

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 différenciation 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 CaCo_3 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 extractible à la dithionite (de $\approx 0,20$ dans le sol de l'Holocène supérieur à $\approx 0,70$ 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 soils of the older profiles. Cation exchange capacity (CEC) and organic matter in the surface horizons increases slightly with age, while, for the most part, CaCO₃ and Ca/Mg ratio decrease. Significant changes occur over time, especially with an increase of dithionite-extractable iron with age (from ~ 0.20 in the Late Holocene soil to ~ 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.

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

ZUSAMMENFASSUNG Die Zeit als Faktor bei der Boden-Entwicklung im Bassin des Rouge River, südliches Zentral-Ontario. Drei postglaziale Böden, die im Bassin des Rouge River im südlichen Zentral-Ontario eine Chronosequenz bilden, wurden untersucht, um Variationen in ihren morphologischen, physikalischen, chemischen und mineralogischen Eigenschaften zu bestimmen. Diese Böden, die sich in Alluvionen gemischter Mineralogie gebildet haben, weisen Oberflächen des späten Holozän (*Entisol*), des mittleren Holozän (*Inceptisol*) und des frühen Holozän (*Inceptisol*) auf. Die Differenzierung der Horizonte und die Dicke der Böden nehmen mit dem Alter zu, während das pH in den Böden der älteren Profile leicht abnimmt. Die Kation Austausch-Fähigkeit (CEC) und organisches Material in den Oberflächen-Horizonten nimmt mit dem Alter leicht zu, während das Verhältnis von CaCO₃ und Ca:Mg abnimmt. Bedeutende Veränderungen treten mit der Zeit auf, insbesondere mit der Zunahme von mittels Dithionit extrahierbarem Eisen (von ~ 0.20 in dem späten Holozän-Böden bis ~ 0.70 in den Profilen des mittleren und frühen Holozän). Illit und Illit-Smektit neigen mit dem Alter zur Abnahme und werden durch kleine Mengen von Chlorit und Vermikulit ersetzt. Trotz einer gewissen Variabilität in verwandten Materialien, die auf Stratifizierung und Verwitterung beruhen, und unbedeutenderen Veränderungen in der Spezies-Komposition, werden die Veränderungen in den Böden-Eigenschaften auf die Prozesse in der Böden-Bildung zurückgeführt, die über die Zeit stattgefunden haben.

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 exist 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 analysis¹ 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 BOUYOUCOS (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.

