Soil Development as a Function of Time in the Rouge River Basin, South-Central Ontario

Le temps en tant que facteur du développement des sols dans le bassin de la rivière Rouge, au centre-sud de l’Ontario

Die Zeit als Faktor bei der Boden-Entwicklung im Bassin des Rouge River, südliches Zentral-Ontario

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Résumé de l'article

Trois sols postglaciaires en chronoséquence ont été étudiés en vue de déterminer les variations de leurs propriétés morphologiques, physiques, chimiques et minéralogiques. Ces sols, qui se sont formés dans des alluvions de minéralogie mixte, identifient des surfaces de l'Holocène supérieur (régosol), de l'Holocène moyen (brunisol) et de l'Holocène inférieur (brunisol). La differentiation des horizons et l'épaisseur du sol augmentent avec le temps, tandis que le pH diminue légèrement dans le solum des profils plus anciens. La capacité d'échange cationique (CEC) et la présence de matière carbonique dans les horizons de surface augmentent légèrement avec le temps, pendant que les rapports de CaCO₃ et de Ca/Mg diminuent en grande partie. Des changements importants surviennent avec le temps, surtout en ce qui a trait à l'augmentation du fer extractable à la dithionite (de ≃ 0,20 dans le sol de l'Holocène supérieur à ≃ 0,70 dans les profils de l'Holocène moyen et inférieur). Les teneurs en illite et en illite-smectite ont tendance à diminuer avec le temps pour être remplacées par de petites quantités de chlorite et de vermiculite. En dépit d'une certaine variation entre les matériaux parentaux en raison de la stratification et de phénomènes d'altération, et de différences mineures entre la composition des espèces, les changements qui affectent les propriétés des sols sont attribuables aux différents processus de formation des sols qui ont eu cours.
SOIL DEVELOPMENT AS A FUNCTION OF TIME IN THE ROUGE RIVER BASIN, SOUTH-CENTRAL ONTARIO

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ABSTRACT Three soils of postglacial age, representing a chronosequence in the Rouge River Basin of south-central Ontario, were studied to determine variations in morphological, physical, chemical, and mineralogical properties. These soils, forming in alluvium of mixed mineralogy represent the Late Holocene (Entisol), Middle Holocene (Inceptisol), and Early Holocene (Inceptisol) surfaces. Horizon differentiation and soil thickness increase with greater age, while pH drops slightly in the sola of the older profiles. Cation exchange capacity (CEC) and organic matter in the surface horizons increase slightly with age, while CaCO$_3$ and Ca/Mg ratio decrease. Significant changes occur over time, especially with an increase of di-thionite-extractable iron with age (from $\sim 0.20$ in the Late Holocene soil to $\sim 0.70$ in the Middle to Early Holocene profiles). Illite and illite-smectite tend to decrease with age, being replaced by small amounts of chlorite and vermiculite. In spite of some variability in parent materials due to stratification and pre-weathering, and minor changes in species composition, the changes in soil properties are attributed to processes of soil formation acting over time.

INTRODUCTION

Assessment of the time factor in soil formation is achieved using the chronosequence concept of JENNY (1941, 1980). This is defined as a sequence of soils developed in similar parent materials, and topographic settings, under the influence of nonvarying climatic and biotic factors whose different states can be attributed to lapse in time since the initiation of soil formation (time zero). The soil genesis process involves weathering and leaching, and determination of gains and losses, as well as transformations and translocations of organic and inorganic constituents. These variations are reflected in the morphological, physical, chemical and mineralogical properties of the soils.

