An examination of podzolization near Lake Michigan using chronofunctions

L. R. Barrett and R. J. Schaetzl

Department of Geography, Michigan State University, East Lansing, Michigan 48824-1115, U.S.A. *Received 29 August 1991, accepted 26 June 1992.*

Barrett, L. R. and Schaetzl, R. J. 1992 **An examination of podzolization near Lake Michigan using chronofunctions.** Can. J. Soil Sci. **72**: 527–541. A chronosequence of sandy soils was investigated on four terraces near Lake Michigan to assess rates of podzolization and changes in soil properties with age. The terraces ranged in age from 3000 to 10 000 BP. Each surface was systematically sampled to determine the modal profile, which was then described and sampled. Quantities of OC, Fe, and Al in the B horizons of modal soils increased with soil age. Silt content of surface horizons also increased with age, possibly due to eolian input or physical weathering. For weighted profile and B horizon Al and Fe averages and a variety of soil development indices, a single logarithmic model generally gave the highest statistical significance of the three chronofunction models used. All pedons sampled failed to classify as Podzols, but the oldest two met the criteria for the Spodosol order. Thus, more than 4000, but less than 10 000, years are required for the development of a spodic horizon in Michigan.

Key words: Soil chronosequence, Podzol development, soil genesis, modal profile

Barrett, L. R. et Schaetzl, R. J. 1992. **Examen de la podzolisation aux abords du lac Michigan au moyen de fonctions chronologiques.** Can. J. Soil Sci. **72**: 527–541. Une chronoséquence de sols sableux a été étudiée sur quatre terrains avoisinant le lac Michigan pour évaluer le taux de podzolisation et la modification des propriétés daphiques en fonction de l'âge du sol. L'âge des terrains allait de 3 000 à 10 000 ans avant nous. Chaque surface était systématiquement échantillonnée pour obtenir le profil modal qui, à son tour, était décrit puis échantillonné. Les quantités de C.O., de Fe et de Al dans l'horizon B des sols modaux augmentaient avec l'âge du terrain. Les teneurs en limon des horizons supérieurs augmentaient également avec l'âge, vraisemblablement à cause d'un apport éolien ou de l'altération du sol sur place. Pour les moyennes pondérées de Al et de Fe du profil ou de l'horizon B ainsi que pour divers indices de pédogénèse, un simple modèle logarithmique fournissait généralement les plus hauts niveaux de signification pour les trois modèles à fonction chronologique utilisés. Des pédons étudiés n'a pu se classer comme podzol mais les deux plus vieux répondaient aux critères de l'ordre des spodosols. Il appert donc qu'il faut au minimum 4 000 ans mais moins 10 000 ans pour la formation d'un horizon spodique au Michigan.

Mots clés: Chronoséquence pédologique, podzolization, pédogénèse, profil modal

Jenny's (1941) functional-factorial model of soil development provides a theoretical framework within which the effects of each of five soil-forming factors (climate, organisms, relief, parent material, and time) can be assessed in a geographic context. If four of the factors are held constant, or if their variation is negligibly small, the functional relationship between the remaining factor and soil properties can be examined. Soil development can be investigated, using a chronosequence, when soil properties are related to surface age. Numerical chronofunctions describing rates of soil development may then be formulated from a chronosequence (Bockheim 1980).

During and following final deglaciation of Michigan's southern peninsula and associated

Great Lakes, the opening of successively lower outlets and further downcutting of existing ones resulted in declining lake levels in these basins (Larsen 1985). A series of sandy lake terraces was formed as lake levels declined (Leverett and Taylor 1915). We studied one such sequence of geomorphic surfaces, as it provided a unique opportunity to examine soil development in southern Michigan.

Previous studies of podzolization have suggested that in some environments Podzols can develop rapidly. For example, in the acid beach sands of Vancouver Island, British Columbia, where precipitation averaged 3200 mm annually and mean annual temperatures were 8.9°C, a Humo-Ferric Podzol (Canada Soil Survey Committee 1978) had developed within 350 yr (Singleton and Lavkulich 1987). In northwest Finland, under annual temperatures averaging 3.0°C and an annual precipitation of 417 mm, a sequence of 16 sandy beach ridges of granitic origin showed visible differentiation of podzol horizons within 400 – 500 yr, and chemical differentiation of horizons within 200 – 300 yr (Jauhiainen 1973). In contrast, under colder climatic conditions (−5.5°C mean annual temperature and 510 mm mean annual precipitation), at least 2300 yr were necessary for the formation of Ae-Bf distinctions, and 4500 yr were necessary to develop a Humo-Ferric Podzol for soils on six calcareous storm ridges near Hudson Bay, Ontario (Protz et al. 1984).

A study of soil development on a sequence of sandy lake terraces ranging in age from 2250 to 10 000 yr in Cheboygan County, Michigan, suggested that podzol morphology required between 3000 and 8000 yr to develop (Franzmeier and Whiteside 1963a,b; Franzmeier et al. 1963). Parent materials in this study were not calcareous. Annual temperatures averaged 6.2°C and precipitation averaged 685 mm. However, there were problems of experimental design: (1) Although the youngest three surfaces were indeed lake terraces and were located within 1 km of each other, the fourth surface was a sandy moraine, located 45 km inland; and (2) Particle size distributions of the morainic parent materials were distinct from those of the beach ridges.

The present study sought to eliminate the difficulties encountered by Franzmeier and Whiteside (1963a,b) by confining study sites to sandy lake terraces and minimizing the distance between study sites. The purpose of this study was to examine podzolization processes and the relationship between soil development and surface age on sandy parent materials in the northwestern part of Michigan's southern peninsula by (1) determining physical and chemical properties and the classification of the typical (modal) pedon on each surface; and (2) modelling soil development using chronofunctions and a variety of soil development indices.

MATERIALS AND METHODS

Study Area

The study area is located in the northwestern portion of Michigan's southern peninsula (Fig. 1). Four lake terraces are prominent features here and can be intermittently traced along the Lake Michigan shoreline. Surface ages as adopted in this study are: Algoma, 3000 BP; Nipissing, 4000 BP, Battlefield, 10 000 BP, and Main Algonquin, 11 000 BP (Leverett and Taylor 1915; Futyma 1981; Hansel et al. 1985; Larsen 1985). We assumed that pedogenesis began on each surface immediately following the close of the associated lake stage and the subaerial exposure of the sediments.

Slopes within the study area are level to gently sloping (<6%). In some places, especially on the Battlefield terrace, there are many small pits and mounds up to 2 m in diameter, indicative of tree uprooting (Schaetzl et al. 1989). Most soils are well or excessively drained, although extensive areas on the Algoma surface are somewhat poorly drained. The parent materials are non-calcareous sandy sediments that were deposited in near-shore lacustrine environments.