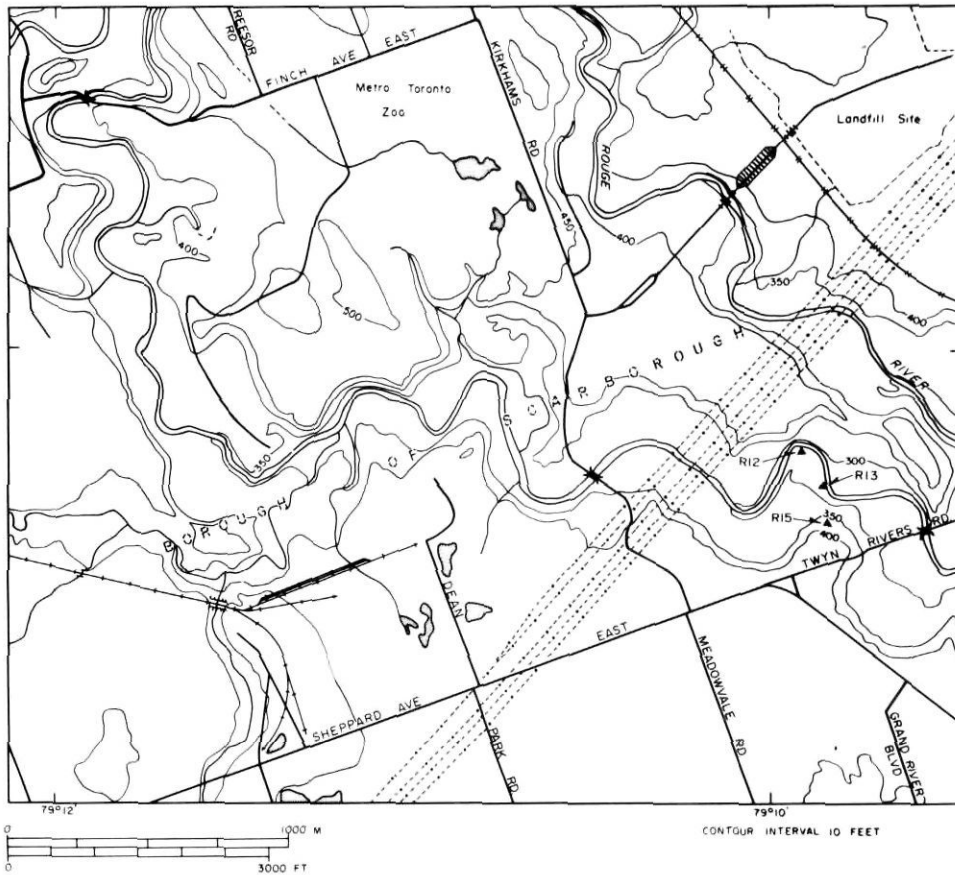


FIGURE 1. Location map of the study area showing sampling sites of the three soils constituting a chronosequence.

Carte de localisation de la région à l'étude et des sites d'échantillonnage des trois sols en chronoséquence.

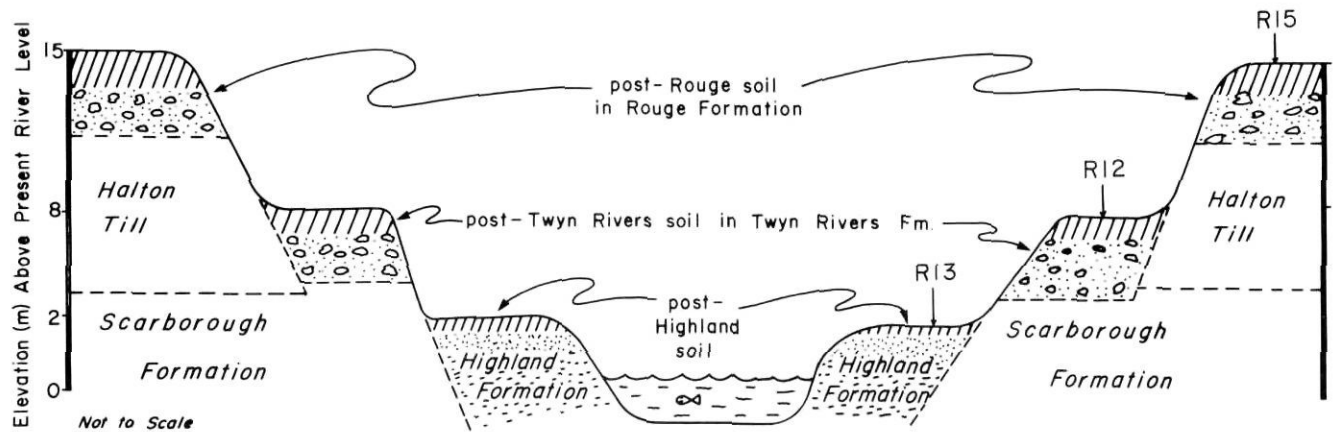


FIGURE 2. Cross section of Rouge River Valley showing positions of Holocene deposits and soils.

Coupe de la vallée de la rivière Rouge montrant l'emplacement des dépôts et des sols datant de l'Holocène.

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 HCl and analyzed using atomic absorption spectrophotometry.

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.

MORPHOLOGY

The morphology of the three soils is presented below. Topsoil color was fairly uniform between the three soils, while subsoil (subsolum) 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 consistence 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.

