SOIL CHARACTERISTICS RELATED TO WEATHERING AND PEDOGENESIS ACROSS A GEOMORPHIC SURFACE OF UNIFORM AGE IN MICHIGAN

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Abstract: Our study explores the range of pedogenic development and near-surface weathering on a large (>250,000 ha) geomorphic surface in northern lower Michigan, via the examination of four typical soils. The surface is associated with proglacial outwash from the Port Huron advance of the Laurentide ice sheet, dated at about 13 ka. In a GIS we determined the four most extensive types of upland soils on this surface, and later sampled them. The range of expression on this outwash plain, when examined pedogenically or from a weathering perspective, is large, but is captured by these four soils. Numerical rankings along a number of pedogenic and weathering axes illustrated the considerable range of development, but they generally were consistent, i.e., rankings for pedogenesis roughly paralleled those for weathering. The most weakly developed soil ranked third or fourth on almost all of the pedogenic and weathering-related parameters, whereas the other three soils exchanged ranks more freely, depending on the parameter being considered. The best developed soils on this surface are located in areas that receive more snowfall and, presumably, had less frequent fires since deglaciation, both of which drive pedogenesis and weathering in this region. Soils on surfaces of uniform age are often used in relative dating applications, by assuming that soil development and weathering are related primarily to surface age. Our study shows that this assumption is violated on large geomorphic surfaces due to the variability of biotic and climatic factors across that surface. Thus, we suggest that the range and variability of soil expression must be considered in all soil chronofunction studies. [Key words: geomorphic surface, soil development, weathering, GIS, chronofunctions.]

INTRODUCTION

One of the most useful ways of examining and analyzing soil data is within a *chronosequence* framework. Chronosequence studies are formulated around a series/group of soils, each on a geomorphic surface of uniform and known age. Among this group of soils, time (soil age) is allowed to vary, while all other soil-forming factors are presumably held constant (Jenny, 1941; Stevens and Walker,

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1970; Yaalon, 1975; Huggett, 1998). That is, between-surface variability in all factors except age is, theoretically, minimized.

When soil data from a chronosequence are plotted against age, with age as the independent variable, the resultant statistical equation is called a chronofunction:

$$S = f\,t\,(\text{time})_{cl,\, o,\, r,\, p\, \ldots} \tag{1}$$

where S is soil, t is time or soil age, cl is climate, o is organisms, r is relief, p is parent material, and the dots represent other, less important and unspecified soil-forming factors. Using this framework, it is possible to determine rates of soil formation, or at the very least glean some insight into how soil morphology and chemistry change over time. Indeed, Bain et al. (1993, p. 276) referred to chronofunctions as "rate-equations of soil formation." Bockheim (1980) summarized many of the published chronofunctions and used those summary data to ascertain if and when some pedogenic processes reached steady-state conditions. In effect, the applications of chronofunctions are myriad.

In a chronofunction, *sensu stricto*, it is assumed that all soil-forming factors other than time are held constant. This is, however, exceedingly difficult to accomplish; there is always some degree of variation in the remaining soil-forming factors. However, chronosequences are usually set up such that the impact of the time factor on soil development so outweighs the other state factors that the effect of time on soil development can be generally determined. In this sense, the other factors amount to statistical "noise." Thus, the variation in the "non-time" factors is always a background issue and a potential error term in chronofunction research. "Noise" is generally due to two causes: (1) the spatial variation, both continuous and discontinuous, that occurs on the geomorphic surface (affecting the parent material and relief factors; Wilding et al., 1965; Drees and Wilding, 1973; Crosson and Protz, 1974; Campbell, 1979; Wilding and Drees, 1983); and (2) the spatio-temporal changes that have occurred in the active soil-forming factors—climate and vegetation. The former condition can often be controlled for through careful site selection (Schellentrager and Doolittle, 1991; Barrett and Schaetzl, 1993), whereas the latter condition is much more difficult to determine and factor into a chronofunction. Climate change and associated vegetational shifts, which vary across time and space, are largely unavoidable.

Phillips (1993, 2001; Phillips et al., 1996) espoused another reason why soils may vary on a given surface, even one that was initially uniform at $\text{time}_{\text{zero}}$: soil development is sensitive to initial conditions and affected by small perturbations, making soils of similar age radically different, even on the same surface. Much of Phillips' reasoning is based in deterministic chaos theory, which focuses on the sensitive dependence of a system on initial conditions and perturbations; even minute differences at some point along a soil's development can lead to increasingly large differences as the system evolves (Huggett, 1998). Soils on a given surface can, therefore, become increasingly variable with time, even if they have all been subject to the same suite of pedogenic factors and exogenous inputs (Ibanez et al., 1990; Barrett and Schaetzl, 1993; Huggett, 1998), because minor perturbations grow and emerge into complex spatial patterns (Phillips et al., 1996). The effects of perturbations are large and long-lived (even if the perturbations themselves are not) because the soil system is *unstable*. Consequently, soils vary both predictably *and* unpredictably on surfaces, and this variability should be factored into chronofunctions, or at least considered when chronofunctions are interpreted (Barrett and Schaetzl, 1993; Eppes and Harrison, 1999).

In this study, we examined four soils that span the range of development on a relatively young, sandy, upland geomorphic surface in Michigan. The purpose of our study was to examine the degree of variation in pedogenesis and weathering on this surface, as indicated by four typifying pedons. In so doing, we hope to assist those who develop and use chronofunctions by heightening their awareness of the potential variation in pedologic development and weathering across geomorphic surfaces. We will also discuss the possible drivers for the wide variety of pedogenic and weathering expression on this surface.

