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BETA SPODIC HORIZONS IN PODZOLIC SOILS (LITHIC HAPLORTHODS AND HAPLOHUMODS)

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Abstract

This paper (1) introduces the concept of the Beta spodic horizon, as a second (lower) horizon of sesquioxide and organic carbon accumulation (*i.e.*, having podzolic or spodic characteristics), below an upper (Alpha) spodic horizon, and (2) examines the characteristics and possible pathways of genesis of the Beta horizon where found, in northern Michigan, USA. Here, the Beta horizon occurs in lithic extragrades of Spodosols, suggesting that its genesis is in someway linked to the physical (bedrock) barrier. Fe and Al data from the Beta point to chelation as one possible mechanism of pedogenesis in this pedon, although an additional mechanism may involve translocation of Fe to the Beta horizon as Fe^{++} during wet periods and concomitant accumulation of carbon within via root decay. Under the former scenario, high amounts of free, and relatively low amounts of organically-bound Fe and Al in the Beta suggest that many of the chelate complexes have subsequently degraded into their constituent ionic and organic components. Radiocarbon dating suggests that turnover of carbon is slower in the Beta than in the Alpha, and that younger organics are preferentially accumulating in the lower parts of the horizon.

Key words

podzolization, Michigan, Spodosols, lithic soils.

1. INTRODUCTION

Bartelli and Odell (1960) defined a Beta horizon as a second zone of clay accumulation in soils with a Bt horizon; the term "Beta" implies that it is the *lower of two similar, usually illuvial, horizons*. To date, the term Beta horizon has been used only for accumulations of illuvial clay that have been deposited

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at the contact with underlying (1) unconsolidated calcareous materials, or (2) calcareous (limestone) bedrock (Bartelli and Odell, 1960; Ballagh and Runge, 1970; Frolking et al., 1983). The above Beta horizons have been described for Mollisol and Afrisol pedons in the mesic temperature regime (Soil Survey Staff, 1975).

Although the influence of shallow bedrock on soil formation has been investigated by several authors (Levine et al., 1989, Bruckert and Bekkary, 1992), their research focus has been on the formation of the argillic horizon or a fragipan, and the bedrock has usually been calcareous. Others (McDaniel and Graham, 1992) have examined the effects of shallow bedrock on organic matter distributions within soils in aridic soil moisture regimes. The effects of bedrock on pedogenesis in cool humid climates where the dominant process is podzolization, as defined by Petersen (1976) and Deconinck (1980), has not previously been investigated.

Finally, although horizonation sequences that are atypical for Spodosols have been the subject of pedological investigations elsewhere (Stoner and Ugolini, 1988; Martin and Lowe, 1989), Spodosol horizonation like that presented herein has not, to my knowledge, been studied previously.

The purpose of this study is to document, describe, and examine the genesis of dark brown, humus- and sesquioxide-rich horizons in lithic, frigid Spodosols. I propose that the term "Beta spodic" horizon be used herein for such horizons when they occur below a spodic horizon, while simultaneously acknowledging that the genesis of clay-rich Beta horizons is somewhat different from that of humus- and sesquioxide-rich spodic horizons. The Beta spodic horizons have not previously been documented or studied, and their genesis is unclear.

2. MATERIALS AND METHODS

The Peshekee Highlands are bedrock-controlled uplands with incised valleys that have been partially filled with Pleistocene glacial deposits. The region spans $\approx$ 1100 km^2 of northern Michigan (Fig. 1). It has been repeatedly glaciated, with final deglaciation occurring between 11,000 and 9,900 years ago (Saarnisto, 1974; Attig et al., 1985). Reconnaissance fieldwork in the Peshekee Highlands confirmed that lithic extragrades of Haplorthods (Podzols) with Entic (weak) and Typic (strong) development are widespread on summit locations; podzolization is the dominant pedogenic process on sandy soils in northern Michigan (Padley et al., 1985; Schaetzl, 1990). Typical pedons on summit landscape positions have developed in a thin layer of unconsolidated sediments over granitic or metamorphic bedrock. Bedrock on upland divides is typically encountered at 50-150 cm. The sediments are usually silt loam to fine sandy loam materials (probably eolian in origin),

