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# A lithosequence of soils in extremely gravelly, dolomitic parent materials, Bois Blanc Island, Lake Huron

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## ABSTRACT

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Eight extremely gravelly pedons on Bois Blanc Island were characterized, and pathways and processes of genesis were examined. The soils are developed in dolomitic gravels and cobbles, and contain 1–50% (mean 15%) fine-earth; most pedons are in coarse-loamy or skeletal particle-size families. In extremely gravelly parent materials with less than 5% fine-earth, B horizons have not formed. Accumulation of organic matter on the surface and between coarse fragments in the upper solum is the main pedogenic process in such soils (Borofolists). In other soils, distinct eluvial and illuvial zones are present, with organic carbon, silts, fine sands and $CaCO_3$ being the primary constituents undergoing translocation. Quantity and mineralogical composition of the fine-earth appear to alter the pathways of pedogenesis. As the amount of fine-earth and the percentage of non-carbonate materials (derived from crystalline rocks) increase, cambic horizons with spodic morphology may develop.

## INTRODUCTION

This study documents and describes soil profiles containing 1–50% fine-earth (less than 2-mm diameter) by weight. Subrounded, gravelly (2–75-mm diameter) and cobbly (75–254-mm diameter) materials dominate the soil profiles, which are located on Bois Blanc Island, in Lake Huron, Michigan. The purpose of this study is to (1) characterize the soils, (2) discuss possible processes of development, and (3) ascertain the effects of relative quantity and mineralogy of the fine-earth fraction on their morphology.

## STUDY AREA

Bois Blanc Island lies near the straits of Mackinac, in northwestern Lake Huron, U.S.A. (Fig. 1). The straits were deglaciated about 11,200 years B.P. (Farrand and Eschman, 1974; Larsen, 1987). At this time, the island was

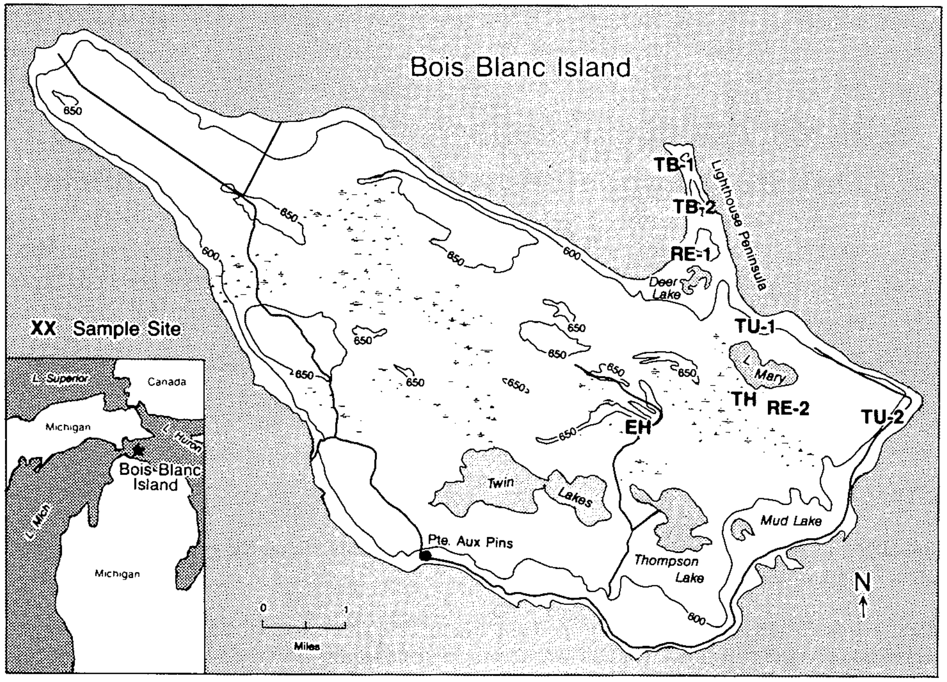

Fig. 1. The study area: Bois Blanc Island, northwestern Lake Huron, Michigan, U.S.A. Pedon locations are labelled as in Table II. Contour interval is 50 ft.

surrounded by glacial Lake Algonquin, which had a higher water level than does the modern Lake Huron. Isostatic rebound after deglaciation coupled with the emergence of lower outlets produced several major lake-level fluctuations during the Holocene (Larsen, 1987). These fluctuations resulted in the formation of at least three and possibly five or more shoreline features and beach terraces on Bois Blanc Island. Each beach terrace has several swells and bars ('storm ridges') composed of subrounded, dolomitic gravels and cobbles that are fragmental in character (U.S. Soil Survey Staff, 1975, p. 50), containing relatively few fine particles. The island has varying thicknesses of strongly calcareous glacial deposits, reflecting the influence of repeated Pleistocene glaciations and local Niagara dolomite bedrock. Sandy and loamy areas are present in the center of the island; these also have abundant coarse fragments.

The climate of the island is cool, humid continental. Mean monthly temperatures and precipitation totals for Cheboygan, a station 10 km to the south of the island, are reported in Table I. In comparison with sites of similar latitude at inland locations, temperature extremes on the island are moderated by surrounding waters. Snow cover is observed for 3–5 months per year. Soils

TABLE I

Mean monthly temperatures (in °C) and precipitation (in mm) for Cheboygan, Michigan

| | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | −7.2 | −7.2 | −2.4 | 4.8 | 11.2 | 16.6 | 20.0 | 19.3 | 15.1 | 9.6 | 2.6 | −4.0 |
| Precipitation | 36 | 30 | 41 | 62 | 65 | 68 | 74 | 75 | 97 | 54 | 62 | 48 |

Period of record was January 1951–December 1980. Source: NOAA (1957–87).

on the island are in the frigid soil temperature regime (U.S. Soil Survey Staff, 1975). None of the soils studied herein has been cultivated.