R13 profile

<i>Horizon</i>	<i>Depth (cm)</i>	<i>Description²</i>
Ahk	0-6	Yellowish brown (10YR 6/3m) and grayish yellow brown (10YR 5/2d) sandy loam, very weak granular structure, friable consistence, slightly plastic and nonsticky.
Cuk	6-17	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.
Ahbk	17-23	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.
Cubk	23-27	Dull yellow orange (10YR 6/3m) and grayish yellow brown (10YR 6/2d) sandy loam, massive, firm consistence, plastic and sticky.
Ahbk	27-46	Dull yellowish brown (10YR 4/3m) and grayish yellow brown (10YR 5/2d) sandy loam, weak granular structure, friable consistence, plastic and slightly sticky.
Cbk	46-76	Dull yellowish brown (10YR 5/4m) and dull yellow orange (10YR 6/3d) sandy loam, massive, firm to friable consistence, slightly plastic and sticky.
Cubk	76 +	Yellowish brown (2.5Y 5/4m) and dull yellow orange (10YR 7/3d) sandy loam, massive, friable consistence, slightly plastic and slightly sticky.

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.

R12 profile

<i>Horizon</i>	<i>Depth (cm)</i>	<i>Description</i>
Ah1	0-6	Brownish black (10YR 2/3m) and dull yellowish brown (10YR 5/3d) sandy loam, granular structure, friable consistence, plastic and slightly sticky.
Ah2	6-11	Brownish black (10YR 3/2m) and dull yellowish brown (10YR 5/3d) sandy loam, granular structure, friable consistence, plastic and slightly sticky.
Bm	11-28	Brown (10YR 4/4m) and dull yellow orange (10YR 6/4d) sandy loam, weak blocky structure, firm consistence, plastic and sticky.
Ck1	28-42	Dull yellowish brown (10YR 5/4m) and dull yellow orange (10YR 6/3d) loamy sand, massive structure, very friable consistence, slightly plastic and nonsticky.
Ck2	42-66	Olive brown (2.5Y 4/4m) and dull yellow orange (10YR 6/3d) loamy sand, massive, very friable to loose consistence, nonplastic and nonsticky.
Cuk	66 +	Dull yellow (2.5Y 6/3m) and dull yellow orange (10YR 6/3d) loamy sand, massive, very friable to loose consistence, nonplastic and nonsticky.

R15 profile

<i>Horizon</i>	<i>Depth (cm)</i>	<i>Description</i>
Ah	0-13	Brownish black (10YR 2/2m, 3/2d) sandy loam, granular structure, friable consistence, plastic and slightly sticky.
Bm1	13-46	Brown (10YR 4/4m) and dull yellow orange (10YR 7/4d) sandy loam, sub-angular blocky structure, firm consistence, plastic and slightly sticky.
Bm2	46-69	Brown (10YR 4/6m) and bright yellowish brown (10YR 7/6d) sandy loam, blocky structure, firm to friable consistence, plastic and slightly sticky.
Ck1	69-99	Yellowish brown (10YR 5/6m) and dull yellow orange (10YR 7/3d) sandy loam, massive, very friable, nonplastic and nonsticky.
Ck2	99-147	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.
Cuk	147 +	Dull yellow (2.5Y 6/3m) and pale yellow (2.5Y 8/4d) loamy sand, massive, friable to very friable consistence, nonplastic and nonsticky.