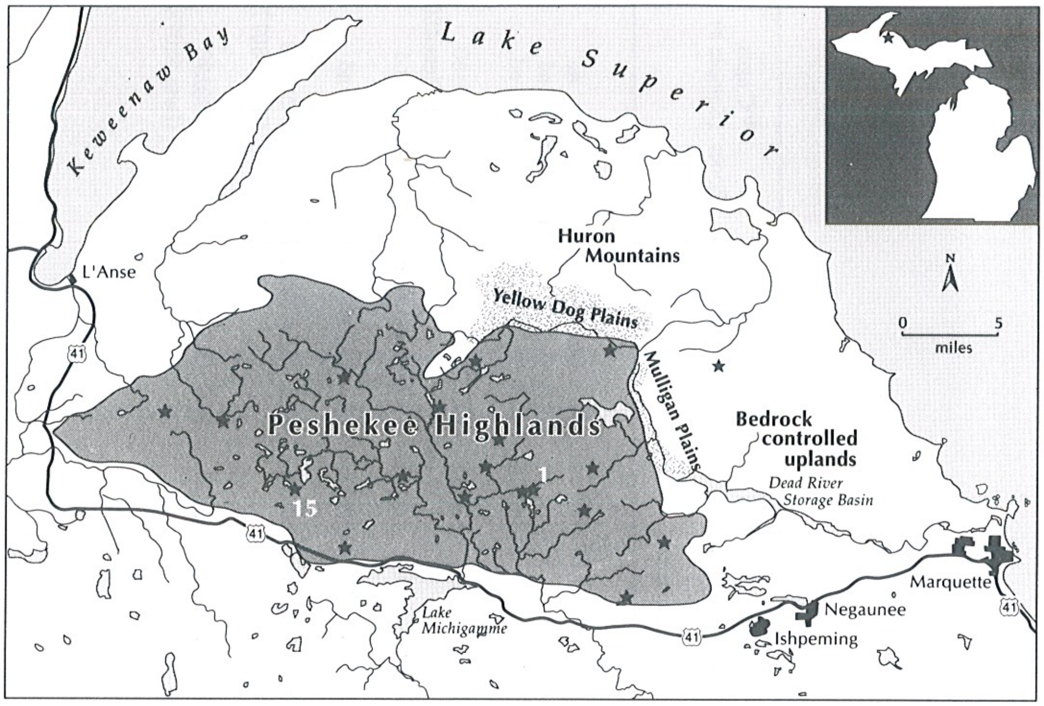

Figure 1.
Study area location. Locations of pedons that were described during reconnaissance field-work are indicated with stars. Pedons MICH-1 and MICH-15 are labelled with stars and numbers.

with or without a lower stratum of gravelly and cobbly sandy loam glacial till. Some pedons contain a thin (1-8 mm), dark colored horizon immediately overlying the lithic contact.

The climatic of the Peshekee Highlands is cool, humid continental; soils are udic and frigid (Soil Survey Staff, 1975). Mean monthly temperatures for Marquette, 50 km ESE of the study area (Fig. 1), range from -11.7° C for January to 18.1° C for July. Mean annual precipitation is 880 mm and mean annual snowfall is 3.33 m. The climate within the Peshekee Highlands is probably slightly cooler and wetter, with substantially more snowfall, than at Marquette, due to the increased elevation (≈350 m) of the former. Snowpacks are > 1 m deep throughout much of the winter; modelled hydrologic data from Schaetzl and Isard (1990) demonstrate that March and April infiltration totals - primarily from snowmelt - greatly exceed those of any other month. The dominant vegetation is second-growth, mixed coniferous-deciduous forest. *Populus tremuloides, Betula papyrifera, Tsuga canadensis, Acer saccharum, Abies balsamea, Quercus borealis, Pinus resinosa* and *P. strobus* are dominant.

Eighteen well-drained pedons on ridge crests within and near the Peshekee

Table 1.
Characterization data for MICH-15A and MICH-1 pedons, by genetic horizon