Second-growth forest covers more than 95% of the island. Northern white cedar (*Thuja occidentalis* L.) is found in nearly pure stands on wet sites and on dry, fragmental soils of high pH (over 8.00). Well-drained soils with more than 5% fine-earth are dominated by mixed coniferous/deciduous stands of eastern white pine (*Pinus strobus* L.), red pine (*P. resinosa* Ait.), sugar maple (*Acer saccharum* Marsh.), red maple (*A. rubrum* L.), northern red oak (*Quercus rubra* L.), yellow birch (*Betula alleghaniensis* Britt.), aspen (*Populus tremuloides* Michx.), and white birch (*Betula papyrifera* Marsh.).

## METHODS

Eight soil pits were excavated on stable uplands (less than 5% slope), at sites that were deemed representative of the gravelly parent materials on the island. Pedons were sampled by horizon. Content of cobbles (over 75-mm diameter) was estimated (Alexander, 1982). Bulk samples of 1500–10,000 g (approximate mean sample weight 3000 g) of the less than 75-mm diameter fraction were transported to the laboratory for characterization. Samples from organic horizons were smaller (50–800 g).

Air-dry samples were sieved to determine weight percentages of coarse fragments (over 2 mm). Particle-size analysis (PSA) of the fine-earth fraction (less than 2-mm diameter) was performed by pipette; carbonates were not removed from the sample before PSA (Lee et al., 1972). Because it is particularly effective on calcareous soils (Kilmer and Alexander, 1949), $(NaPO_3)_{13}\cdot Na_2O$ was used as the dispersant for the PSA. Soil pH was determined in $H_2O$, using 2:1 ratios for mineral soil samples and 8:1 ratios for organic horizons. Organic matter (OM) content of the fine-earth fraction was estimated by weight loss on ignition at 550°C (Sheldrick, 1984), and converted to organic carbon (OC) percentages by the equation $OC=OM/1.9$ (Broadbent, 1953). Inorganic carbon content was determined gravimetrically, using an $HCl\text{–}FeCl_2\cdot 4H_2O$ solution (Sheldrick, 1984). With the exception of PSA, all samples were run in duplicate and mean values are reported here.

The mineralogy of the 0.05–0.25-mm fraction (fine and very fine sand) was determined by X-ray diffraction (XRD). After grinding to pass a 0.05-mm sieve, the sands were placed on a slide as dry, random mounts, thereby minimizing the possibility of a particle-size gradient between the top and bottom of the sample. The samples were scanned with Cu K$\alpha$ radiation (35 kV, 20 mA) on a Phillips XRG 3100 diffraction unit. X-ray counts at peaks and background were determined by computer. The content of certain minerals was estimated semi-quantitatively by comparing selected peak heights for dolomite (*d*-spacing 2.89 Å), plagioclase feldspar (3.18 Å), and orthoclase feldspar (3.25 Å) with that of quartz (3.34 Å). These peaks were selected to avoid low-angle reflections and to minimize $2\theta$ distance between peaks being compared, thereby increasing both the precision and accuracy of the quantification procedure (Moore and Reynolds, 1989). Three slides were prepared and X-rayed for each horizon, and mean values are reported.

Mineralogy of the fine gravel fraction (2–6.3-mm diameter) was determined on 100–250-g samples by hand-separating acidic igneous (e.g. granite and rhyolite) and basic igneous (basalt, gneiss and schist) clasts from the remaining components (carbonate species, chert and quartz) (cf. Lee et al., 1972). Weight percentages were then calculated for the three subgroups.

The contents of crystalline rock fragments in the fine gravel fraction and of feldspars in the fine and very fine sand fraction were determined because these components can release cations such as Al and/or Fe that are involved in the podzolization process. It is preferable to exclude carbonate minerals (U.S. Soil Survey Staff, 1990) from this grouping, both because of their ubiquity and because Ca and Mg cations are usually antagonistic to podzolization. Chert and quartz are capable of releasing Al and/or Fe only if these elements are present as impurities, and were thus grouped with the carbonate rocks.

## RESULTS

### *Borofolists*

Typic Borofolists (TB-1 and TB-2; Tables II and III) on Bois Blanc Island occur as accumulations of litter in various stages of decomposition, above and within fragmental parent materials (Fig. 2). They are most common on wave-worked deposits corresponding to the lowest and most recent shoreline on the island, that of Lake Algoma. Beach deposits of this lake were subaerially exposed approximately 3200 years B.P. (Larsen, 1987).

