation in the Great Valley near Harrisburg has been given by Sevon (1985).

These data present a possible technique for dating some of the classic erosion surfaces that have been identified by geomorphologists (Sevon et al., 1983). The prime example would be the dating of the Harrisburg surface. This geomorphic surface has been correlated with the limestone valley floor areas in Nittany Valley and the Great Valley near Harrisburg. Utilizing the data in Table 6, a date of about 2 to 3 million years may be a reasonable estimate of the age of this surface, assuming that no significant erosion has taken place in this time period.

Table 6. Accumulation of residual soil from a limestone with 6% 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.

Dissolution rate mm/1000 yrs	Time (years) 10,000	100,000	1,000,000	2,000,000
	meters of residuum			
10	0.01	0.1	1.0	2.0
30	0.03	0.3	3.0	6.0
100	0.10	1.0	10.0	20.0

It is interesting to note the weathering rate (saprolite formation) for crystalline piedmont rocks in Virginia has been reported to be 4 meters/million yrs (Pavich, 1986), and for Maryland 1.2 to 2.2 meters/million yrs (Cleavers et al., 1970, 1974). When these weathering rates are compared to a limestone weathering rate of 30 mm/1000 yrs for Pennsylvania (Table 6), it is obvious that the limestone rate is an order of magnitude higher. What is also interesting is although weathering rates are different, the amount of soil material accumulated is similar (3 meters in a million years; Table 6). This difference is due to the fact that crystalline rocks retain much of their original volume, while pure limestones lose 90% of their volume during weathering. This leads to the conclusion that residual limestone and crystalline rock soils of equal thickness would be of similar age. If we extend this generalization to clastic rock soils, obviously it has many shortcomings. For example, very resistant rocks such as the Tuscarora formation (orthoquartzite) and other rocks don't fit this generalization. Thus, the generalization has validity but only for parent rocks that weather at a rate that is an order of magnitude slower than limestone, and in an isovolumetric manner.

Higher values of saprolite formation for crystalline rocks are also given by Cleaves (1993). He attributes the higher rates to varying rock lithology and rock fractures. Fractures and fracture zones also significantly affect the observed thickness of limestone residuum. Parizek and White (1985) show an accumulation of limestone residuum in a fracture zone of 9 to 12 meters as compared to 3 to 8 meters on adjacent areas (Figure 3). Thus, the general weathering rates given should be used with caution with the realization that short range variations occur, particularly in fractured limestone areas. In addition, other factors such as erosion may also greatly affect soil thickness.

LANDSCAPE DEVELOPMENT

The limestone valley floors generally show a gently rolling landscape except near major streams; in these areas a significant amount of relief occurs. In the central part of the state, the limestone uplands are at an elevation of about 1,200 feet, and the stream bottoms are at 950 to 1,000 feet. Thus, there is 200-250 feet of relief in some Central limestone valley areas. The difference in elevation between the stream bottoms and uplands decrease towards the southeast part of the state (Triassic-Piedmont area). Regardless of the area of the state, the amount of relief decreases rapidly in a relatively short distance away from the major streams, and the relief on the valley uplands is usually on the order of ten's of feet.

