Secondary Carbonates in Three Fine and Fine-loamy Alfisols in Michigan

Randall J. Schaetzl, William E. Frederick, and Lawrence Tornes

ABSTRACT

Secondary pedogenic carbonates are usually associated with ustic or drier soil moisture regimes; when found elsewhere, their interpretation can be troublesome. We studied three Alfisol pedons in Michigan that contained secondary carbonates on ped faces. The purpose of the research was to (i) characterize these accumulations, (ii) examine possible genetic explanations for the accumulations, (iii) determine if these soils have calcic horizons, given the recent redefinition of this diagnostic horizon, and (iv) evaluate how current "k horizon" nomenclature might apply to these soils. Three different drainage classes and two soil temperature regimes were represented in the sampled pedons: a fine, mixed Glossic Eutroboralf; a fine, illitic, mesic Aquic Hapludalf; and a fine-loamy, mixed, mesic Aeric Endoaqualf. All three pedons had thin (<50 cm) leached zones near the surface, and carbonate coatings (calcans) on ped faces within the lower B and/or upper C horizons. Two of the three pedons had horizons that met calcic horizon criteria. Horizons of preferential carbonate accumulation sometimes occurred near subtle textural breaks in the lower solum. Some B horizons in one pedon contained carbonate accumulations in amounts that exceeded that of the presumed parent material. The calcans have probably resulted both from vertical translocation of carbonates, followed by precipitation at depth, as well as internal redistribution of carbonates from ped interiors to ped faces. Use of the k subscript is warranted for some horizons in these soils. We recommend that its usage should be similar to t or s, i.e., horizons with evidence of secondary carbonates merit the k subscript.

In the Midwest, well-drained soils formed from calcareous parent materials often have acidic sola due to the effects of infiltrating water and its associated weak acids. The depth of leaching in these soils is generally a function of original carbonate content, water chemistry (pH), and cumulative quantity of infiltrating water (Allen and Whiteside, 1954). The last of the above three is in turn dependent on precipitation characteristics, amount of runoff, soil permeability and water-holding capacity, and time or soil age. Thus, soils on old, stable surfaces in humid climates are often more deeply leached than are young soils or those in drier climates.

The Late Wisconsinan glaciated region of Michigan and nearby states is an appropriate locale to study carbonate dynamics in udic and aquic soil moisture regimes. This area has stable landscapes that are approximately 15 000 yr old, composed of parent materials with abundant admixtures of finely disseminated carbonates derived from glacial grinding of dolomite and limestone bedrock. These initial conditions have resulted in extensive areas of Alfisols and Entisols with acidic sola overlying calcareous materials (Veatch, 1953; Allan and Hole, 1968; Hole, 1976).

The boundary between the upper, acidic and the lower, calcareous horizons is often interpreted in the Midwest as the lower limit of the solum, and is often an abrupt boundary. Wenner et al. (1961) termed the top of this boundary the *point of effervescence*. Below the boundary, carbonate content increases markedly, which in turn affects pedologic processes (e.g., clay translocation) and soil characteristics (e.g., pore characteristics, base saturation, pH). Allan and Hole (1968) presented evidence that the boundary zone has unique pedological properties and influences pedogenesis. Wenner et al. (1961) generally observed gradually increasing contents of $CaCO_3$ with depth immediately below the point of effervescence. They also noted, in some profiles, a "zone of carbonate accumulation in the intermediate depths." Visible evidence of accumulated secondary carbonates in these soils was not mentioned.

Conversely, visible accumulations of secondary carbonates are common in soils of dry (ustic and aridic) climates, where carbonate films, threads, concretions (glaebules), and pendants occur between and below peds and around roots (Gillam, 1937; Sherman and Ikawa, 1958; Wilding et al., 1990). In more strongly developed, aridic soils, laminar caps, caliche, and calcrete are taken as evidence of translocated carbonate (Gile et al., 1966). In many soils of dry climates, eolian influx is a major source of carbonates and amounts of secondary carbonates continue to increase with time (Gile et al., 1966; Machette, 1985; Gile, 1993). Here, depth of leaching or carbonate content in illuvial zones can often be correlated with soil age. In humid climates carbonates are continually leached from upper horizons. Depth of maximum carbonate accumulation is dependent on influx from dry deposition and rain (Junge and Werby, 1958; Holliday, 1988), soil CO_2 contents (Amrhein et al., 1985; McFadden et al., 1991), and the modal depth of infiltration (Jenny and Leonard, 1934; Arkley, 1963). In some ecotonal locations, carbonate-enriched cutans (calcans, hypocoatings) overprinted by argillans have been used to infer periods of aridity followed by more humid conditions (Reheis, 1987; Kemp, 1995).

Although most carbonates in humid climate soils are, when mobilized, removed from the solum and leached into groundwater, secondary accumulations of pedogenic carbonate have been reported (Allan and Hole, 1968). Nonetheless, they have been little studied (Jenny and Leonard, 1934). Where found, such accumulations are generally due to unique local circumstances such as marl parent materials in wet settings (Haile-Mariam and Mokma, 1990), microtopographic variation (Sobecki and

R.J. Schaetzl, Dep. of Geography, Michigan State Univ., East Lansing, MI 48824-1115; W.E. Frederick, Natural Resources Conservation Service, 1405 South Harrison Road, East Lansing, MI 48823: and L. Tornes, 811 State Rt. 61 North, Sunbury, OH 43074-9509. Received 25 July 1995. *Corresponding author (schaetzl@pilot.msu.edu).

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Wilding, 1982), or upwardly moving, carbonate-rich groundwater (Knuteson et al., 1989). Wenner et al. (1961) could find no visible evidence of secondary carbonate accumulations in soils in Ohio, even though laboratory data suggested the existence of a thin zone of illuvial $CaCO_3$ in some pedons.