Soil formation often involves increases in finer textures (BIRKELAND, 1984, p. 164-165), changes in structure (MAHANEY, 1974), solum thickness and horizon development (MAHANEY and FAHEY, 1980; CHARTRES, 1980), changes in surface and subsurface color DICKSON and CROCKER, 1954; MAHANEY, 1974, 1975, 1978), and removal of carbonates (CROCKER and MAJOR, 1955). Many chronosequence studies reveal that over time organic matter content increases, and soluble salts, basic cations and pH decrease (CROCKER and MAJOR, 1955; DICKSON and CROCKER, 1954; FRANZMEIER et al., 1963). The development of Fe oxides in the soil provides an index of time (ALEXANDER, 1974; CAMPBELL, 1971; MAHANEY and SANMUGADAS, 1986) and changes in clay mineralogy and total clay content reflect the time factor (AHMAD et al., 1977).

The Rouge River Basin of south-central Ontario provides an excellent location for the study of pedogenic processes operating in Holocene surficial materials. Stream incision and deposition of lag gravels and fine-grained alluvium have created a flight of stream terraces that are an integral part of the postglacial geological record. While minor differences in vegetation occur between the lower (2 m) and higher terrace tracts (8 and 15 m), analysis of the soils in these deposits provides important information on the role of time in soil development. The main objective in this paper is to determine the sequence and rate of soil development in postglacial fluvial materials in south-central Ontario.

FIELD AREA

The valleys of south-central Ontario are characterized by alluvial terraces and floodplain deposits formed by postglacial stream activity. Fluvial sediments in the Rouge River Valley (Fig. 1) are derived from a wide range of glacial and nonglacial deposits, which have shale, limestone, granitic, and gneissic clasts incorporated in them. Stream incision has given rise to surfaces of three distinct ages, shown in Figure 2. Sample site locations representing these surfaces are shown in Figure 1. The deposits are named from oldest to youngest: Rouge, Twyn Rivers, and Highland formations. Soils formed in these deposits are given the prefix “post”, to avoid a terminologic proliferation. The two oldest soils, post-Rouge and post-Twyn Rivers, developed mainly in pebbly loamy alluvium; the youngest soil — post-Highland — developed in pebbly sandy alluvium. Because the valleys are post-Glacial Lake Iroquois in age, the terraces and soils formed in them are considered to be of postglacial age. The soils are classified as a Cumulic Regosol (post-Highland soil), and Orthic Melanic Brunisols (post-Twyn Rivers and post-Rouge soils; CANADA SOIL SURVEY COMM., 1977). The post-Highland surface soil is estimated to be at least 3700 years old (Fig. 3) and undergoing continual deposition of sediments by river flooding. Using greater profile depth and horizon complexity with increasing age we consider the post-Twyn Rivers soil to be of Middle Holocene age, and the post-Rouge soil to be of Early Holocene age.

Soils were sampled in terrace surfaces with less than 1-2° slope. The climate of the area is humid continental, cool summer, no dry season type described by BROWN et al. (1968) and MAHANEY and ERMUTH (1974). The mean monthly temperature ranges from 20°C in July to -7° in January; extremes reach 40°C in July and -34°C in January. A frost-free period of 150 days lasts from mid-May to early-October. Wind in the area is dominantly westerly, and mean annual precipitation is 850 mm.

Soils were sampled in areas covered with sugar maple (Acer saccharum) and beech (Fagus grandifolia) stands (two highest surfaces) and willow (Salix fragilis; Salix nigra) stands (low surface). Some clearing for cultivation had occurred at site R12; sites R15 and R13 were undisturbed. While variations in vegetation occur between the low and higher terraces, the major differences in soil expression across the sequence are considered to result from increasing time.

METHODS

Duplicate soil samples were collected from each soil profile described in detail. Soil descriptions follow CANADA SOIL SURVEY COMM. (1977) and BIRKELAND (1984), while soil color was determined from the Standard Soil Color Charts of OYAMA and TAKEHARA (1970). Soil samples were air dried and passed through 2 mm sieves. For particle size analysis samples were treated with H2O2 to remove organic constituents, and with sodium pyrophosphate to achieve deflocculation. All samples were agitated with a Branson 350 cell dismembrator to separate clay constituents. Sands were separated by wet sieving using 63 μm sieves and coarse grain sizes were determined after dry sieving. Fine grain sizes of silt plus clay were determined by sedimentation following BOUYOCOS (1962) and DAY (1965). Samples (< 2 μm) were later centrifuged onto clay tiles and analyzed for clay mineral content by XRD (JACKSON, 1965; WHITTIG, 1965). Organic carbon was determined by the Walkley Black method (1934) and CaCO3 by acid neutralization. Soil pH was measured by electrode from a 1:1 paste in H2O. Cations were extracted with NH4OAc and determined using a Perkin Elmer 373 atomic absorption spectrophotometer. Iron was extracted with citrate-dithionite according to procedures established by MEHRA and JACKSON (1960) and determined by atomic

