CONCURRENT STABILIZATION OF SOME INTERIOR DUNE FIELDS IN MICHIGAN

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Abstract: Inland dunes occur over a large part of east-central lower Michigan, where they mantle glaciolacustrine and outwash surfaces that were exposed around 12,000 yrs. B.P. The dunes are parabolic, with northwest-oriented limbs, and occur in swampy landscapes, suggesting that paleoclimatic conditions at the time of their formation were much drier and possibly windier. In order to determine whether the dunes stabilized concurrently or randomly in time and space, surface soils were studied on 30 dunes in the area and quantitatively analyzed for relative differences. Soils data from the dunes indicate concurrent stabilization, following a period of regional mobilization of aeolian sand. Surface soils have formed by podzolization, in uniform parent materials, and are morphologically similar throughout the area. All the soils are weakly developed, with subtle variations on a A-E-Bs-BC-C horizonation sequence. Munsell colors of Bs horizons are remarkably uniform, with 27 of 30 sites exhibiting values of 4 and chromas of 6. Chemical data suggest that Fe and Al translocation has been uniform throughout the region. When compared with soils of known age in northwest lower Michigan, the data indicate that dunes in the region had stabilized at least by 4000 yrs. B.P., leaving an approximately 8000-yr. interval in which they could have formed. In contrast to the prevailing southwesterly winds of today, dune-forming winds were dominantly from the northwest. [Key words: aeolian sedimentation, dunes, soil, Great Lakes, Michigan.]

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INTRODUCTION

Sand-dune assemblages are common on and near the shore zones of Michigan and the Great Lakes region (Leverett and Taylor, 1915; Olson, 1958; Farrand and Bell, 1982). Because of their attractiveness for development and recreation, and because they are fragile ecosystems, these areas have recently undergone renewed interest from many scholars and land-use planners. Increasingly, geomorphic and paleoenvironmental investigations have been undertaken in these systems (e.g., Thompson, 1992; Larsen, 1994; Anderton and Loope, 1995; Lichter, 1995) in order to reconstruct the paleoenvironmental conditions under which as they formed and to determine the variables that control their development.

In contrast to the well-studied coastal dunes, the variety of dunes present within the interior of Michigan are poorly understood. This study focuses on east-central lower Michigan, where extensive deposits of aeolian sand occur in swampy landscapes 20 to 100 km from Lake Huron (Leverett and Taylor, 1915; Farrand and Bell, 1982) (Fig. 1). Traditionally, soil scientists (e.g., Huchinson, 1979; Iaquinta, 1994) have confused these landforms with former beach ridges of proglacial lakes in the region (Leverett and Taylor, 1915; Eschman and Karrow, 1985). However, rather than being low, linear to sublinear shoreline features, they are aeolian dunes with limbs oriented toward the northwest (Fig. 1) and steep slipfaces on their eastward-facing slopes.

Given the presence of these dunes on a landscape that only emerged from beneath late Pleistocene ice and attendant proglacial lakes around 12,000 yrs. B.P. (Eschman and Karrow, 1985), widespread mobilization of aeolian sand must have occurred in Michigan sometime during the latest Pleistocene and/or Holocene. Late Quaternary mobilization of aeolian sand has been widely reported in interior locations of the eastern and central United States, with the oldest dunes typically found to the east. In Connecticut, for example, parabolic dunes occur on the bed of glacial Lake Hitchcock, which drained around 12,700 yrs. B.P. The dunes initially formed by northeast winds circulating from a hypothesized glacial anticyclone, but later were reworked by northwest winds between 12,400 and 11,000 yrs. B.P. (Thorson and Schile, 1995). In Minnesota, parabolic dunes with northwest-oriented limbs formed and stabilized between 8000 and 5000 yrs. B.P. (Grigal et al., 1976; Keene and Shane, 1990). On the Great Plains, dune migration apparently occurred locally during cool arid episodes such as the late Wisconsin (e.g., Wright et al., 1985; Forman and Maat, 1990; Arbogast, 1996a) and regionally during warm arid intervals within the middle and late Holocene (e.g., Ahlbrandt et al., 1983; Muhs, 1985; Forman and Maat, 1990; Madole, 1995; Arbogast, 1996b). Nothing is known about the spatial and temporal patterns of dune evolution in the interior of Michigan, in contrast to these locations.