The purpose of this study was to examine the characteristics of three Alfisols in Michigan and to discuss the possible genesis of secondary carbonates, idenifiable in the lower B and upper C horizons of these soils. Abundant secondary carbonates exist in these soils as whitish carbonate coatings, filaments, and threads (pseudomycelia) on faces of peds. Documenting the existence of these features and describing their characteristics and genesis are important to soil scientists and taxonomists, in that similar soils must be consistently described and interpreted. This study will also determine whether soils such as the ones studied here meet the recent redefinition of the calcic diagnostic horizon (Soil Survey Staff, 1994). If some soils in the humid Midwest have carbonate accumulations sufficient to meet calcic criteria, a reevaluation of these criteria may be necessary.

Pedons from two fine and fine-loamy mapping units in different Michigan counties were chosen because active soil survey crews there had frequently observed violently effervescent, white coatings on ped faces in these soils; they were thought to be illuvial carbonates. Evidence for such coatings in soils of fine and fine-loamy textural families had previously been reported by soil mappers throughout Michigan and in soils developed on Wisconsinan tills elsewhere (Glocker, 1994, personal communication). Similar soils in Ohio, developed on finer textured basal till, also have secondary carbonates in what have been described as BC and upper C horizons (Smeck, 1990, personal communication). Pedons were chosen from two widely separated locations in order to assure this study has regional applicability.

MATERIALS AND METHODS

Three pedons were studied, two from Calhoun County and one in Iosco County (Fig. 1). A Glynwood pedon (Aquic Hapludalf) was sampled within a Glynwood mapping unit, and a Capac pedon (Aeric Endoaqualf) was sampled from a Blount (Aeric Epiaqualf) mapping unit. The Glynwood and Capac sites are within 25 m of each other. A Nester pedon (Glossic Eutroboralf) within a Nester mapping unit was also sampled (Fig. 1). All sites are on rolling ground moraines of Late Wisconsinan age, in clayey and loamy tills (Farrand and Bell, 1984). Sampled pedons are at sites of <3% slope. Soils are within the udic or aquic soil moisture regimes. Mean annual precipitation is approximately 720 mm in Iosco County and 815 mm in Calhoun County, with a pronounced early summer maximum (Eichenlaub et al., 1990). The pedons in Calhoun County were located in an abandoned field; the Nester pedon was at the edge of a corn field. Both sites were presumably forested prior to settlement by Europeans.

Pedons were described from backhoe pits that were approximately 2 m deep. Pedon description and sampling followed techniques recommended by the Soil Survey Division Staff (1993), and were performed jointly by Michigan State University (MSU) and Natural Resources Conservation Service

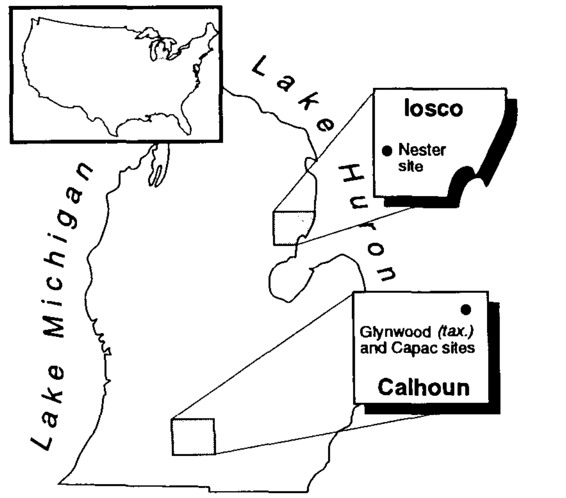

Fig. 1. General locations of the two sample sites in Iosco and Calhoun counties, Michigan.

(NRCS) personnel. Samples from horizons in the upper 2 m were removed from the pit face; deeper horizons were sampled by bucket auger. At the Glynwood site, carbonate coatings (calcans) and ped interiors were collected from samples taken at 130- to 150-cm depths. Calcan samples were collected by "shaving" them from the exteriors of the peds with a sharp knife. The shaved ped was then collected as a ped interior sample. It was not possible to collect comparable samples from the thinner and more discontinuous calcans in the Nester pedon, although a sample was taken of the ped interiors only (C2 horizon). Micromorphological analyses were not performed on the soils; our interpretations are based on macromorphological data.

The following analyses were run on each sample at the National Soil Survey Laboratory in Lincoln, NE: particle-size analysis included fine clay fractionation (although fine clay was not determined for the Nester samples), pH in 1:1 solution/soil mixtures, using H_2O and $CaCl_2$, carbonates within the clay fraction, and $CaCO_3$ equivalent of the <2-mm fraction by measuring CO_2 evolved after treating with HCl (Soil Survey Investigations Staff, 1992). Duplicate saran-coated clod samples were removed from selected horizons and analyzed for bulk density and 1.5 mPa available water capacity (Soil Survey Investigations Staff, 1992). Additionally, core samples (9.7-cm diam.) were taken in triplicate from all horizons shallower than 1.5 m and analyzed for oven-dry bulk density and total porosity of the <2-mm fraction at MSU. Porosity was determined by weight loss of water-saturated cores after oven drying at 105°C. Replicate saturated hydraulic conductivities (K_{sat}) were determined in situ for several horizons of the Glynwood pedon using a constant head of water within double rings of 9.7- and 15.2-cm diameter (cf. Swartzendruber and Olson, 1961; Sheldrick, 1984).