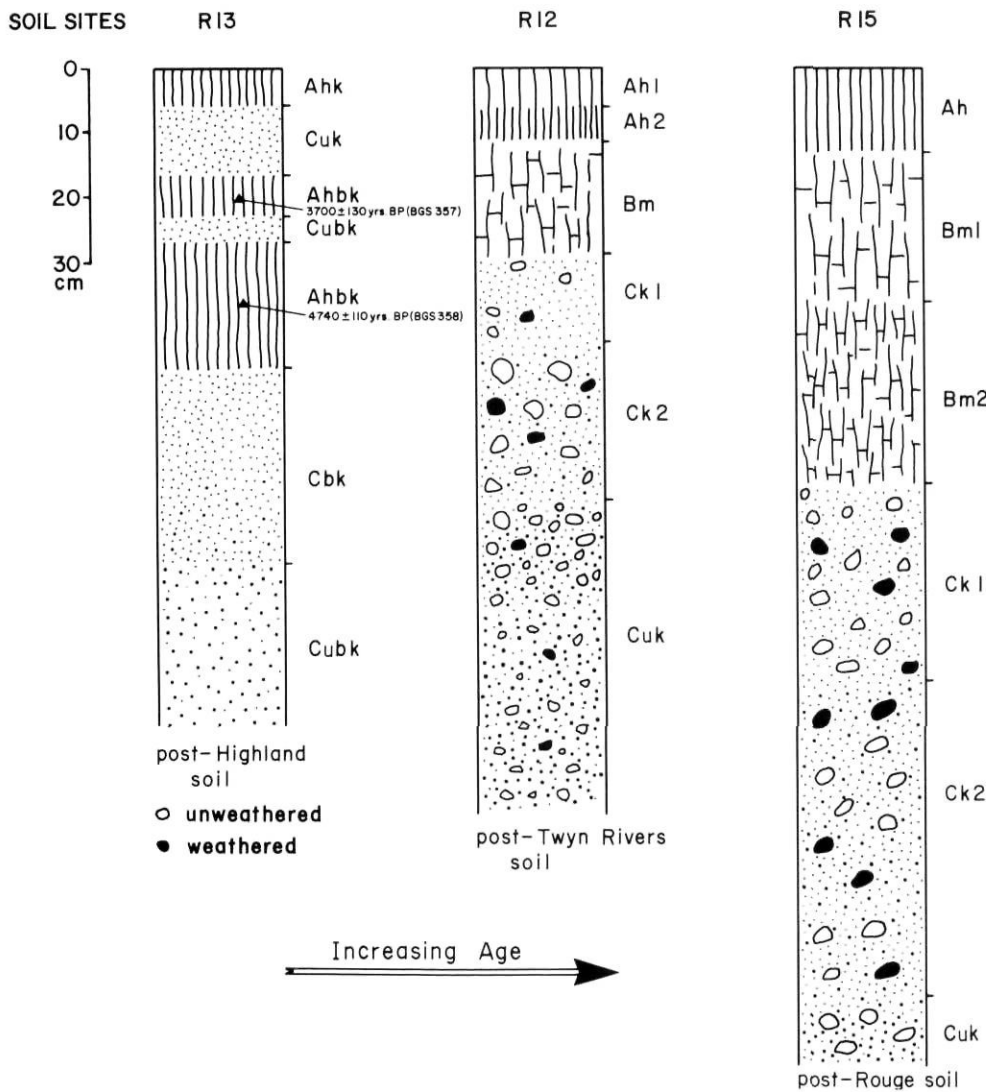


FIGURE 3. Soil profiles in the Rouge River chronosequence showing relative horizon development and radiocarbon ages for the buried soils in the R13 soil profile.

Profils des sols en chronoséquence de la rivière Rouge montrant le développement propre à chacun des sols et les datations au radiocarbone faites dans les profils enfouis du sol n° R13.