Comparing the development of soils on different geomorphic surfaces is an effective way to date the relative age of landforms, assuming that other soil-forming factors (climate, relief, parent material, and organisms) are constant (Gellatly, 1985; Robertson-Rintoul, 1986). Surface soils on dunes of the Midwest, in particular, have been used frequently as indicators of relative age. On the Great Plains, recently active dunes support soils with A/C horizonation, whereas older dunes

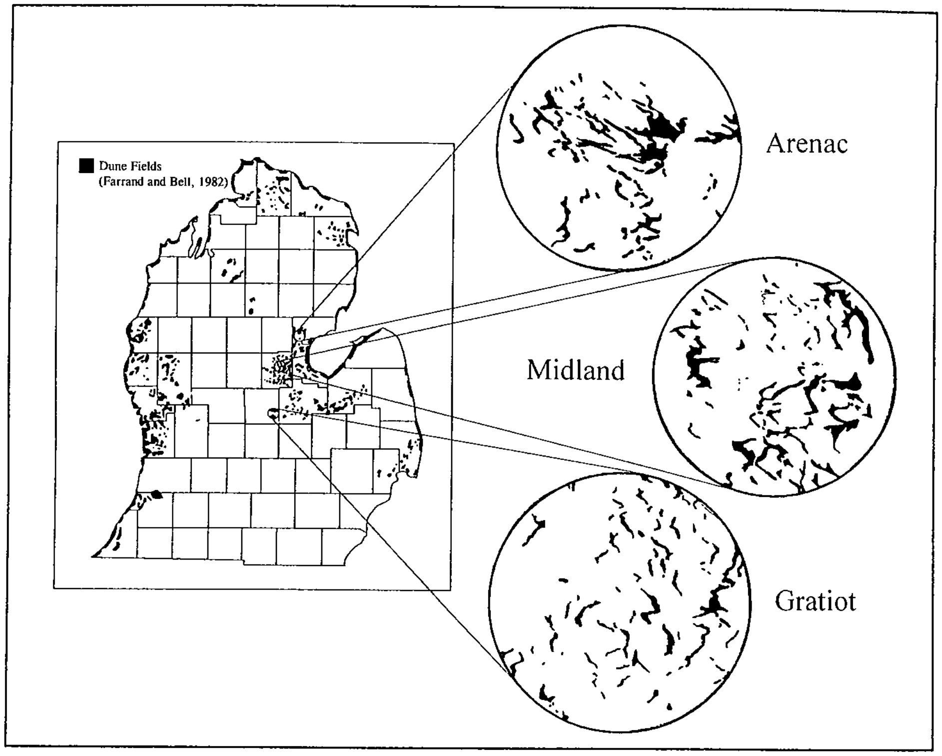

Fig. 1. Location of study area within specified counties in east-central lower Michigan. Dark polygons in the map of lower Michigan are deposits of aeolian sand (1:500,000) as mapped by Farrand and Bell (1982). Inset circles show, as dark polygons, any landforms that are delineated by one or more closed contour lines; most are composed of aeolian sand. Contour interval = 5 feet (1.5 m). Circle diameter = 4 km. The circles show only a subset of the dunes studied.

support soils with Bw or Bt horizons (Muhs, 1985; Arbogast, 1995; Madole, 1995). Olson (1958) found that incipient E horizons can be observed in dune soils as young as 1000 yrs. old in southern Michigan, especially where the forest litter is very acidic. In Indiana, soils in sand dunes range in development from those with weak color B horizons on young surfaces to those with strong Bt horizons on older dunes. In addition, older dunes usually contain more subsurface lamellae than younger dunes (Miles and Franzmeier, 1981). Similar observations have been made elsewhere, for example in Denmark (Nørnberg, 1977).

Spodosols, which commonly develop in sandy parent materials in northern Michigan are particularly good indicators of the relative age of late Quaternary landscapes because they form distinctive pedogenic features rapidly, and these can be related to absolute age (e.g., Olson, 1958; Franzmeier and Whiteside, 1963a; Protz et al., 1988; Bowman, 1989; Barrett and Schaetzl, 1992). Podzolization is the general term for the bundle of processes that produce distinctive Spodosol morphology (Rourke et al., 1988). Data from studies of podzolization in Michigan and elsewhere can be related to known surface ages, and the resulting relationships applied in a relative-dating sense to surfaces whose ages are as yet unknown (Franzmeier and Whiteside, 1963a). Spodosols and soils developing toward Spodosols were analyzed by Barrett and Schaetzl (1992, 1993a) on four sandy lake terraces that range in age from 3000 to 11,000 yr B.P. Results indicated that E horizons achieved high color values (lightness) by 3000 yrs., but changed little subsequently. B horizons, in contrast, continued to darken, thicken, and become more strongly cemented with increasing age. Generally, Barrett and Schaetzl (1992) found that 3000 to 4000 yrs. are required for Spodosol morphology to form in northwestern lower Michigan. Although studies of podzolization on sandy surfaces of varying age exist (e.g., Protz et al., 1984, 1988), only those within 300 km of the study site are of value from the standpoint of relative age.

In this study, we measured several quantifiable parameters in 30 soils on dune crests in east-central lower Michigan. The sites lie within three distinct dune fields (10 in each) scattered throughout the region. The primary goal of the study was to determine whether the dunes in the three areas have been stable for a similar length of time (i.e., are of similar age) or whether they stabilized randomly in time and space. Second, we sought to estimate a minimum-limiting age of the dunes by comparing the degree of surface-soil development to soils of known age in northwest lower Michigan.