Horizon	Depth	Color*	Whole soil Sand	Silt	Clay	Sand fractions[b] vc	c	m	f	vf	Silt fractions c	m	f	Texture[c]	Org. Carbon	Structure[d]	Consist.[e]	Roots	^{14}C ages (Sample #)
	cm		------------% < 2mm										------		--%--				
Pedon: MICH 15A																			
Oi	0-5	---	---	---	---	---	---	---	---	---	---	---	---		nd[f]	none	none	nd	nd
Oa	5-9	N 2/0	---	---	---	---	---	---	---	---	---	---	---		32.4	1,2,gr	vfr-fr	c m&f	nd
E	9-11	5 YR 4/2	19.6	77.6	2.8	0.4	2.5	4.3	5.1	7.3	24.3	34.8	18.6	SiL	1.3	1,3,pl	fr	m vf&f; c m	nd
2Bhs	11-23	2.5 YR 2.5/2 & 5 Y 5 3/3	54.1	42.0	4.0	4.7	14.2	11.4	12.2	11.7	23.2	13.8	5.0	SL	10.5	2,2,gr	fr	m vf&f c m; f co	300±60 (Beta 48076)
2Bs	23-25	5 YR 3/4	52.9	45.6	1.5	4.9	11.3	4.0	19.4	13.2	21.7	20.0	3.9	FSL	9.7	2,2-3,sb	fr	f f, m&co	nd
2Bhs' (Beta Bhs)	35-39	10 R 2.5/2	62.3	34.9	2.9	6.4	14.8	10.4	18.4	12.3	16.1	16.1	2.8	SL	12.2	3,3,sb	fi	f f&m	nd
Beta 2Bs material[h]	39	5 YR 2.5/2	22.5	65.0	12.6	3.0	4.0	2.3	4.3	9.0	nd	nd	nd	SiL	11.8	3,3-4, sb	fr-fi	–	1450±70 (Beta 48077)
Beta 2Bhs material[h]	39	2.5 YR 2.5/2	28.0	54.9	17.1	2.7	3.2	3.9	7.4	10.7	nd	nd	nd	SiL	15.0	3,3,sb	fr	–	890±90 (Beta 48078)

Pedon: MICH 1

Oi	0-1	---	---	---	---	---	---	---	---	---	---	---	---	---	nd	none	none
A	1-2	N 2/0	52.5	43.5	3.9	1.1	3.8	13.0	21.7	12.9	12.4	23.4	7.7	FSL	nd	2,3,gr	vfr
E	2-8	5 YR 5/2	47.2	50.9	1.9	1.3	2.2	1.1	34.1	8.6	24.0	16.9	10.0	SiL	nd	2,3,gr	vfr
Bhs	8-10	5 YR 2.5/2	48.8	48.3	2.9	1.8	3.3	11.8	18.5	13.3	21.8	17.1	9.4	SL	nd	1,3,sb	vfr
Bs1	10-33	5 YR 3/3	52.1	46.2	1.7	2.2	3.1	12.8	18.5	15.5	21.2	19.9	5.0	FSL	nd	1,3,sb	vfr
Bs2	33-46	7.5 YR 3/4	64.0	34.2	1.8	5.6	5.9	4.8	33.4	14.3	18.3	11.8	4.1	FSL	nd	1,4,sb	vfr
2BC	46-64	10 YR 3/3	83.2	14.5	2.3	5.7	8.5	27.8	31.2	10.0	8.2	4.6	1.7	LS	nd	1,4,sb	fr
Beta 2Bhs[i]	64	5 YR 3/3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	vfr
3R (granitic gneiss)	64+ (varies from 18-68 cm within soil pit)																

a: Moist colors.
b: vc = very coarse (2-1 mm dia), c = coarse (1-0.5 mm), m = medium (0.5-0.25 mm), f = fine (0.25-0.125 mm), vf = very fine (0.125-0.50 mm).
c: Texture of the fine earth fraction. LS = loamy sand, SL = sandy loam, FSL = fine sandy loam, SiL = silt loam. Providing the texture of the whole earth fraction, some horizons would require additional modifiers, such as "gravelly" or "cobbly".
d: Structure grade (1 weak, 2 moderate, 3 strong), size (1 very fine, 2 fine, 3 medium, 4 coarse, 5 very coarse) and shape (gr granular, sb subangular blocky, pl platy).
e: Moist consistence, vfr = very friable, fr = friable, fi = firm.
f: No data.
g: Root abundance: f = few, c = common, m = many; Root size: vf = very fine, f = fine, m = medium, co = coarse.
h: This sample represents masses of more or less homogenous material that was immediately overlying bedrock, and is not a laterally continous soil horizon *per se*. The Beta 2Bs and Beta 2Bhs materials represent abnormally light and dark parts of the Beta horizon, respectively, and were not necessarily taken from the same profile as were the samples above.
i: This horizon was immediately overlying bedrock, and was so thin (< 2 mm) as to preclude acceptable sampling.