Most Alfisols developed on calcareous parent materials in the Midwest have the upper limit of carbonates as the lower limit of the solum. This definition is especially useful for soil mapping. However, because we had access to large soil pits, we could use soil fabric and structure as guides for determining whether a horizon was part of the solum. Carbonates alone were not deemed sufficient to relegate a horizon to C status; horizons that lacked pedogenic structure were designated as C. We allowed both B and C horizons to have k suffixes.

Table 1. Morphologic characteristics of the three pedons.

Horizon	Depth, cm	Moist color	Textural class†	Structure‡	Moist consistence	Cutans (moist colors)	Redoxymorphic features and moist colors
				Glynwood taxadjunct			
Ap	0–22	10YR 3/2	l	2f&mgr	friable	none	none
E	22–33	10YR 5/4	fsl	2msab	friable	none	none
Bt	33–43	10YR 4/4	cl	2f&msab	firm	few faint 10YR 4/3 argillans; few prominent 10YR 7/3 calcans	common 10YR 5/6
Btk1	43–56	10YR 4/6	cl	2f&msab	firm	many distinct 10YR 3/3 argillans; few prominent patchy 2.5Y 7/4 calcans	few 10YR 5/2; common 10YR 5/8
Btk2	56–74	10YR 4/4	cl	2fsab	firm	few faint 10YR 4/3 argillans; few prominent discontinuous 10YR 7/1 and 5/2 calcans	common 10YR 5/6; few 2.5Y 5/2
Btk3	74–85	10YR 4/3	l	2f&msab	firm	few faint 10YR 4/4 argillans; many prominent discontinuous 10YR 6/2 calcans	common 10YR 5/6; few 5YR 4/6
Btk4	85–137	10YR 4/4	l	3f&msab parting to c&vcpl	firm	few faint 5YR 3/2 argillans; many prominent discontinuous 10YR 6/2 and 7/1 calcans	many 10YR 4/6; common 2.5YR 6/2
Bk1	137–157	10YR 4/3	fsl	3cpl	firm	many prominent continuous 10YR 8/1 calcans	common 10YR 5/6
Bk2	157–173	10YR 4/3	l	3cpl	firm	common prominent 10YR 8/1 calcans	common 10YR 5/6
C1	173–194	10YR 4/3	cl	2cpl	firm	few prominent discontinuous 10YR 8/1 calcans	few 10YR 5/6
C2	194–213	10YR 4/3	cl	2cpl	firm	few prominent discontinuous 10YR 8/1 calcans	few 10YR 5/8
C3	213–236	10YR 4/3	cl	2cpl	firm	very few prominent discontinuous 10YR 6/2 calcans	
				Capac			
Ap	0–22	10YR 3/2	l	1msab parting to 1fgr	friable	none	none
B/E	22–32	10YR 3/3 (B) 10YR 5/2 (E)	scl	1msab	firm	none	common 7.5YR 4/4
Bt1	32–50	10YR 4/3	scl	2msab	firm	common distinct 10YR 3/2 argillans	many 10YR 4/6 and 10YR 5/2
Bt2	50–70	10YR 4/3	scl	3msab	firm	common prominent and distinct 10YR 4/2 and 3/2 argillans	many 10YR 5/6 and 10YR 5/2
Btk	70–82	10YR 5/3	cl	2mab	firm	few distinct 10YR 4/2 argillans; few prominent 10YR 6/2 and 8/2 calcans	common 10YR 4/6
Bk1	82–136	10YR 4/3	cl	1m&cpl parting to 2fab	very firm	many prominent 10YR 8/1 and 6/1 calcans	common 10YR 4/6; few 10YR 5/2
Bk2	136–152	10YR 5/3	l	1cpl parting 2mab	very firm	common prominent 10YR 7/1 calcans	common 10YR 5/6 and 10YR 5/4; few10YR 6/2
Bk3	152–184	10YR 5/3	l	1cpl parting to 2mab	very firm	few prominent discontinuous 10YR 7/2 calcans	common 10YR 5/4 and 10YR 5/6
C	184–216	10YR 4/3	cl	m parting to 2cpl	very firm	few prominent patchy 10YR 7/2 calcans	few 10YR 5/6
				Nester			
Ap	0–15	10YR 3/2	sl	1f&msab	friable	none	none
B/E	15–25	7.5YR 4/4	scl	2msab	friable	very few distinct 5YR 4/3 argillans	none
Bt	25–56	7.5YR 4/4	cl	1mpr parting to 2msab	firm	common distinct 7.5YR 4/2 argillans	none
BC	56–89	7.5YR 4/4	cl	1mpr parting to 2msab	firm	common distinct 7.5YR 4/2 argillans	none
C1	89–124	7.5YR 5/4	cl	m	firm	few prominent 10YR 7/2 calcans	none
C2	124–160	7.5YR 5/4	cl	m	firm	common prominent 10YR 7/1 calcans	none
2C3	160–203	7.5YR 6/4	c	m	firm	common prominent 10YR 7/2 calcans	none
2C4	203–241	7.5YR 6/4	c	m	firm	few prominent 10YR 7/2 calcans	none

† = loam; fsl = fine sandy loam; cl = clay; sl = sandy loam; scl = sandy clay loam; c = clay.
‡ Structure grade: 1 = weak, 2 = moderate, 3 = strong. Structure class: f = fine, m = medium, c = coarse, vc = very coarse. Structure shape: gr = granular, sab = subangular blocky, ab = angular blocky, pl = platy, m = massive.

RESULTS AND DISCUSSION

Physical Characteristics

All three pedons were formed in clay loam parent material, although the Nester soil was underlain by clay (2C) material of probable glaciolacustrine origin (Tables 1 and 2). All three contained argillans in the upper B horizons (Table 1).