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,

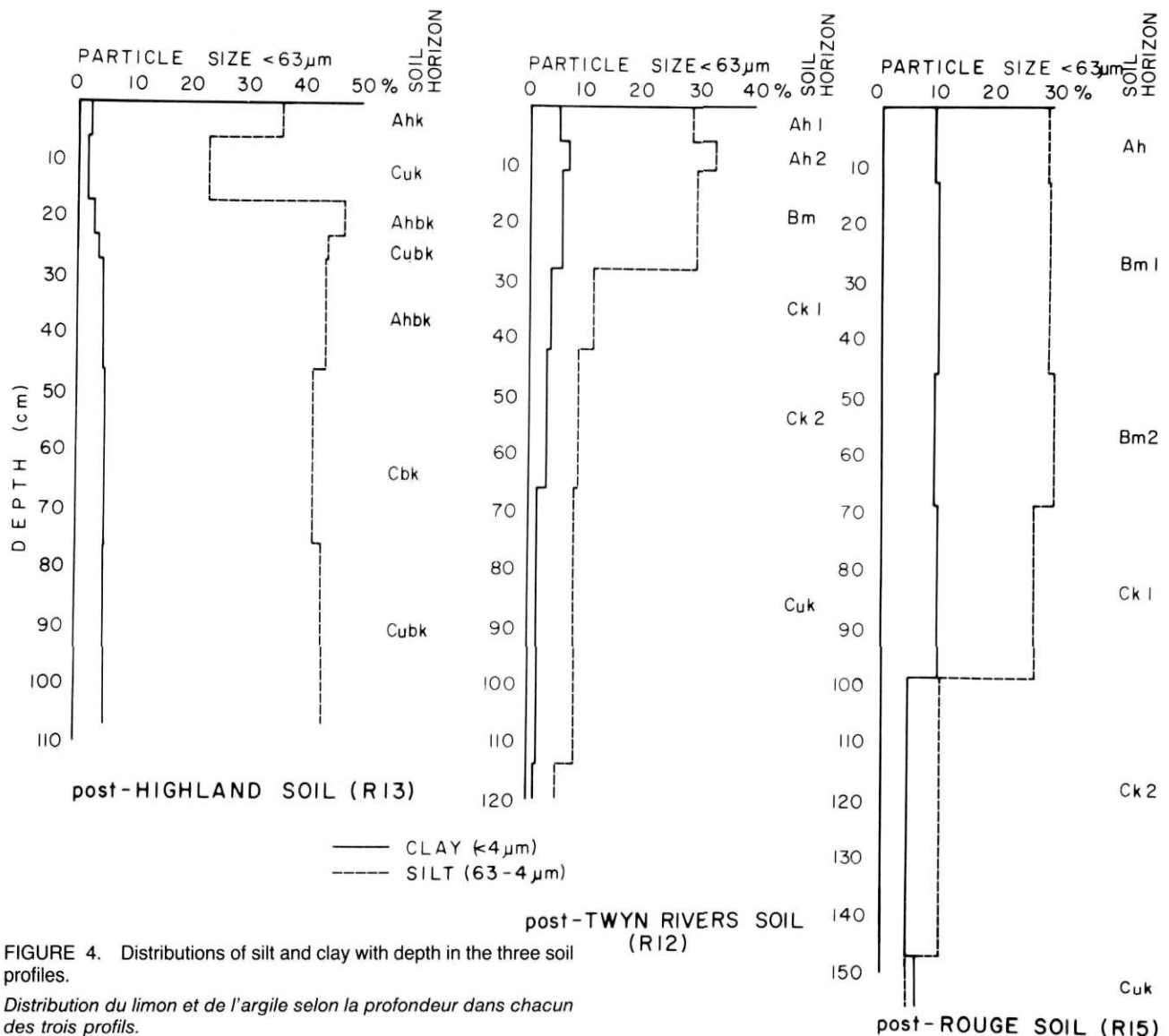


FIGURE 4. Distributions of silt and clay with depth in the three soil profiles.

Distribution du limon et de l'argile selon la profondeur dans chacun des trois profils.

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 CaCO_3 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 CaCO_3 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 CaCO_3 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

TABLE I

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

Site	Horizon	Depth (cm)	K	H	I	I-S	V	Chl	Q	P	Calc
R13	Ahk	0-6	x	tr	x	-	tr	-	xxx	x	x
	Cuk	6-17	-	-	-	-	-	-	xxx	x	-
	Ahbk	17-23	x	tr	x	tr	tr	-	xxx	x	tr
	Cubk	23-27	tr	tr	tr	-	tr	-	xxx	x	tr
	Ahbk	27-46	tr	-	tr	tr	tr	-	xxx	x	tr
	Cbk	46-76	tr	tr	x	x	tr	-	x	x	tr
	Cubk	76+	tr	-	x	x	tr	-	xx	x	x
R12	Ah1	0-6	tr	-	-	tr	x	tr	xx	x	tr
	Ah2	6-11	tr	-	-	-	-	tr	xx	tr	-
	Bm2	11-28	tr	-	tr	tr	x	tr	xx	x	-
	Ck1	28-42	tr	-	tr	tr	tr	tr	xxx	tr	-
	Ck2	42-66	tr	tr	tr	tr	tr	-	xx	x	tr
	Cuk	66+	-	-	-	-	-	xxx	x	x	
R15	Ah	0-13	-	-	-	-	tr	-	xxx	x	x
	Bm1	13-46	x	-	-	-	xx	x	xxx	x	tr
	Bm2	46-69	tr	tr	tr	tr	x	tr	xx	tr	-
	Ck1	69-99	tr	-	tr	-	tr	-	xx	tr	-
	Ck2	99-147	tr	tr	tr	x	tr	-	xx	x	tr
	Cuk	147+	tr	-	-	x	tr	-	xx	tr	xxx

* 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).