Local climate reflects the proximity of the waters of Lake Michigan. The mean annual air temperature at Pellston (Fig. 1) for the period 1951–1980 is 5.2°C, with a mean July temperature of 18.6°C and a mean January temperature of −9.1°C. Mean annual precipitation at Cross Village (Fig. 1) is 730 mm, with a mean of 200 cm of snowfall each year between October and May. Snowcover

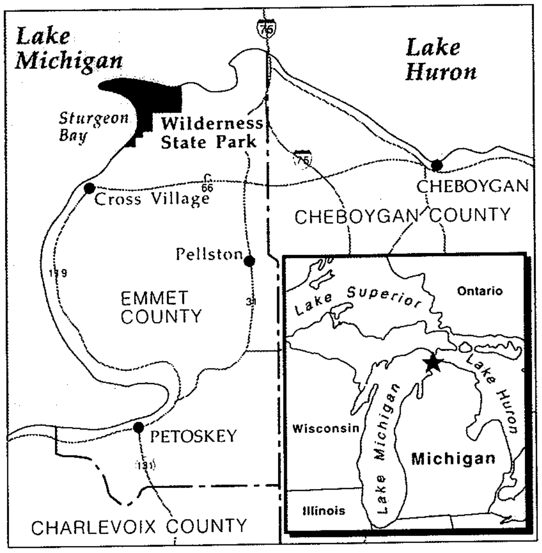

Fig. 1. Location of study sites, Emmet County, Michigan, USA.

(> 2.5 cm in depth) exists for an average of 130 d per year.

Vegetation within the study area consists primarily of second-growth mixed deciduous-coniferous forest. Common tree species at the study sites include, in approximate order of abundance, aspen (*Populus* spp.), paper birch (*Betula papyrifera*), white pine (*Pinus strobus*), red maple (*Acer rubrum*), red pine (*Pinus resinosa*), and jack pine (*Pinus banksiana*). On the more moist Algoma surface, balsam fir (*Abies balsamea*), paper birch, aspen, and northern white cedar (*Thuja occidentalis*) are abundant.

Field Methods

At least two sampling areas of about 2.5 ha each were chosen on each surface except the Algoma, where only one area was identified because of the small extent of well-drained soils on that surface. Using a systematic sampling design, an average of 18 sites was sampled on each surface by bucket auger, to the upper C horizon or to a depth of about 150 cm, whichever was shallower. Textures, horizon thicknesses, and moist colors were recorded, as was the presence of coarse fragments or ortstein in each horizon. The POD Index, a numerical index that assesses degree of podzolic development based on soil color and number of subhorizons (Schaetzl and Mokma 1988), was calculated for each augered pedon, and the median POD index value was then determined for each surface. Given this information, a "modal" pedon for each surface was chosen from among those pedons having the median POD index value. The original auger hole was then located and a pit excavated at the auger hole. Standard field descriptions were made (Soil Survey Staff 1981), and bulk samples were taken by genetic horizon for laboratory analysis.

On the Algoma surface, all sites had a POD Index value of zero, indicating little or no podzolic development, but since many sites on that surface showed signs of poor drainage or atypical parent materials, the modal pedon was selected as the one with the fewest constraining characteristics. When this pedon was described and sampled (Algoma-1), it was found to contain a buried A horizon, suggesting that it had actually developed in eolian, rather than lacustrine, sand. Therefore, another pedon approximately 150 m away was identified and sampled and is hereafter referred to as Algoma-2.

Laboratory Methods

Horizon samples were air dried and passed through a 2-mm sieve. Sand content was determined by sieving, silt and clay content by pipette (Singer and Janitzky 1986). Reaction was measured in a 2:1 soil-water mixture. Organic C content was determined by a modified Walkley-Black method (Singer and Janitzky 1986). Extractions of Fe and Al were taken in Na citrate-bicarbonate-dithionite (CBD), Na pyrophosphate (McKeague 1978), and acid ammonium oxalate (Soil Conservation Service 1990). Fe and Al concentrations of the extracts were measured by DCP spectrometry. Optical density of the oxalate extract (ODOE) was measured at 430 nm (Soil Conservation Service 1990; Daly 1982).

Indices of Development

In addition to calculating POD Index values (Schaetzl and Mokma 1988) for auger sites and for sampled pits, the Index of Profile Anisotropy (IPA) (Walker and Green 1976), the modified Index of Profile Anisotropy (mIPA) (Birkeland 1984), and the Podzolization Index (K_{Al}) (Duchaufour and Souchier 1978) were also determined. The IPA measures individual horizon deviation from the overall profile weighted mean value of a particular property; the mIPA measures deviations from the parent material. For both the IPA and mIPA, weighted values are calculated for the entire profile to give an indication of profile anisotropy, and a separate index value is calculated for each soil property. Index values increase with increasing profile anisotropy; a perfectly isotropic profile has

Table 1. Physical properties of the five pedons

Horizon	Depth (cm)	Matrix color	Coarse fragments >2.0 mm (% total)	VCS 2-1 mm	CS 1-0.5 mm	MS 0.5-0.25 mm	FS 0.25-0.1 mm	VFS 0.1-0.5 mm	Total: Sand 2.0-0.05 mm	Total: Silt 0.05-0.002 mm	Total: Clay <0.002 mm	CS/FS	Ortstein^z
				(% of 2.0 - 0.05 mm)					(% of fine earth)				
						Algoma-1							
Ae	0–10	10YR 4/2	0.1	0.6	4.4	56.1	38.7	0.1	98.8	1.1	0.1	0.1	
Bfj	10–38	10YR 5/4	0.0	0.0	4.8	71.2	24.0	0.1	99.6	0.4	0.0	0.2	
C	38–68	10YR 6/4	0.0	0.0	3.2	68.9	27.8	0.1	99.7	0.2	0.0	0.1	w;1
IIAb	68–70	10YR 3/2	0.1	0.1	8.7	66.9	24.2	0.2	99.4	0.6	0.0	0.4	
IIC	70+	10YR 6/4	0.4	0.8	15.4	65.6	17.9	0.3	99.4	0.5	0.0	0.9	
						Algoma-2							
Ae	0–10	10YR 4/2	0.3	0.4	23.5	73.5	2.4	0.1	99.3	0.7	0.1	9.8	
Bfj	10–40	10YR 4/4	0.2	0.2	20.1	76.4	3.2	0.1	99.5	0.4	0.1	6.3	
C	40–83	10YR 6/4	1.9	0.9	32.4	64.4	2.2	0.1	99.4	0.6	0.0	14.7	
IIC	83+	10YR 5/3	60.7	8.2	36.2	48.8	4.9	2.0	92.7	7.1	0.2	7.4	
						Nipissing							
Ah	0–3	N 2/0	0.6	0.7	9.4	80.5	8.8	0.5	95.9	3.9	0.2	1.1	
Ae1	3–15	10YR 4/1	0.1	0.2	7.9	81.4	9.9	0.7	97.6	2.3	0.1	0.8	
Ae2	15–30	10YR 5/3	0.3	0.1	6.3	82.2	10.9	0.4	98.3	1.7	0.1	0.6	
Bfj1	30–45	10YR 5/6	2.3	0.1	7.1	85.1	7.6	0.2	98.6	1.2	0.2	0.9	s;1
Bfj2	45–75	7.5YR 5/8	7.6	0.3	11.7	83.2	4.8	0.1	98.6	1.2	0.2	2.4	w;1
Bfj3	75–98	10YR 5/4	2.3	0.9	22.0	73.2	3.8	0.1	99.3	0.7	0.1	5.8	w;2
BC	98–110	10YR 5/6	21.6	1.2	14.4	75.7	8.4	0.3	98.9	1.0	0.1	1.7	w;1
C	110+	10YR 6/4	10.6	0.2	4.8	84.2	10.6	0.2	99.5	0.4	0.1	0.5	
						Battlefield							
Ah	0–3	10YR 2/1	0.5	0.8	10.0	65.3	22.8	1.1	92.2	7.5	0.2	0.4	
Ae1	3–18	10YR 4/2	0.4	0.5	10.1	67.0	21.1	1.3	95.1	4.8	0.1	0.5	
Ae2	18–23	7.5YR 4/2	2.1	0.6	7.8	64.0	26.7	0.9	94.0	5.6	0.4	0.3	
Bfj1	23–30	7.5YR 4/6	1.6	0.8	7.6	64.9	26.0	0.7	93.9	5.6	0.5	0.3	
Bfj2	30–35	7.5YR 3/4	0.9	0.6	7.2	63.2	28.7	0.4	97.2	2.5	0.3	0.3	s;20
Bfj3	35–55	10YR 5/6	0.4	0.5	7.1	62.5	29.6	0.3	98.4	1.4	0.2	0.2	w;5
BC	55–67	10YR 6/6	0.4	0.5	3.9	46.2	48.5	0.9	99.2	0.7	0.1	0.1	w;5
C1	67–82	10YR 6/4	0.2	0.3	2.8	56.1	40.4	0.5	99.5	0.5	0.1	0.1	
C2	82+	10YR 6/4	0.1	0.5	14.2	72.8	12.4	0.1	99.7	0.2	0.0	1.2	