The fine-earth content of Borofolists is typically less than 4–5% (Tables II and IV). Fine-earth in the interstices of the uppermost, gravelly horizons qualifies as organic soil material, hence the Folist suborder (U.S. Soil Survey Staff, 1975). All profiles have O–C or O–A–C horizon sequences. Dark (N 2/0 moist) coatings of colloidal organic matter cover 50–100% of the

TABLE II

Physical characterization data

| Horizon | Depth (cm) | Color moist (dry) | Particle-size (mm) distribution (wt.% of whole soil) | | | | | | Particle-size (μm) distribution (% of fine-earth) | | | | Particle-size class |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | > 75 | 19.1–75 | 12.7–19.1 | 6.35–12.7 | 2.0–6.35 | < 2 | 250–2000 | 50–250 | 2–50 | < 2 | |
| *Typic Borofolist, euic (TB-1)* | | | | | | | | | | | | | |
| Oi | 24–23 | n.d. | 0 | 0 | 0 | 0 | 0 | | | | | | |
| Oe | 23–21 | 2.5YR 2/2<br>(7.5YR 3/2) | 0 | 0 | 0 | 0 | 0 | | | | | | |
| Oa1 | 21–14 | 7.5YR 2/0<br>(10YR 2/2) | 0 | 0 | 4.1 | 30.8 | 7.3 | 57.8 | | | | | |
| Oa2 | 14–0 | (N 2/0)<br>(10YR 3/2) | 0 | 7.5 | 6.7 | 50.8 | 32.9 | 2.1 | | | | | exgr frag |
| C | 0–36+ | 5YR 3/1 | $5.0^{*1}$ | 23.1 | 21.3 | 36.7 | 13.1 | 0.9 | 23.4 | 2.1 | 3.8 | 70.6 | exgr C |
| *Typic Borofolist, euic (TB-2)* | | | | | | | | | | | | | |
| Oi | 7–6 | n.d. | 0 | 0 | 0 | 0 | 0 | | | | | | |
| Oe | 6–1 | 2.5YR 2.5/2<br>(7.5YR 3/2) | 0 | 0 | 0 | 0 | 0 | | | | | | |
| Oa | 1–0 | 2.5YR 2/0<br>(5YR 2.5/2) | 0 | 0 | 0 | 0 | 0 | | | | | | |
| A | 0–10 | 10R 2/1<br>(10YR 4/3) | 0 | 46.6 | 34.0 | 16.0 | 1.7 | 1.7 | 21.1 | 6.1 | 3.0 | 69.8 | exgr C |
| C1 | 10–51 | 7.5YR 3/2 | $25.0^{*1}$ | 41.5 | 18.6 | 13.4 | 0.3 | 1.1 | 10.1 | 4.8 | 79.7 | 5.4 | exgr sil |
| C2 | 51–76+ | 10YR 6/3 | $60.0^{*1}$ | $12.0^{*1}$ | $10.0^{*1}$ | $8.0^{*1}$ | $5.0^{*1}$ | $5.0^{*1}$ | 66.3 | 3.7 | 28.7 | 1.3 | exco csl |
| *Typic Udorthent, sandy–skeletal, frigid*$^{*2}$ *(TU-1)* | | | | | | | | | | | | | |
| Oi | 29–27 | n.d. | 0 | 0 | 0 | 0 | 0 | | | | | | |
| Oa | 27–0 | N 2/0<br>(N 2/0) | $5.0^{*1}$ | 43.6 | 26.4 | 15.4 | 3.5 | 6.1 | | | | | exgr frag |
| E | 0–16 | 10YR 4/2 | 0 | 16.1 | 23.1 | 32.7 | 22.4 | 5.9 | 89.3 | 0.4 | 7.3 | 3.0 | exgr cs |
| Bw | 16–36 | 10YR 3/3 | 0 | 11.3 | 23.5 | 44.0 | 15.4 | 5.9 | 76.6 | 1.5 | 19.1 | 2.8 | exgr lcs |
| 2C | 36–58+ | 10YR 6/3 | $10.0^{*1}$ | 8.9 | 2.7 | 15.3 | 38.4 | 24.7 | 90.0 | 0.6 | 6.2 | 3.3 | exgr cs |

TABLE II (continued)