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).

While CaCO₃ 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 CaCO₃ dropped from 6.3 to 0.9 % in 300 years in sand dunes, HISSINK (1938) demonstrated that CaCO₃ 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 CaCO₃ in 1000 years. Geologic researchers in Illinois have used the depth of CaCO₃ leaching as a means of determining the relative age of the parent material. Surface tills of Wisconsinan age in Illinois are leached from 0.5 to 1.5 m depths, whereas tills of Illinoian age are leached to depths of 2.5 to 3.5 m (THORP, 1968). This suggests a somewhat weaker environment for CaCO₃ leaching in south-central Ontario where removal appears to be a slow process. However,

TABLE II

Selected chemical properties of the <2 mm fractions of the soil horizons described in the text

Site*	Horizon	Depth (cm)	pH 1:1	E.C. (mmhos/cm 25°C)	CEC (meq/100)	Extractable Cations (meq/100g)					Base Saturation %	Organic Carbon %	N %	C/N	CaCO ₃ %	Fe ₂ O ₃ (Dithionite extractable) %	
						Ca ⁺²	Mg ⁺²	Na ⁺	K ⁺	Ca/Mg							ESP
R13	Ahk	0-6	7.04	0.70	7.99	7.13	0.39	0.07	0.21	18	0.88	97	2.54	0.172	14.8	26.35	0.20
	Cuk	6-17	7.27	0.34	1.58	3.88	0.19	0.10	0.05	20	6.33	100	0.27	0.025	10.8	21.34	0.13
	Ahbk	17-23	7.20	0.50	10.69	7.50	0.31	0.07	0.07	24	0.66	74	1.79	0.161	11.1	50.05	0.23
	Cubk	23-27	7.27	0.45	4.18	6.25	0.23	0.05	0.04	27	1.20	100	0.60	0.056	10.7	26.77	0.20
	Ahbk	27-46	7.27	0.62	8.37	8.75	0.27	0.07	0.05	32	0.84	100	1.45	0.144	10.1	22.53	0.21
	Cbk	46-76	7.36	0.44	3.44	4.88	0.25	0.13	0.05	20	3.78	100	0.46	0.055	8.4	32.78	0.21
	Cubk	76+	7.46	0.48	2.88	6.00	0.23	0.23	0.05	26	7.99	100	0.31	0.030	10.3	33.00	0.19
R12	Ah1	0-6	7.13	0.46	11.07	5.00	0.37	0.07	0.15	14	0.63	50	2.92	0.211	13.8	nil	0.76
	Ah2	6-11	6.94	0.36	8.70	3.88	0.23	0.07	0.07	17	0.81	49	1.93	0.134	14.4	nil	0.63
	Bm	11-28	6.18	0.30	5.24	2.63	0.08	0.10	0.05	33	1.91	55	0.73	0.064	11.4	nil	0.51
	Ck1	28-42	6.45	0.45	2.62	5.63	0.19	0.05	0.04	30	1.91	100	0.31	0.035	8.9	22.98	0.29
	Ck2	42-66	6.77	0.50	2.20	6.25	0.19	0.12	0.05	33	5.40	100	0.17	0.025	6.8	60.45	0.29
	Cuk	66+	7.06	0.35	1.61	6.25	0.17	0.07	0.02	37	4.35	100	0.08	0.005	14.0	66.25	0.16
R15	Ah	0-13	6.94	1.40	10.88	4.88	0.08	0.07	0.23	61	0.64	48	2.75	0.181	15.2	nil	0.54
	Bm1	13-46	7.04	0.28	5.30	2.70	0.19	0.05	0.05	14	0.94	56	0.73	0.052	14.0	nil	0.59
	Bm2	46-69	7.25	0.49	5.95	6.25	0.25	0.14	0.09	25	2.35	100	0.50	0.052	9.6	20.68	0.70
	Ck1	69-99	7.49	0.35	2.97	6.25	0.25	0.13	0.05	25	4.38	100	0.22	0.026	8.5	64.05	0.39
	Ck2	99-147	7.53	0.42	2.97	6.25	0.23	0.12	0.05	27	4.04	100	0.27	0.025	10.8	73.00	0.33
	Cuk	147+	7.65	0.26	2.70	7.50	0.27	0.07	0.07	28	2.59	100	0.08	0.010	8.0	69.65	0.33