STUDY AREA

We studied four soils on a geomorphic surface associated with the Port Huron readvance of the Laurentide ice sheet in Kalkaska County in northwestern lower Michigan (Fig. 1). The four sampled soils (hereafter named sites 1 through 4) are located on well-drained sites on the dry, Port Huron outwash apron, dated at ca. 13 ka by radiocarbon (Blewett, 1991; Blewett et al., 1993; Blewett and Winters, 1995; Schaetzl and Weisenborn, 2004). Use of these sites enabled us to hold surface/sediment age, drainage/wetness, and texture of the parent material relatively constant.

The soils in this region, by virtue of their coarse textures; cool, snowy climate; and mixed coniferous-deciduous vegetation, are strongly influenced by podzolization (Messenger et al., 1972; Barrett and Schaetzl, 1992; Lundström, van Breemen, and Bain, 2000; Lundström, van Breemen, Bain, et al., 2000). In podzolization, infiltrating water containing dissolved organic acids drives translocation of Al, organic carbon, and Fe from the E to B (Bh, Bhs, and Bs) horizons. In this region, strong podzolization leads to the formation of soils that eventually may classify as Spodosols, with some variant on O-A-E-Bhs-Bs-BC-C horizonation (Schaetzl and Isard, 1991; Soil Survey Staff, 1999). If present, carbonates in the parent material must be weathered and leached from the system before podzolization, and certain types of chemical weathering, can proceed.

Climate and vegetation intricately co-vary across this landscape, and thus we were unable to hold these two pedogenic factors constant across all four sites (Mokma and Vance, 1989; Schaetzl, 2002). Across even short distances, notable changes in macroclimate occur, due to the narrow-but-intense lake effect snowbelt of Lake Michigan that lies 30–70 km inland. Among the four study sites, the amount of snowfall is highly predictable: 4 > 3 > 2 > 1 (Eichenlaub et al., 1990; Mikesell et al., 2004). Increased snowfall strengthens podzolization because it increases the number and size of slow, steady, and prolonged infiltration events (during snowmelt), thereby facilitating weathering, leaching, and translocation of Al, organic matter, and Fe (Schaetzl and Isard, 1991, 1996). Additionally, soil under deep snow cover is less likely to freeze and thus stays permeable throughout the winter and

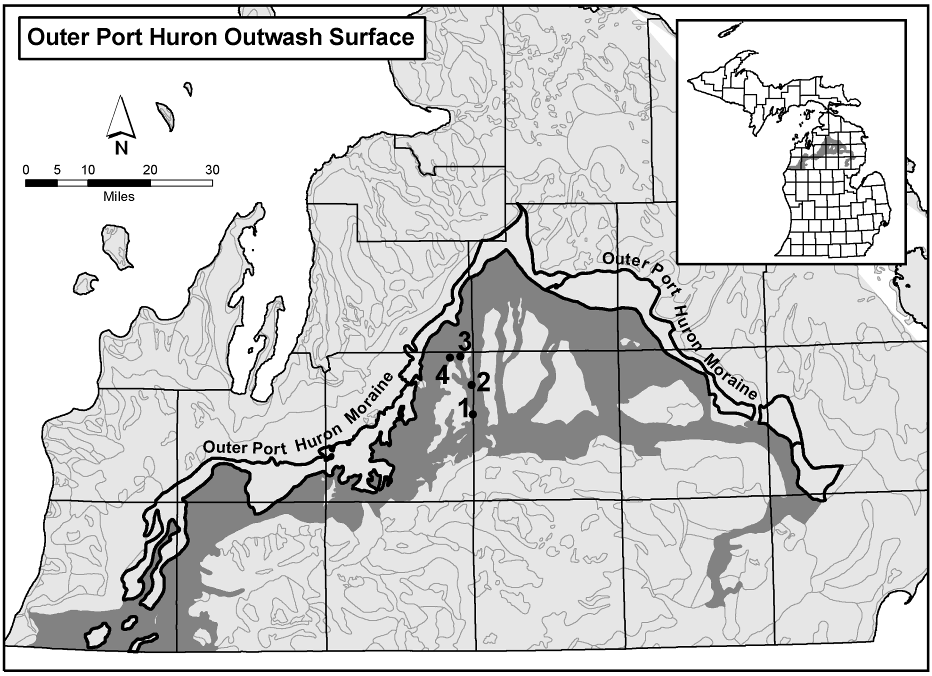

Fig. 1. The extent of the outwash plain of the Port Huron moraine in northern Michigan. To make this map, we liberally included all surfaces that could have received meltwater during the Port Huron advance. This surface is, presumably, of uniform age across the region. Also shown are the locations of the four soil pits; site numbers refer to these site names used in the text: (1) Grayling; (2) Weak Rubicon; (3) Strong Rubicon; (4) Kalkaska. Thin lines on the map reflect minor landform subdivisions, based on Farrand and Bell (1982). The polygon with the thick outline is the outer Port Huron moraine.

spring when podzolization is potentially most intense (Schaetzl and Isard, 1991; Isard and Schaetzl, 1995, 1998).

In the study area, snowfall is heaviest in the western, and topographically highest, areas. Areas in the east receive much less snowfall (Fig. 1). Inversely paralleling the snowfall gradient is a floristic trend, from an open, xeric, fire-prone jack pine (*Pinus banksiana*) stand at site 1, to white (*Pinus strobus*) and red pine (*Pinus resinosa*) stands at sites 2 and 3, to a northern hardwood stand with sugar maple (*Acer sachharum*), white pine, hemlock (*Tsuga canadensis*), and yellow birch (*Betula allegeniensis*) at site 4 (Schaetzl, 2002; Mikesell et al., 2004). Thus, although we chose our sites so as to minimize climate and floristic variation, these two factors do change predictably across our geomorphic surface, as they do on many other large geomorphic surfaces (Mokma and Vance, 1989; Schaetzl, 2002).