					Main Algonquin								
Ah	0–8	N 3/1	0.6	0.8	13.5	77.2	7.6	0.9	92.2	7.6	0.2	1.8	
Ae	8–30	10YR 5/2	0.9	0.3	11.1	79.6	8.2	0.8	95.1	4.8	0.1	1.4	
Bfj1	30–38	7.5YR 3/2	0.5	0.2	7.2	81.9	10.4	0.3	96.5	3.1	0.4	0.7	s;30
Bfj2	38–65	7.5YR 4/6	0.2	0.1	4.4	81.5	13.8	0.2	97.8	1.8	0.3	0.3	s;23
Bfj3	65–93	10YR 4/6	0.1	0.1	3.8	81.9	14.1	0.2	99.1	0.8	0.1	0.3	w;5
BC	93–125	10YR 5/4	0.0	0.1	2.3	71.6	25.9	0.1	99.7	0.3	0.1	0.1	
C	125+	10YR 6/4	0.7	0.4	6.3	68.9	24.0	0.3	99.6	0.4	0.1	0.3	

[z] Ortsein strength (w = weakly cemented; s = strongly cemented); maximum observed diameter of cemented fragments (cm).

an index value of 0. The K_{Al} is a graphical method of determining profile anisotropy in Al content of podzols; it was calculated herein for both Al_d and Al_o (Duchaufour and Souchier 1978). Chronofunctions were developed using the surface ages reported earlier. Three chronofunction models were utilized: (1) linear (untransformed data); (2) single logarithmic (soil property data are log-transformed); and (3) logarithmic (both surface age and soil property data are log-transformed) (Bockheim 1980).

RESULTS AND DISCUSSION

Physical Properties

Data on coarse fragment and sand contents support the general notion of parent material uniformity among pedons. The five pedons generally have coarse fragment contents below 3% (wt wt^{-1}) in the solum. Except for the Nipissing Bfj2 horizon, the only horizons with higher coarse fragment contents are below the solum (Table 1). All horizons contain greater than 92% sand; medium sand is the modal size fraction in all subhorizons. Fine sand makes up a relatively larger component of the Algoma-1, Battlefield, and Main Algonquin (hereafter referred to as "Algonquin") pedons, while coarse sand is prominent in the Nipissing pedon (Table 1). Despite slight differences in particle size distribution, the depositional environments for the parent materials of these pedons were probably uniform. Although the Algoma pedons are underlain by a deposit of calcareous coarse sands and boulders (as exemplified by the Algoma-2 IIC horizon), based on field observations and proximity, the parent materials for all pedons in the study area were not calcareous and were of similar, quartz-rich mineralogy.

Maximum silt content is found in near-surface horizons, and decreases gradually with depth (Table 1). The percentage of silt in the near-surface horizons increases with surface age, suggesting that silt may have accumulated in these horizons with time. Depth functions of the very fine sand fraction are similar to the silt depth functions in some pedons (e.g., Battlefield, Algonquin), although not as pronounced.

Sandy podzolic soils with relatively high silt contents in the surface horizons have been reported elsewhere (Jauhiainen 1973; Nørnberg 1977, 1980; Protz et al. 1984), although the mechanism(s) that produce such distributions have not been well studied. Protz et al. (1984) and Nørnberg (1977, 1980) suggested that silt-rich surface horizons are the result of in situ physical weathering of sand to silt-sized particles in upper horizons, such that surface horizon silt content increases with soil age. Jauhiainen (1973), however, felt that silt-enriched surface horizons were best attributed to eolian inputs. Neither hypothesis can be discounted for our study.

Chemical Properties

Organic C contents of the surface horizons show no discernible trend with age (Table 2). Subsurface OC and ODOE maxima are found in the upper B horizons of the Battlefield and Algonquin pedons, but are absent in the Nipissing and Algoma pedons. In the Battlefield pedon, however, the ODOE of the Bfj2 horizon (0.223) is much greater than that of the Bfj1 (0.090), despite the fact that the OC contents of the Bfj1 and Bfj2 horizons are alike (0.8%). The ODOE distribution, therefore, does not appear to mirror the OC distribution. Because the ODOE test was designed to indicate the presence of fulvic acids (Daly 1982), the high ODOE of some horizons would suggest that fulvic acids, which may be important in the translocation of Fe and Al in Spodosols (DeConinck 1980), are abundant in ortstein-rich horizons. The magnitude of the subsurface ODOE maximum increases with surface age, suggesting increasing amounts of fulvic acids in B horizons with time. ODOE maxima apparently coincide with the horizons containing the largest and most strongly cemented ortstein fragments (Table 1). A similar association of fulvic acids with ortstein in Florida was attributed to the greater reactivity of fulvic acids as opposed to humic acids (Lee et al. 1988).

Depth functions for extractable Fe and Al indicate that these elements have been translocated from the upper horizons to the B horizon (Table 2; Fig. 2). B horizon maximum values and B-E differences for Fe and Al are generally lacking in the two Algoma pedons, but increase with surface age for soils on the remaining three surfaces, except that the Al maximum in the Bfj2 horizon of the Algonquin pedon is less than the corresponding maximum for the Bfj2 horizon of the Battlefield pedon. Although depth function patterns for extractable Al are similar to those for Fe, the Al maxima occur slightly deeper than do the Fe maxima (Fig. 2). Fe maxima are found in the uppermost B subhorizon (Nipissing Bfj1, Battlefield Bfj1, and Algonquin Bfj1) on the three oldest surfaces, whereas Al maxima occur in the second B subhorizon (Nipissing Bfj2, Battlefield Bfj2, and Algonquin Bfj2). Al maxima that occur deeper than Fe maxima have been reported for podzols in the USA (Franzmeier and Whiteside 1963b), Japan (Mizota 1982), Finland (Koutaniemi et al. 1988), and Quebec (DeKimpe and Martel 1976; Kodama and Wang 1989). This trend may occur because Al is more mobile than Fe, and thus initially deposited at greater depth (Mizota 1982), or because the Al is preferentially remobilized after deposition and translocated still deeper (DeKimpe and Martel 1976). Higher Al mobility may also account for the slight increase in C horizon Al content with surface age (Table 2). Small amounts of relatively colorless Al may be translocated deeper than is Fe, forming a horizon below the solum, slightly enriched in Al, that may be interpreted as a C horizon (Koutaniemi et al. 1988). For sandy Spodosols, laboratory criteria may consistently place the B-C horizon boundary deeper than color and other field-based morphologic attributes would indicate (Schaetzl 1987, p. 147). Thus the upper C horizon, as determined in the field, could actually exhibit small accumulations of Al.