The lower Btk3 and upper Btk4 horizons of the Glynwood pedon had slightly larger sand contents and lower clay contents than did horizons immediately above and below. Similarly, the Bk2 and upper Bk3 horizons of

Table 2. Physical characteristics of the three pedons.

Horizon	Depth	Coarse fragments >2 mm	Clay <2 µm	Silt 2-50 µm	Sand >50 µm	Fine clay <0.2 µm	Coarse clay 0.2-2 µm	Clay CO_3 <2 µm	Fine silt 2-20 µm	Coarse silt, 20-50 µm	Very fine sand, 0.05-0.1 mm	Fine sand, 0.1-0.25 mm	Medium sand, 0.25-0.5 mm	Coarse sand, 0.5-1.0 mm	Very coarse sand, 1.0-2.0 mm
	cm	% of whole soil	% of 2-mm fraction												
									Glynwood taxadjunct						
Ap	0-22	6	16.8	31.2	52.0	8.2	8.6	0	21.4	9.8	10.9	23.9	12.9	3.1	1.2
E	22-33	12	15.9	27.8	56.3	5.1	10.8	0	18.0	9.8	11.6	25.5	14.4	3.8	1.0
Bt	33-43	4	36.6	27.0	36.4	15.2	21.4	0	19.2	7.8	8.8	15.7	8.5	2.2	1.2
Btk1	43-56	7	32.5	31.1	36.4	10.0	22.5	1.5	22.0	9.1	10.2	14.3	8.4	2.3	1.2
Btk2	56-74	6	28.3	37.7	34.0	6.4	21.9	3.4	28.0	9.7	8.8	13.4	8.2	2.3	1.3
Btk3	74-85	7	24.8	40.3	34.9	5.0	19.8	4.6	29.0	11.3	8.4	13.7	8.3	2.9	1.6
Btk4 upper	85-103	10	23.1	40.8	36.1	4.8	18.3	4.0	28.6	12.2	9.4	14.2	7.7	3.0	1.8
Btk4 middle	103-120	4	23.8	39.8	36.4	5.1	18.7	4.3	28.0	11.8	10.7	13.7	8.5	2.2	1.3
Btk4 lower	120-137	12	20.7	34.8	44.5	4.5	16.2	3.3	23.0	11.8	12.8	18.1	9.7	2.8	1.1
Bk1	137-157	3	15.2	27.0	57.8	3.6	11.6	3.6	17.1	9.9	10.9	25.8	17.0	3.2	0.9
Bk2	157-173	5	23.2	36.9	39.9	5.8	17.4	3.9	26.2	10.7	10.4	16.8	8.7	2.5	1.5
C1	173-194	6	27.5	36.0	36.5	7.6	19.9	4.5	26.3	9.7	8.7	13.3	9.1	3.3	2.1
C2	194-213	8	31.5	39.5	29.0	8.7	22.8	5.2	30.5	9.0	7.4	10.9	7.1	1.8	1.8
C3	213-236	5	32.3	41.7	26.0	9.0	23.3	2.1	31.6	10.2	7.0	10.6	6.0	1.6	0.8
Calcans	–	–	26.2	35.8	38.0	–	–	9.0	27.4	8.5	7.7	13.6	9.9	4.7	2.1
Ped interiors	–	–	26.7	37.8	35.5	–	–	5.2	27.2	10.6	9.5	13.3	7.9	2.7	2.1
										Capac					
Ap	0-22	6	19.6	31.2	49.2	9.4	10.2	0	24.2	7.0	9.8	20.4	14.3	3.1	1.6
B/E	22-32	14	23.4	21.4	55.2	13.2	10.2	0	16.8	4.6	10.0	24.0	15.3	4.2	1.7
Bt1	32-50	8	26.1	21.1	52.8	15.3	10.8	0	16.3	4.8	9.6	23.8	13.9	3.6	1.9
Bt2	50-70	10	28.6	23.2	48.2	14.9	13.7	0	18.5	4.7	10.3	20.1	12.6	3.6	1.6
Btk	70-82	11	29.6	38.8	31.6	8.6	21.0	4.0	31.5	7.3	8.2	12.2	8.4	1.9	0.9
Bk1-upper	82-100	5	29.9	39.1	31.0	8.2	21.7	4.9	30.9	8.2	7.2	11.9	7.7	2.6	1.6
Bk1-middle	100-116	5	30.0	37.0	33.0	8.0	22.0	5.8	30.3	6.7	7.5	12.8	8.2	2.7	1.8
Bk1-lower	116-136	10	31.2	36.7	32.1	8.0	23.2	6.1	30.5	6.2	8.3	11.8	7.8	2.4	1.8
Bk2	136-152	10	25.1	33.1	41.8	6.9	18.2	4.0	26.0	7.1	9.7	15.4	11.1	3.6	2.0
Bk3-upper	152-168	12	22.2	32.7	45.1	6.7	15.5	3.3	24.5	8.2	10.2	18.9	11.2	3.4	1.4
Bk3-lower	168-184	10	26.0	37.3	36.7	7.5	18.5	3.0	28.7	8.6	8.5	14.4	8.5	2.9	2.4
C1	184-201	11	28.2	38.7	33.1	8.2	20.0	4.6	31.3	7.4	8.9	12.7	8.3	2.3	0.9
C2	201-216	5	27.8	37.3	34.9	8.4	19.4	4.6	30.0	7.3	8.9	12.9	8.7	2.8	1.6
C3	216-232	9	32.0	41.7	26.3	9.0	23.0	4.9	33.6	8.1	6.7	10.4	6.0	2.1	1.1
										Nester					
Ap	0-15	6	16.6	27.4	56.0	nd†	nd	0	20.1	7.3	4.3	19.0	28.1	3.8	0.8
B/E	15-25	7	26.5	23.1	50.4	nd	nd	0	17.7	5.4	3.7	16.5	26.1	3.6	0.5
Bt	25-56	2	38.8	19.4	41.8	nd	nd	0	15.4	4.0	2.7	14.6	21.3	2.7	0.5
BC	56-89	4	31.9	31.0	37.1	nd	nd	3.4	25.2	5.8	2.6	12.0	19.0	2.8	0.7
C1	89-124	4	34.1	33.0	32.9	nd	nd	8.5	27.3	5.7	2.4	10.7	16.5	2.6	0.7
C2	124-160	5	33.0	33.3	33.7	nd	nd	7.3	26.9	6.4	2.7	10.6	17.4	2.6	0.4
2C3	160-203	7	48.9	39.4	11.7	nd	nd	14.4	32.6	6.8	0.9	4.3	4.6	1.8	0.1
2C4	203-241	8	49.6	39.5	10.9	nd	nd	14.4	34.3	5.2	1.1	4.6	4.0	1.0	0.2