The soil at site 4 is the best developed soil—a medial Spodosol—and classifies within the Kalkaska series (Typic Haplorthods). Sites 2 and 3 both are within intermediately developed Spodosols, classifying within the Rubicon series (Entic Haplorthods); the soil at site 3 was better developed, and thus we named sites 2 and 3 “Weak Rubicon” and “Strong Rubicon,” respectively. The soil with the weakest development on the outwash surface is an Entisol, classifying within the Grayling (Typic Udipsamments) series (site 1; Mikesell et al., 2004).

METHODS

Field Methods and Physical Characterization

We selected four sites that spanned the extent of soil development on the Port Huron outwash surface. At each of these sites a large backhoe pit was opened and the soil profile described and sampled according to standard procedures (Soil Survey Division Staff, 1993). Coarse fragments (> 2 mm dia.) were removed from each air-dry sample by sieving, resulting in a sample containing only the fine earth fraction (<2 mm). Two passes through a sample splitter resulted in a well-mixed, 1 kg sample, which was used for subsequent analyses. Soil pH (2:1 soil:water slurry) was measured with a model #720A Orion pH meter. Particle size analysis was performed by pipette (Soil Survey Laboratory Staff, 1996).

Weathering-Related Methods

We chose to focus on several indicators of weathering in these soils, the first of which is hornblende etching. During the pipette analysis, the fine sand fraction (125–250 um dia.) was captured and placed in a bath of 3% sodium hypochlorite (NaOCl) to remove organic matter, followed by a water rinse and oven-drying. The heavy fraction of the fine sand was separated using a sodium polytungstate solution (specific gravity 2.95 g cm^{-3}). Hornblende particles, with a specific gravity of 2.9–3.3 g cm^{-3} (Blackburn and Dennen, 1988), sank to the bottom of a separatory funnel and were extracted from the lighter minerals.

Natural weathering of hornblende corrodes it in a crystallographically controlled manner, resulting in etch pits on the surface of the mineral and a "sawtooth" or "denticulated" margin on which the "teeth" are parallel to the *z*-axis (Berner et al., 1980; Velbel, 1989; Mikesell et al., 2004; Fig. 2). Amplitudes of the denticulated margins of 300 hornblende grains from each horizon were then determined under a petrographic microscope at 200×. We choose a sample size of 300 grains because it provides adequate confidence limits (Van der Plas and Tobi, 1965). To precisely ascertain the degree of hornblende etching (HE), we directly measured denticulation amplitudes with a graded ocular and assigned each grain to a class based on the scheme of Locke (1979). Classes ranged from 0 to 8, with class breaks every 4 um. Grains that showed no apparent etching were assigned to Class 0; the most severely denticulated grains were in Class 8.

As quartz is a weathering-resistant mineral, we chose as our second index of weathering the ratio of quartz to feldspar (Q/F) grains (Ruhe, 1956). Samples from the fine sand fraction from each horizon were placed in a container and impregnated with epoxy resin. From this resin block, thin sections were cut, acid-etched, and stained with Alizarin red to help distinguish plagioclase from quartz. We then counted 300 quartz and feldspar grains under a petrographic microscope, and summed the plagioclase and K-feldspar counts.

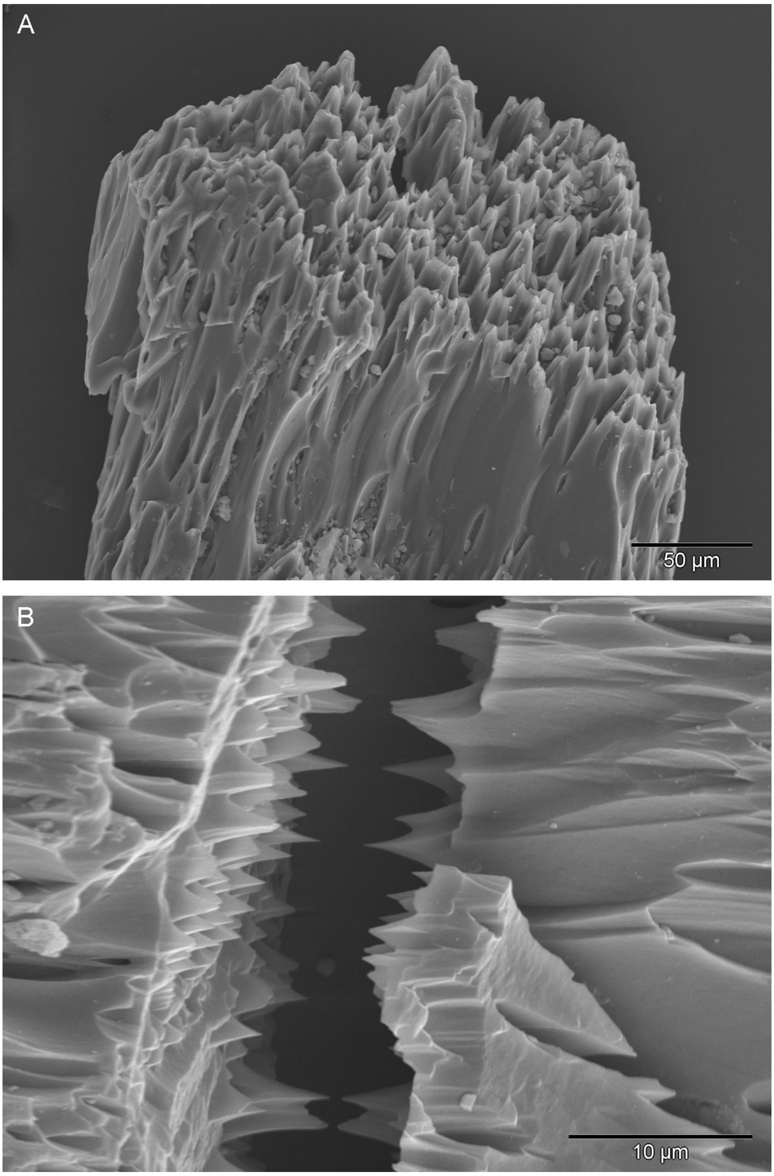

Fig. 2. Scanning electron micrographs of naturally weathered hornblende from Michigan soils. (A) Typical etch pits, denticulated margins, and "teeth" parallel to the long axis (c-axis). (B) Enlarged, lens-shaped etch pits in naturally weathered hornblende grains, representative of an advanced stage of side-by-side coalescence, resulting in denticulations.