STUDY AREA

The study area consists of three distinct dune fields in east-central lower Michigan (Fig. 1). Surficial geology reflects late Wisconsinan glaciation, which last dominated the area during the Port Huron stade around 13,000 yrs. B.P. (Eschman, 1985). As Port Huron ice stagnated, a shallow, proglacial lake reestablished itself; it had been present prior to the Port Huron stade, but its level repeatedly fluctuated as new outlets were opened or closed (Eschman and Karrow, 1985). Although the lakes in this basin are referred to by many names, depending on age, level, and configuration of each strandline (e.g., lakes Whittlesey, Warren, Lundy, Grassmere), we will use the generic name Lake Saginaw for this water body. The study area probably became permanently subaerial following the retreat of Lake Grassmere around 12,000 yrs. B.P. (Eschman and Karrow, 1985).

Deposits of aeolian sand mantle late Wisconsinan deposits throughout the region, but are most prevalent in an approximately 125-km-long transect that extends from southeastern Gratiot County, through Midland County, and northeast into Arenac County (Fig. 1). Dunes in Gratiot and Midland counties overlie lacustrine sediments associated with Lake Saginaw. In contrast, dunes in Arenac County mantle the Port Huron outwash plain and ascend the western flank of the Port Huron moraine. The dunes, typically either isolated or linked, are parabolic features that range in length from 100 to >1000 m (Fig. 1). They have slopes ranging from 6 to 12% in Gratiot and Midland counties, although the larger dunes in Arenac County have slopes ≥25% (Redmond and Engberg, 1967). Local relief from dune crest to base ranges from 2–5 m in Gratiot and Midland counties to >12 m in Arenac County.

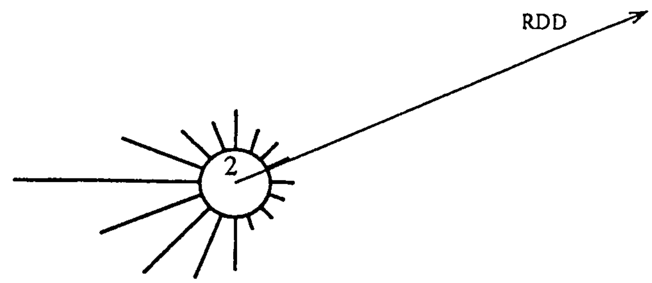

Fig. 2. Wind rose (wide unimodal) for Flint, Michigan, for the period 1966–1975, based on eight daily observations. Flint is located about 80 km SE of the center of the study area. Potential drift magnitude at Flint was calculated on the basis of a mean diameter in the medium sand (0.25–0.50 mm) range, at devegetated sites. Winds are dominantly southwesterly, with a northeasterly resultant drift direction (RDD). Numerical value within circle is the reduction factor, whereas the value below the circle is the drift potential in vector units (see Fryberger and Dean [1979] for details).

The closest weather station to the center of the study area is at Midland, where the mean annual temperature is 8.8°C, with July and January temperatures averaging 22.0°C and −4.9°C, respectively. Dominant winds at present are from the west and southwest (Fig. 2). Mean annual precipitation is 75.2 cm, with the highest monthly mean (7.8 cm) occurring in June and the lowest (3.9 cm) in February. Mean annual snowfall is 92.2 cm (Feenstra, 1979).

The study area lies within a diffuse floristic boundary that generally extends latitudinally across southern Michigan. The well-documented boundary separates two major vegetation associations (Potzger, 1948; Barnes and Wagner, 1981; Medley and Harman, 1987). South of the tension zone, broadleaf deciduous species such as *Acer saccharum* (sugar maple), *Fagus grandifolia* (beech), and *Quercus* spp. (oak) dominate. To the north, *A. saccharum, F. grandifolia, Pinus strobus* and *P. rubrum* (white and red pine), *Tsuga canadensis* (eastern hemlock), and *Betula allegheniensis* (yellow birch) occur in a mixed coniferous-deciduous assemblage. Prior to European settlement, sand dunes in the study area were probably vegetated by a combination of *Pinus* and *Quercus* because they are droughty and excessively drained (Veatch, 1931; Brewer, 1982). Current vegetation on dunes within the study area consists primarily of open deciduous forest, with small oak and aspen *(Populus* spp.) dominating.

Surface soils on dunes in the study area have largely resulted from podzolization, which is accelerated in cool, moist climates where coniferous vegetation is found on coarse-textured deposits (Messenger et al., 1972). In this process, aluminum and organic carbon (OC), with or without iron, are readily eluviated, forming a whitish E horizon depleted in these compounds. The B (commonly a spodic) horizon accumulates OC, Al, and/or Fe—hence its dark and/or dark reddish brown "spodic-like" colors (Mokma, 1993). With time, E horizons become whiter and thicker, while B horizons redden, darken, and thicken, progressively accumulating more illuvial compounds (Schaetzl and Mokma, 1988).