* Site locations are on Figure 1.

the depth of CaCO_3 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 CaCO_3 . 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 Fe_2O_3 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 Fe_2O_3 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 SiO_2 and Al_2O_3 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 SiO_2 to form clay minerals. Here Al_2O_3 ranges from 7-10 % in the parent materials, increasing to 11.3 in the sola of the two older soils. The amount of SiO_2 available for reaction to form clay minerals depends on loss by leaching from the soil en-

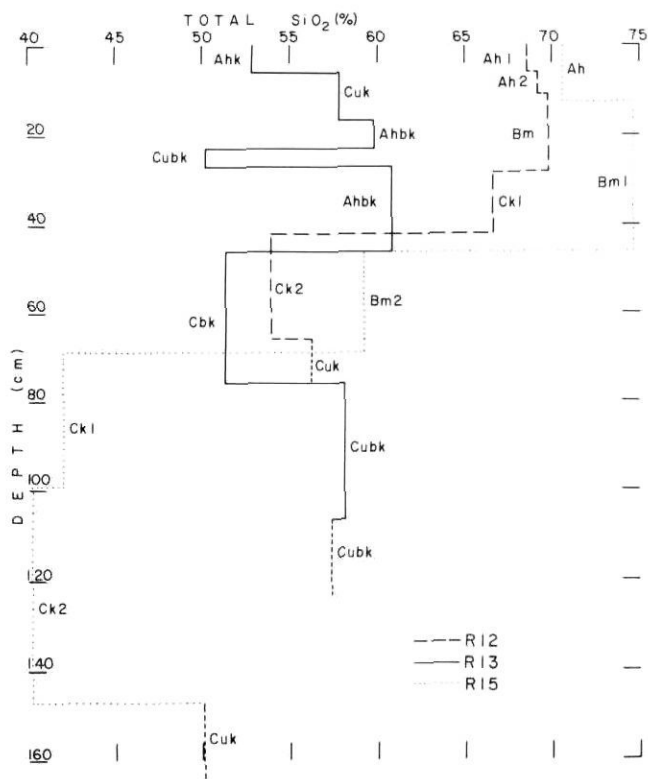


FIGURE 5. Distribution of SiO_2 with depth in the Rouge River soil chronosequence.

Distribution du SiO_2 selon la profondeur dans la chronoséquence des sols de la rivière Rouge.