Two other indices of weathering were calculated using various elemental indices, as determined by X-ray fluorescence. Samples of the fine sand fraction were first ground to silt size. Three grams of this finely ground powder were then diluted by adding 9.0 g of lithium tetraborate ($Li_2B_4O_7$) and 0.5 g of ammonium nitrate

(NH_4NO_3) as an oxidizer. This mixture was then melted in a platinum crucible at 1000°C of oxidizing flame for >20 minutes while being stirred on an orbital mixing stage. The melt was poured into platinum molds to make glass disks, which were analyzed with an X-ray fluorescent spectrometer. XRF major-element (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P, Rb, Sr, and Zr) analyses were reduced by a fundamental parameter data reduction method, while XRF trace-element data were calculated using standard linear regression techniques. Software for reduction was supplied from Bruker's Spectraplus software. Two soil weathering indices were developed based on the assumption that, with time and increased weathering, elements derived from resistant, immobile minerals such as zircon (Zr) and anatase, rutile, and tourmaline (Ti) increase in abundance relative to elements derived mainly from weatherable minerals, which are assumed to be mobile and translocatable in soils (Ruhe, 1956; Santos et al., 1986). Two weathering indices were therefore calculated by:

$$\text{Weathering Index \#1} = [(\mathrm{Ti} + \mathrm{Zr})/(\mathrm{Ca} + \mathrm{Mg} + \mathrm{K} + \mathrm{Mn} + \mathrm{Na} + \mathrm{P})] \times 100, \quad (2)$$

$$\text{Weathering Index \#2} = [(\mathrm{Ti} + \mathrm{Zr})/(\mathrm{Ca} + \mathrm{Mg} + \mathrm{K} + \mathrm{Mn} + \mathrm{Na} + \mathrm{P} + \mathrm{Rb} + \mathrm{Sr})] \times 100. \quad (3)$$

In addition, an index designed to reflect the degree to which these soils have been podzolized and/or leached was calculated as:

$$\text{Podzolization/Leaching Index} = [(\mathrm{Si} + \mathrm{Ti} + \mathrm{Zr})/(\mathrm{Al} + \mathrm{Fe})] \times 100. \quad (4)$$

Soil Development–Related Methods

Podzolization is expressed chemically as grain coatings on existing minerals, and as the overall depletion of certain minerals and elements from the soil. Therefore, we first wanted to know the types and amounts of the various types of Fe and Al compounds that exist as coatings in our soil samples (McKeague and Day, 1966; McKeague, 1967; Parfitt and Childs, 1988). All samples except those from O horizons were subjected to three extractants: sodium citrate-dithionite (CD), acidified ammonium-oxalate (AAO), and sodium pyrophosphate (PP; Ross and Wang, 1993). CD primarily extracts "free" Fe and Al, denoted by Fe_d and Al_d, from pedogenic oxide minerals (Jackson et al., 1986). AAO extracts "active" Fe and Al (Fe_o and Al_o) from noncrystalline hydrous oxides. The term "active" is given to oxides that are small in size, have a high surface area, and a high degree of reactivity. PP extracts Fe and Al (Fe_p and Al_p) from organically bound complexes and, to a lesser degree, noncrystalline hydrous oxides. The supernatants were analyzed for Fe and Al by Inductively Coupled Plasma Spectrometry (U.S. Environmental Protection Agency, 1986) on a Thermo Jarrell Ash 61 E inductively coupled plasma spectrometer.

In addition to these parameters, we also calculated two different soil development indices, which incorporate several pedogenic parameters into their formulations. Schaetzl and Mokma's (1988) POD Index is a field-based index specifically developed for Spodosols and soils progressing toward that morphology (Goldin and

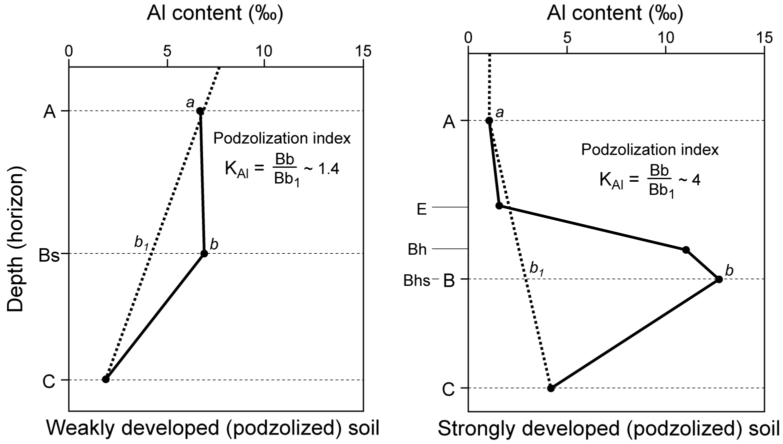

Fig. 3. Graphical representation of the K_{Al} index of Duchaufour and Souchier (1978). The data used in these figures are from fictitious soils, not those studied herein.