Table 2.
Chemical data for MICH-15B pedon, by incremental depth units

Unit No.	Horizon	Depth	Fe_d	Al_d	Fe_p	Al_p	Fe_o	Al_o	Fe_d-Fe_o[a]	ODOE	FA/HA[b]	pH	
		cm	----------	----------	----------	g kg^{-1}	----------	----------	----------			H_2O	$CaCl_2$
1	Oa	0-3	6.3	2.2	3.2	1.8	4.2	1.7	2.1	0.31	31.3	4.14 [c]	3.52 [c]
2	E	4-8	5.4	1.0	1.0	0.8	2.0	1.1	3.4	0.11	4.4	4.32	3.71
3	E-2Bhs trans	10-14	10.9	4.1	8.4	8.4	20.7	12.1	<0	1.20	6.2	nd	3.98
4	2Bhs	18-24	15.3	14.1	5.3	10.7	16.7	21.6	<0	1.55	17.9	4.61	4.07
5	2Bs	27-29	12.3	12.3	3.1	10.0	15.4	60.8	<0	1.13	19.9	4.43	4.15
6	2Bhs'	31	14.0	6.9	11.8	11.3	28.6	17.8	<0	2.03	16.1	4.37	3.88
7	2Bhs'	32	19.3	40.0	12.8	10.1	23.8	11.9	<0	2.34	15.4	nd	3.78
8	2Bhs'	33	75.4	12.5	12.8	11.3	19.0	14.3	56.4	2.35	6.5	4.48	3.76
Beta 2Bs[d]		33	42.8	85.4	9.6	22.2	24.3	19.5	18.5	1.52	11.4	4.43	4.02
Beta 2Bhs[d]		33	10.5	7.7	11.0	9.9	23.1	11.7	<0	1.79	6.6	4.23	3.86
Thin (1 mm) "skin" on bedrock			nd	nd	nd	nd	19.2	33.3	nd	3.35	nd	nd	nd

a: According to McKeague et al. (1971, 33), Fe_d - Fe_o provides an estimate of "more or less crystalline Fe-oxides." Merrits et al. (1991, 259) refer to this component as "finely divided crystalline Fe oxides", which would be mainly goethite.
b: Fulvic/humic acid ratio.
c: 8:1 water: soil ratio.
d: The Beta 2Bs and Beta 2Bhs materials represent abnormally light and dark parts of the Beta horizon, respectively, and were not necessarily taken from the same profile as were the samples above.

Highlands were examined in detail; most were in the Peshekee (loamy, mixed, frigid Lithic Haplorthods) or Michigamme (coarse-loamy, mixed, frigid Typic Haplorthods) soil series. Two typifying pedons, sampled as members of the Peshekee series (MICH-1 and MICH-15) are the focus of this paper (Fig. 1). Both pedons were described and sampled by genetic horizon (USDA-SCS, 1984); MICH-15 was additionally sampled in 2-6 cm incremental units. Data from MICH-15 derived from genetic horizon samples are termed MICH-15A (Table 1); data from the incremental samples are termed MICH-15B (Table 2). Replicate bulk density samples were taken from selected horizons by the core method.

Samples were analyzed for particle-size by pipette (Day, 1965). Silt fractionation was accomplished by elutriation, following dispersion in $(NaPO_3)_{13}.Na_2O$ and slow shaking overnight (Follmer and Beavers, 1973). Sample pH was determined in replicated H_2O:soil and $CaCl_2$:soil mixtures. Organic carbon was determined by loss on ignition (LOI) at 550°C from replicated samples, using the equation of Grewal et al. (1991). Because the OC values that resulted from this equation were strongly correlated (r > 0.999) with those obtained by the more traditional equation of Davies (1974), only the former are reported. Replicated Fe and Al extractions included: (1) acid ammonium oxalate in darkness, (2) sodium pyrophosphate, and (3) sodium-dithionite (Daly, 1982; Sheldrick, 1984; Anonymous, 1990). Extracts were analyzed for Fe and Al content by DCP spectroscopy. The optical density of the oxalate extracts (ODOE) was measured at 430 nm on a Perkin-Elmer 320 spectrophotometer. Fulvic and humic acids were extracted according to the method of Higashi et al. (1981). The radiocarbon age of the alkali-soluble fulvic and humic acid fractions from the Bhs horizons from MICH-15 was analyzed by Beta Analytic Inc., Coral Gables, FL. The pedons were classified according to the Soil Survey Staff (1992).

3. RESULTS AND DISCUSSION

Most upland soils in the study area have morphologies and O-A-E-Bhs-Bs-BC-C-R or O-A-E-Bhs-Bs-BC-R horizonation that are typical of many Spodosols in the midlatitudes (e.g., Rode, 1937; Petersen, 1976; Mokma and Buurman, 1982; Rourke et al., 1988) and in northern Michigan (Soil Conservation Service, 1980; Schaetzl, 1990), with the exception that some pedons contain a thin, reddish-brown to brown horizon immediately above the bedrock contact. The regolith-bedrock contact is sharp and abrupt; any weathered residuum that may have existed was probably removed by Late Pleistocene glacial abrasion. Thus, the brown horizon that occurs in contact with the bedrock is interpreted to be a genetic soil horizon.