| Horizon | Depth (cm) | Color moist (dry) | Particle-size (mm) distribution (wt.% of whole soil) | | | | | | Particle-size (μm) distribution (% of fine-earth) | | | | Particle-size class |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | > 75 | 19.1–75 | 12.7–19.1 | 6.35–12.7 | 2.0–6.35 | < 2 | 250–2000 | 50–250 | 2–50 | < 2 | |
| *Typic Udorthent, sandy–skeletal, frigid (TU-2)* | | | | | | | | | | | | | |
| Oe/Oa | 3–0 | 5YR 2.5/1&<br>N 2/0 (Oa) | 0 | 0 | 0 | 0 | 0 | | | | | | |
| A/E | 0–4 | 7.5YR 2/0<br>(7.5YR 5/0) | 0 | 2.0 | 8.1 | 19.1 | 23.3 | 47.5 | 75.7 | 3.9 | 20.1 | 0.3 | vgr frag |
| E | 4–10 | 10YR 4/1 | 0 | 12.7 | 2.7 | 7.9 | 30.5 | 46.1 | 93.2 | 1.3 | 5.3 | 0.2 | vgr cs |
| Bw1 | 10–15 | 10YR 5/3 | 0 | 15.0 | 14.8 | 16.2 | 21.4 | 32.7 | 87.1 | 1.2 | 6.3 | 5.4 | exgr lcs |
| Bw2 | 15–58 | 10YR 5/3 | 10.0*[1] | 35.8 | 10.3 | 7.3 | 17.2 | 19.3 | 86.1 | 0.4 | 10.6 | 2.9 | exgr lcs |
| 2C | 58–70+ | 10YR 6/3 | 60.0*[1] | 15.0*[1] | 7.0*[1] | 7.0*[1] | 6.0*[1] | 5.0*[1] | 80.0*[1] | 10.0*[1] | 8.0*[1] | 2.0*[1] | exco cs*[1] |
| *Rendollic Eutrochrept, loamy–skeletal, frigid (RE-1)* | | | | | | | | | | | | | |
| Oi | 5–3 | n.d. | 0 | 0 | 0 | 0 | 0 | | | | | | |
| Oe | 3–0 | 10R 2.5/1<br>(7.5YR 3/2) | 0 | 0 | 0 | 0 | 0 | | | | | | |
| A | 0–2 | 7.5YR 2/0<br>(7.5YR 3/0) | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| E | 2–13 | 10YR 4/1 | 0 | 17.6 | 34.7 | 25.6 | 8.4 | 13.7 | 43.2 | 2.3 | 51.0 | 3.5 | exgr sil |
| Bw1 | 13–16 | 10YR 2/2 | 0 | 12.6 | 27.0 | 39.4 | 15.7 | 5.3 | 56.4 | 2.7 | 8.2 | 32.8 | exgr sCl |
| Bw2 | 16–35 | 10YR 2/2 | 0 | 26.7 | 38.7 | 28.0 | 3.9 | 2.7 | 55.6 | 2.9 | 6.2 | 35.3 | exgr sCl |
| Bw3 | 35–50 | 10YR 2/2 | 0 | 28.6 | 24.8 | 34.6 | 9.6 | 2.4 | 30.6 | 4.1 | 58.1 | 7.2 | exgr sil |
| 2C | 50–80+ | 10YR 3/3 | 15.0*[1] | 42.5 | 15.8 | 11.5 | 13.2 | 1.9 | 75.2 | 1.4 | 21.0 | 2.4 | exgr lcs |
| *Rendollic Eutrochrept, loamy–skeletal, frigid (RE-2)* | | | | | | | | | | | | | |
| Oi | 7–5 | n.d. | 0 | 0 | 0 | 0 | 0 | | | | | | |
| Oa | 5–0 | 5YR 2.5/1<br>(7.5YR 4/1) | 0 | 0 | 0 | 0 | 0 | | | | | | |
| E | 0–27 | 7.5YR 6/2 | 0 | 10.0 | 17.9 | 32.0 | 26.8 | 13.3 | 85.8 | 1.7 | 10.2 | 2.3 | exgr cs |
| Bw1 | 27–53 | 10YR 5/3 | 0 | 16.5 | 21.8 | 24.5 | 10.8 | 26.4 | 77.0 | 10.5 | 5.8 | 6.7 | exgr lcs |
| Bw2 | 53–60 | 10YR 5/4 | 0 | 11.3 | 16.0 | 14.3 | 21.9 | 36.6 | 15.7 | 14.2 | 59.8 | 10.4 | exgr sil |
| 2BC | 60–71 | 10YR 3/3 | 0 | 14.3 | 34.6 | 33.7 | 13.3 | 4.1 | 59.3 | 15.2 | 18.1 | 7.4 | exgr sl |
| 3Cd | 71–97+ | 10YR 7/2 | 20.0*[1] | 25.0 | 8.5 | 11.8 | 11.4 | 23.2 | 85.7 | 9.3 | 4.2 | 0.8 | exgr cs |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Rendollic Eutrochrept with Bs horzions, loamy-skeletal, frigid (REBs-1)* | | | | | | | | | | | | | |
| Oi | 2–0 | n.d. | 0 | 0 | 0 | 0 | 0 | | | | | | |
| A | 0–8 | N 2/0<br>(10YR 4/1) | 0 | 6.4 | 7.1 | 14.4 | 23.3 | 48.8 | 46.4 | 12.5 | 36.5 | 4.6 | vgr sl |
| E | 8–18 | 7.5YR 5/2 | 10.0*[1] | 27.7 | 12.0 | 9.0 | 10.8 | 30.5 | 51.8 | 12.1 | 32.7 | 3.4 | exgr sl |
| Bs1 | 18–35 | 10YR 4/6 | 10.0*[1] | 18.0 | 8.0 | 12.0 | 15.4 | 36.7 | 45.2 | 10.6 | 35.6 | 8.6 | exgr sl |
| Bs2 | 35–46 | 7.5YR 4/4 | 5.0*[1] | 7.0 | 9.5 | 23.4 | 32.3 | 22.8 | 38.1 | 20.7 | 32.6 | 8.6 | exgr sl |
| 2BC | 46–54 | 10YR 4/3 | 20.0*[1] | 23.0 | 23.4 | 18.9 | 7.6 | 7.1 | 15.7 | 14.2 | 10.4 | 59.8 | exgr C |
| 2Cd | 54–75+ | 10YR 4/4 | 70.0*[1] | 2.2 | 3.4 | 5.8 | 8.1 | 10.6 | 88.5 | 1.6 | 8.2 | 1.7 | exco cs |
| *Rendollic Eutrochrept with Bs horizons, loamy-skeletal, frigid (REBs-2)* | | | | | | | | | | | | | |
| Oi | 5–4 | n.d. | 0 | 0 | 0 | 0 | 0 | | | | | | |
| Oe | 4–3 | 5YR 2.5/1<br>(10YR 2/2) | 0 | 0 | 0 | 0 | 0 | | | | | | |
| Oa | 3–0 | N 2/0<br>(10YR 2/1) | 0 | 0 | 0 | 0 | 0 | | | | | | |
| A | 0–6 | 5YR 2.5/1 | 0 | 41.9 | 24.5 | 19.1 | 6.1 | 8.4 | 61.3 | 10.2 | 25.1 | 3.4 | exgr lcs |
| EA | 6–15 | 10YR 4/1 | 5.0*[1] | 27.9 | 21.6 | 23.7 | 11.2 | 10.6 | 69.7 | 5.2 | 24.8 | 0.3 | exgr lcs |
| Bs | 15–38 | 10YR 4/3 | 5.0*[1] | 11.7 | 14.9 | 32.7 | 19.8 | 16.0 | 87.5 | 1.6 | 6.9 | 4.0 | exgr cs |
| Bhs | 38–57 | 5YR 2.5/1 | 5.0*[1] | 13.1 | 12.0 | 20.1 | 33.9 | 15.9 | 80.8 | 1.7 | 11.3 | 6.2 | exgr lcs |
| 2C | 57–80+ | 10YR 3/3 | 20.0*[1] | 34.8 | 20.6 | 20.1 | 3.6 | 1.0 | 32.6 | 17.3 | 43.8 | 6.3 | exgr sl |

*[1] Estimated.