1. Particle size analysis follows FOLK (1968) where sand separates range from 2000-63 μm, silt from 63-2 μm, and clay < 2 μm.
FIGURE 1. Location map of the study area showing sampling sites of the three soils constituting a chronosequence.

FIGURE 2. Cross section of Rouge River Valley showing positions of Holocene deposits and soils.

RESULTS

The three soils were sampled to different depths as shown on Figure 3. Because the soils in each terrace are similar, results from one of each soil stratigraphic unit are presented. Only the parameters of importance to soil genesis are discussed below.

absorption spectroscopy. Samples for total Ca, Mg, K, Na, Fe, Si and Al analyses were mixed with lithium carbonate and boric acid, and the mixture fused at 1000 °C in a muffle furnace for 20 minutes (OMANG, 1969; BOAR and INGRAM, 1970). The cold melt was extracted with HC1 and analyzed using atomic absorption spectrophotometry.
MORPHOLOGY

The morphology of the three soils is presented below. Topsoil color was fairly uniform between the three soils, while subsoil (subsoil) color varied with a trend from light 10YR 5 and 6 values to darker 10YR 4 values over time. A parallel trend was observed with topsoil structure which ranged from weak granular in the youngest soil to a stronger grade of granular development in the older pedons. Structure below the topsoils in the lower solum and subsoil ranged from depositional stratification in the youngest profile (post-Highland soil) to weak blocky aggregates in the B horizons of the older soils (post-Twyn Rivers and post-Rouge soils). The consistency of the topsoil horizons did not differ appreciably, but some differences in the lower horizons were discernible. Coatings on ped faces occurred only in the B horizon of the oldest profile (post-Rouge soil). Increasing age of the soil was reflected by increased pedon depth, solum thickness, horizon complexity (especially the development of B horizons). Exact differences in profile depth as a function of age are complicated by the presence of buried soil horizons in the post-Highland soil.

R12 profile

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ahk</td>
<td>0-6</td>
<td>Yellowish brown (10YR 6/3m) and grayish yellow brown (10YR 5/2d) sandy loam, very weak granular structure, friable consistence, slightly plastic and nonsticky.</td>
</tr>
<tr>
<td>Cuk</td>
<td>6-17</td>
<td>Dull yellow (2.5Y 6/3m) and grayish yellow (2.5Y 6/2d) loamy sand, massive, friable to very friable consistence, slightly plastic and nonsticky.</td>
</tr>
<tr>
<td>Ahbk</td>
<td>17-23</td>
<td>Grayish yellow brown (10YR 4/2m) and brownish gray (10YR 5/1d) sandy loam, very weak granular structure, friable to firm consistence, plastic and slightly sticky.</td>
</tr>
<tr>
<td>Cubk</td>
<td>23-27</td>
<td>Dull yellow orange (10YR 6/3m) and grayish yellow brown (10YR 6/2d) sandy loam, massive, firm consistence, plastic and sticky.</td>
</tr>
<tr>
<td>Ahbk</td>
<td>27-46</td>
<td>Dull yellowish brown (10YR 4/3m) and grayish yellow brown (10YR 5/2d) sandy loam, weak granular structure, friable consistence, plastic and slightly sticky.</td>
</tr>
<tr>
<td>Cbk</td>
<td>46-76</td>
<td>Dull yellowish brown (10YR 5/4m) and dull yellow orange (10YR 6/3d) sandy loam, massive, firm to friable consistence, slightly plastic and sticky.</td>
</tr>
<tr>
<td>Cubk</td>
<td>76+</td>
<td>Yellowish brown (2.5Y 5/4m) and dull yellow orange (10YR 7/3d) sandy loam, massive, friable consistence, slightly plastic and slightly sticky.</td>
</tr>
</tbody>
</table>