Selected characterization data for pedons MICH-1 and MICH-15 are presented in Tables 1 and 2. Pedon MICH-1 typifies the majority of the eighteen pedons examined during reconnaissance fieldwork; it formed in 20-60 cm of fine sandy loam to silt loam material over cobbly loamy sand till (the 2BC horizon). The till immediately overlies fresh bedrock. Thus, like most well-drained pedons in the study area, it contains a lithologic discontinuity between the presumed eolian sediments and the underlying till. Clay contents in both materials are usually below 4%, but there is some evidence of clay illuviation into the Alpha and Beta horizons, and expecially into select "volumes" of light and dark Beta materials (Table 1).

Pedon MICH-1 is not unlike many of the other well-drained, lithic Spodosols in the region, except that it also contains a dark reddish brown (5YR 3/3) "skin" immediately overlying the crystalline bedrock; I will refer to this layer as a Beta spodic horizon[1]. The upper Bhs and Bs horizons will be referred to as the Alpha horizon(s). In most Lithic Haplorthod pedons in the

1. The term "Beta spodic" implies that this horizon has many morphological characteristics of a spodic horizon (Soil Survey Staff, 1992), and occurs below a Bs, Bh or Bhs horizon. Use of the term spodic in "Beta spodic" does not imply that the horizon meets the criteria for a spodic horizon (Soil Survey Staff, 1992).

Peshekee Highlands this layer is seldom more than 2-4 mm in thickness, and has a "greasy" feel, suggesting the presence of abundant amorphous materials and/or organic carbon.

Pedon MICH-15 lacks a till component but contains a subtle discontinuity within the "eolian" materials, possibly due to reworking of these materials during a waning phase of deposition, as is suggested by the relatively high amounts of fine silt and low amounts of coarse and very coarse sand in the upper material. MICH-15 was chosen for intensive study because it has a strongly developped Beta (2Bhs') spodic horizon, which is 4-8 cm in thickness and very dusky red (10R 2.5/2) to black (N 2/0) in color (Table 1). Although the horizon contains a few fine and medium roots (Table 1), it should not be considered a root mat horizon, *sensu* Righi et al. (1982) and Martin and Lowe (1989). It lacks observable, layered micro-stratigraphy and is lower in OM content than most root mat horizons.

The O horizon of MICH-15 is thicker than is typical for the other 17 pedons examined. Also, B horizons colors for the MICH-15 pedon were darker than for comparable pedons in the region. These two characteristics reflect organic matter production (and preservation) rates that may be higher than at other reconnaissance sites. Pedon MICH-15 is acidic, with pH's in water commonly < 4.5 (Table 2). Further discussion in this paper will center on pedon MICH-15.

Bulk densities (D_b) of the 2Bhs and 2Bs horizons had values of 0.57 and 0.59, respectively. The low D_b values illustrate the high porosities of these soils, which are due in large part to their presumed eolian origins, as well as to high organic matter content and prolific root expansion and subsequent decay within a space-limited substrate. Slight clay increases occur in illuvial horizons, both Alpha and Beta, of both pedons. The spodic morphologies (colors, textures, structure, horizination, etc.) and chemisty (high amounts of OM, and extractable Fe and Al) of these soils demonstrates, however, that podzolization, not lessivage (Fridland, 1958), is a dominant process.

In this paper, it is assumed that Na citrate-dithonite extracts crystalline, amorphous, and organically bound Fe and Al (Mehra and Jackson, 1960; McKeague et al., 1971), acid ammonium oxalate extracts amorphous and organically-bound Fe and Al (McKeague and Day, 1966), and Na pyrophosphate extracts organically-bound Fe and Al (McKeague, 1967). Extractable forms of these metals will be abbreviated Fe_d, Al_d, Fe_o, Al_o, Fe_p and Al_p, respectively.