*[2] Mineralogy families were not determined for the pedons under study.

Particle-size class abbreviations: frag=fragmental materials; ex=extremely; v=very; co=cobbly; gr=gravelly; c=coarse; f=fine; s=sand(y); si=silt(y); C=clay; l=loam(y). Terminology follows the U.S. Soil Survey Staff (1975).

TABLE III

Chemical and mineralogical data

| Horizon | <2-mm fraction | | | 2–6.3-mm fraction*1 | | 0.05–0.25-mm fraction | | |
|---|---|---|---|---|---|---|---|---|
| | pH $H_2O$ | Org. C by LOI (%) | Inorg. C (%) | Granitic gravels*2 (%) | Basaltic gravels*3 (%) | Dolomite/ quartz*4 | Plagioclase/ quartz*4 | Orthoclase/ quartz*4 |
| *Typic Borofolist (TB-1)* | | | | | | | | |
| Oi | 5.2 | | | | | | | |
| Oe | 5.6 | 46.6 | | | | | | |
| Oa1 | 7.6 | 31.5 | | | | | | |
| Oa2 | 7.8 | 20.0 | | 0 | tr*5 | | | |
| C | 7.9 | 13.5 | 8.1 | tr | tr | 76.3 | 0 | 1.0 |
| *Typic Borofolist (TB-2)* | | | | | | | | |
| Oi | 5.6 | | | | | | | |
| Oe | 5.8 | 45.5 | | | | | | |
| Oa | 5.1 | 37.3 | | | | | | |
| A | 7.6 | 16.2 | 4.7 | 1.0 | tr | 32.3 | 0.3 | 0.3 |
| C1 | 7.9 | 14.0 | 6.7 | 0 | 0 | 175.0 | 0.3 | 6.0 |
| C2 | 8.1 | 1.7 | 7.1 | n.d. | n.d. | 115.3 | 2.7 | 4.7 |
| *Typic Udorthent (TU-1)* | | | | | | | | |
| Oi | 5.4 | | | | | | | |
| Oa | 6.4 | 28.1 | | | | | | |
| E | 7.8 | 2.3 | 0.9 | 0 | tr | 59.0 | 1.3 | 1.7 |
| Bw | 7.9 | 2.0 | 0.9 | 0 | tr | 54.0 | 0.3 | 0.3 |
| 2C | 7.8 | 1.4 | 0.5 | 0 | tr | 14.0 | 1.0 | 4.3 |
| *Typic Udorthent (TU-2)* | | | | | | | | |
| Oe/Oa | 5.8 | 44.0 | | | | | | |
| A/E | 6.6 | 9.9 | 0 | tr | 0 | 0.3 | 6.0 | 9.3 |
| E | 6.7 | 1.5 | 0.4 | tr | tr | 1.0 | 1.3 | 2.0 |
| Bw1 | 7.6 | 1.5 | 0.5 | tr | tr | 13.3 | 3.0 | 2.0 |
| Bw2 | 8.1 | 2.8 | 0.5 | tr | tr | 165.3 | 3.7 | 3.3 |
| 2C | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| *Rendollic Eutrochrept (RE-1)* | | | | | | | | |
| Oi | 5.4 | | | | | | | |
| Oe | 4.9 | 44.7 | | | | | | |
| A | 4.6 | 17.2 | 0 | | | | | |
| E | 5.5 | 2.0 | 0.1 | 0.2 | tr | 1.0 | 13.3 | 4.7 |
| Bw1 | 6.6 | 5.8 | 1.2 | 0 | 0.5 | 11.7 | 6.0 | 6.0 |
| Bw2 | 7.9 | 8.4 | 1.9 | tr | 0.9 | 37.7 | 1.3 | 1.7 |
| Bw3 | 7.8 | 9.9 | 4.8 | 0.7 | tr | 110.3 | 4.7 | 1.3 |
| 2C | 8.2 | 1.2 | 3.1 | 1.4 | 1.0 | 342.3 | 15.0 | 28.7 |
| *Rendollic Eutrochrept (RE-2)* | | | | | | | | |
| Oi | 5.4 | | | | | | | |
| Oa | 4.6 | 34.9 | | | | | | |
| E | 5.1 | 1.3 | 0 | tr | tr | 0.3 | 2.0 | 3.0 |
| Bw1 | 6.6 | 1.7 | 0.2 | tr | tr | 7.0 | 2.7 | 45.0 |
| Bw2 | 7.7 | 0.7 | 0.3 | tr | 0.5 | 4.3 | 2.7 | 3.3 |
| 2BC | 7.9 | 2.8 | 0.3 | tr | tr | 2.3 | 9.3 | 5.0 |
| 3Cd | 8.1 | 0.5 | 1.5 | tr | 1.1 | 14.0 | 2.0 | 12.7 |