In Gratiot County, soils on stable dunes are mapped as mixed, mesic Typic Udipsamments, whereas in Midland County similar surfaces contain sandy, mixed, mesic Entic Haplorthods. Because Arenac County is in the frigid soil-temperature regime, soils on dune crests there are mapped as sandy, mixed, frigid, Entic Haplorthods (Redmond and Engberg, 1967). In all three areas, interdune landscapes are flat and wet, and Mollic Psammaquents and Entic Haplaquods dominate (Redmond and Engberg, 1967; Feenstra, 1979; Hutchinson, 1979).

METHODS

Field Methods

A total of 30 dunes were studied, all of which lie in a N/NE-trending transect that extends from Gratiot County, through Midland County, and into Arenac County (Fig. 1). Sand dunes were identified on USGS topographic maps and county soil surveys. Ten dunes, with relatively high relief (≥m) and parabolic configurations, were selected for study in both the Gratiot-Saginaw State Game Area and the Tittabawasee State Forest in Arenac County. In Midland County, 9 of the 10 dunes were in the Tittabawasee State Forest. At each site, soil pits were excavated to a depth of 1.5 m on flat, stable dune crests. Soils were described using standard methods (Soil Survey Division Staff, 1993). Horizon-based samples of approximately 400 g were collected for laboratory analyses. To quantify Spodosol development on the basis of field (morphologic) data (i.e., horizonation, horizon thickness, color), Schaetzl and Mokma (1988) developed the POD Index. For calculation of the POD Index, a soil must have E and B horizons; otherwise a zero is assigned. NonSpodosols typically have POD Indices <2 because they lack distinctive E horizons and/or contain weak Bs horizons that are relatively light in color. Strongly developed soils, and most Spodosols, have well-developed E horizons that overlie dark Bh and Bhs horizons. As a result, POD Indices on these soils range from 6 to 12+ (see Schaetzl and Mokma, 1988, p. 234, for details). We calculated POD Indices for all soils in this study as a means of assessing relative soil development among the dune sites.

Laboratory Methods

Munsell colors were determined on field-moist samples, under a fluorescent light in the laboratory, by two persons working independently. The samples were then oven dried at 40°C and sieved to remove large organic detritus and gravels (>2 mm). The remaining sample was repeatedly halved, using a sample splitter, to a final weight of approximately 30 g. This 30-g sample was then used for all subsequent analyses.

Fe and Al were extracted from all B and C horizon samples using sodium citrate–dithionite and acid ammonium oxalate (Soil Survey Laboratory Staff, 1996). Fe and Al contents of the extracts (Fe_d, Fe_o, Al_d, and Al_o, respectively) were determined on a DCP spectrometer. Sodium citrate-dithionite extracts Fe and Al in "free" form, that is, not bound within phyllosilicate mineral lattices (Mehra and Jackson, 1960). As such, it is a good indicator of Fe and Al released by weathering and not yet translocated out of the profile. Oxalate-extractable Fe and Al are often assumed to be in organically bound and/or inorganic amorphous forms, as oxalate does not extract crystalline oxides well (McKeague and Day, 1966). Fe_o and Al_o are commonly thought of as Fe and Al undergoing translocation or having been recently translocated in the podzolization process. Forms of Fe and Al extracted by oxalate can eventually be converted to dithionite-extractable Fe and Al. Fe_d includes Fe_o, and Al_d includes Al_o. Sand contents were determined by dispersing samples in a $Na_2CO_3[NaPO_3]_6$ solution, shaking overnight, and wet sieving through a 53-μm sieve. Silt and clay contents were then determined by hydrometer analysis of the residue that passed through the sieve (Carter, 993). Sands were dry sieved to isolate the very coarse (vcs), coarse (cs), medium (ms), fine (fs), and very fine (vfs) sand fractions (Carter, 1993). Reaction was measured in 2:1 water-soil mixtures using an Orion 720A combination pH/ISE meter.

Soil data were analyzed using several statistical techniques. Raw-data input into these analyses included POD Indices, solum and B horizon thicknesses, pH data for A, Bs, BC, and C horizons, and Fe_d, Fe_o, Al_d, and Al_o contents for Bs and C horizons. Also included were Fe_o/Fe_d data for Bs horizons (a measure of relative crystallinity of the Fe within) and Bs/C ratios (a measure of illuviation) for each of the four extractants (Fe_d, Fe_o, Al_d, Al_o). Horizon-weighted amounts of Fe_d, Fe_o, Al_d, Al_o, and $Fe_d - Fe_o$ (an indication of Fe oxides that are crystalline or have been recrystallized) were determined by multiplying the amounts of each by the horizon thickness. Solum-weighted amounts of each particle-size separate were then calculated by summing each horizon-weighted total and dividing the sum by solum thickness. Analysis of variance (ANOVA) tests were performed to determine whether statistically significant differences existed, at $\alpha = .05$, for each of the variables listed above.