Increases in all forms of extractable Fe and Al, when compared to overlying eluvial horizons, are found in both Alpha and various parts of the Beta spodic horizons of MICH-15 (Fig. 2). The depth functions for the forms of most of the extractable Fe and Al have a bimodal distribution with a primary minimum in the eluvial zone, and a secondary minimum in the lower 2Bhs and 2Bs horizons (Fig. 2b, c, d), sustantiating the interpretation that the Beta

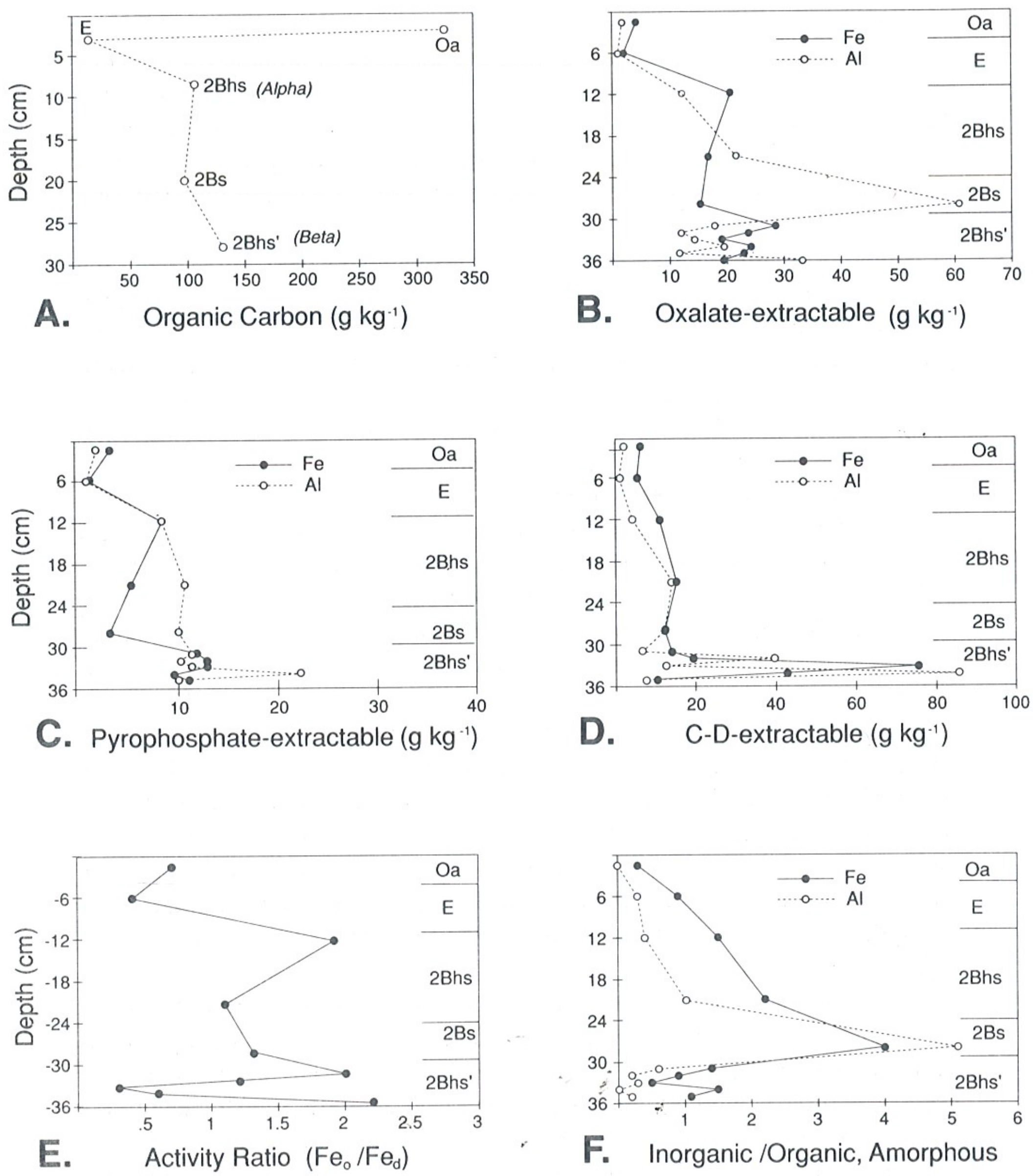

Figure 2.
Depth functions for pedon MICH-15:
A. organic carbon,
B. ammonium oxalate-extractable Fe and Al,
C. sodium pyroophosphate-extractable Fe and Al,
D. sodium citrate-dithionite-extractable Fe and Al,
E. activity ratio (Fe_o/Fe_d) (Blume and Schwertmann, 1969),
F. inorganically bound Fe and Al, calculated as:
$[Fe_o - Fe_p]/Fe_p$
$[Al_o - Al_p]/Al_p$

is not simply a lower extension of an overlying spodic horizon, but a distinct zone of accumulation. Especially prominent are the large amounts of Fe_d, Al_d, and Fe_d-Fe_o in the Beta horizon (Fig. 2d, Table 2). There is no evidence that the 2Bs horizon is wholly an eluvial zone and that the MICH-15 pedon is bisequal. Rather, the 2Bs horizon is simply seen as a lower part of the Alpha, and if the Beta were not present, would likely grade downward into 2BC and 2C horizons.