TABLE III (continued)

| Horizon | <2-mm fraction | | | 2–6.3-mm fraction*[1] | | 0.05–0.25-mm fraction | | |
|---|---|---|---|---|---|---|---|---|
| | pH $H_2O$ | Org. C by LOI (%) | Inorg. C (%) | Granitic gravels*[2] (%) | Basaltic gravels*[3] (%) | Dolomite/ quartz*[4] | Plagioclase/ quartz*[4] | Orthoclase/ quartz*[4] |
| *Rendollic Eutrochrept with Bs horizons (REBs-1)* | | | | | | | | |
| Oi | 5.7 | | | | | | | |
| A | 6.6 | 9.5 | 0.1 | 0.9 | tr | 0.3 | 9.7 | 3.0 |
| E | 6.9 | 0.8 | 0.2 | 1.3 | 1.4 | 0 | 4.3 | 4.0 |
| Bs1 | 6.2 | 1.7 | 0.2 | 0.7 | 2.4 | 0 | 2.3 | 15.7 |
| Bs2 | 6.1 | 5.5 | 0.4 | 0.5 | 3.1 | 0.7 | 1.3 | 1.7 |
| 2BC | 8.0 | 5.0 | 4.2 | 1.5 | 3.5 | 91.7 | 6.7 | 2.7 |
| 2Cd | 8.5 | 1.1 | 5.8 | 1.7 | 2.6 | 169.0 | 11.0 | 9.3 |
| *Rendollic Eutrochrept with Bs horizons (REBs-2)* | | | | | | | | |
| Oi | 5.4 | | | | | | | |
| Oe | 4.7 | 44.8 | | | | | | |
| Oa | 4.4 | 33.2 | | | | | | |
| A | 4.8 | 13.7 | 0.4 | tr | tr | 0 | 1.0 | 1.3 |
| EA | 4.5 | 3.0 | 0.2 | 0.8 | 0 | 0 | 3.7 | 5.0 |
| Bs | 5.3 | 1.4 | 0.1 | tr | tr | 0.7 | 3.7 | 4.0 |
| Bhs | 7.0 | 3.4 | 0.7 | 0.5 | 1.1 | 109.7 | 14.7 | 3.3 |
| 2C | 7.7 | 2.5 | 3.2 | 0.5 | 1.2 | 14.3 | 12.0 | 2.0 |

*[1] Weight percentage; the remainder of the gravels are primarily dolomite, with lesser amounts of chert and quartzite.

*[2] Includes rhyolitic species.

*[3] Includes schists and gneisses.

*[4] Ratio of XRD peak heights (× 100); mean of three observations.

*[5] Trace amounts (less than 0.1%).

surfaces of coarse fragments in O and A horizons, decreasing to 5–10% coverage in the upper C horizon. The amount of crystalline (igneous and metamorphic) fine gravel clasts is typically 0.1% or less, with the remainder being composed chiefly of dolomite and chert (Tables III and IV). The unweathered character of these soils is suggested by dolomite peak heights for the fine and very fine sand fraction that often exceed those of quartz, and by inorganic carbon contents greater than 5.0%.

Borofolist sites usually support nearly homogeneous white cedar stands. This species produced acidic litter that decomposes slowly. Needles removed from living trees had pH 5.2, whereas litter less than 1 year old was more acid (pH 4.9 and 4.5). The mor-like 'mat' that overlies the gravel-rich, often fragmental O horizons is thin (less than 10 cm) and acid (pedon TB-1; Table III). The organic cap is presumably much thinner now than before European settlement, as a result of extensive fires on the island in the early 1900s (see Diebold, 1941). Abundant charcoal fragments within the upper sola of these soils is taken as possible evidence of post-settlement fires.

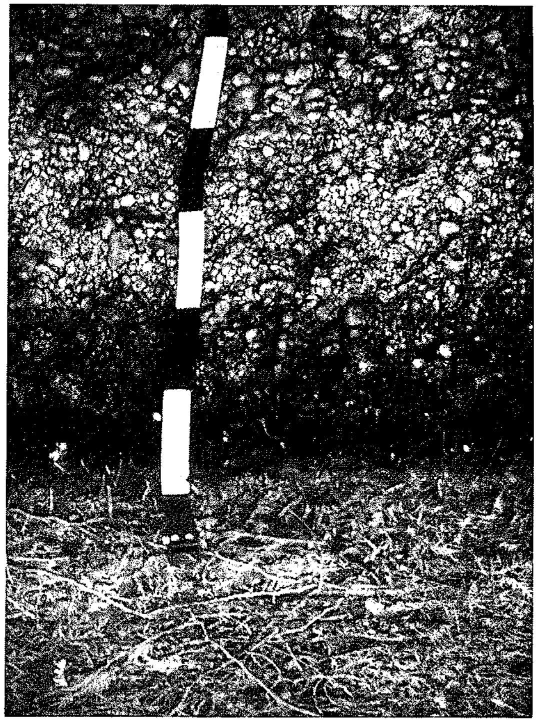

Fig. 2. The TB-1 profile (Typic Borofolist, euic). The tape is divided into 10-cm increments.

TABLE IV

Comparative soils data (in profile weighted mean percentages), by taxonomic groupings

| Group*[1] | Coarse fragments | Crystalline species in fine gravel fraction | Feldspar/quartz peak height*[2] |
|---|---|---|---|
| Borofolists | 95.1 | 0.1 | 4.3 |
| Udorthents | 84.3 | 0.0 | 5.0 |
| Eutrochrepts (Bw horizons) | 87.1 | 0.8 | 22.7 |
| Eutrochrepts (Bs horizons) | 82.7 | 2.2 | 12.6 |

*[1] Values for all pedons in each group are combined and averaged, providing a weighted profile mean.
*[2] Sum of plagioclase/quartz and orthoclase/quartz peak heights (Table III).