Finally, in order to determine prevailing dune-forming winds, and to compare with modern winds, "sand-rose" diagrams were constructed for each of the three dune fields. Using the method outlined by Fryberger and Dean (1979), the azimuth of the axis of all identifiable dunes within an 8-km radius around the centroid of each study area was determined, the readings were summed, and a sand-rose diagram was calculated.

RESULTS

Soils: Morphology

Soils on dune crests were remarkably similar in morphology, both within and between dune fields. Most profiles had typical spodic morphologies and weakly developed A-E-Bs-BC-C horizonation (Fig. 3), although several had no E horizon and a small number exhibited E/B instead of E horizons. All had clearly formed in a single, generally uniform parent material. Horizon colors were also remarkably similar between pedons. The most common Munsell colors for each horizon were: A (10YR 2/1 and 2/2), E (10YR 4/3), Bs (7.5YR 4/6 and 10YR 4/6), BC (10YR 5/6),

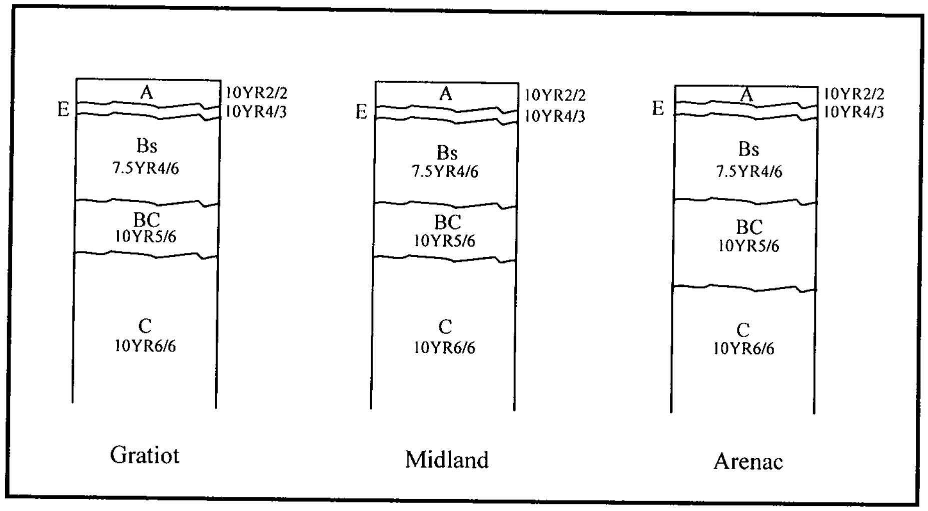

Fig. 3. Generalized soil morphology for dunes in Gratiot, Midland, and Arenac counties. Although most soils have A-E-Bs-BC-C horizonation, some locations exhibited no E horizon, while others contained E/B horizons.

and C (10YR 6/6 and 5/6). Indeed, 27 of 30 Bs horizons examined had Munsell color values of 4 and chromas of 6.

Data on soil texture support the general notion of parent-material uniformity among pedons. Textural-class data indicated that all soil horizons consist of >99% sand, .6–.9% silt, and no measurable clay (Table 1). Horizons of all the pedons at the Gratiot and Midland sites had dominantly medium sand textures (Soil Survey Division Staff, 1993). For the Arenac soils, soil textures were noticeably finer; 9 of the 44 horizons sampled were fine sand. One possible explanation for this variation in sand composition could be the different depositional history of the Arenac study area. The aeolian sands here were initially deposited as glacial outwash and then deflated into dunes, whereas at the Gratiot and Midland sites the sands first accumulated in lake-marginal environments or as shallow-water lacustrine deposits prior to aeolian mobilization.

Soils: Statistical Analyses

The general similarities among the soils, as indicated by field observations, were confirmed for the most part by statistical analyses. The only morphologic variable that differed significantly was B horizon thickness, which varies from 41.6 cm in Arenac County to 35.0 cm and 32.9 cm in Midland and Gratiot counties, respectively (Table 1). Although overall solum thickness also is greater in Arenac County (79.2 cm) than in Midland and Gratiot counties (76.6 and 75.0 cm, respectively), it is not significantly different. POD Indices were not statistically different between sites, but were nonetheless lower in Gratiot County (0.0) than in Midland and Arenac counties (0.4 in each). Overall, these results suggest that the soils in the northern part of the region are slightly more developed than those to the south. This is logical because the strength of podzolization increases from southeast to northwest across Michigan's lower peninsula, primarily due to climatic factors (Schaetzl and Isard, 1991). Thus, the most strongly podzolized soils are located in the northern and western parts of the lower peninsula. Given this interpretation based on climatic gradients, subtle differences in POD Indices and in solum and B horizon thicknesses were expected and are acceptable within the hypothetical framework of the study.