The accumulation of Al, along with OC, in the B horizon is important to the identification of spodic materials; Fe accumulation is often also a characteristic feature of spodic horizons (Soil Survey Staff 1988). The three different Fe and Al extractants used in the present study, citrate–bicarbonate–dithionite

Table 2. Chemical properties of the five pedons

Horizon	pH (2:1 H_2O)	OC	Fe_d	Al_d	Fe_p	Al_p	Fe_o	Al_o	ODOE	$(Fe_o-Fe_p)/Fe_p$	$(Al_o-Al_p)/Al_p$	Fe_o/Fe_d	Al_o/Al_d
					(g kg^{-1})								
							Algoma-1						
Ae	4.8	7	1.4	0.3	0.8	0.2	1.2	0.4	0.13	0.5	1.0	0.9	1.3
Bfj	5.8	1	0.5	0.1	0.1	0.1	0.2	0.2	0.02	1.0	1.0	0.4	2.0
C	6.5	1	0.3	0.0	0.0	0.0	0.1	0.2	0.01	n.d.	n.d.	0.3	n.d.
IIAb	7.2	3	0.3	0.1	0.0	0.1	0.1	0.2	0.06	n.d.	1.0	0.3	2.0
IIC	7.5	0	0.4	0.0	0.0	0.0	0.2	0.2	0.06	n.d.	n.d.	0.5	n.d.
							Algoma-2						
Ae	5.2	2	0.6	0.1	0.1	0.1	0.3	0.1	0.02	2.0	0.0	0.5	1.0
Bfj	5.9	1	0.5	0.1	0.1	0.1	0.1	0.2	0.01	0.0	1.0	0.2	2.0
C	6.5	0	0.5	0.0	0.0	0.1	0.1	0.1	0.00	n.d.	0.0	0.2	n.d.
IIC	7.6	3	0.8	0.1	0.1	0.1	0.1	0.1	0.01	0.0	0.0	0.1	1.0
							Nipissing						
Ah	4.3	20	0.7	0.3	0.2	0.2	0.3	0.5	0.05	0.5	1.5	0.4	1.7
Ae1	4.8	2	0.6	0.1	0.0	0.1	0.1	0.2	0.01	n.d.	1.0	0.2	2.0
Ae2	5.1	1	0.8	0.1	0.1	0.1	0.3	0.2	0.03	2.0	1.0	0.4	2.0
Bfj1	5.0	1	1.2	0.4	0.3	0.3	0.7	0.7	0.02	1.3	1.3	0.6	1.8
Bfj2	5.2	1	1.3	0.7	0.2	0.5	0.9	2.3	0.02	3.5	3.6	0.7	3.3
Bfj3	5.2	1	0.8	0.4	0.2	0.3	0.4	0.9	0.02	1.0	2.0	0.5	2.3
BC	5.8	1	0.9	0.5	0.1	0.3	0.5	1.3	0.02	4.0	3.3	0.6	2.6
C	6.6	0	0.8	0.2	0.1	0.1	0.2	0.4	0.01	1.0	3.0	0.3	2.0
							Battlefield						
Ah	4.0	18	0.6	0.2	0.1	0.1	0.2	0.3	0.04	1.0	2.0	0.3	1.5
Ae1	4.3	3	0.4	0.1	0.0	0.0	0.1	0.1	0.01	n.d.	n.d.	0.3	1.0
Ae2	4.4	5	1.3	0.3	0.4	0.2	0.7	0.5	0.05	0.8	1.5	0.5	1.7
Bfj1	4.8	8	2.8	1.9	1.2	1.2	2.3	3.6	0.09	0.9	2.0	0.8	1.9
Bfj2	5.0	8	1.9	2.9	0.6	1.7	1.4	5.6	0.22	1.3	2.3	0.7	1.9
Bfj3	5.0	4	1.1	1.5	0.2	0.8	0.6	3.1	0.04	2.0	2.9	0.6	2.1
BC	5.4	1	0.6	0.9	0.1	0.6	0.4	2.0	0.02	3.0	2.3	0.7	2.2
C1	5.4	1	0.4	0.5	0.1	0.4	0.3	1.3	0.01	2.0	2.3	0.8	2.6
C2	5.5	1	0.3	0.3	0.1	0.2	0.2	0.7	0.01	1.0	2.5	0.7	2.3
							Algonquin						
Ah	4.5	22	1.1	0.3	0.2	0.2	0.3	0.3	0.04	0.5	0.50	0.3	1.0
Ae	4.6	3	1.0	0.1	0.1	0.1	0.3	0.1	0.01	2.0	0.00	0.3	1.0
Bfj1	5.4	8	3.8	1.5	1.3	0.9	3.2	2.8	0.28	1.5	2.11	0.8	1.9
Bfj2	5.6	4	2.0	1.8	0.6	1.0	1.7	3.3	0.10	1.8	2.30	0.9	1.8
Bfj3	5.8	2	0.8	0.8	0.2	0.6	0.7	1.9	0.04	2.5	2.17	0.9	2.4
BC	5.9	1	0.6	0.3	0.1	0.3	0.2	0.9	0.02	1.0	2.00	0.3	3.0
C	6.1	1	0.5	0.3	0.1	0.3	0.3	0.8	0.02	2.0	1.67	0.6	2.7