2. Colors are given in the moist (m) and air-dry (d) states. Parent material is designated as Cu following BIRKELAND (1984). Consistence is given in the moist state.

R13 profile

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AhI</td>
<td>0-6</td>
<td>Brownish black (10YR 2/3m) and dull yellowish brown (10YR 5/3d) sandy loam, granular structure, friable consistence, plastic and slightly sticky.</td>
</tr>
<tr>
<td>Bm</td>
<td>11-28</td>
<td>Brown (10YR 4/4m) and dull yellow orange (10YR 6/4d) sandy loam, weak blocky structure, firm consistence, plastic and sticky.</td>
</tr>
<tr>
<td>Ck1</td>
<td>28-42</td>
<td>Dull yellowish brown (10YR 5/4m) and dull yellow orange (10YR 6/3d) loamy sand, massive, very friable to loose consistence, slightly plastic and nonsticky.</td>
</tr>
<tr>
<td>Ck2</td>
<td>42-66</td>
<td>Olive brown (2.5Y 4/4m) and dull yellow orange (10YR 6/3d) loamy sand, massive, very friable to loose consistence, nonplastic and nonsticky.</td>
</tr>
</tbody>
</table>

R15 profile

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ah</td>
<td>0-13</td>
<td>Brownish black (10YR 2/2m, 3/2d) sandy loam, granular structure, friable consistence, plastic and slightly sticky.</td>
</tr>
<tr>
<td>Bm1</td>
<td>13-46</td>
<td>Brown (10YR 4/4m) and dull yellow orange (10YR 7/4d) sandy loam, sub-angular blocky structure, firm consistence, plastic and slightly sticky.</td>
</tr>
<tr>
<td>Bm2</td>
<td>46-69</td>
<td>Brown (10YR 4/6m) and bright yellowish brown (10YR 7/6d) sandy loam, blocky structure, firm to friable consistence, plastic and slightly sticky.</td>
</tr>
<tr>
<td>Ck1</td>
<td>69-99</td>
<td>Yellowish brown (10YR 5/6m) and dull yellow orange (10YR 7/3d) sandy loam, massive, very friable, nonplastic and nonsticky.</td>
</tr>
<tr>
<td>Ck2</td>
<td>99-147</td>
<td>Bright yellowish brown (10YR 6/6m), olive brown (2.5Y 4/4m) and dull yellow orange (10YR 6/3d and 6/4d) sandy clay loam, massive, very friable to loose consistence, nonplastic and nonsticky.</td>
</tr>
<tr>
<td>Cuk</td>
<td>147+</td>
<td>Dull yellow (2.5Y 6/3m) and pale yellow (2.5Y 8/4d) loamy sand, massive, friable to very friable consistence, nonplastic and nonsticky.</td>
</tr>
</tbody>
</table>
SOIL DEVELOPMENT AS A FUNCTION OF TIME

PARTICLE SIZE

Data resulting from particle size analyses of the three soils are shown in Figure 4. While the distributions of sand and silt varied somewhat, the values for clay increased slowly with depth in the post-Highland soil. However, in the older post-Twyn Rivers soil, silt and clay are higher in the solum than in the subsoil and parent material. A similar pattern occurs in the post-Rouge soil where clay in the solum reaches 10%. The trend towards greater clay content in surface soil horizons with increasing age suggests increased production of clay over time as a function of weathering. It is also possible that these variations occur either as a function of paleohydrological changes in stream regimen during deposition, or as a result of airfall influx.