Amounts of amorphous and organically-bound Fe and Al in the Beta generally are slightly higher than, or similar to, amounts in the Alpha. Assuming that the translocation of these forms of Fe and Al are due, in large part, to chelate complexes *sensu* Atkinson and Wright (1957), then these depth trends suggest that many of the chelate complexes that form in the upper solum are either initially illuviated into the Alpha spodic and later remobilized, or translocated through the upper solum and deposited at depth, either in the 2Bs or the 2Bhs' horizons.

The presence of abundant amorphous compounds is a primary requisite for the presence of active podzolization and a spodic horizon (Soil Survey Staff, 1975, 1992). Blume and Schwertmann's (1969) "activity ratio" (AR) is designed to reflect the relative crystallinity or amorphous character of Fe oxides in soils (Fig. 2e). AR values > 0.5 typically characterize spodic horizons (Blume and Schwertmann, 1969), although data from Barrett and Schaetzl (1992) suggest that sandy spodic horizons in Michigan typically have AR values > 0.8. AR values > 1.0 for much of the upper solum of MICH-15 imply that podzolization is active throughout the pedon and that most of the extractable Fe in the Alpha horizon is in amorphous forms. The lower ARs in parts of the Beta, coupled with the high Fe_d and Fe_d-Fe_o values (Fig. 2d), suggest that at least some of the Fe in the Beta horizon is in crystalline, ferric oxyhydroxide forms, perhaps as goethite and lepidocrocite (Fitzpatrick and Schwertmann, 1982).

Given that the contact between the R horizon and the regolith is relatively unweathered and abrupt, it is unlikely that these presumed oxyhydroxide minerals have weathered out of the bedrock. Because the site is on a ridge crest, it is equally unlikely that oxides have been laterally translocated to the pedon by water flowing immediately above the lithic contact. Rather, Fe_p and Al_p values (Fig. 2c), as well as inorganic/organic amorphous ratios (Fig. 2f), are relatively low in the Beta probably because illuviated organo-metallic complexes in the Beta have biodegraded (McKeague et al., 1971), releasing the Fe and Al and allowing these species to become more ordered and (re)crystallized with time. Amounts of Fe_d-Fe_o, which is often interpreted to be a measure of crystalline forms of pedogenic Fe (Merritts et al., 1991), are quite high in the parts of the Beta (Table 2), further supporting this explanation. In fact, much of the illuviated Fe and Al would have had to recrystallize in the Beta to account for the high Fe_d-Fe_o values therein (Table 2), since Fe not extracted by oxalate (Fe_d-Fe_o) has been shown to be "more or less crystalline" (McKeague et al., 1971).

Amounts of amorphous Fe (Fe_o) and Al (Al_o) in frigid Spodosols typically peak in the upper and middle B horizon (Wang et al., 1986). The large Al_o peak in the 2Bs horizon (Fig. 2b), coupled with the large amounts of inorganic amorphous Al (Fig. 2f) suggest that aluminosilicates such as proto-imogolite or allophane may be present in this horizon (Wang et al., 1986). Nonetheless, if the presence of imogolite in the 2Bs horizon is possible its absence in the Beta is even more likely, since the ratio of inorganic to organic, amorphous materials in the Beta is considerably lower for Al than for Fe: in some cases near zero (Fig. 2f).

In summary, the relatively low amounts of inorganic amorphous Fe and Al (Fig. 2f) in the Beta horizon, coupled with high ODOE and OC values (Table 2), point to an organic-chelate origin for the illuviated sesquioxides therein, followed by biodegradation and, finally, recrystallization. Recrystallization within the Beta may be accentuated by wet/dry redox cycles that would be common in these lithic soils: wetting and saturation occurring after rains or snowmelt, due to temporary perching of water on the shallow bedrock, and drying occurring due to high summer transpiration requirements by the forest and lack of adequate deep water reserves in the subsoil. Indeed, it is possible that translocation of Fe may be infrequently assisted by reduction under anaerobic (perched water table) conditions at and near the bedrock contact, followed by desiccation at a later time as water is lost by root uptake (McKenzie et al., 1960). Chemical reduction would be also promoted in MICH-15 due to the abundance of organic matter, which would promote vigorous microbial activity.