Edmonds, 1996; Arbogast and Jameson, 1998; Wilson, 2001; Schaetzl, 2002). It assumes that, as soils develop toward Spodosols, (1) their E horizons get lighter (increase in Munsell value) and get less red (Munsell hue) and (2) their B horizons get thicker and develop more subhorizons, and attain redder hues and lower color values. POD index value increases as soils show greater evidence of podzolization. In contrast to the field-based POD Index, we also calculated Duchaufour and Souchier's (1978) podzolization index for each soil; it is based on laboratory data. Knowing that soils undergoing podzolization lose aluminum from their eluvial zones and gain it in their B horizons, they developed an index to reflect this trend (Fig. 3). To generate the K_{Al} index, the amount of aluminum (in this case, the combined amount of Al_o and Al_p) in the A and C horizons is plotted by depth. A line connecting these two points on the depth plot is drawn, as is a horizontal line at the depth of the Al_{max}. The ratio of two subsets of the horizontal line, as illustrated in Figure 3, is the K_{Al} index, which represents the ratio of translocated to inherited Al in the maximally developed B horizon.

GIS Methods

In order to determine the extent of the various soil series on the Port Huron outwash plain, we first downloaded the all county-level SSURGO soils shapefiles that were available (in March 2005) for this region from the USDA-NRCS. All counties that intersect this surface were available as shapefile coverages except for Manistee and Missaukee (Fig. 1). We defined the Port Huron outwash surface based on the regional surficial geology map (Farrand and Bell, 1982; Fig. 1), and then, using ArcMap software (ESRI, Redlands, CA), we "clipped" the various, county-level soil maps to this outwash polygon to derive a map and database of the soils on the Port Huron outwash plain (Table 1). These data were slightly reconfigured from those that were originally generated in the GIS from the SSURGO databases; we

Table 1. Characteristics and Areal Extent of the Soils Occupying >1% of the Port Huron Outwash Plain[a]

Soil series	Subgroup classification	Extent of Port Huron surface (% of total)	Other information
Grayling	Mixed, frigid Typic Udipsamments	20.3	Dominant, minimally developed sandy soil
Croswell	Sandy, mixed, frigid Oxyaquic Haplorthods	16.0	A moderately well drained Rubicon
Rubicon	Sandy, mixed, frigid Entic Haplorthods	9.7	Dominant, weakly developed Spodosol
Graycalm	Mixed, frigid Lamellic Udipsamments	7.0	Like Grayling but has weak lamellae
Kalkaska	Sandy, mixed, frigid Typic Haplorthods	6.5	Dominant, strongly developed Spososol
Islandlake	Sandy, mixed, frigid Lamellic Haplorthods	5.9	Like Kalkaska, but has lamellae
Au Gres	Sandy, mixed, frigid Typic Endoaquods	4.3	A somewhat poorly drained Rubicon
Ausable	Sandy, mixed, frigid Histic Humaquepts	4.0	Muck over sand
Tawas	Sandy or sandy-skeletal, mixed, euic, frigid Terric Haplosaprists	3.2	Muck over sand or sand + gravel
Leafriver	Sandy, mixed, frigid Histic Humaquepts	2.3	Thin muck over loamy sand
Chinwhisker	Sandy, mixed, frigid Lamellic Oxyaquic Haplorthods	2.0	A moderately well drained Graycalm
Kinross	Sandy, mixed, frigid Typic Endoaquods	1.3	A poorly drained Rubicon
Roscommon	Mixed, frigid Mollic Psammaquents	1.3	A poorly drained Grayling
Dawson	Sandy or sandy-skeletal, mixed, dysic, frigid Terric Haplosaprists	1.2	Muck over sand

[a] See text for the methods used to determine the extent of the soils. Excludes polygons mapped as "water," "access denied," "wind-eroded land," "borrow soils," "gravel pits," and "pits." All the soils listed are within sandy textural families.

eliminated all the deep muck soils from the database, as it is not possible to determine their original, mineral parent material. We also excluded polygons mapped as "water," "access denied," "wind-eroded land," "borrow soils," "gravel pits," and "pits," resulting in a geomorphic surface that covered an area of >250,000 ha.

RESULTS AND DISCUSSION

Areal Extent and Variability of Soils

In the final soil spatial database, when sorted by areal extent, the 21 most widespread soils, which comprise 89.9% of the Port Huron outwash surface, all classify within sandy textural families. Grayling is the dominant soil, areally, occupying 20.3% of the surface (Table 1). Rubicon and its moderately well-drained equivalent, Croswell, are the second and third most common soils, together occupying 25.7% of the outwash surface. Kalkaska is sixth in abundance, while Islandlake soils—like Kalkaska but having subsoil textural bands, are seventh. Indeed, most of the major soils on this surface are either in the Grayling, Rubicon, or Kalkaska soil series, or are part of their catenas (Table 1). It is also important to note that five of the six most extensive soil series on this surface are well drained; only the moderately well drained Croswell is not. Thus, the generally "dry, sandy, upland" character of this geomorphic surface, with its small pockets of Histosols in kettles, so evident in the field, is confirmed by the data in Table 1. Based on these data, we feel justified in choosing these three soils as representative of the upland parts of this geomorphic surface, and in using their pedogenic and weathering characteristics as a surrogate for the soils of the geomorphic surface, in general.

Soil Development

The Port Huron outwash plain is dominated by clean sand parent materials, with small amounts of gravel in certain locales (Tables 1 and 2). The four soils we sampled are typical of this landform (Tables 1 and 2), having formed in nearly uniform sands, with all but one horizon in the "sand" textural class (Soil Survey Division Staff, 1993; Table 2). Medium sand dominates the five sand fractions. Most horizons had no measureable clay, and none had more than 3.5% clay. Thus, the "time," "relief," and "parent material" state factors have been held as constant as possible in this study.