MINERALOGY

The results of X-ray diffraction analysis of the three profiles are presented in Table I. A comparison of individual horizons shows a tendency for illite in the youngest post-Highland soil to be replaced by vermiculite and chlorite in the older soils. Randomly interstratified illite-smectite, which is found in the parent materials of the post-Highland and post-Rouge soils, appears to decrease or disappear in the sola of the two oldest soils, possibly as a result of alteration to vermiculite and chlorite. Kaolinite content in the three soils is comparatively lower, although the highest amounts are found in the Ah horizons, which suggests aeolian influx.

SOIL CHEMISTRY

The data in Table II show several trends with age that are important in interpreting the overall soil evolutionary process. The organic carbon, N percent, and C/N ratios for the surface and buried sola in the post-Highland soil, as well as the sola of the two older profiles, indicate that the soils are in or close to equilibrium with present environmental factors. The increase in C/N with depth suggests that some carbon may be moving downward in all three soils, a factor which complicates the use of radiocarbon in dating buried horizons in the post-Highland soil. Soil pH tends to increase with depth; however,
for the most part soils were neutral to mildly alkaline. Only the Bm horizon in the post-Twyn Rivers soil decreased to slightly acidic.

The CaCO₃ content and the degree to which it has been leached from soil sola reflect on the parent materials and relative soil age. The percentage of CaCO₃ is high in all horizons of the post-Highland soil whereas considerable reduction and/or disappearance occurs in the older soils. In the sola of the post-Twyn Rivers and Rouge soils the percentage of CaCO₃ is either nil or reduced to one-third or less the value in the parent material.

Cation exchange values varied little between soils of different age, and the highest values occurred in surface (Ah horizons) or subsurface (Ahb) organic-rich horizons. Exchange sodium percentages (ESP) tend to decrease with age from the Ahk and buried A horizons in the post-Highland soil to the surface horizons in the older soils. The extractable Ca/Mg ratios in the surface horizons first decreased and then increased with age (e.g., 18, 14, 61, respectively). In general, the extractable iron data show that dithionite-citrate values, representing the combined organic + amorphous + crystalline Fe (total free iron), increased substantially between the post-Highland and the older soils. The Fe content in the post-Twyn Rivers and post-Rouge soils, while similar in amount, varies in position within the profile, suggesting that more time is required for movement downward into the B horizons.

DISCUSSION

Examination of the three soils in the chronosequence showed definite changes in soil parameters which reflect development over time. The most important expression of soil evolution results from the development of a B horizon.
SOIL DEVELOPMENT AS A FUNCTION OF TIME

TABLE I

X-ray diffraction analyses* of the clay size (<2 μm) material in the horizons of profiles R13, R12 and R15, Rough River drainage basin, south-central Ontario