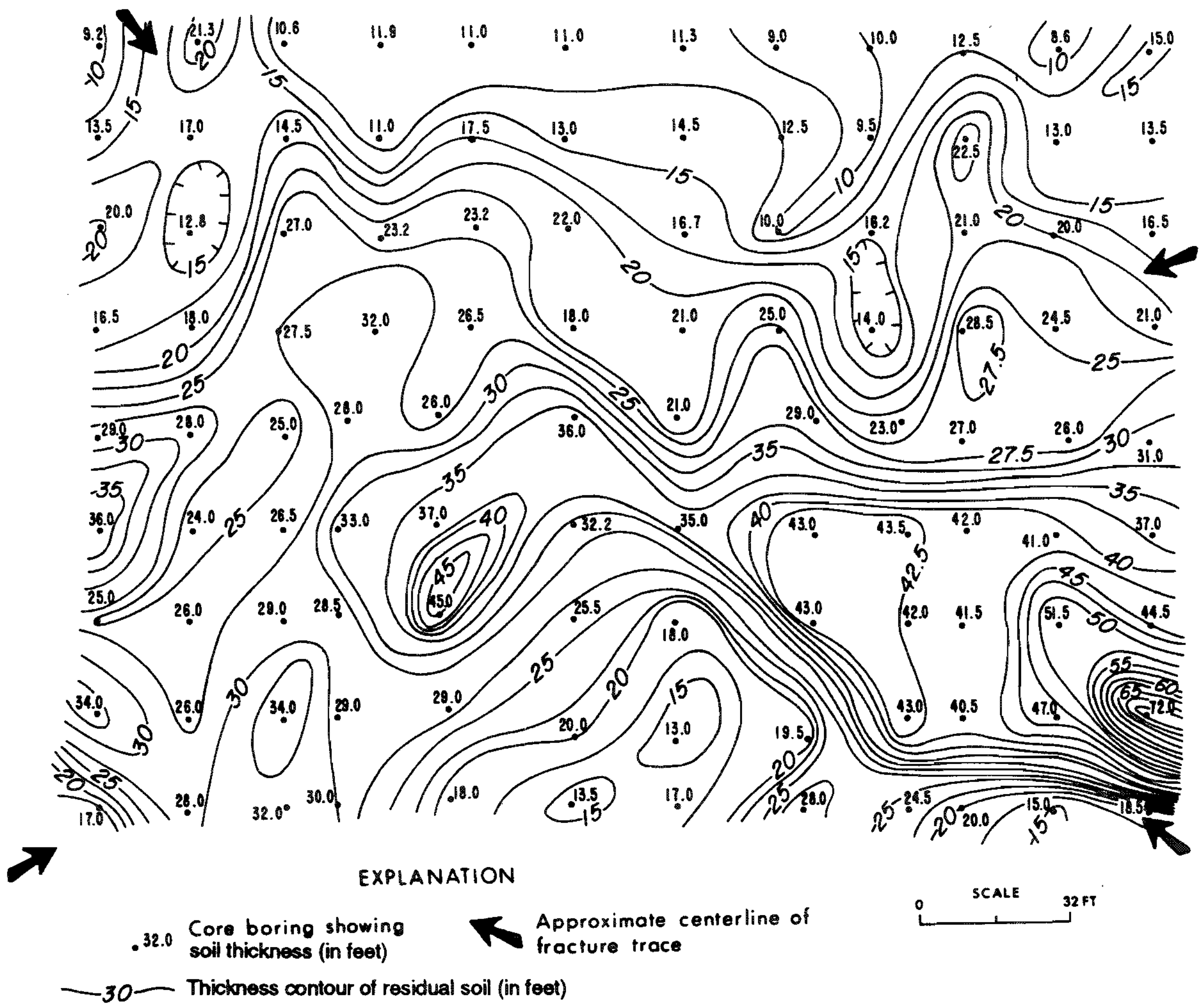

Figure 3. Thickness of residual soil developed (in feet) in the vicinity of a fracture trace intersection in the Nittany Dolomite, East Halls Cafeteria, Penn State University (From Parizek and White, 1985).

Although Pennsylvania's karst areas are mainly underdrained, many limestone soil areas show an integrated drainage network with drainage ways working headward into the surrounding upland areas. These headward working drainage ways are most evident close to major streams draining the valleys. Thus, many of the valleys have areas that show a fluviokarst drainage system exhibiting karst landforms superimposed on a fluvial landscape (White and White, 1979). Karst areas underlain by dolomitic limestone show more subdued landforms with fewer sink holes and other karst features than areas underlain by calcitic limestone (Parizek and White, 1985). The reason is that although the solubilities of calcite and dolomite are nearly equal, the kinetics (rate) of calcite dissolution is much more rapid than the kinetics of dolomitic dissolution (Parizek and White, 1985; White, 1988). Although this is the case, according to White (1984; 1988) the denudational rates for both types of carbonate rock is about the same because the water leaching through the dolomite system can complete its saturation below the ground water table.

Observations of excavations in limestone soils often show highly variable depths to bedrock within short distances. This is due to varying lithogies and fractures of the limestone. In general, however, the relatively flat upland areas have deeper soils (deeper to bedrock) than the sloping areas.

Another interesting aspect of the genesis of limestone soils is a landscape overturning model proposed by Simpson (1979). This model was developed in Nittany Valley at a site 2 miles north of the Penn State University Campus. In this model (Figure 4), a sink hole forms (stage 2) which fills with material (stages 3 and 4) and then other sink holes form in the area that was the source area of the sediment for the filling in stages 3-5. Next the sediment from the filling of stages 3, 4, and 5 is eroded into the new sink holes. This model could be viewed as a group of pistons that are being lowered into the earth's crust.

The limestone soils are usually referred to as residual soil. The generally accepted concept of a residual soil is that of a soil formed in place. This concept has validity for soils that undergo isovolumetric change during formation but has less credibility for limestone soils. The reason is that if we assume all of the parent material of the soil came from the underlying rock, the upper few cm of a soil that is 5 meters thick came from rock that was 50 meters above its present elevation. In addition, the upper part of the pedon may have moved laterally some distance with respect to the underlying bedrock, particularly if the bedrock is not horizontal.