Organic materials in the interstices of the fragmental Oa horizons (pedon TB-1) occur as weak, medium, subangular blocky or granular peds, and have pH greater than 7.50 (Table III). At least some of the interstitial material is fecal pellets. Small earthworms are not uncommon in these soils, especially in Oa and A horizons.

### *Udorthents*

Typic Udorthents occur on parent materials similar to those of Borofolists but generally having more fine-earth (Tables II and IV). Udorthents often have a distinct eluvial–illuvial sequum, although the Bw horizons may be less an illuvial zone than a weathered, 'color' B horizon and are too coarse-textured to classify as cambic horizons. A horizons are thin or nonexistent in these soils. Gravel amounts and distributions suggest that these soils, like the Borofolists, have formed in shoreline deposits of ancestral Lake Algoma, although they are also found on older (Nipissing: 4000–4500 years B.P. and Algonquin: 11,200–10,300 years B.P. (Larsen, 1987)) deposits nearer the center of the island. Whereas Borofolists support impoverished stands of white cedar, hardwood forest (sugar maple, white birch and aspen) is found on Udorthents.

Udorthents with thick (over 20 cm) accumulations of fragmental materials (as O horizons) over a sandy–skeletal solum resemble Borofolists, but the latter soils lack E and Bw horizons (Tables II and III). Other sandy–skeletal Udorthents on the island have thinner O horizons and may contain as much as 50% fine-earth in the solum, most of which is coarse sand (TU-2; Table II). In these soils, the percentages of coarse gravel clasts may increase markedly near the base of the solum, often below a lithologic discontinuity. Eluvial horizons with uncoated coarse fragments (10YR 7/2 and 7/3; 7.5YR 6/0 moist) often occur above illuvial horizons that have dark reddish brown (5YR 3/2 moist) coatings on more than half of the clast surfaces, commonly on upper surfaces. Udorthents exhibit distinct, albeit small, feldspar peaks in the fine sand fraction, even within surface horizons. Additional similarities between Borofolists and Udorthents include a virtual lack of clasts from crystalline rocks in the fine gravel fraction and pH over 7.5 at very shallow (0–10-cm) depths (Tables III and IV).

### *Eutrochrepts with Bw horizons*

Rendollic Eutrochrepts (RE-1 and RE-2, Tables II and III) occur in loamy–skeletal families and often exhibit lithologic discontinuities. E horizons may exceed 10 cm in thickness, B horizons are often well developed, requiring subdivision (e.g. Bw1, Bw2 and Bw3), and are finer textured than are those of Udorthents. The increased clay and silt content of the Eutrochrepts' Bw horizons when compared with Udorthents may be both pedogenic and inherited from the parent material. A very dark, though thin and discontinuous Bh horizon at the top of the B is not uncommon (see Protz et al., 1984; Schuppli et al., 1988).

Lithologically, Eutrochrepts differ from the previous soils (Folists, Orthents) in the content of crystalline fine gravels and in feldspar peak heights in the fine sand fraction, which suggest improved fertility in Eutrochrepts (see Rivard and DeKimpe, 1980; Table IV). As in Udorthent pedons, those soils with a slightly higher percentage of fine-earth also tend to have more coarse sand, in effect compensating for the diminished coarse fragment content.

Eutrochrepts occur at higher elevations on Bois Blanc Island than do Udorthents and Borofolists, on surfaces associated with ancestral Lakes Nipissing and Algonquin. These soils may therefore be older than the Borofolists and some Udorthents.

Northern hardwoods are the most common forest assemblage found on these soils. White cedar is found as a minor component of the forest in locations where coarse fragments overwhelmingly dominate the solum (more than approximately 97–98%). At less gravelly sites white and yellow birch, sugar maple, white pine, and red maple comprise the majority of the overstory vegetation.

### *Eutrochrepts with Bs horizons*

Eutrochrepts with Bs horizons (pedons REBs-1 and -2; Tables II and III) are found near the center of the island, on deposits associated with later (lower) stages of glacial Lake Algonquin. These pedons narrowly miss the classification limits for Spodosols (U.S. Soil Survey Staff, 1975), and were sampled as Haplorthods because they exhibit strong, characteristic, Spodosol morphology. These soils are in loamy–skeletal families. As in other soils, contents of coarse fragments in these soils often exceed 70–80% (Table IV), and lithologic discontinuities are common. Free $CaCO_3$ has been removed from the eluvial and upper B horizons of these soils.

Gravel clasts within the eluvial zone have distinct weathering rinds and low particle densities, and although they lack organans, thin (less than 0.5 mm) coatings of silty and fine sandy material are present on most clasts. This may be due to the process of 'decarbonatization': disintegration of carbonate fragments without essentially disturbing the rock structure (Ciric, 1967), which begins at the periphery of the fragment and spreads inward.

Vegetation on spodic-like, Eutrochrept polypedons is typically mixed coniferous/deciduous forest.

## DISCUSSION

Soils developed in extremely gravelly and fragmental parent materials in humid climates are often replete with lithologic dicontinuities and low in water-holding capacity (Collins, 1976; Protz et al., 1984; Harden, 1988). Gravelly soils of late Pleistocene or Holocene age often lack indications of intense weathering (Wascher et al., 1960; Gaikawad and Hole, 1965). In such soils, parent material effects are predominant and dramatically influence the pathways of pedogenesis (Lee et al., 1972; Protz et al., 1984). Despite the extreme characteristics of these soils, many of the processes that are typical of less gravelly forest soils, such as podzolization, lessivage, and decalcification, are also found here. Subtle variations on these processes, however, are evident and may have been imposed by characteristics of the parent material. Interactions between parent material and process are discussed below.