The primary differences between the soils are related more to inherited (parent-material) than to developmental (horizon or solum) characteristics. Significant differences exist in mean coarse, medium, fine, and very fine sand fraction amounts for the C horizons of the soils in the three study areas, whereas very coarse sand, total sand, and total silt contents in the C horizons are not significantly different (Table 1). The mean amount of medium sand in the C horizon in Arenac County is less than that in Midland and Gratiot counties (42.7 vs. 59.3 and 57.8%, respectively), and, as a result, the fine sand percentage in Arenac County is thus greater (50.1 vs. 31.0 and 30.0%) (Table 1). Parent-material (C horizon) chemical data also differ significantly with respect to Fe_d content (Table 1). The mean C horizon Fe_d was slightly higher in Arenac and Gratiot counties (.09 and .10 g kg^{-1}, respectively) than in Midland (.07 g kg^{-1}). The statistical validity of this difference is essentially meaningless, however, since the values are extremely small. Significant differences in parent materials do not exist for the other chemical measures (pH, Al_d, Al_o, Fe_o) (Table 1).

As with the physical and chemical properties of the parent material (C horizon), combined B horizon and other developmental properties were also similar in the three sites (Table 1). Mean pH values were not significantly different among the three sites for A, Bs, or BC horizons. Most pedons had pHs in the range of 4.0 to 5.6 in the solum and 5.8 to 6.4 in the C horizon. Mean B horizon amounts of Fe and Al also were not statistically different among the three sites, although in all four instances (Al_d, Al_o, Fe_d, Fe_o), the mean values for Arenac were highest.

Fe_o/Fe_d ratio data can be used to assess the relative amount of Fe that has been released by weathering (Fe_d) and is still in "active" (Fe_o) forms. High Fe_o/Fe_d index values indicate greater potential Fe mobility, and lowered crystallinity, in the soil (Singer et al., 1978). Although this "index" is not particularly useful for assessing relative age, it does provide information on soil processes. No statistical difference exists for the mean B horizon Fe_o/Fe_d and $Fe_d - Fe_o$ values among the three study areas. Fe_o/Fe_d ratios, most of which are >.50, suggest that all of the pedons examined are actively undergoing podzolization.

B/C ratios for iron and aluminum are appropriate measures for relative age because they allow comparisons of profile development between study areas by eliminating the effect of variability in Fe and Al content of the parent material (Robertson-Rintoul, 1986). Although these data do not show any significant differences among study sites (Table 1), the mean B/C ratio for all four types of extraction data is, surprisingly, greatest in the Midland County soils. The high values, however, reflect data from only a few pedons, as indicated by the very high standard deviations for the Midland sites (Table 1). Nonetheless, the ratio data suggest similarity among the three sites rather than differences because small changes in parent mate-

Table 1. Statistical Data for Soils at the Three Study Sites, and ANOVA Differences of Means Test Probabilities

	M (SD)			
Variable	Arenac	Midland	Gratiot	p^a
POD Index[b]	0.40(0.8)	0.40(0.8)	0.0(0.0)	.18
B thickness (cm)	41.6(8.9)	35.0(8.1)	32.9(4.8)	.02
Solum thickness (cm)	79.2(12.9)	76.6(11.5)	75.0(7.9)	.34
A horizon pH	4.6(0.5)	4.2(0.3)	4.4(0.3)	.07
Bs horizon pH	5.3(0.4)	5.4(0.3)	5.5(0.3)	.17
BC horizon pH	5.6(0.5)	5.3(0.3)	5.9(0.3)	.10
C horizon pH	5.9(0.3)	6.0(0.4)	6.2(0.3)	.18
VCS[c] (%)	0.1(0.2)	0.3(0.5)	0.5(0.6)	.12
CS[d] (%)	1.2(1.6)	7.2(5.2)	9.4(4.5)	.00
MS[e] (%)	42.7(11.3)	59.3(5.8)	57.8(4.4)	0.0
FS[f] (%)	50.1(10.5)	31.0(8.9)	30.0(5.1)	.00
VFS[g] (%)	5.3(2.8)	1.5(1.0)	1.5(1.3)	.00
Sand (%)	99.4(0.5)	99.3(0.7)	99.2(0.3)	.32
Silt (%)	0.6(0.4)	0.7(0.7)	0.8(0.4)	.32
Clay (%)	0.0(0.0)	0.0(0.0)	0.0(0.0)	1.00
C horizon Al_d (%)	0.04(0.01)	0.04(0.01)	0.05(0.01)	.15
C horizon Al_o (%)	0.05(0.01)	0.05(0.02)	0.06(0.02)	.08
C horizon Fe_d (%)	0.09(0.02)	0.07(0.01)	0.10(0.02)	.00
C horizon Fe_o (%)	0.02(0.01)	0.02(0.01)	0.02(0.01)	.16
Fe_o/Fe_d (raw values)	0.59(0.09)	0.61(0.15)	0.62(0.13)	.17
(Al_d% in B)/(Al_d% in C)	3.55(1.0)	3.80(1.3)	3.49(1.0)	.82
(Fe_d% in B)/(Fe_d% in C)	2.20(0.05)	2.83(0.8)	2.23(0.8)	.07
(Al_o% in B)/Al_o% in C)	4.33(1.1)	4.85(1.8)	3.68(0.6)	.15
(Fe_o% in B)/(Fe_o% in C)	5.42(1.0)	6.88(3.1)	6.37(1.6)	.29
B horizon total Al_d (%* thickness in cm)	5.27(1.1)	4.73(1.5)	4.89(1.3)	.65
B horizon total Al_o (%* thickness in cm)	9.08(3.0)	7.90(1.8)	7.72(2.1)	.39
B horizon total Fe_d (%* tickness in cm)	7.89(1.9)	6.39(2.0)	6.97(2.0)	.24
B horizon total Fe_o (%* thickness in cm)	4.61(1.2)	3.63(0.8)	4.24(1.3)	.17
Fe_d minus Fe_o (%* thickness in cm)	3.28(1.1)	2.75(1.9)	2.72(1.4)	.65