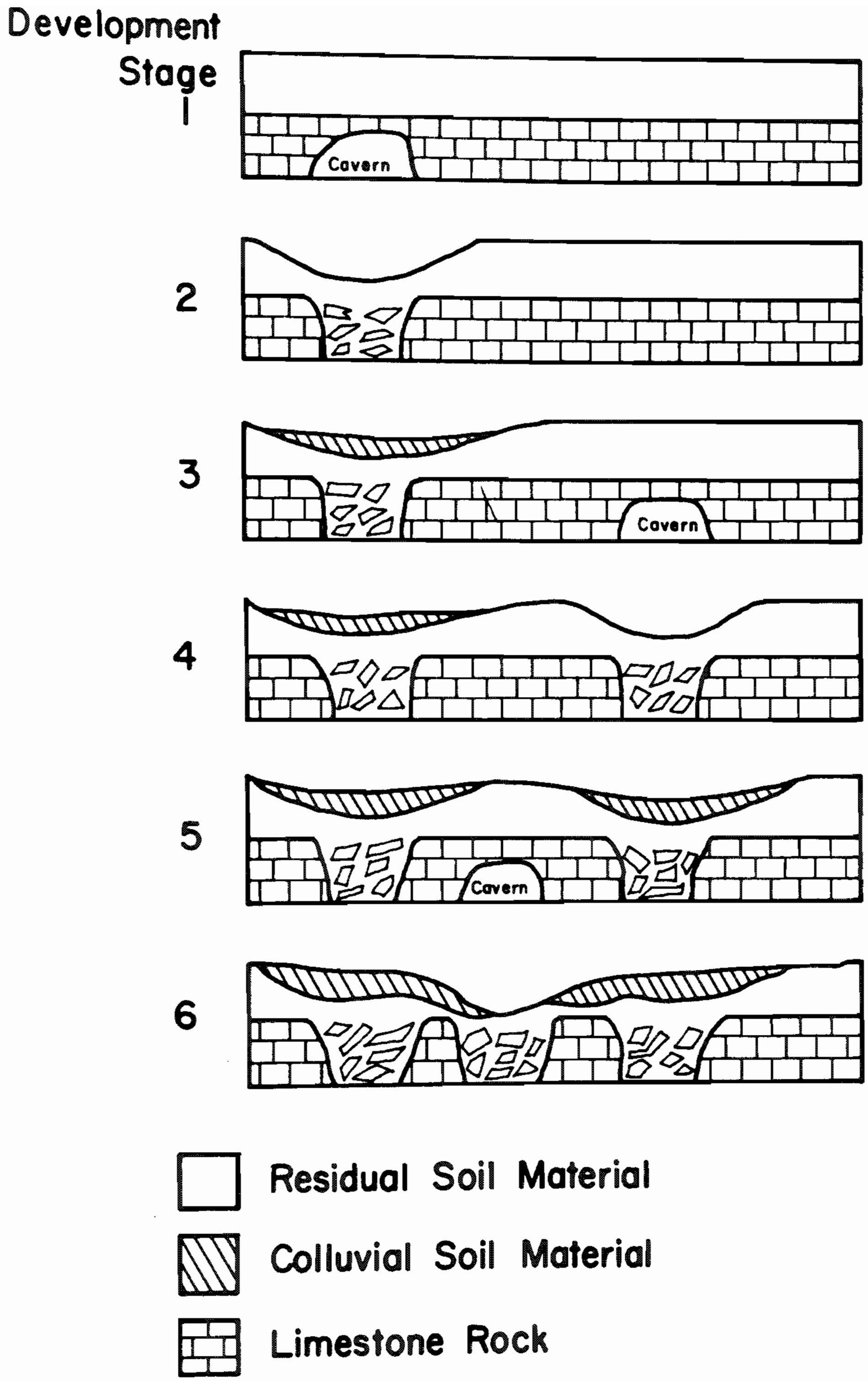

Figure 4. Soil developmental sequence for soils developed from limestone in Nittany Valley (from Simpson, 1979).

CLIMATE

The effect of climate on limestone soils is uncertain. Although this may be the case, Goudie (1995) indicates a relationship of increasing dissolution of limestone with increasing annual precipitation. Pennsylvania has an average precipitation rate of about 100 cm. Goudie's data shows a dissolution rate of about 30 mm/1000 years for a mean annual precipitation rate of about 100 cm. This rate agrees with rates for Pennsylvania given by Ewing (1885) and Parizek and White (1985). Goudie's data indicates that local variations in annual precipitation will lead to variations in accumulated residuum. Thus, the southeastern part of the state which receives more precipitation and which has a higher moisture surplus (precipitation-evapotranspiration, Ranney et al., 1973) for leaching may have thicker limestone soils than the central part of the state.