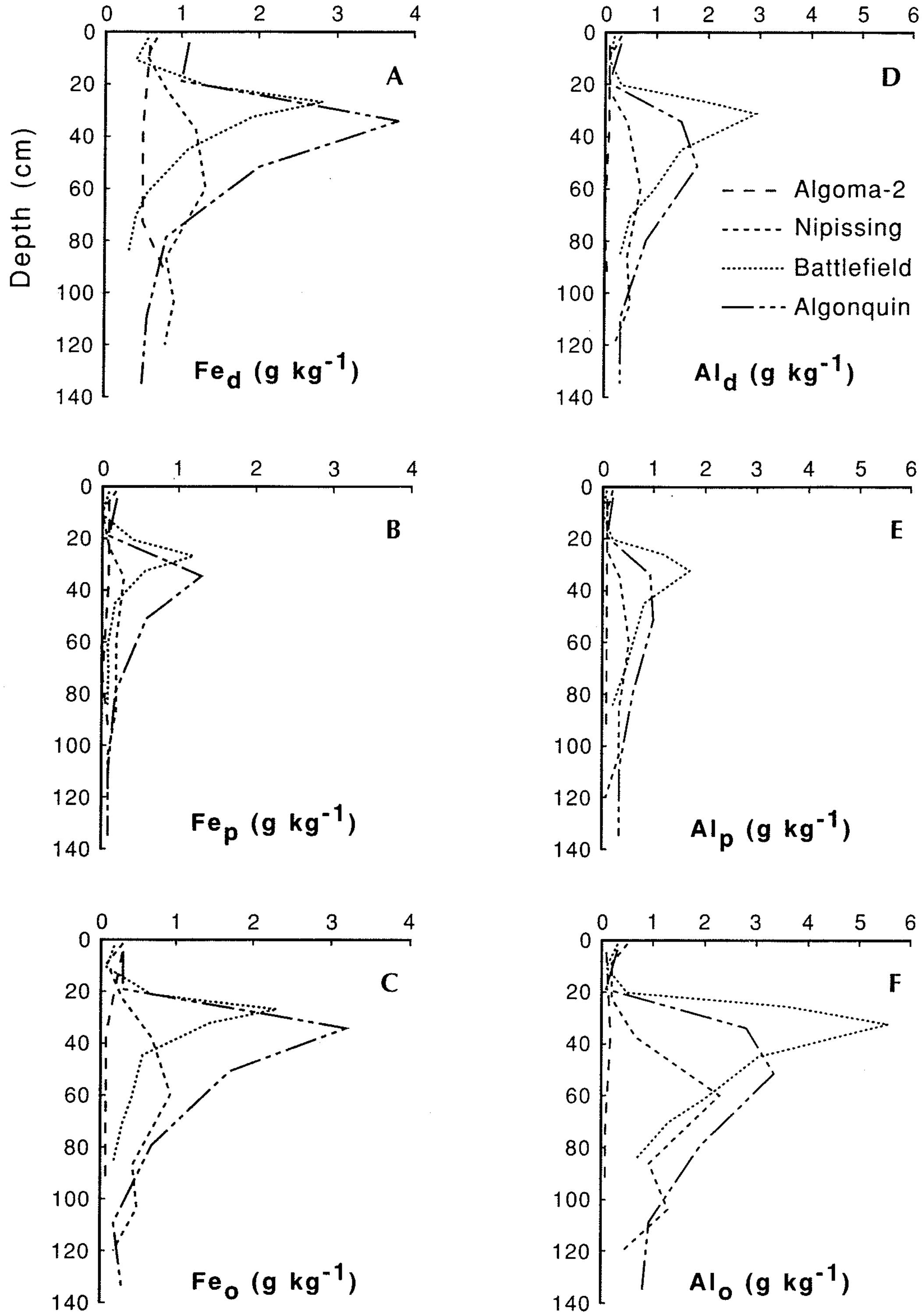

Fig. 2. Fe and Al depth functions for the pedons studied.

(CBD), Na pyrophosphate, and acid ammonium oxalate, attack different forms of the Fe and Al present in the soil (McKeague 1978). Relationships of Fe and Al among the various extractants for all horizons are: $Fe_d > Fe_o \geq Fe_p$ and $Al_o \geq Al_d \geq Al_p$ (Table 2).

Combinations or ratios of extractable Fe and Al data can be used to infer pedogenic processes. The ratio Fe_o/Fe_d has been called an "activity ratio" and was used as a relative measure of the crystallinity of free iron oxides by Blume and Schwertmann (1969). Low Fe_o/Fe_d ratios indicate a large proportion of crystalline Fe oxide compounds (Singer et al. 1978); higher ratios (0.3 - 1.19, with a mean of 0.87) suggest low crystalline oxyhydroxide content (Evans and Wilson 1985). Fe_o/Fe_d values for the pedons in the present study are within 0.2 - 0.9, suggesting that much of the Fe content is in noncrystalline forms. The Nipissing, Battlefield, and Algonquin pedons have Fe_o/Fe_d ratio depth functions quite typical of Podzols (Blume and Schwertmann 1969). The magnitude of this Bf_{max}, which is absent in the Algoma pedons, increases with surface age. The fact that the maximum Fe_o/Fe_d values occur in the Bfj horizons indicates that a substantial proportion of the Fe present in illuvial horizons is amorphous. The Al_o/Al_d ratio depth functions mirror those of Fe_o/Fe_d, although the values of the ratios are much higher (Table 2). The proper interpretation for the Al_o/Al_d ratio is unclear, however, due to the uncertainty of the exact source of the Al extracted by these reagents.

Ratios of inorganic amorphous to organic amorphous iron $[(Fe_o - Fe_p)/Fe_p]$ and aluminum $[(Al_o - Al_p)/Al_p]$ in the B horizons of some Spodosols have been used to indicate whether amorphous Fe and Al species are in predominantly organic or inorganic form (Wang et al. 1986). In the present study, these ratios are generally <1 in eluvial horizons, and increase with depth (Table 2). Although the values of these ratios are not large (Wang et al. 1986), a substantial proportion of the amorphous Fe and Al in the B horizons of these pedons is apparently not organically bound.

Chronofunctions

We compared soil properties between pedons using the sum of the mean values for the horizons, weighted for horizon thicknesses in cm. Profile organic C and most profile Fe and Al data are positively correlated with surface age; however, neither pH nor ODOE showed a statistically significant relationship (at $P < 0.05$) to surface age (Table 3). A chronofunction for profile-weighted Fe_p, shown as an example of a significant ($P < 0.05$) regression equation, is presented in Fig. 3A. Of the three models used, the single logarithmic model appears to provide the best overall results, in terms of significance level and the amount of explained variability (adj. r^2). Nevertheless, the results from all three models are often significant at $P < 0.05$.

Because the concentrations of Fe, Al, and OC data change more predictably with age in the B horizon than in other horizons, weighted B horizon means should more closely reflect changes in soil development than weighted profile means. Weighted B horizon means, when regressed against surface age, yield significant equations for all Fe, Al, and OC properties studied and for all models attempted (Table 3). Fe_p shows an especially good fit (Fig. 3). Levels of statistical significance and r^2 values for equations derived from weighted B horizon means were higher than for the equations derived from corresponding weighted profile means, except for OC, where the weighted profile mean is probably most sensitive to surface (Ah horizon) OC concentrations.

The five pedons were evaluated on four separate indices of soil development (Table 4). The IPA, mIPA, and K_{Al} indices were developed to measure the degree of profile anisotropy with regard to particular soil properties; the K_{Al} was developed specifically for podzolic soils (Walker and Green 1976; Duchaufour and Souchier 1978). For the pedons studied here, the index values for the IPA and mIPA are similar, and, when regressed against surface age, yield similar equations (Table 4). Both the IPA and mIPA values for Fe_d, Al_d, Fe_o, and Al_o resulted in statistically significant equations, as did the IPA of Al_p and OC, indicating that profile anisotropy (for these soil properties) increases with soil age. The regression of IPA for Fe_d exhibits a significant linear relationship with

Table 3. Chronofunction data for plots of weighted profile properties and weighted B horizon properties vs. surface age (X)

