Chronosequence in Almar River Fluvial-Terrace Soil

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ABSTRACT

The aim of this work was to analyze how soils formed fundamentally from the erosion of granites evolve under a subhumid Mediterranean climate as a function of age. Their evolution was evaluated by means of the changes in components and properties, as well as the use of developmental indices. The soils are Xerorthents (Holocene), Haploxeralfs (Upper Pleistocene), and Palexeralfs (Middle Pleistocene). The properties have been subject to several trends: (i) some properties increase with regularity throughout the chronosequence (available water and coefficient of linear extensibility [COLE] of the Bt horizons) (ii) other properties increase strongly only during the first phases, while some continue to increase with age but only moderately (Ap horizon water retention and cation-exchange capacity, Bt horizon dithionite–citrate-extractable Fe, solum thickness, clay accumulation, quartz content, and quartz/feldspar ratio), whereas other Middle Pleistocene age soil properties cease to increase (the Ap horizon silt and available water, and Bt horizon water retention and cation-exchange capacity; (iii) others decrease with age, with pronounced decreases during the first phases (Ap and Bt horizon feldspar content and sand content and Bt horizon bulk density); and (iv) some properties are not age related (the Ap horizon base saturation and N content and the Bt horizon silt content). The horizon development indices and the soil development indices indicate good relationships with age. In most cases the rate of increase declines strongly for the oldest soils. In the great majority of cases, the properties and development indices continue to evolve through the chronosequence without reaching a steady state.

MOST SOIL PROPERTIES are time-dependent variables (Jenny, 1941). Therefore it is likely that soils of different ages will display their properties in different ways, especially under conditions in which the actions of other soil formation factors remain constant. Thus, the study of how the properties of soils vary with age is of great interest and may offer useful information in regard to their genesis.

Studies of soil chronosequences have focused on widely differing materials such as fluvial, eolian, lacustrine, marine, dune, morainal, volcanic ash, and even anthropogenic deposits such as the slag heaps of abandoned mines. Of all these types of chronosequences, river terraces have undoubtedly been the focus of most attention since they are very good examples of natural soil sequences whose evolution has been shaped by time. Although river terraces do cover an extended period of time, the changes occurring in their soils should not be attributed exclusively to the action of this parameter; rather, climatic changes and those due to the development of biological organisms should also be taken into account, insofar as these will also have affected soil development.

The aims of our study were several: (i) to evaluate how the properties and development of soils change with the progression of time; (ii) to define soil development age trends; and (iii) to analyze whether the development

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Abbreviations: Fe_d, dithionite–citrate-extractable Fe; COLE, coefficient of linear extensibility; MI, morphological index; AI, analytical index; MineI, mineralogical index.

of the soils under study becomes fixed at a steady state or not.

MATERIALS

The soils examined in this study are from a sequence of river terraces formed by the Almar River in the province of Salamanca (central western Spain).

Over geological time this river has left a typical scaled relief, with abundant horizontal surfaces placed between sharp scarps. According to Vreeken (1975), these are post-incised sequences. The river terraces analyzed are located in the neighborhood of Macotera village (UTM coordinates: 466694 and 471698 of National Grid Map 479).

A representative profile was chosen from each of the seven geomorphological surfaces distinguished, although in some cases, due to lateral changes, two profiles were sampled (Table 1). The sequence comprised all soils from the riverbank to a terrace 64 m above the riverbed.

The soil surfaces have been dated by Santonja et al. (1976, 1982, 1984) and the IGME (1982), mainly by archaeological and stratigraphic methods.

The fluvial deposits have thicknesses ranging between 1.5 and 5 m and are composed mainly of gravel and sand that originated from the erosion of granitic rock, slate, quartzite, and siliceous sediment.

The present-day climate can be classified as subhumid (mean annual rainfall 412 mm), mesic (mean annual temperature, 11 °C), of the continental Mediterranean type.

The climax vegetation is composed of holm oak (*Quercus rotundifoliae* Lam.) with *Genistra histrix* Lange. In certain areas this vegetation has been altered by human activity for crop cultivation and in others it is characterized by more or less open holm oak populations with abundant undergrowth.

METHODS

Field and Laboratory Methods

The descriptions of the morphological properties and the physical and chemical analyses of the soils were conducted according to traditional methods (Soil Survey Staff, 1951, 1984). The mineralogy of the sand and silt fractions was determined by x-ray diffraction.