The varying degrees of soil development that exist on this outwash surface, which are largely due to the effects of the "organisms" and "climate" state factors, are summarized in Table 3, as:

$$\text{Kalkaska (\#4)} > \text{Strong Rubicon (\#3)} \approx \text{Weak Rubicon (\#2)} \gg \text{Grayling (\#1)}. \quad (5)$$

Spatial differences in soil development on this surface are assumed to be primarily due to the impact of snowfall, which varies spatially and predictably, and which also secondarily impacts vegetative patterns (Comer et al., 1995; Schaetzl, 2002; Mikesell et al., 2004). The northwestern part of the outwash plain, by virtue of its high elevation and proximity to Lake Michigan, is within the lake effect snowbelt. Vegetation on the Haplorthods that dominate this part of the landscape is typically mixed coniferous-deciduous northern hardwoods, with eastern hemlock, American beech, sugar maple, red oak, and white birch dominating. Fire frequencies here were, presumably, low in presettlement time. Strongly developed soils like Kalkaska (#4) are located in and near this core snowbelt area, presumably because O horizons remain thicker (due to less fire) and snowmelt infiltration is of greater magnitudes and persists for longer periods of time in spring (Schaetzl, 2002).

In the eastern part of the outwash plain, farther from the snowbelt, less developed soils such as Grayling (#1) dominate the landscape (Schaetzl and Isard, 1996; Schaetzl, 2002). Here, frequent wildfires historically have shaped the vegetation

Table 2. Physical, Chemical and Morphological Data for the Four Soil Pedons Studied[a]

Horizon	Depth (cm)	Munsell color (moist)	pH (2:1 soil:water)	Coarse fragments (>2 mm dia.; est. vol. pct.)	Sand (%)	Silt (%)	Clay (%)	Texture class[b]	Mean particle size (um)
Kalkaska (site 4 on Fig. 1) USPLS location: SE ¼, NE ¼, Sec. 5, T28N, R5W									
Oi	0–3	–		0					
A	3–16	7.5YR 2/0	4.7	0	88.3	11.6	0.0	S	345
E	16–24	5YR 4/3	4.2	0	87.5	12.4	0.0	S	359
Bhs	24–31	5YR 2.5/2	4.0	0	83.3	13.2	3.5	LS	340
Bs1	31–58	7.5YR 4/6	6.1	0	95.1	4.9	0.0	S	355
Bs2	58–85	5YR 5/8	6.6	4	97.4	2.5	0.0	S	413
Bw	85–128	10YR 4/6	6.7	4	98.2	1.8	0.0	S	343
2E/Bt	128–160+	10YR 4/6 (E) 7.5YR 4/4 (Bt)	6.9	8	98.1	2.0	0.0	S	384
Strong Rubicon (site 3 on Fig. 1) USPLS location: SW ¼, NE ¼, Sec. 3, T28N, R5W									
Oi	0–5	–		0					
A	5–9	7.5YR 3/2	5.4	2	90.3	9.7	0.0	S	364
E	9–18	7.5YR 4/2	6.1	2	90.3	8.2	1.4	S	363
Bs1	18–28	5YR 4/6	5.7	6	90.5	8.8	0.7	S	374
Bs2	28–48	7.5YR 4/6	6.4	6	93.5	6.5	0.0	S	362
BC	48–79	10YR 5/6	7.1	8	98.1	2.0	0.0	S	422
C	79–170+	10YR 6/4	7.2	8	98.6	1.4	0.0	S	391
Weak Rubicon (site 2 on Fig. 1) USPLS location: NW ¼, SE ¼, Sec. 36, T28N, R5W									
Oi	0–4	–		0					
A	4–9	N 2/0	4.0	0	96.8	3.3	0.0	S	421
E	9–20	7.5YR 4/2	6.1	0	95.1	3.7	1.2	S	401
Bs1	20–41	5YR 3/4	6.1	0	95.3	4.8	0.0	S	389
Bs2	41–62	10YR 4/6	6.9	0	98.8	0.1	1.0	S	378
BC	62–126	10YR 5/4	7.2	1	99.6	0.5	0.0	S	323
C	126–165+	10YR 6/4	7.5	1	99.7	0.0	0.4	S	291
Grayling (site 1 on Fig. 1) USPLS location: NW ¼, NW ¼, Sec. 30, T27N, R4W									
Oi	0–7	–		0					
A	7–11	7.5YR 3/2	4.4	0	91.0	9.0	0.0	S	364
Bs	11–36	7.5YR 4/6	6.1	0	96.4	3.6	0.0	S	386
BC	36–62	10YR 5/6	6.9	0	99.4	0.7	0.0	S	409
C	62–116	10YR 5/4	7.2	2	99.6	0.4	0.0	S	406
2C	116–140	10YR 5/3	7.2	6	98.9	1.1	0.0	S	409
3C	140–165+	10YR 5/3	7.3	0	99.4	0.6	0.0	S	369

[a] In part, after Mikesell et al. (2004).

[b] S: sand; LS: loamy sand. Textures according to the Soil Survey Division Staff (1993).

Table 3. Ranked Pedogenesis and Weathering Indicators, for the Four Soils Studied[a]