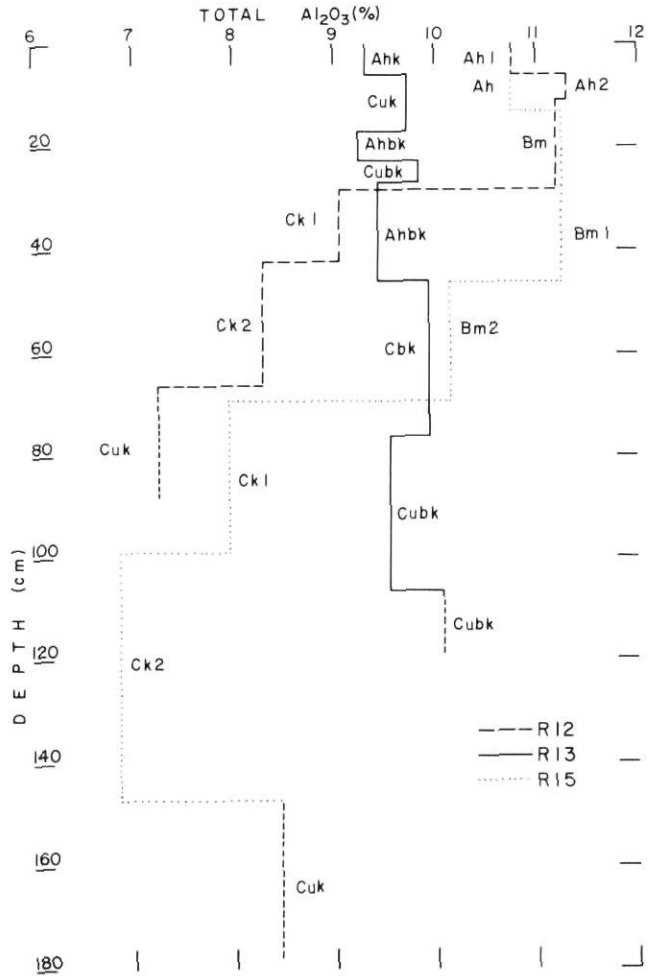


FIGURE 6. Distribution of Al_2O_3 with depth in the Rouge River soil chronosequence.

Distribution du Al_2O_3 selon la profondeur dans la chronoséquence des sols de la rivière Rouge.

vironment. The amount of SiO₂ 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 SiO₂ 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 SiO₂ 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 SiO₂ removed.

Analysis of total amounts of CaO, MgO, K₂O, Na₂O, and Fe₂O₃ 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, K₂O, Na₂O and Fe₂O₃, 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, K₂O, and Na₂O yield fairly uniform

distributions with depth suggesting little movement through the profiles, including the loess/fluvial gravel units in the older R12 and R15 soils. The depth-distributions for Fe₂O₃, 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.

CONCLUSION

In summary, this study shows with age changes occur in morphological, physical, mineralogical and chemical soil properties in south-central Ontario. Some of these changes may be attributed to variability in the parent material, while others, such as profile depth, solum thickness, structure development, leaching of CaCO₃, and genesis of clay minerals are due to pedogenic processes during soil development. Some of the chemical data serve to corroborate this sequence of events. Although weathering rates appear low to moderate, it is not possible to specify the precise time required for formation of specific soil properties.

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TABLE III
*Distribution of total elements (%) in the Rouge River
chronosequence, south-central Ontario*

Site	Horizon	Depth	CaO	MgO	K ₂ O	Na ₂ O	Fe ₂ O ₃	Si/Al Quotient*
R13	Ahk	0-6	7.9	1.1	1.3	2.1	2.6	5.7
	Cuk	6-17	8.0	1.2	1.8	2.4	2.5	6.0
	Ahbk	17-23	7.6	1.4	1.4	2.2	2.8	6.5
	Cubk	23-27	9.1	1.5	1.9	2.3	2.2	5.1
	Ahbk	27-46	7.0	1.4	1.6	2.3	2.7	6.2
	Cbk	46-76	8.6	1.3	1.5	2.2	2.3	5.5
	Cubk	76+	9.8	1.4	1.9	2.3	2.2	6.1
R12	Ah1	0-6	2.1	0.8	1.7	2.2	2.8	6.4
	Ah2	6-11	1.9	0.7	1.8	2.3	3.1	6.1
	Bm	11-28	2.0	0.8	2.0	2.4	2.4	6.2
	Ck1	28-42	8.6	0.8	1.5	2.0	2.3	7.3
	Ck2	42-66	15.8	1.7	1.4	1.6	2.7	6.5
	Cuk	66+	16.5	1.1	1.2	1.5	2.8	7.7
R15	Ah	0-13	1.8	0.7	1.8	2.2	2.8	6.5
	Bm1	13-46	1.8	0.8	1.9	2.3	3.1	6.6
	Bm2	46-69	8.3	1.4	1.6	1.8	4.0	5.9
	Ck1	69-99	24.1	1.4	1.0	1.5	2.5	5.3
	Ck2	99-147	22.6	1.9	1.0	1.3	2.6	5.9
	Cuk	147+	18.7	1.2	1.4	1.6	2.5	5.9

* Si/Al quotient determined from total percentages of SiO₂ and Al₂O₃ in Figures 5 and 6.

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