In order to analyze the soil development trend with age, representative samples were chosen. The properties of the Ap horizon always refer to those of the horizon closest to the surface. When two or more Bt horizons within one soil are referred to, the following have been selected: (i) the maximum value of all the Bt horizons for clay content, water retention at 0.03 and 1.5 MPa, available water contents and cation-exchange capacity; (ii) for the sand and silt, those corresponding to the horizon with the maximum enrichment in clays were selected; (iii) in the case of clay, we also calculated the accumulation indices at the preset depths of 15, 50, 100, 150, 200, and 250 cm in the profile (cumulative values of the percentage of clay particles by horizon thickness in meters); (iv) the mineralogy of the sand and silt fractions was always calculated by taking the values corresponding to the second-most superficial horizon of each profile; (v) solum thickness was calculated as the sum of the thicknesses corresponding to Ap and Bt horizons (measured in centimeters) plus one-half the thickness of the BC and CB transition horizons; (vi) the thickness of the Bt horizon was also considered in this way, logically without taking the Ap horizons into account.

Soil Development Indices

Several studies have stressed the considerable difficulty in evaluating the degree of development shown by soils due to the enormous amount of data about different soil properties that such studies usually generate. To overcome this problem, quantitative indices have been developed; using a single value, these quantitative indices evaluate the degree of evolution among different soils. They can also be applied to the different horizons of a single soil (Buntly and Westin, 1965; Walker and Green, 1976; Bilzi and Ciolkosz, 1977; Harden, 1982; Birkeland, 1984a,b). These indices were calculated by determining the intensity of the change occurring between the properties of the horizons and those of the original material.

Morphological Indices

To calculate the MI we followed the guidelines of Harden (1982), using seven properties chosen by this author, namely: (i) structure (type and degree of development); (ii) total texture (textural class plus type of stickiness and plasticity of the wet consistence); (iii) dry consistence (class); (iv) moist consistence (class); (v) clay films (abundance, thickness, and location); (vi) melanization (color value); and (vii) rubification (color hue and chroma).

A detailed morphological description of the soil profile was the starting point for the calculations. Quantification of the field properties was modeled after Bilzi and Ciolkosz (1977). They assigned points on the basis of the difference between the properties observed in the soil horizons and the original material. The Bilzi–Ciolkosz index yields very good results for comparing soils developed from different original materials, although in the particular case of chronosequences developed

Table 1. Soils, geomorphic surfaces, and ages.

Profile code	Stratigraphic position	Elevation	Geologic age	Approximate age	Classification†
		m		yr	
AM4	Floodplain	4	Holocene	500	Typic Xerorthent
AM7	Floodplain	7	Holocene	10 000	Typic Haploxeralf
AM14	5th terrace	14	Late Pleistocene	50 000	Typic Haploxeralf
AM18a	4th terrace	18	Late Pleistocene	100 000	Typic Haploxeralf
AM18b	4th terrace	18	Late Pleistocene	100 000	Typic Haploxeralf
AM36	3rd terrace	36	Middle Pleistocene	300 000	Typic Palexeralf
AM47	2nd terrace	47	Middle Pleistocene	500 000	Typic Palexeralf
AM64	1st terrace	64	Middle Pleistocene	600 000	Typic Palexeralf

† Soil Survey Staff (1975).

on river terraces it is not completely satisfactory, as demonstrated by Meixner and Singer (1981). For comparative purposes, better results are obtained using the indices of Harden (1982), in large part because of the introduction of thickness and the ability to combine several properties.

To calculate the MI, the following steps were observed (Harden, 1982; Busacca, 1987): (i) description of the soil profile; (ii) assessment of parent materials (measurement of fresh deposits or deep C horizons); (iii) quantification of each field property for each horizon (assessing 10 points to step increases); (iv) normalization of quantified properties (division by maximum quantified property) to obtain the MI for each property and horizon; (v) multiplication of the value obtained in the previous step by the thickness (in centimeters) of the horizon and adding all of the values corresponding to all of the horizons of a given soil which yields the MI for a single property for each profile; (vi) adding together all the normalized values from step iv and dividing by the number of properties considered, which gives MI (general properties) per horizon; (vii) multiplying the latter values by the thickness corresponding to each horizon and then adding these products, which gives the general MI for each profile.

So that the thickness of the soil will not be overvalued in these indices, Harden and Taylor (1983), Birkeland (1984a,b), and Busacca (1987) proposed that the values could be divided by the true thickness of each soil. In this same sense, Birkeland (1984b) suggested the use of a constant thickness for each of the soils, choosing the thickness of the deepest soil in the chronosequence as a homogenization factor, artificially thickening the thinnest soils until the thickness of the deepest soil is reached. We obtained good results by dividing the value of the index by the true thickness of each soil (data not shown) and also for a standard thickness of 2 m.