Criterion of comparison[b]	Grayling	Weak Rubicon	Strong Rubicon	Kalkaska
Pedogenesis indicators				
Solum thickness (cm)	62 (2)	62 (2)	48 (4)	128 (1)
E horizon thickness (cm)	0 (4)	11 (1)	9 (2)	8 (3)
B horizon thickness (cm)	25 (4)	42 (2)	30 (3)	61 (1)
POD Index[c]	0 (3)	2 (1)	0 (3)	1.5 (2)
K_{Al} Index[d]	5.1 (4)	10.8 (2)	11.9 (1)	9.8 (3)
A or E horizon pH (lower of the two)	4.4 (3)	4.0 (1)	5.4 (4)	4.2 (2)
B horizon pH (lowest of any subhorizon)	6.1 (3)	6.1 (3)	5.7 (2)	4.0 (1)
Hue of reddest B horizon	7.5YR (4)	5YR (1)	5YR (1)	5YR (1)
Color value of darkest B horizon	4 (3)	3 (2)	4 (3)	2.5 (1)
Citrate-dithionite-extractable Fe in Bs and Bhs horizons (%), weighted (multiplied) by B horizon thickness (cm)	2.75 (4)	7.14 (3)	13.60 (1)	10.92 (2)
Pyrophosphate-extractable Fe in Bs and Bhs horizons (%), weighted (multiplied) by B horizon thickness (cm)	1.75 (3)	1.68 (4)	4.20 (1)	3.89 (2)
Oxalate-extractable Fe in Bs and Bhs horizons (%), weighted (multiplied) by B horizon thickness (cm)	0.75 (4)	1.47 (3)	3.30 (1)	2.88 (2)
Citrate-dithionite-extractable Al in Bs and Bhs horizons (%), weighted (multiplied) by B horizon thickness (cm)	2.75 (4)	5.04 (3)	6.20 (2)	7.53 (1)
Oxalate-extractable Al in Bs and Bhs horizons (%), weighted (multiplied) by B horizon thickness (cm)	4.76 (4)	7.77 (3)	8.60 (2)	9.62 (1)
Overall mean rank for pedogenesis	3.50	2.21	2.14	1.64
Overall median rank for pedogenesis	4	2	2	1.5
Weathering indicators				
Hornblende denticulation[e] (categories 0–8, with 0 being lowest), weighted profile mean	1.19 (4)	1.38 (3)	1.66 (2)	2.59 (1)
Hornblende denticulation, profile maximum (category)	3.24 (4)	5.79 (3)	7.16 (2)	8.21 (1)
Hornblende denticulation at 50 cm depth (mean of categories)	1.75 (4)	2.04 (2)	1.77 (3)	2.79 (1)
Q/F ratio, weighted profile mean	8.49 (2)	5.66 (4)	9.49 (1)	8.37 (3)
Q/F ratio, profile maximum	10.5 (3)	7.8 (4)	24.0 (1)	16.7 (2)
Q/F ratio, profile minimum	5.3 (3)	4.6 (4)	6.1 (2)	6.3 (1)
Silt content in A horizon (%)	9.0 (3)	3.3 (4)	9.7 (2)	11.6 (1)
Silt content: maximum in any near-surface horizon (%)	9.0 (3)	4.8 (4)	9.7 (2)	13.2 (1)
Weathering Index #1 (profile maximum): $\frac{(Ti + Zr)}{(Ca + Mg + K + Mn + Na + P)} \times 100$	9.9 (4)	11.0 (2)	21.1 (1)	10.1 (3)
Weathering Index #1 (overall profile rank, based on visual inspection of Fig. 4)	4	2	1	2
Weathering Index #2 (profile maximum): $\frac{(Ti + Zr)}{(Ca + Mg + K + Mn + Na + P + Rb + Sr)} \times 100$	8.0 (3)	9.5 (2)	17.0 (1)	8.0 (3)

(*table continues*)

Table 3. (Continued)

Criterion of comparison[b]	Grayling	Weak Rubicon	Strong Rubicon	Kalkaska
Weathering Index #2 (overall profile rank, based on visual inspection of Fig. 4)	4	3	1	2
Podzolization/Leaching Index (profile maximum): $\frac{(\mathrm{Si}+\mathrm{Ti}+\mathrm{Zr})}{(\mathrm{Al}+\mathrm{Fe})}\times 100$	25.7 (4)	27.7 (2)	26.1 (3)	30.1 (1)
Overall mean rank for weathering	3.46	3.00	1.69	1.69
Overall median rank for weathering	3	3	2	1

[a] In part, after Mikesell et al. (2004).

[b] Numbers in parentheses represent the rank for the variable in question, with 1 being maximum and 4 being minimum.

[c] The POD Index (Schaetzl and Mokma, 1988) is a field-based index of podzolization; higher values indicate increased soil development.

[d] The K_{Al} Index (Duchaufour and Souchier, 1978) is a lab-based index; higher values indicate increased soil development. In this study, we used the combined $Al_o + Al_p$ data as a surrogate for total Al, as was used in the original formulation of the K_{Al} Index.

[e] Denticulation categories are defined in the text. They range from 0 to 8, with 0 being lowest. See Mikesell et al. (2004) for details.

patterns on these sandy plains (Simard and Blank, 1982; Higman et al., 1994). Jack pine barrens and closed-canopy, dry northern forest were the fire climax vegetation on Grayling (Typic Udipsamments) and Graycalm (Lamellic Udipsamments) soils in this part of the outwash plain. Snowfall is also considerably less here than in the snowbelt, and continuous snowpacks are established much later in the fall, minimizing snowmelt infiltration and slowing soil development (Schaetzl, 2002).

The two Rubicon soils—both comparable in development with mean pedogenesis ranks of 2.21 (weak Rubicon, #2) and 2.14 (strong Rubicon, #3), and median ranks of 2 (Table 3)—were separated largely based on field criteria. In the field, it was evident that the "Strong Rubicon" pedon was more strongly developed, with a more chemically and morphologically contrasting E-B sequum, and more ortstein (Bsm material), than was the "Weak Rubicon" soil. The Strong Rubicon site was also closer to the core of the snowbelt than was the Weak Rubicon site.

In conclusion, soil development varies significantly on this geomorphic surface, and its variability is somewhat predictable, at certain scales (Schaetzl, 2002; Hupy et al., 2004). On large surfaces such as this one, only rarely should soils be assumed to be uniform enough to be useful in a soil chronofunction.