	OC (g kg^{-1})	ODOE	pH	Fe$_d$	Al$_d$	Fe$_p$	Al$_p$	Fe$_o$	Al$_o$
				(g kg^{-1})					
				Weighted profile properties					
Model 1[z]									
a	0.026	0.014	6.37	0.047	−0.011	−0.0042	−0.0055	0.0092	−0.01
b	0.00032	0.0000031	−0.000087	0.0000053	0.0000086	0.0000021	0.0000053	0.0000056	0.000017
adj r^2	0.98***	0.36	0.22	0.45	0.84*	0.90**	0.83*	0.67	0.75*
Model 2									
a	−1.44	−1.12	10.85	−0.21	−0.42	−0.093	−0.20	−0.26	−0.81
b	0.19	0.018	−0.10	0.034	0.054	0.013	0.034	0.035	0.11
adj r^2	0.97**	0.31	0.32	0.51	0.90**	0.92**	0.89**	0.71*	0.82*
Model 3									
a	−9.04	−9.13	2.60	−6.36	−18.71	−10.85	−23.05	−11.29	−15.96
b	0.86	0.65	−0.10	0.44	1.76	0.78	2.18	0.93	1.54
adj r^2	0.98***	0.26	0.32	0.51	0.75*	0.88*	0.38	0.55	0.68
				Weighted B horizon properties					
Model 1									
a	−0.70	−0.015	n.d.	0.023	−0.04	−0.0038	−0.012	−0.013	−0.051
b	0.000053	0.0000097	n.d.	0.000014	0.000018	0.0000051	0.0000097	0.000013	0.000034
adj r^2	0.78*	0.99***	n.d.	0.85*	0.85*	0.98***	0.86*	0.86*	0.77*
Model 2									
a	−2.54	−0.46	n.d.	−0.63	−0.89	−0.24	−0.48	−0.65	−1.70
b	0.33	0.059	n.d.	0.087	0.110	0.032	0.061	0.084	0.22
adj r^2	0.79*	0.96**	n.d.	0.91**	0.89*	0.99***	0.91**	0.90**	0.85*
Model 3									
a	−12.92	−15.25	n.d.	−9.80	−20.36	−14.36	−17.12	−16.42	−19.02
b	1.31	1.38	n.d.	0.87	2.00	1.23	1.60	1.56	1.94
adj r^2	0.90**	0.98***	n.d.	0.82*	0.85*	0.96**	0.82*	0.70*	0.73

[z] Regression models:
1. (Linear) $Y = a + bX$;
2. (Single logarithmic) $Y = a + (b \ln X)$;
3. (Logarithmic) $\ln Y = a + (b \ln X)$.

*,**,*** Significant at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively.

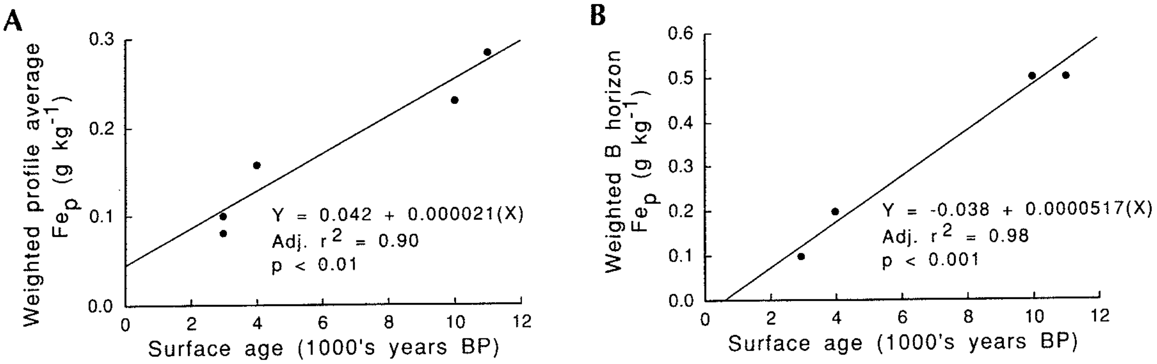

Fig. 3. Fe_p as a function of surface age. (A) Weighted profile mean Fe_p. (B) Weighted B horizon mean Fe_p.

surface age, having the highest r^2 value of those examined (Fig. 4A). The K_{AI} chronofunctions are also statistically significant (Table 4; Fig. 4B), further confirming the increasing anisotropy of the soils. The POD Index (Schaetzl and Mokma 1988) was developed for Spodosols; POD Index values increase non-linearly with time (Fig. 4C). The exponential relationship of this index with time has been demonstrated for other Michigan Podzols (Schaetzl and Mokma 1988).

The high proportion of statistically significant chronofunctions derived from weighted profile averages, weighted B horizon averages, and soil development indices (Tables 3 and 4) indicate that the soil properties and morphologies examined vary systematically with surface age; most such trends can be described adequately with linear or logarithmic functions.

Several regression equations have a negative value for the *y*-intercept (Tables 3 and 4). This feature can be explained by any of three possible scenarios: (1) The implication of such a chronofunction is that at *X* (time) = 0, the soil property might have had a negative value. Because in most cases these soil properties (e.g., Fe content) cannot take on a negative value, the negative *y*-intercept value probably indicates that soil development does not proceed in a strictly linear or logarithmic manner, and that extrapolation of these functions linearly backward from $X = 3000$ (Algoma) to $X = 0$ is not valid. The line described by the regression equation may be an approximation of a curve that is nearly linear over the range $X = 3000$ to $X = 11\,000$ (Richardson and Edmonds 1987), but is strongly curvilinear from $X = 0$ to $X = 3000$. (2) Alternatively, as with many index values, the negative *y*-intercept may imply that development of the soil property was delayed due to necessary preconditioning of the parent materials (the index value remained zero until the soil had developed for a period of time, e.g., Fig. 4A,B). (3) Step-wise soil development due to intrinsic or extrinsic thresholds (Muhs 1984) may result in negative *y* intercept values.

Use of chronofunctions has become increasingly common since Bockheim's (1980) study, but no one regression model has proven to be superior for all soil properties. Instead, most researchers have found that more than one model may fit the data (e.g., Birkeland 1984; James 1988; Bockheim 1990). Of the three regression models attempted, the single logarithmic model ($Y = a + b \ln X$) provided significant equations most often. Bockheim (1980) also found that the single logarithmic model most consistently yielded the highest correlation coefficients.

SOIL CLASSIFICATION

The five pedons were classified according to the Canadian system of soil classification (Canada Soil Survey Committee 1978), Soil Taxonomy (Soil Survey Staff 1988), and a significant revision to the Soil Taxonomy

Table 4. Chronofunction data for plots of soil development indices (Y) vs. surface age (X)