Analytical Indices

For the results of the physical and chemical analyses, we calculated the indices of Birkeland (1984a). These indices are a modification of the index of profile anisotropy (IPA) of Walker and Green (1976) and are calculated thus:

$$\mathrm{mIPA} = D/\mathrm{PM}$$

where D represents the numerical difference between the value of the horizon property considered and its value in the original material, and PM refers precisely to this latter value.

To calculate the AI, we followed the steps described above for the MI (Step iv, AI for each property and horizon; Step v, AI for each property and profile; Step vi, general AI for all properties and horizon; Step vii, general AI for all properties and profile). As was done for the MI, calculations were made for normalized thicknesses (AI divided by the thickness of each soil) and for standard thicknesses of 2 m.

In this study, we calculated the AI for a single property and profile for nine properties: sand content, clay content, water retention at 0.03 and 1.5 MPa, available water, organic matter content, $CaCO_3$ content, pH, and cation-exchange capacity. We also calculated the general AI (all properties) for horizon and the general AI for profile.

Mineralogical Indices

Likewise we calculated MineI as a function of the contents of quartz and feldspars of the total sand and total silt fractions of the soil.

To calculate these MineI, we followed the same steps as for the AI, calculating the general MineI as a function of the values of the quartz/feldspar ratio.

RESULTS AND DISCUSSION

The calculated ages for these Spanish soils have been contrasted (Fig. 1) with the values obtained by others (Meixner and Singer, 1981; Harden, 1982; Busacca, 1987) for California soils that were formed under conditions similar to ours: fluvial terraces formed by materials originating from the erosion of granitic rock, Mediterranean climate, and average annual precipitation of 310 to 640 mm. We illustrate the results for the rate of soil formation in Fig. 1. We have simply calculated these values on the basis of the proportion between the soil depths in millimeters (A horizon + B horizon + 1/2 AC horizon + 1/2 BC horizon, excluding CA, CB, and C horizons) and the soil age in years (soils with anomalous performances have not been represented). A strong agreement was found between the respective values of Spanish and California soils.

The formation rate of the soils drastically decreases with age. The soils deepen at a rate of 0.2 to 0.6 mm/yr for those that are <1000 yr old in these soil conditions. The soil that is 10 000 yr old has formed at 0.1 mm/yr. The soil that is 100 000 yr old has formed at 0.01 mm/yr. The rate decreased to 0.005 mm/yr at 500 000 years old, and finally decreased to 0.001 mm/yr at about 1 million yr.

A selection of the results of the morphological, physical, chemical, and mineralogical analyses of these soils is offered in Tables 2 and 3.

In this chronosequence, it is possible to observe a progressive and pronounced development of the soil with age. In the current flood plain there are Xerorthents. The soils of the Upper Pleistocene surfaces have become Haploxeralfs. Finally, in the Middle Pleistocene there are Palexeralfs.

Soil Development Indices vs. Horizon Depth with Age

Figures 2, 3, and 4 summarize the values of the three general indices: MI, AI, and MineI. It can be seen how the distributions of these indices follow a progressive evolution with age, and form two general developmental trends. One corresponds to the global values of the

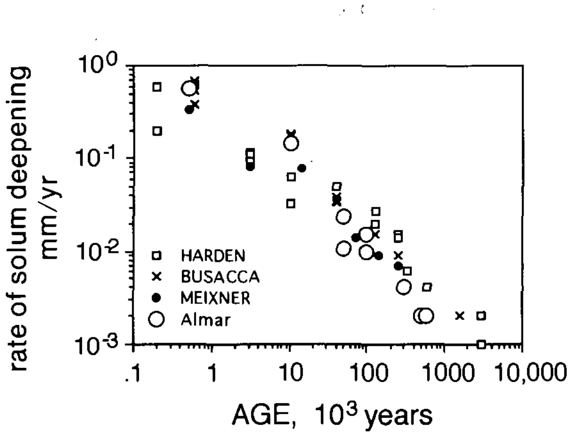

Fig. 1. Profile deepening rate vs. age of some soils from California and Spain.

Table 2. Major macromorphological characteristics of the soils studied.