<table>
<thead>
<tr>
<th>Site</th>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>K+</th>
<th>H+</th>
<th>I-S</th>
<th>V</th>
<th>Chl</th>
<th>Q</th>
<th>P</th>
<th>Calc</th>
</tr>
</thead>
<tbody>
<tr>
<td>R13</td>
<td>Ahk</td>
<td>0-6</td>
<td>x</td>
<td>tr</td>
<td>-</td>
<td>tr</td>
<td>-</td>
<td>xx</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Cuk</td>
<td>6-17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>nil</td>
</tr>
<tr>
<td></td>
<td>Ahbk</td>
<td>17-23</td>
<td>x</td>
<td>tr</td>
<td>x</td>
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<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>Cukb</td>
<td>23-27</td>
<td>tr</td>
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<td>tr</td>
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<td>-</td>
<td>-</td>
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<td></td>
<td>Ahbk</td>
<td>27-46</td>
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<tr>
<td></td>
<td>Ckbk</td>
<td>46-76</td>
<td>tr</td>
<td>tr</td>
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<td></td>
<td>Cbkbk</td>
<td>76+</td>
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<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>R12</td>
<td>Ah1</td>
<td>0-6</td>
<td>tr</td>
<td>-</td>
<td>-</td>
<td>tr</td>
<td>x</td>
<td>tr</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Ah2</td>
<td>6-11</td>
<td>tr</td>
<td>-</td>
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<td>tr</td>
<td>x</td>
<td>tr</td>
<td>x</td>
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<tr>
<td></td>
<td>Bm2</td>
<td>11-28</td>
<td>tr</td>
<td>-</td>
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<td>x</td>
<td>tr</td>
<td>x</td>
<td>x</td>
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<tr>
<td></td>
<td>Ck1</td>
<td>28-42</td>
<td>tr</td>
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<td>tr</td>
<td>tr</td>
<td>x</td>
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<td></td>
<td>Ck2</td>
<td>42-66</td>
<td>tr</td>
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<tr>
<td></td>
<td>Cuk</td>
<td>66+</td>
<td>-</td>
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<td>R15</td>
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<tr>
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<td>x</td>
<td>-</td>
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<td>x</td>
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<td>x</td>
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</tr>
<tr>
<td></td>
<td>Bm2</td>
<td>46-69</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
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<td></td>
<td>Ck1</td>
<td>69-99</td>
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<td>tr</td>
<td>x</td>
<td>x</td>
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<td></td>
<td>Ck2</td>
<td>99-147</td>
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<td></td>
<td>Cuk</td>
<td>147+</td>
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<td>tr</td>
<td>x</td>
<td>xxx</td>
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</tbody>
</table>

* Mineral abundance is based on peak height: nil (-); minor amount (tr); small amount (x); moderate amount (xx); abundant (xxx). Clay minerals are: kaolinite (K), halloysite (H); mixed-layer illite-smectite (I-S); vermiculite (V) and chlorite (Chl). Primary minerals are: quartz (Q); plagioclase (P), and calcite (Calc).

while \( \text{CaCO}_3 \) in the sola of the three soils decreased with age, the rate of change is considered slow when compared with similar studies elsewhere. SALISBURY (1925) found that \( \text{CaCO}_3 \) dropped from 6.3 to 0.9% in 300 years in sand dunes, HISSINK (1938) demonstrated that \( \text{CaCO}_3 \) in Dutch polders was completely leached in 260 years, and CROCKER and MAJOR (1955) estimated removal from the top 5 cm of soil in 50 years or less at Glacier Bay, Alaska. In areas closer to southern Ontario, OLSON (1958) determined that the top 2 m of sand dunes along the southern shore of Lake Michigan were leached of \( \text{CaCO}_3 \) in 1000 years. Geologic researchers in Illinois have used the depth of \( \text{CaCO}_3 \) leaching as a means of determining the relative age of the parent material. Surface tills of Wisconsinian age in Illinois are leached from 0.5 to 1.5 m depths, whereas tills of Illiniosian age are leached to depths of 2.5 to 3.5 m (THORP, 1968). This suggests a somewhat weaker environment for \( \text{CaCO}_3 \) leaching in south-central Ontario where removal appears to be a slow process. However,

and increase in solum thickness. Many researchers studying geomorphic surfaces have found similar trends (GAMBLE et al., 1970; MAHANEY, 1974, 1978). In addition, increased horizonation, higher grades of structure, changes in soil color and consistence attest to the increased action of pedogenic processes operating over time. The orderly textural changes with depth in the three soils may reflect weathering in situ, variations in the original parent material, or airfall influx of material. The amount of clay increased in the sola of the three soils with age; however, with depth clay increased in the younger soil and decreased in the two older soils. The presence of cutans in the oldest soil suggests that some clay is moving downward. This is further substantiated by the pattern of clay distributions with depth (Fig. 4).

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the depth of CaCO₃ leaching increases with the relative age of the parent material. Leaching at depth in the soil systems, however, may be retarded due to insufficient water or available water may be saturated with CaCO₃. Low values for CEC suggest insufficient time to form clay and build up humus in this environmental setting.