		OC	ODOE	pH	Fe_d	Al_d	Fe_p	Al_p	Fe_o	Al_o
		(g kg^{-1})					(g kg^{-1})			
						Index of Profile Anisotropy (IPA)				
Model 1^z										
	a	0.08	0.0012	0.80	−0.032	−0.0060	0.0029	−0.0072	−0.0031	−0.025
	b	0.000031	0.0000046	−0.000027	0.0000069	0.0000067	0.0000023	0.0000042	0.0000064	0.000014
	adj r^2	0.78*	0.53	0.33	0.92**	0.72*	0.55	0.79*	0.77*	0.77*
Model 2										
	a	−1.41	−0.20	2.11	−0.32	−0.33	−0.10	−0.20	−0.29	−0.71
	b	0.20	0.027	−0.17	0.042	0.043	0.014	0.026	0.038	0.091
	adj r^2	0.82*	0.46	0.40	0.89*	0.80*	0.50	0.83*	0.73*	0.85*
Model 3										
	a	−8.17	−13.81	1.86	−13.30	−18.93	−13.25	−14.43	−14.09	−22.95
	b	0.79	1.16	−0.27	1.15	1.76	1.04	1.20	1.22	2.27
	r^2	0.65	0.33	0.40	0.74*	0.60	0.32	0.90*	0.55	0.71*
						Modified Index of Profile Anisotropy (mIPA)				
Model 1										
	a	0.075	0.0095	1.07	−0.011	−0.88	0.0053	−0.0051	−0.0014	−0.028
	b	0.000038	0.0000039	−0.000036	0.0000089	0.0000065	0.0000019	0.0000038	0.0000059	0.000014
	adj r^2	0.75	0.41	0.00	0.93**	0.81*	0.63	0.69	0.83*	0.77*
Model 2										
	a	−1.75	−0.16	2.47	−0.41	−0.32	−0.08	−0.19	−0.27	−0.72
	b	0.24	0.023	−0.19	0.054	0.041	0.011	0.024	0.036	0.091
	adj r^2	0.82*	0.35	0.00	0.88*	0.84*	0.55	0.75*	0.83*	0.83*
Model 3										
	a	−8.93	−11.06	1.69	−14.90	−16.19	−10.04	−13.29	−14.42	−25.25
	b	0.89	0.87	−0.22	1.33	1.44	0.68	1.07	1.26	2.52
	adj r^2	0.64	0.27	0.00	0.75*	0.91**	0.43	0.82	0.52	0.71*
						Duchaufour-Souchier Index (K_{Al})^y				
Model 1										
	a					−1.35				−1.28
	b					0.00086				0.0010
	adj r^2					0.75*				0.80*

Model 2		
a	−42.22	−51.56
b	5.40	6.63
adj r^2	0.79*	0.87*
Model 3		
a	−12.26	−12.78
b	1.55	1.63
adj r^2	0.91**	0.78*

[z] Regression models used:
1. (Linear) $Y = a + bX$;
2. (Single logarithmic) $Y = a + (b \ln X)$;
3. (Logarithmic) $\ln Y = a + (b \ln X)$.

[y] The Duchaufour-Souchier Index only uses amounts of Al in its calculation.

*, **, Significant at $P < 0.05$ and $P < 0.01$, respectively.

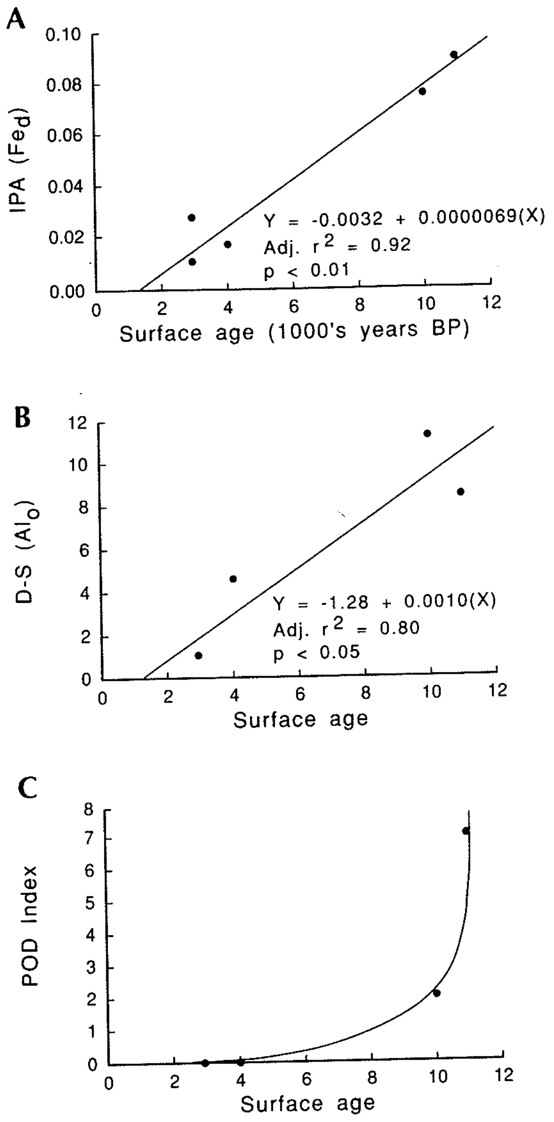

Fig. 4. Chronofunctions for indices of soil development. (A) Index of Profile Anisotropy (IPA) for Fe_d. (B) $K_{Al}(Al_o)$. (C) POD Index (hand-drawn curve).

system (Soil Survey Staff 1992; Table 5). Although all five pedons failed to classify as Podzols under the Canadian system, pedons on the two oldest surfaces met the criteria for the Spodosol order. Therefore, at least 4000, but less than 10 000, years are required for the development of a spodic horizon in Michigan, which compares favorably to the findings of Franzmeier and Whiteside (1963a,b).

Table 5. Classification of the five pedons according to the Canadian system of soil classification (Canada Soil Survey Committee 1978), Soil Taxonomy (Soil Survey Staff 1988), and a proposed revision to the Soil Taxonomy system (Soil Survey Staff 1992)

Pedon	Canadian	Soil taxonomy	Revised soil taxonomy
Algoma-1	Eutric Brunisol	Typic Udipsamment	Typic Udipsamment
Algoma-2	Eutric Brunisol	Typic Udipsamment	Typic Udipsamment
Nipissing	Dystric Brunisol	Spodic Udipsamment	Typic Udipsamment
Battlefield	Dystric Brunisol	Entic Haplorthod	Entic Haplorthod
Algonquin	Dystric Brunisol	Typic Haplorthod	Typic Haplorthod

CONCLUSIONS

Soil development was investigated on four geomorphic surfaces in Michigan, USA, which ranged in age from 3000 to 11 000 BP. The modal soils on the surfaces varied from Eutric Brunisols to Dystric Brunisols (Typic Udipsamments to Typic Haplorthods). The profile distributions of OC and extractable Fe and Al with depth indicated active podzolization processes. Increasing amounts of these substances had become translocated with soil age. The majority of the Fe and Al translocated in these soils appeared to be amorphous; a substantial proportion of the amorphous sesquioxides in the illuvial horizons may not have been organically bound. The single logarithmic chronosequence model appeared to provide the best regressions, but the simple linear model and the logarithmic model also provided satisfactory results. Negative y-intercept values for many of the chronofunctions (e.g., those for weighted profile Fe and Al content) indicate that either a non-linear chronofunction model would be superior or that development of the specific soil property occurred only after an initial period of soil pre-conditioning.

ACKNOWLEDGMENTS

We thank D. L. Mokma for providing laboratory facilities and for comments on a draft of this paper. D. P. Lusch and J. R. Harman gave advice and comments at earlier stages of the investigation. Cartographic work was supplied by the Center for Cartographic Research and Spatial Analysis, Dept. of Geography, Michigan State University.

Birkeland, P. W. 1984. Holocene soil chronofunctions, Southern Alps, New Zealand. Geoderma **34**: 115–134.

Blume, H. P. and Schwertmann, U. 1969. Genetic evaluation of profile distribution of aluminum, iron, and manganese oxides. Soil Sci. Soc. Am. Proc. **33**: 438–444.