† nd = not determined.

the Capac pedon are slightly coarser textured than some other horizons within that pedon. Rather than indicate these subtle textural changes as lithologic discontinuities, we simply recognize that (i) the sediments in the sampled horizons at the Glynwood and Capac sites have a direct glacial depositional origin (i.e., were deposited as glacial till), and (ii) till can be heterogeneous when examined over short distances and at small scales. Indeed, the near homogeneity, with respect to texture, of the upper 2.5 m of till in each pedon is unusual for the area (Zobeck, 1976; Nolan, 1995). Perhaps more importantly, the near homogeneity of the upper (excluding 2C) parent materials in all three pedons with respect to carbonate content (all were between 24 and 27% on a weight basis) is deemed more important to this study than slight differences in texture.

Bulk densities were high in these fine-textured soils (Table 3). Most densities in lower B and upper C horizons of the Glynwood and Nester pedons exceeded 1.9 Mg m^{-3} by the clod method and 1.8 Mg m^{-3} by the core method (Table 3). Porosities decreased with depth, from values as high as 55.2% in the Ap horizon of Glynwood pedon to well below 40% in the lower solum. Nolan (1995) found that the C horizon in Capac soils in Calhoun County is very slowly permeable, and at some times of the year (most commonly after snowmelt), perches water.

Secondary carbonate accumulations existed as continuous coatings, threads, and filaments on ped faces (Fig. 2). These calcans occurred as shallow as 33 cm and as deep as 236 cm, although their maximum expression usually occurred in the lower B and upper C horizons, at about 100 to 150 cm (Table 1). On some ped faces, they were as thick as 2 mm. Where this thick, the calcans exist as soft coatings, occasionally referred to in the

Table 3. Other characteristics of the three pedons.

Horizon	pH in $CaCl_2$	pH in H_2O	1.5 mPa H_2O	Bulk density (oven-dry clod)	Bulk density (core)	Porosity	Saturated hydraulic conductivity	$CaCO_3$ (mass/mass basis)	$CaCO_3$ (vol/mass basis)	Pedogenic $CaCO_3$#
			%	Mg m^{-3}		%	mm h^{-1}	% <2 mm	Mg m^{-3}	kg/(1 cm × 1 m^2 volume)
						Glynwood taxadjunct				
Ap	6.5	6.8	8.3	1.58	1.13	55.2	64	tr†	tr‡	0
E	6.6	7.3	6.3	1.78	1.59	39.7	15	tr	tr	0
Bt	6.9	7.6	13.6	1.66	1.72	39.9	3	tr	tr	0
Btk1	7.4	7.9	12.7	1.77	1.61	43.3	36	5	0.08	0.7
Btk2	7.6	8.1	10.5	1.74	1.76	39.2	28	24	0.42	3.9
Btk3	7.6	8.2	9.8	1.88	1.85	34.1	nd	26	0.48	4.4
Btk4-upper	7.6	8.1	9.5	nd§	1.86	35.6	1	28	0.52	4.6
Btk4-middle	7.6	8.1	8.8	1.89	1.86	34.4	nd	26	0.48	4.6
Btk4-lower	7.6	8.2	7.7	nd	1.80	37.1	nd	25	0.45	3.9
Bk1	7.6	8.2	5.9	1.91	1.95	32.7	nd	20	0.39	3.7
Bk2	7.6	8.1	8.6	nd	1.88	35.0	nd	25	0.47	4.4
C1	7.6	8.2	10.2	nd	nd	nd	nd	24	0.46¶	4.2
C2	7.7	8.2	11.1	nd	nd	nd	nd	25	0.48¶	4.3
C3	7.7	8.1	11.3	nd	nd	nd	nd	24	0.46¶	4.2
Calcans	7.6	8.1	8.2	nd	nd	nd	nd	40	0.76¶	nd
Ped interiors	7.6	8.2	9.3	nd	nd	nd	nd	24	0.46¶	nd
						Capac				
Ap	6.1	6.6	9.0	nd	nd	nd	nd	tr		
B/E	6.5	7.0	8.6	nd	nd	nd	nd	tr		
Bt1	6.7	7.3	9.7	nd	nd	nd	nd	0		
Bt2	7.0	7.6	10.9	nd	nd	nd	nd	tr		
Btk	7.6	8.2	10.6	nd	nd	nd	nd	29		
Bk1-upper	7.6	8.2	10.4	nd	nd	nd	nd	31		
Bk1-middle	7.7	8.2	10.4	nd	nd	nd	nd	29		
Bk1-lower	7.7	8.2	10.6	nd	nd	nd	nd	28		
Bk2	7.7	8.2	8.7	nd	nd	nd	nd	23		
Bk3-upper	7.7	8.2	7.9	nd	nd	nd	nd	22		
Bk3-lower	7.7	8.2	9.3	nd	nd	nd	nd	24		
C1	7.7	8.2	10.2	nd	nd	nd	nd	26		
C2	7.7	8.2	10.7	nd	nd	nd	nd	26		
C3	7.7	8.2	11.6	nd	nd	nd	nd	26		
						Nester				
Ap	5.3	5.7	5.4	1.66	1.36	42.5	nd	0	0	0
B/E	5.7	6.4	8.7	1.82	1.71	42.7	nd	0	0	0
Bt	6.4	7.0	12.6	1.82	1.66	43.8	nd	0	0	0
BC	7.6	8.2	10.8	1.90	1.76	42.1	nd	18	0.32	2.9
C1	7.6	8.3	10.2	1.99	1.89	38.0	nd	26	0.49	4.6
C2	7.7	8.3	10.7	1.94	1.86	38.1	nd	27	0.50	4.6
2C3	7.7	8.3	14.5	nd	nd	nd	nd	36	0.68¶	6.2
2C4	7.7	8.3	10.4	nd	nd	nd	nd	37	0.70¶	6.3
Ped interiors	nd	nd	11.7	nd	nd	nd	nd	38	0.72¶	nd