The percent base saturation of the limestone soils may also be affected by the amount of precipitation, and moisture surplus. Pedon data (Ciolkosz and Thurman, 1994) does not support this conclusion for most Hagerstown soils studied. Although this appears to be the case, there does appear to be an association of leaching and time as indicated by the thickness of the residual material. Data from Hagerstown soils indicates that when bedrock is > 2.5 meters below the soil surface, the soils classify as Ultisols (Table 7) while shallower to rock soils classify as Alfisols. If we compare these data with that in Table 6, we could conclude that it would take a little less than a million years to form an Ultisol soil in Pennsylvania from pure limestones.

Table 7. Characterization data for three Hagerstown pedons (Ciolkosz and Thurman, 1994).

Pedon 14-80				Pedon 36-14				Pedon 36-15			
		Percent				Percent				Percent	
Depth (cm)	Horizon	Base Sat.	Clay < 2 µm	Depth (cm)	Horizon	Base Sat.	Clay < 2 µm	Depth (cm)	Horizon	Base Sat.	Clay < 2 µm
0-8	A	28.4	7.4	0-20	Ap	65.5	22.6	0-18	Ap	39.4	18.6
8-33	E	15.3	16.3	20-36	BA	52.3	40.1	18-30	BA	63.3	30.8
33-46	BE	8.8	30.4	36-56	Bt1	58.5	58.7	30-58	Bt1	58.1	53.7
46-61	Bt1	19.4	50.5	56-84	Bt2	46.2	58.0	58-84	Bt2	62.5	59.1
61-89	Bt2	22.7	64.6	84-117	Bt3	28.6	60.1	84-109	Bt3	57.5	58.0
89-124	Bt3	19.7	65.4	117-132	Bt4	21.0	48.1	109-157	BCt1	52.9	59.4
124-150	Bt4	20.6	58.7	132-163	Bt5	18.5	37.8	157-203	BCt2	37.0	49.9
150-183	Bt5	21.8	73.1	163-190	Bt6	16.7	32.3	203-244	BCt3	19.2	45.6
183-254	BC	26.2	50.4	190-239	BC	10.4	25.3				

The effect of temperature on limestone solubilization has been debated and Goudie (1995) supports the premise that the main effect of higher temperatures is to increase the CO_2 content of soil air through plant root and organism respiration which counter balances CO_2's greater solubility in cold than in warm water. In addition, temperature may also assist in directing the pathway of iron oxide genesis in the hematite pathway for Hagerstown soils. This is of particular significance since the limestone soils are old soils which have gone through a number of glacial-interglacial cycles. Thus, paleotemperatures during the sangamonium (interglacial) which may have been as much as $8^{o}C$ warmer during the summer than today (Harrison et al., 1995) may have greatly forced the rubification of Hagerstown as well as other Pennsylvania soils.

The limestone soils we observe today are 1-3 million years old. These soils have developed under a wide range of climatic conditions associated with a number of glacial-interglacial cycles. Rainfall, temperature, vegetation, and landscape stability has varied greatly during the development of these soils. As a result, these soils are polygenetic and the relationships between present soil characteristics and past or present climatic conditions has not been adequately determined. Although Cronce (1988a) has described characteristics of limestone soils, apparently related to past cold climatic conditions, further work is needed to clarify the relationship of present soil properties to climates of the past.

CONCLUSIONS

In Pennsylvania, soils formed from limestones are found dominantly in the Ridge and Valley and in the Triassic-Piedmont areas of the state. Soils formed from other carbonate influenced rocks (calcareous shales, calcareous sandstones, and interbedded shale and limestone) are also found in these areas as well as in the Southwestern Plateau. The limestone soils form from the insoluble residue (IR) after the carbonate of the limestones have been leached. Dark colored limestones with low quantities of IR material form the parent material for the red clayey Hagerstown soils while the high IR, lighter colored limestones form the parent material for the yellowish brown, silty Duffield soils. The color of the Hagerstown is due to hematite while the color of the Duffield is due to goethite. These soils can be very old in that it takes about one million years for three meters of Hagerstown material to accumulate from the weathering of the bedrock. The limestone residuum is not the only parent material for these soils. Some eolian silts have been deposited on these soils and these materials have contributed to the very large increase in clay content between the A and B horizons, particularly for the Hagerstown soils. Most limestone soils are well drained and cover the bulk of the landscape. The moderately well to poorly drained soils in the limestone landscapes are found in depressional areas and are formed completely or in part from local colluvium. In addition, most of these wet limestone soils have weakly developed fragipans, while the well drained limestone soils do not have fragipans (Table 2) (see Ciolkosz et al., 1995b), for a discussion of Pennsylvania fragipans).

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