The depth function for organic carbon (Fig. 2a) shows a surface maximum in the Oa horizon and subsurface maxima in the Alpha and Beta horizons. The latter peaks are probably associated with chelate-sesquioxide complexes (cp. Figs. 2a, 2c). Organic matter is also added to the Beta horizons, however, by decay of roots which proliferate at the soil-bedrock interface (McDaniel and Graham, 1992) and in horizons with high water-holding capacities such as the Alpha and Beta. Martin and Lowe (1989) documented the presence of root mat horizons above root-restricting and impermeable (in their case, a duripan) horizons and determined that inputs of organic matter from root decay were substantial.

The mean residence time (MRT) radiocarbon dates from the MICH-15 pedon are reported in Table 1. The low MRT age of the carbon from the 2Bhs horizon (300 ± 60) is not atypical for Spodic horizons elsewhere (e.g. Tamm and Holmen, 1967; Guillet and Robin, 1972; Pagé and Guillet, 1991). Buurman (1984) noted that radiometric ages from forested horizons are more an indication of speed of organic matter turnover than of profile age. Thus, rapid turnover of organic materials is suggested for the MICH-15 2Bhs horizon.

Older MRT dates from the Beta confirm that this horizon is an "accumulation zone" for organics, some of which are very old, and that rates of organic matter turnover are less than in the Alpha. Fulvic/humic acid ratios (Table 2) also suggest that podzolization is more rapid and ongoing in the Alpha, especially the lower part, than in the Beta.

^{14}C dates are younger in upper than in the lower parts of the Beta, which is similar to the pattern found by Ballagh and Runge (1970). They explained this type of ^{14}C depth function by noting that more recently illuviated clay-organic complexes become deposited on the bottom of the Beta, due to flocculation by basic cations. In the Peshekee pedon, this type of explanation may also hold, although it is likely that some older organics in the lower Beta are not illuvial, but simply old rootlets that have decomposed in place.

Although the MICH-15 pedon was sampled as a member of the Peshekee series (loamy, mixed, frigid Lithic Haplorthods), laboratory data require that it classify as a Lithic Haplohumod (Soil Survey Staff, 1992). Humods have more than 6% organic carbon in the spodic horizon; the 2Bhs horizon contains 10.5% organic carbon. Although carbon and pH data are lacking for pedon MICH-1, it would likely also classify as a Haplohumod. The high amounts of organic carbon in these soils are a consequence of the limited soil volume within which root decay and organic acid translocation/deposition can occur.

4. CONCLUSIONS

This paper presents a study of soil genesis as constrained by the presence of shallow bedrock; it also defines and characterizes a Beta (spodic) horizon that is found in the two pedons that were intensively studied. The Beta Bhs horizon is a dark, humus- and sesquioxide-rich layer that is present to varying degrees in many of the Spodosol pedons examined. It occurs below a Bs, Bh or Bhs (Alpha) horizon that may or may not classify as a spodic horizon. Implicit in the definition is the fact that a discernable horizon or horizons occur between the Alpha and Beta, that are less pedogenically developed.

The genesis of the Beta horizon studied here, as applies for Betas elsewhere, involves mechanisms and processes by which Fe, Al, and OC are translocated and illuviated at depth. OC may also accumulate as root additions.

For the Beta argillic horizons of Bartelli and Odell (1960), the barrier was physico-chemical: calcareous bedrock or outwash. For these Beta spodic horizons the barrier was a physical one: hard bedrock. The bedrock provides a barrier to eluviating sesquioxides, facilitating their accumulation and hence the development of a second, lower spodic or spodic-like horizon, not unlike the Beta Bt (argillic) horizon of Bartelli and Odell (1960), which occurs below an upper (Alpha) Bt. Some of the illuviated sesquioxide complexes in the Beta appear to have undergone biodegradation and subsequent recrystallization. The bedrock may occasionally perch water, which could lead to migration of Fe^{++} and subsequent accumulation at depth.

Finally, this study indirectly draws attention to the effects of "sub-solum" processes - those processes and products that are ongoing in the horizons that are typically viewed as parent material, and thus are often ignored or poorly understood. That many organic chelate complexes involved in podzolization in the solum eventually leach completely through the profile and into the groundwater is evidenced by the dark brown colors of many surface waters in Spodosol landscapes. This study draws attention to these products; many have accumulated in the Beta horizon.

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