Bockheim, J. G. 1980. Solution and use of chronofunctions in studying soil development. Geoderma **24**: 71–85.

Bockheim, J. G. 1990. Soil development rates in the Transantarctic Mountains. Geoderma **47**: 59–77.

Canada Soil Survey Committee. 1978. The Canadian system of soil classification. Research Branch, Canada Department of Agriculture, Ottawa, ON. Publ. 1646. 164 pp.

Daly, B. K. 1982. Identification of Podzol and Podzolized soils in New Zealand by relative absorbance of oxalate extracts of A and B horizons. Geoderma **28**: 29–38.

DeConinck, F. 1980. Major mechanisms in formation of spodic horizons. Geoderma **24**: 101–128.

DeKimpe, C. R. and Martel, Y. A. 1976. Effects of vegetation on the distribution of carbon, iron, and aluminum in the B horizons of northern Appalachian Spodosols. Soil Sci. Soc. Am. J. **40**: 77–80.

Duchaufour, P. and Souchier, B. 1978. Roles of iron and clay in genesis of acid soils under a humid, temperate climate. Geoderma **20: 15–26.**

Evans, L. J. and Wilson, W. G. 1985. Extractable Fe, Al, Si, and C in B horizons of podzolic and brunisolic soils from Ontario. Can. J. Soil Sci. **65**: 489–496.

Franzmeier, D. P. and Whiteside, E. P. 1963a. A chronosequence of Podzols in Northern Michigan. I. Ecology and description of pedons. Mich. Q. Bull. **46**: 2–19.

Franzmeier, D. P. and Whiteside, E. P. 1963b. A chronosequence of Podzols in Northern Michigan. II. Physical and chemical properties. Mich. Q. Bull. **46**: 20–36.

Franzmeier, D. P., Whiteside, E. P. and Mortland, M. M. 1963. A chronosequence of Podzols in northern Michigan. III. Mineralogy, micromorphology, and net changes occurring during soil formation. Mich. Q. Bull. **46**: 37–57.

Futyma, R. P. 1981. The northern limits of glacial Lake Algonquin in Upper Michigan. Quarternary Research **15**: 291–310.

Hansel, A. K., Mickelson, D. M., Schneider, A. F. and Larsen, C. E. 1985. Late Wisconsinan and Holocene history of the Lake Michigan basin. Pages 39–53 *in* P. F. Karrow and P. E. Calkin, eds. Geological Association of Canada Special Paper 30, Ottawa, ON.

James, L. A. 1988. Rates of organic carbon accumulation in young mineral soils near Burroughs Glacier, Glacier Bay, Alaska. Phys. Geog. **9**: 50–70.

Jauhiainen, E. 1973. Age and degree of podzolization of sand soils on the coastal plain of northwest Finland. Commentationes Biologicae **68**: 1–32.

Jenny, H. 1941. Factors of soil formation. McGraw-Hill, New York, NY.

Kodama, H. and Wang, C. 1989. Distribution and characterization of noncrystalline inorganic components in Spodosols and Spodosol-like soils. Soil Sci. Soc. Am. J. **53**: 526–534.

Koutaniemi, L., Koponen, R. and Rajanen, K. 1988. Podzolization as studied from terraces of various ages in two river valleys, Northern Finland. Silva Fennica **22**(2): 113–133.

Larsen, C. E. 1985. Lake level, uplift, and outlet incision, the Nipissing and Algoma Great Lakes. Pages 63–77 *in* P. F. Karrow and P. E. Calkin, eds. Geological Association of Canada Special Paper 30, Ottawa, ON.

Lee, F. Y., Yuan, T. L. and Carlisle, V. W. 1988. Nature of cementing materials in ortstein horizons of selected Florida Spodosols: II. Soil properties and chemical form(s) of aluminum. Soil Sci. Soc. Am. J. **52**: 1796–1801.

Leverett, F. and Taylor, F. B. 1915. The Pleistocene of Indiana and Michigan and the history of the Great Lakes. US Geological Survey, Washington, DC. Monogr. 53.

McKeague, J. A. (ed.) 1978. Manual on soil sampling and methods of analysis. Canadian Society of Soil Science, Ottawa, ON.

Mizota, C. 1982. Clay mineralogy of spodic horizons from Cryorthods in Japan. Soil Sci. Plant Nutr. **28**: 257–268.

Muhs, D. R. 1984. Intrinsic thresholds in soil systems. Phys. Geog. **5**: 99–110.

Nornberg, P. 1977. Soil profile development in sands of varying age in Vendsyssel, Denmark. Catena **4**: 165–179.

Nørnberg, P. 1980. Mineralogy of a podzol formed in sandy materials in northern Denmark. Geoderma **24**: 25–43.

Protz, R., Ross, G. J., Martini, I. P. and Terasmae, J. 1984. Rate of Podzolic soil formation near Hudson Bay, Ontario. Can. J. Soil Sci. **64**: 31–49.

Richardson, J. L. and Edmonds, W. J. 1987. Linear regression estimations of Jenny's relative effectiveness of state factors equation. Soil Sci. **144**: 203–208.

Schaetzl, R. J. 1987. The effects of tree-tip microtopography on soil genesis, Northern Michigan. Ph.D. thesis, University of Illinois, Urbana, IL 232 pp.

Schaetzl, R. J., Burns, S. F., Johnson, D. L. and Small, T. W. 1989. Tree uprooting: review of impacts on forest ecology. Vegetatio **79**: 165–176.

Schaetzl, R. J. and Mokma, D. L. 1988. A numerical index of podzol and podzolic soil development. Phys. Geog. **9**: 232–246.

Singer, M., Ugolini, F. C. and Zachara, J. 1978. In situ study of podzolization on tephra and bedrock. Soil Sci. Soc. Am. J. **42**: 105–111.

Singer, M. J. and Janitzky, P. 1986. Field and laboratory procedures used in a soil chronosequence study. USGS Bulletin 1648. US Govt. Printing Office, Washington, DC. 49 pp.

Singleton, G. A. and Lavkulich, L. M. 1987. A soil chronosequence on beach sands, Vancouver Island, British Columbia. Can. J. Soil Sci. **67**: 795–810.

Soil Conservation Service. 1990. Batch acid oxalate extract, inductively coupled plasma spectroscopy of iron, aluminum, manganese, and silicon and optical density of extract. Soil Cons. Service Misc. Report, Version 1. USDA-SCS, Lincoln, NE. 9 pp.

Soil Survey Staff. 1981. Soil Survey Manual. Ch. 4 supplement. USDA-SCS. US Govt. Printing Office, Washington, DC.

Soil Survey Staff. 1988. Keys to soil taxonomy (fourth edition). SMSS Tech. Monograph no. 6. Cornell University, Ithaca, NY.

Soil Survey Staff. 1992. Keys to Soil Taxonomy. 5th ed. SMSS Tech. Monograph no. 19. Pocahontas Press, Blacksburg, VA.

Walker, P. H. and Green, P. 1976. Soil trends in two valley fill sequences. Aust. J. Soil Res. **14**: 291–303.

Wang, C., McKeague, J. A., and Kodama, H. 1986. Pedogenic imogolite and soil environments: Case study of Spodosols in Quebec, Canada. Soil Sci. Soc. Am. J. **50**: 711–718.