† trace.
‡ calculated as: ($CaCO_3$ % × D_b)/100.
§ not determined.
¶ assumes a D_b of 1.90 Mg m^{-3} for this horizon.
# Calculated (modified from Gile, 1995) as:

$$\text{Pedogenic carbonate (kg) for a volume element 1 cm in thickness and 1 m}^2\text{ in horizontal cross section} = \frac{D_b[1 - (\text{coarse fragment content in }\%/100)]CaCO_3\text{ content in }\%}{10}$$

where D_b is the bulk density of the fine earth fraction in Mg m^{-3}, as derived from core data (Table 2), [1 − (coarse fragment content in %/100)]$CaCO_3$ content (in %) is the correction for the volume occupied by the coarse fragments, and $CaCO_3$ is the carbonate content of the horizon minus that of the parent material (the latter value is taken as 0.46% for Glynwood and 0.72% for Nester).

literature as "soft powdery lime". Generally, the color of the coatings became higher in value and lower in chroma with depth, possibly due to less organic matter intermixing with the $CaCO_3$ materials at depth. In the Glynwood pedon the colors ranged from very pale brown (10YR 7/3) in the Bt horizon, to pale yellow (2.5Y 7/4) in the Btk1, to light gray (10YR 7/1) in the Btk2, to finally, white (10YR 8/1) in the lower Bk and upper C horizons (Table 1). Similar calcan colors were observed in the Capac soil, whereas in the Nester pedon, light gray (10YR 7/2) coatings were observed only in C horizons.

The five forms of secondary carbonates recognized by the National Soil Survey Center include petrocalcic horizons, masses, concretions, nodules, and ped coats (Soil Survey Quality Assurance Staff, 1991). We typically identified only ped coats (calcans) in these soils. All three pedons had calcans in the upper C horizons; the Glynwood and Capac pedons also had calcans in the lower B (designated Bk) horizon (Table 1). Carbonate

Fig. 2. Calcans on the surface of a prism from the Glynwood taxadjunct pedon.

coatings were common along root channels and ped faces (Sherman and Ikawa, 1958). Distinct carbonate nodules and concretions, as reported in many soils of ustic and aridic soil moisture regimes (Gillam, 1937), were rare, and where observed were very small (<2-mm diam.). We agree with Wilding et al. (1990) that carbonate films and threads, as seen in these soils, are useful morphologic criteria for the identification of secondary pedogenic carbonates in the field. Wilding et al. (1990) also suggested that horizons with pedogenic carbonates should have wavy or irregular boundaries due to preferential flow of carbonate-saturated water. All horizon boundaries in the mid-sola of the Glynwood and Capac pedons were described as wavy.

The high clay contents, coupled with moderate and strong structure grades in the B horizons of these soils, may restrict infiltration pathways primarily to areas between peds, restricting the form of secondary carbonates to calcans (rather than concretions) on such depositional sites. Additionally, these soils have not had ample time to form distinct concretions, since they are, at most, 15 000 yr old (Eschman, 1985). The K_{sat} values were higher than expected for these fine-textured soils (Table 3), attesting to the strong structure grade and relative ease with which water can flow between peds in fine-textured soils. In horizons where peds were coarse and with a strong grade (and where consistence was firm), few if any secondary carbonates were observed within the ped matrix.

In the Glynwood and Capac pedons, prominent calcans from the mid- and upper-Bt horizons to ≈ 100 cm below justified our description of these layers as Btk and/or Bk horizons (Table 1). Because these horizons had soil structure and some roots, they are best described as part of the solum - Bk rather than Ck horizons. In the Nester soil, the calcans were less common and thinner, roots were absent, and rock structure dominated. These horizons were described as C.