The ratio of extractable Ca/Mg appears to provide a parameter sensitive to change over time. A slight decline in Ca/Mg in the sola of the two older soils appears related to downward movement in the profiles, whereas the increase in Ca/Mg in the Ah horizon of the post-Rouge soil may be due to Ca recycling by plants.

The distribution of dithionite extractable Fe has been used by a number of workers as an index of soil development (ALEXANDER, 1974; MAHANEY and SANMUGADAS, 1986). The results in this study for dithionite extractable Fe show that it increases and changes position in the profile with age. The low values for the post-Highland soil compared with the older soils suggest it is considerably younger. Similar Fe₂O₃ values for the older soils indicate they are not too far apart in age; a comparison of values for the B horizons, however, suggest that R15 contains 1.4x as much Fe₂O₃ as R12.

Changes in clay mineralogy, reflecting the soil development process, have been cited by many workers (BREWER and WALKER, 1969; FRANZMEIER et al., 1963; MAHANEY, 1974, 1978; and MAHANEY and FAHEY, 1980). In this study decreasing illite and increasing proportions of vermiculite and chlorite suggest moderate weathering and slow removal of bases in the sola of the older soils. The origin of mixed-layer illite-smectite is unknown but it may be inherited from shale clasts in the parent material. The distribution pattern suggests it weathers easily to form other 2:1 and 2:1:1 clay minerals. Kaolinite is strongest in the sola of the older soils suggesting it may form either from reconstitution in situ or from hydration of feldspars.

Distributions of SiO₂ and Al₂O₃ with depth (Fig. 5 and 6) show an increase in soil sola (B horizons) and several trends with age that are important in clay mineral genesis. Aluminum released from weathering over the pH ranges in these profiles (7-8) may remain as an insoluble oxide for reaction with SiO₂ to form clay minerals. Here Al₂O₃ ranges from 7-10 % in the parent materials, increasing to 11.3 in the sola of the two older soils. The amount of SiO₂ available for reaction to form clay minerals depends on loss by leaching from the soil en-
The amount of SiO$_2$ in the parent materials clusters at approximately 55%, increasing to 70% in the solum of the post-Twyn Rivers soil and 75% in the post-Rouge soil. The amount of SiO$_2$ increases in the soil sola over time in spite of its higher solubility (100 ppm at pH’s of 7 to 8; KRAUSKOPF, 1967, p. 168), indicating that the leaching rate is not very great. With increasing SiO$_2$ content aluminosilicates may form.

The ratio of Si/Al necessary for clay minerals to form is 2.0 or more (Table III). In this soil sequence Si/Al ratios range from 5.3 to 7.7 with sufficient cation content for the development of chlorite, vermiculite and illite. It is also possible that some of the clay minerals in the older soils form by alteration of micas or from pre-existing clay minerals derived from glacial and nonglacial deposits in the basin. Such alterations allow changes in the interlayer areas where ions can be exchanged, new ions introduced, or SiO$_2$ removed.

Analysis of total amounts of CaO, MgO, K$_2$O, Na$_2$O, and Fe$_2$O$_3$ were made to determine parent material uniformity as well as the magnitude of movement in the three profiles. The data in Table III reveal only slight differences between MgO, K$_2$O, Na$_2$O and Fe$_2$O$_3$; while CaO is significantly lower in the parent materials (Cuk and Cubk horizons) in the R12 profile. Slight changes in CaO in the R13 profile, between the A and C horizons, reflect the small amount of time available for leaching in the lower pedon; however, in the R12 and R15 soil sola considerably greater amounts of CaO have been removed. The data for MgO, K$_2$O, and Na$_2$O yield fairly uniform distributions with depth suggesting little movement through the profiles, including the loess/fluvioglacial gravel units in the older R12 and R15 soils. The depth-distributions for Fe$_2$O$_3$, while uniform in R13, tend to increase slightly in the B horizons of profiles R12 and R15, the apparent result of slight increases in the amount of iron liberated by soil-forming processes.

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