Chemical weathering is continuing in these soils but may have been inhibited in rate and intensity because

(1) saturated hydraulic conductivities are so great that contact time between the water and soil solution is minimal (Levine et al., 1989),

(2) coarse textures provide for a limited amount of chemically reactive surface area per unit volume of soil, and

(3) water may flow through gravelly materials as small rivulets, failing to wet many rock surfaces (Elboushi, 1975).

Despite the high $CaCO_3$ content of the parent materials, the soils on Bois Blanc Island show abundant evidence of vertical translocation of organic materials, silts, and very fine sands. Although some of this translocation may have been accomplished via pedoturbation, infiltrating water has been operative as an agent of translocation, as shown by distinct eluvial and illuvial zones in many pedons.

Unlike that in most soils, pedogenesis in extremely gravelly soils may be as much determined by the character and amount of the gravel+sand fraction (size, mineralogy, degree of pre-weathering, etc.) as by the more chemically reactive clays and fine silts (Rivard and DeKimpe, 1980). As the content of fine-earth increases, however, the effects of sand and silt lithology may become increasingly important. Lithologic discontinuities, high coarse-fragment content, and extreme natural variability in pore-size distribution may promote irregular water movement through the solum, both in the vertical dimension (as 'hanging water'; Miller and Gardner, 1962; Vogelsanger, 1983) as well as the horizontal (as rivulets of flow between otherwise dry gravels (Elboushi, 1975)). Hill and Parlange (1972) and Starr et al. (1978) demonstrated that wetting fronts become unstable at fine over coarse layer contact zones, and often break up into 'fingers' or narrow columns of water.

Wetting fronts (or parts thereof) that slow or stop at sites of abrupt textural change may lead to deposition of solutes or suspended particles (Bartelli and Odell, 1960). Silt and clay deposits in spodic-like Eutrochrepts, occurring as lenses and laminar accumulations, are especially well developed immediately above and within the upper parts of coarse, gravelly zones at lithologic discontinuities. Although somewhat masked by overall horizon means, these increases in silt and clay are evident in pedons REBs-1 (2BC horizon) and REBs-2 (Bhs horizon: Table II). Deposition of this fine material could be promoted by changes in hydraulic conductivity at the discontinuity, which would stop wetting fronts and lead to the deposition of suspended materials

(Vogelsanger, 1983). Translocation by infiltrating water may also be partly responsible for coatings of (apparently) illuvial material on coarse fragments in B horizons (see Protz, 1983). Coatings on coarse fragments were observed within most illuvial horizons, and consisted primarily of colloidal organic matter with some silt and clay. These coatings are principally found on the upper surfaces of large clasts, and are thickest in cracks or depressions on these surfaces. Numerous small (less than 1-mm diameter) fecal pellets and other unrecognizable material in these depressions further suggests that they may be used by earthworms and other soil fauna for nesting and diapause (see Webster, 1965). Lack of particles coarser than fine sand in these coatings/deposits lends support to this hypothesis.

Observations on Bois Blanc indicate that age is an important, although perhaps not the primary, determinant of soil character. A general, albeit crude, development sequence of Borofolists–Udorthents–Eutrochrepts can be observed as one progresses from younger to older geomorphic surfaces. Soils with Bs horizons would not be expected on the youngest (Algoma) surface, as time has not been sufficient to form spodic morphology here (Franzmeier and Whiteside, 1963). Here, Borofolists and Udorthents dominate. The importance of age in pedogenesis is challenged by observations of polypedons of Udorthents, Borofolists, and Eutrochrepts within tens of meters of each other on similar geomorphic (Nipissing and Algonquin) surfaces. The influence of parent material effects in the determination of pathways and degree of soil development is illustrated by (1) observations of less-developed Udorthents near Eutrochrepts with spodic morphology, on Algonquin surfaces, and (2) lack of Borofolists on Algonquin surfaces, possibly because fragmental parent materials with less than 5% fine-earth seldom occur there.

B horizons have not formed in fragmental parent materials (Borofolists). Weak, coarse-textured Bw horizons form in Udorthents, where the fine-earth fraction exceeds approximately 5% and where the content of crystalline gravels and feldspar in the sand fraction is very low. Increased silt + clay, crystalline gravels, and feldspar content in Eutrochrepts promote stronger development; cambic (Bw) and spodic-like (Bs) horizons may occur. The relative abundance of crystalline clasts in the gravel fraction and feldspars in the sand fraction of Eutrochrepts with Bs horizons suggests that a source of Fe and Al is critical to their formation (Pedro et al., 1978). Soils that are exceptionally rich in quartz sand and low in Fe- and Al-bearing minerals generally cannot provide adequate amounts of metal cations for the development of a spodic horizon, and often develop into Quartzipsamments (Fanning and Fanning, 1989, p. 339). Data from soils on Bois Blanc Island suggest that similar pedogenic relationships hold for parent materials low in Fe- and Al-bearing minerals but high in dolomite and chert; such sediments will develop into Udorthents.

### *Taxonomic considerations*

At the family level, the modifier 'micro' is used in Histosols to indicate a lithic contact shallower than 18 cm. To convey additional information without major modifications of the classification criteria, it is suggested that the 'micro' family modifier also be used to indicate a contact with fragmental materials within 18 cm.

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