Based on field observations, the calcans do not coat argillans. This finding is apparently supported by laboratory data. The "shaved" Glynwood calcans have essentially the same clay content as do the ped interiors (26.2

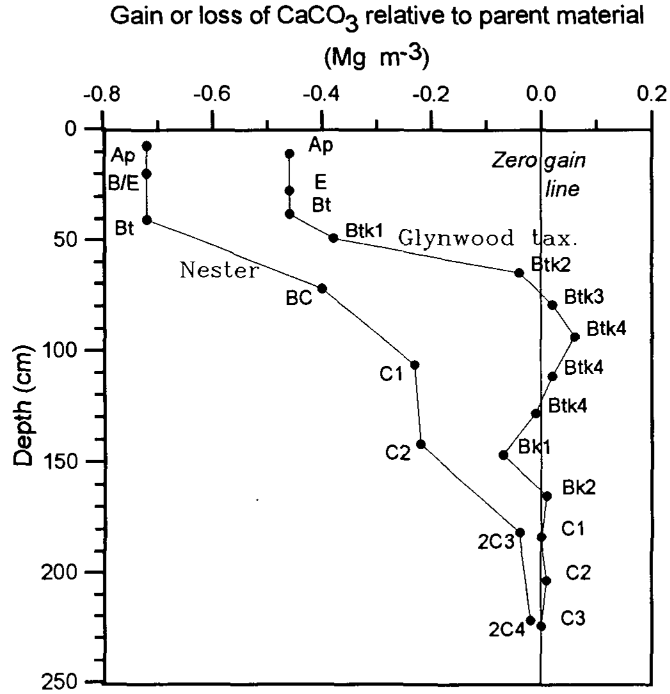

Fig. 3. Volumetric carbonate content (gravimetric content × bulk density) of sampled horizons of the Nester and Glynwood taxadjunct pedons. Dots represent the midpoint of each horizon.

vs. 26.7%; Table 2), suggesting that argillans (which would have been shaved off and included in the calcan sample) are not present on ped faces that contain calcans.

Carbonate Content and Redistribution

The Nester pedon exhibited no net gain of <2-µm carbonates (above parent material values) in any horizon (Fig. 3, Table 3). Calcans in this pedon were discontinuous, even in horizons where they were common (Table 1). Calcans here, as in other soils, may be due to either translocation from above and/or internal redistribution from ped interiors to ped faces. These data suggest that (i) the pedon has experienced considerable leaching (the uppermost 56 cm is leached of carbonates) and (ii) redistribution of the carbonates has occurred, but (iii) no localized zone of net gain of carbonates has occurred, at least within the upper 2.5 m.

The Glynwood pedon exhibited a net gain in carbonates in the Btk3 and Btk4 horizons, both on a volume/mass and a mass/mass basis, when compared with parent material values (Fig. 3, Table 3). Likewise, the Bk2 horizon exhibited a net gain in carbonates, whereas the Bk1, above, did not. From a process perspective, the low carbonate content of the Bk1 may be due to its slightly coarser texture (Table 2), which could have led to increased translocation out of the horizon. Texture has been shown to be a factor in the development of carbonate-rich horizons in certain instances (Gile, 1995), and is accounted for in soil taxonomy's calcic horizon criteria (Soil Survey Staff, 1994). The Bk1 horizon has the highest clay-free fine sand content (30.4%) of all the Ca-illuvial horizons in the Glynwood pedon. The low 1.5 mPa water content of the lower Btk3 and Btk4 horizons (Table 3), compared with horizons above and below, indicate that unsaturated flow of water from this horizon would be common only during dry periods. This process could translocate dissolved carbonates and deposit them in the surrounding finer textured horizons.

As in the Nester pedon, calcans in the Glynwood pedon are not apparent in upper horizons where the clay-free fine sand contents are high, and the thickness and frequency of calcans is highest where clay-free fine sand contents are low. The clay-free fine sand content decreases notably between 56 and 120 cm in this pedon, from 30.3% in the E horizon to a low values of 18.0 to 18.5 in the Btk3, upper Btk4, and mid-Btk4 horizons. These last three all exhibit a net gain in carbonates above parent material levels. Clay-free fine sand values increase markedly in the lower Btk4, to 22.8%, and carbonate contents drop as well (Fig. 3a, Table 3). Although these data are not sufficient to require that a lithologic discontinuity be described, they do suggest a relationship between lower clay-free fine sand contents (and, possibly, finer textures in general) and the presence of relatively large amounts of secondary carbonates.

The Capac pedon has a distinct increase in mass-based carbonate content (above that of the parent material) in the lower Bt and upper Bk horizons that is as large or larger than the depth trend observed in the Glynwood (Table 3). It also has thick calcans in the mid-solum region, where clay-free fine sand contents are low.

Clearly, the presence of thick calcans in Bk horizons, coupled with the carbonate data (Fig. 3), point to a definite zone of carbonate enrichment in some Bt and Bk horizons of the Glynwood and Capac pedons. Internal redistribution, from ped interiors to ped faces, has probably occurred in all three pedons, and is probably the dominant process responsible for calcans in the Nester pedon and in the Bk and C horizons of the Glynwood pedon. The distinct leached zone in the upper 50 cm of the Glynwood pedon, as well as the abundant carbonate-rich coatings on ped faces and the "bulge" in volumetric carbonate content in lower horizons, however, point additionally to vertical translocation of carbonates into Bk horizons.

Although carbonate enrichment from Ca-saturated groundwater occurs in Bk and Ck horizons in some soils (e.g., Carty et al., 1988), we do not believe that it is an important process here. If it had been, we would have expected to see calcans at shallow depths in the somewhat poorly drained Capac soil. Instead, this soil had abundant calcans only below 82 cm, which is deeper than the upper limit of abundant calcans in the moderately well-drained Glynwood, some 25 m upslope. Likewise, the lateral flow of carbonate-enriched groundwaters from the lower-lying Capac soil to the Glynwood is not likely here because in this humid climate the dominant flow of soil water throughout the year is downward. Such processes can, however, occur on landscapes that are not morphologically dissimilar to the Capac–Glynwood landscape, but where evapotranspiration exceeds precipitation for much of the year (Redmond and McClelland, 1959; Knuteson et al., 1989).