[a]ANOVA difference of means probability (between all three sites).
[b]ANOVA not calculable. T-test runs, however, suggest that statistically significant differences do not exist between the three study sites for POD Index.
[c]Very coarse sand.
[d]Coarse sand.
[e]Medium sand.
[f]Fine sand.
[g]Very fine sand.

rial (the denominator of the ratio) have a large impact on the resulting quotient. The higher mean B/C ratios obtained within the pedons sampled in Midland County may not indicate that those pedons are better developed than others, since the denominator of the ratio (C horizon data) is routinely low in Midland County (Table 1).

Soils: Comparison with Soils in Northwest Lower Michigan

In an effort to estimate a minimum-limiting age for the dune soils in east-central lower Michigan, combined B horizon Fe and Al data were correlated with data derived by Barrett and Schaetzl (1992) from soils on lake terraces of known age in northwestern lower Michigan. Although this comparison is biased in an absolute sense because environmental variables are not equal in the two areas, it is valid for minimum-age control of Saginaw soils because conditions are *most* favorable for podzolization toward the northwest (Schaetzl and Isard, 1991). As a result, soils of similar development in the two areas would have likely taken *longer* to form in east-central lower Michigan than in northwestern lower Michigan.

When data from the two areas are compared, the results are consistent, indicating that the dune soils in our study area probably began forming prior to 4000 yrs. B.P. (Fig. 4). Al_o from dunes in east-central lower Michigan, for example, suggests soil ages of 4000 to 6000 yrs. (Fig. 4A). Similarly, Fe_o and Fe_d imply that the onset of pedogenesis began in dunes in east-central lower Michigan by at least 5000 yrs. B.P. (Figs. 4B, 4C).

Dune-Forming Winds

Dune-axis orientation roses from the study area (Fig. 5) illustrate dune-drift directions, with the arm lengths proportional to the number of dune axes oriented in a particular direction (Fryberger and Dean, 1979). Results from east-central lower Michigan indicate that prevailing winds were northwesterly (315) in Arenac County and west/northwesterly (292) in Gratiot and Midland counties at the time the dunes formed. In contrast, modern prevailing winds are largely from the southwest (215) (Fig. 2).

CONCLUSIONS

The degree of soil development, especially with regard to rapidly evolving soils such as Spodosols, has been successfully related to soil age (Franzmeier and Whiteside, 1963b; Barrett and Schaetzl, 1992). Thus, various properties of Spodosols can be used as relative-age dating tools in Michigan and elsewhere. Such properties include accumulated Fe and Al in the combined B horizon, thickness of horizons, types of horizons, and various other pedogenic indices (see Barrett and Schaetzl, 1992, for a review). In sandy soils in northern Michigan, for example, Franzmeier and Whiteside (1963b) concluded that E horizons begin to develop after 2250 yrs., and Bhs horizons (B horizons enriched in humus and sesquioxides) start to form after 8000 yrs. In northwest lower Michigan, Barrett and Schaetzl