Weathering

After establishing the range of soil development on this surface, we examined the pedogenic data in light of the various weathering-related parameters, assuming that weathering trends would parallel pedogenic trends (Table 3). With regard to weathering-related parameters, the ranking is:

$$\text{Kalkaska (\#4)} \geq \text{Strong Rubicon (\#3)} > \text{Weak Rubicon (\#2)} > \text{Grayling (\#1)}. \quad (6)$$

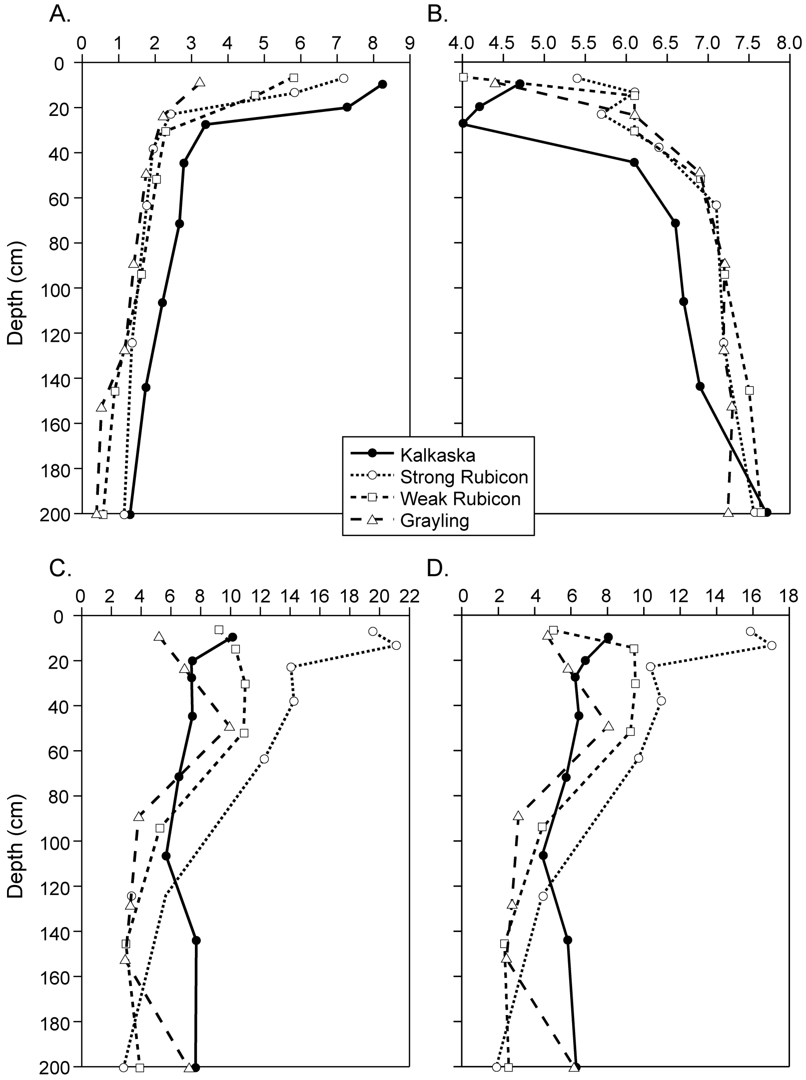

Fig. 4. Depth plots of weathering-related parameters, by horizon, for the four soils studied. (A) Hornblende denticulation (mean category rank); (B) pH in water (1:1 soil: water ratio); (C) Weathering Index #1 = [(Ti + Zr)/(Ca + Mg + K + Mn + Na + P)] × 100; (D) Weathering Index #2 = [(Ti + Zr)/(Ca + Mg + K + Mn + Na + P + Rb + Sr)] × 100.

With regard to weathering, Kalkaska and Strong Rubicon were nearly identical (each with a mean rank of 1.69), while Weak Rubicon and Grayling exhibited much lower mean weathering ranks (3.00 and 3.46, respectively; Table 3). Weathering data were generally similar to pedogenic data, the main difference being the Strong Rubicon soil, which ranks more highly on the various weathering parameters than on pedogenic development (Table 3; Fig. 4).

Despite the subtle non-agreement in rank between the soils along weathering and pedogenesis axes, the data indicate that the magnitude of the weathering-related, inter-pedon differences is large (Table 3). The wide variation in weathering character is especially noteworthy, given the similar (and relatively young) age of the soils. Much of this difference appears to be related to soil pH. For example, hornblende etching amplitudes at lower pHs, i.e., higher in the profile, are 6 to 10 times greater than are amplitudes at higher pHs (2–3 units higher!) in these soils (Mikesell et al., 2004). Viewed in this way, hornblende in the upper soil horizons appears to have etched 6 to 10 times faster than has hornblende in lower horizons.

Weathering parameters, inferred from elemental data, indicate that intra-pedon weathering is less variable with depth (Fig. 4). When weathering is evaluated using hornblende etching, upper horizons are much more strongly weathered than are horizons at depth. However, neither weathering index validated this depth trend, again pointing to the wide variation in an apparently time-related parameter on a surface of uniform age.

CONCLUSIONS

It is often assumed that soil development and weathering are highly time dependent; hence the wide application of chronofunctions within soil geomorphology (Bockheim, 1980; Schaetzl et al., 1994; Schaetzl and Anderson, 2005). However, the inherent spatial variability of soils, even across a single surface of uniform age and parent material, can present theoretical and application-related problems (Harrison et al., 1990). Whether this variability is due to predictable changes in one or more of the soil-forming factors, the passing of pedogenic thresholds, the development of pedogenic accessions, or simply to chaotic or divergent soil evolution, is often difficult to ascertain (Phillips, 1993). Indeed, because geomorphic surfaces are so spatially variable, one needs to ask which soil on a surface is most representative, and therefore applicable, in a soil chronofunction (Sondheim and Standish, 1983; Harrison et al., 1990; Vidic, 1998; Eppes and Harrison, 1999). For this reason, we advocate that researchers developing soil chronofunctions, in which they generally assume that soil properties are largely a function of time, sample large numbers of pedons and work with central tendency values, while factoring in data that relate to scatter or "range of expression" (Harden et al., 1991; Barrett and Schaetzl, 1993).

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