The calcans and the net gain in carbonates in some horizons may be due to the following process scenario: (i) dissolution of carbonates in near-surface horizons and downward translocation in solution, (ii) slowing of the wetting front or perching in slightly coarser textured horizons that overlie finer textured ones, due to the low porosities and permeabilities in the latter (which are within the lower solum and upper C horizons) (Nolan, 1995), (iii) withdrawal of water by roots, leading to (iv) supersaturation of the soil solution with respect to Ca ($Ca[HCO_3]_2$) and (v) precipitation of carbonates as calcans.

Soil Classification and Horizon Terminology

The Nester pedon classified as a fine, mixed Glossic Eutroboralf. The pedon at the Glynwood site was coarser textured than is allowed in the Glynwood series, and is therefore technically considered a Glynwood taxadjunct (fine, illitic, mesic Aquic Hapludalf). The Capac soil classified as a fine-loamy, mixed, mesic Aeric Endoaqualf.

The Glynwood taxadjunct and the Capac pedons contain calcic horizons. According to the Soil Survey Staff (1994), one way that a 15 cm or thicker, nonindurated soil horizon can classify as calcic is by having 15% or more $CaCO_3$ equivalent (listed as "$CaCO_3$ mass/mass basis" in Table 3), provided that that amount is also 5% more than an underlying horizon. By these criteria, the Bk4 horizon in the Glynwood taxadjunct and the Bk1 horizon in the Capac are calcic horizons. It is also possible that one or more of the horizons in these three pedons could have met another calcic horizon criterion: 15% or more $CaCO_3$ equivalent and 5% (by volume) or more identifiable secondary carbonates. Since we did not quantify this last characteristic in the field, and we do not have quantified micromorphological data, we cannot classify any horizons based on this criterion. The presence of calcic horizons in the Glynwood taxadjunct and Capac pedons does not affect their family-level classifications.

The NRCS has recently had discussions regarding if and how carbonate-rich horizons with evidence of translocation, in otherwise leached soils, should be recognized and designated. Gile et al. (1965) introduced and advocated the use of K (uppercase) as a master horizon of carbonate accumulation where horizons contain 90% or more K-fabric. Birkeland (1984) uses the term K, which has led to the popularization of the master horizon K nomenclature in some circles. Nonetheless, the NRCS does not recognize a K master horizon (Soil Survey Staff, 1994).

Use of the lowercase k as a horizon suffix has also been fraught with inconsistency and confusion. Historically, the horizon modifier k (formerly "ca") has been used in various pedologic applications. The Soil Survey Staff (1994) currently defines the k suffix for horizons with an accumulation of alkaline-earth carbonates, commonly $CaCO_3$. Most commonly, k has been used for carbonate-enriched horizons in subhumid or drier soils (Belohlavy and Lewis, 1991). Indeed, one impetus for this study centered around the needs of soil mappers in

Michigan for a consistent definition of k terminology in the udic and aquic soils of Michigan. Mappers had differing opinions, for example, about how horizons with secondary carbonates should be described: as B, Bw, BC, or Bk? Another question centered on the definition of solum in these soils: If depth of leaching defines the solum, then are all horizons with secondary carbonates C horizons? Are they also Ck horizons? Van Wesenbeeck and Kachanoski (1991) used the term Ck for a horizon in a coarse-textured, forested, Typic Hapludalf in Ontario, where Ck probably was used to represent unleached C horizon material, not accumulated carbonates per se.

According to current NRCS guidelines (Soil Survey Quality Assurance Staff, 1991), use of the k suffix implies a pedogenic origin for the secondary carbonates, such as solution and subsequent precipitation. Either horizontal or vertical translocation of the dissolved carbonate is considered pedogenic and is ample proof that the redeposited material is "secondary" in nature. Additionally, pedogenic translocation of carbonates can occur primarily within, rather than between, horizons (Rabenhorst and Wilding, 1986; West et al., 1988). Horizons with secondary carbonates visible to the unaided eye, and accompanied by some other pedogenic alterations, are B horizons. Designating a horizon Bk, however, requires a net accumulation of carbonates above that in the original parent material. Any B horizons with secondary carbonates in amounts less than that of the presumed parent material are to be designated Bw or BC horizons (Soil Survey Quality Assurance Staff, 1991). The Ck horizons lack significant evidence for pedogenesis other than showing a net gain in carbonates. Thus, quantification of the carbonate content of the horizon and the presumed parent material (as we have attempted here), or estimations thereof, is required for designating horizons Bk or Ck, as it is for determining if they meet calcic horizon criteria. Often, however, simple morphological descriptors work as well or better than more expensive and time-consuming chemical analyses (e.g., Mokma 1993), and if adopted by the NRCS, make mapping and description of soils with these attributes easier and more repeatable for those persons that lack access to laboratory facilities.

Thus, we suggest that the current k subordinate horizon distinction be redefined so as to be analogous to t, s, h, or others. Under this scenario, no quantitative determination of carbonate content would be necessary. Morphologic evidence of secondary carbontes alone would be sufficient to designate a horizon Bk or Ck. The A, B, or C horizons could all theoretically have a k suffix, although most k suffixes would be described for B and C horizons. If this terminology is adopted, redefinition of the solum to include k horizons would not be necessary. The k suffix would imply that the horizon is unleached and yet has some imprinting of pedogenesis (the secondary carbonates). Just as the letter g, as in a Cg horizon, provides useful pedogenic information about the nature of the C horizon, so could Ck. The Bk horizons would have to have evidence of pedogenesis beyond that of carbonate accumulations alone. Use of k in this manner would convey the most information about the genesis and morphology of the horizons with secondary carbonates, while at the same time would require neither extensive laboratory work nor redefinition of the long-established definition of the solum.

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