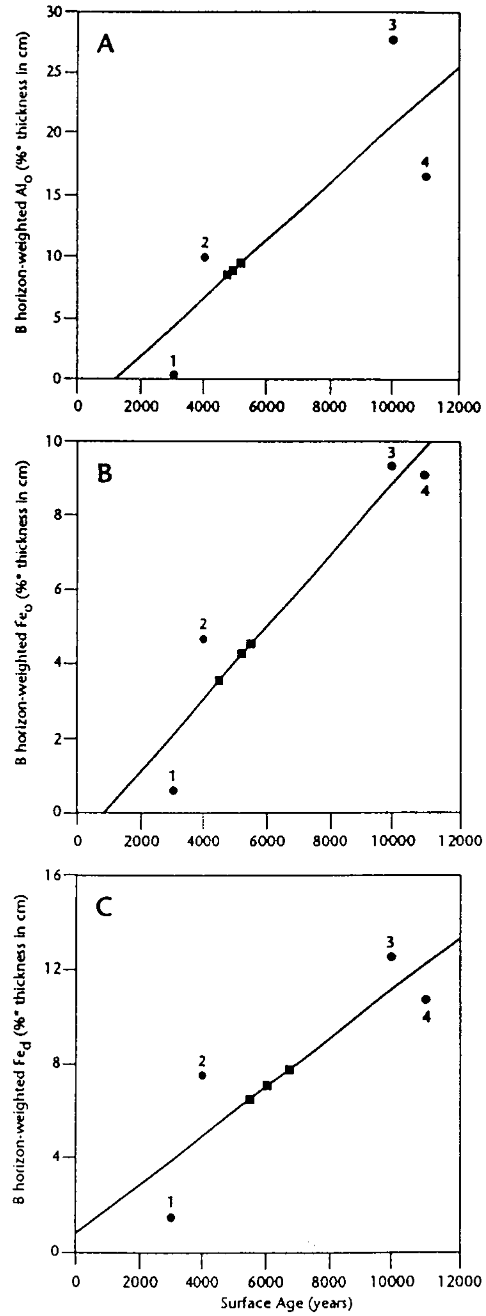

Fig. 4. Comparison of data (Barrett and Schaetzl, 1992) for chemical extractants from dune soils in Gratiot, Midland, and Arenac counties, with similar data for soils on surfaces of known age (1 = Algoma; 2 = Nipissing; 3 = Battlefield; 4 = Algonquin) in northwest lower Michigan. The data indicate that dune soils in east-central lower Michigan (dark squares) would be at least 4000 years old if they were located in northwest lower Michigan.

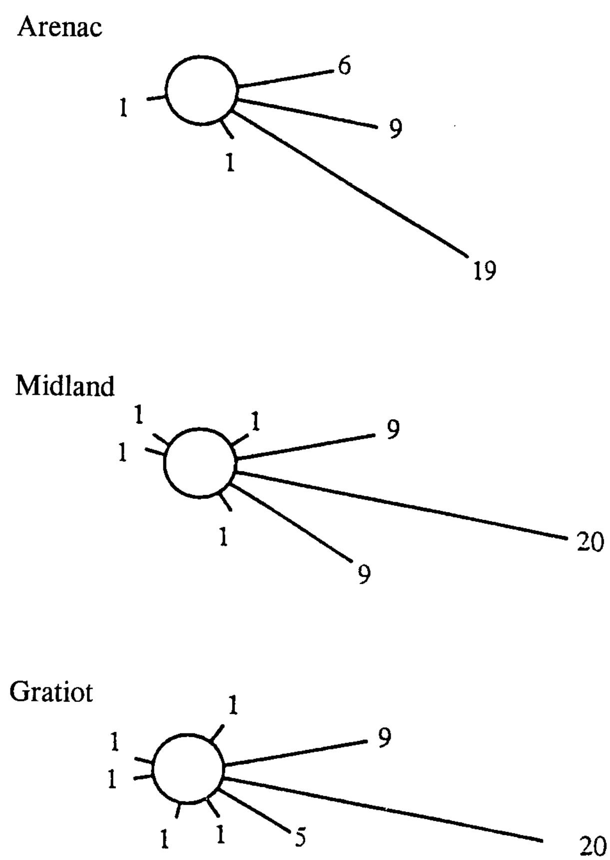

Fig. 5. Rose diagrams for each of the three dune fields. Diagram depicts the orientation of the limbs of all identifiable parabolic dunes within an 8-km radius around the centroid of each study area. Lengths of the arms are proportional to frequency of occurrence. Long arms in the SE direction imply that the dune had limbs oriented toward the NW.

(1992) found that spodic (strong Bs) horizons take 4000 to 10,000 yrs. to form. Thus, the above findings generally support the notion that Spodosol morphology takes at least 4000 yrs. to develop in northwest lower Michigan.

When examined as three groups, the soils on dunes in east-central lower Michigan are remarkably similar in development, indicating that the dunes stabilized more or less concurrently, following widespread mobilization of aeolian sand. All soils examined had weakly developed spodic morphologies, suggesting stabilization prior to 4000 yrs. B.P. No soils, however, contained a Bhs horizon, a pedogenic feature thought to take about 8000 yrs. to form in northwestern lower Michigan (Franzmeier and Whiteside, 1963b) and probably longer in east-central lower Michigan.

When B horizon Fe and Al data from the dune soils are compared to soils of known age in northwest lower Michigan (Barrett and Schaetzl, 1992), the results indicate that dunes in east-central lower Michigan stabilized prior to 4000 yrs. B.P. This conclusion correlates well with the minimum age suggested by soil morphology. Since the study area became permanently subaerial only around 12,000 yrs. B.P., the dunes must have formed in an 8000-yr. interval during the latest Pleistocene and/or earlier Holocene, when prevailing winds were west/northwesterly. Given that podzolization occurs more slowly in east-central lower Michigan, relative to the northwest, it is likely that the window for mobilization of dunes is narrower than 8000 yrs. In order to resolve this issue, and to reconstruct the paleoenvironmental variables responsible for large-scale mobilization of aeolian sand in the interior of Michigan, detailed radiometric dating of the dunes is essential and is being pursued.

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