Profile code	Horizon	Depth	Moist color	Structure†	Gravel (>2 mm)	Sand (2-0.05 mm)	Silt (0.05-0.002 mm)	Clay (<0.002 mm)	Water retention	
									0.03 MPa	1.5 MPa
		cm			%				– $g\ kg^{-1}$ –	
AM4	Ap1	0-25	7.5 YR 5/4	vf1cr	48.3	81.4	13.7	4.9	67	25
	Ap2	25-38	7.5 YR 5/4	0	53.5	82.0	11.2	6.8	55	29
	2C1	38-70	10 YR 6/4	0	42.5	96.7	1.2	2.1	12	10
	2C2	70-90	10 YR 7/4	0	61.4	95.8	2.2	2.0	10	09
	2C3	90->120	10 YR 6/6	0	23.3	93.8	1.8	4.4	32	21
AM7	Ap	0-40	7.5 YR 4/3	vf1cr	31.1	63.5	26.6	9.9	13.8	5.1
	Bt	40-115	2.5 Y 5/3	m3abk	43.0	53.8	13.9	32.3	23.7	13.5
	BCt	115-170	2.5 Y 6/3	m1,2abk	75.0	69.1	5.8	25.1	17.1	11.3
			7.5 YR 5/6							
	CBt	170->200	5 Y 6/3	m1sbk	45.6	61.0	16.7	22.3	21.5	11.9
AM14	Ap	0-30	7.5 YR 5/4	m2cr	43.9	56.0	32.3	11.7	15.9	5.5
	Bt	30-55	5 YR 4/6	c2sbk	43.4	42.1	15.8	42.1	24.7	16.3
	Btg	55-83	2.5 Y 5/3	c3pr	24.9	40.3	7.9	51.8	28.5	20.0
			2.5 Y 6/4							
	2Btk	83-105/140‡	10 YR 6/6	m	63.2	46.3	12.8	40.9	28.2	17.3
			10 YR 4/2							
			10 YR 4/3							
	2CBtk1	105/140-200	5 Y 7/3	m	21.3	58.0	22.4	19.6	21.7	12.1
	2CBtk2	200->225	5 Y 6/3	m	16.9	61.9	17.6	20.5	20.1	11.5
AM18a	Ap	0-22/55	7.5 YR 5/4	m2cr	35.1	68.9	23.9	7.2	12.1	4.1
	2Bt1	22/55-60/70	10 YR 5/3	f2sbk	51.3	38.4	12.5	49.1	30.4	20.9
			2.5 YR 3/6							
	2Bt2	60/70-92	10 YR 6/3	c3pr	2.9	23.5	18.3	58.2	45.5	29.4
	3BCt	92-114	2.5 Y 5/4	m3pr	1.1	23.5	33.3	43.2	43.6	28.7
	3Ck1	114-150	5 Y 5/3	m	8.2	46.4	33.9	19.7	25.9	16.9
	4Ck2	150-200	5 Y 5/3	m	2.2	20.0	47.0	33.0	32.0	20.7
	5Ck3	200->250	5 Y 5/3	m	1.0	31.4	36.3	32.3	30.1	17.7
AM18b	Ap	0-37	10 YR 4/4	m2cr	29.0	52.4	34.6	13.0	17.7	6.1
	Bt	37-70	2.5 YR 4/8	c3sbk	53.9	37.6	10.8	51.6	27.4	19.7
			5 YR 5/8							
			7.5 YR 5/4							
	2Btg	70-103	5 YR 5/8	c2pr	21.8	47.9	5.9	46.2	27.0	20.7
			2.5 Y 6/3							
	2BCtk	103-190	2.5 Y 5/3	m	52.9	44.2	15.9	39.8	29.2	17.5
	2CBt	190->230	2.5 Y 5/3	m	46.4	67.1	9.3	23.6	14.3	10.4
AM36	Ap	0-30	10 YR 4/4	f2sbk	19.4	52.8	33.4	13.8	17.4	6.2
	Bt1	30-55/65	5 YR 5/8	c3abk	24.8	33.4	23.6	43.0	27.8	17.4
			7.5 YR 6/4, 10 YR 6/4							
	Bt2	55/65-110/120	2.5 YR 5/8, 5 YR 5/8	c3pr	47.5	22.1	7.2	70.7	42.1	29.5
			10 YR 5/3							
	CBtk1	110/120-170	2.5 Y 6/4	m	41.4	55.4	11.2	33.4	26.3	16.8
			5 Y 7/4, 7.5 YR 6/4							
	CBtk2	170-205	7.5 YR 6/4, 2.5 Y 6/4		77.3	51.9	7.6	40.5	28.4	17.4
			5 Y 7/4							
	CBtk3	205-225	7.5 YR 6/4	m	43.5	73.2	1.4	25.4	18.0	11.6
			2.5 Y 6/4							
			5 Y 7/4							
	2Ck	225->280	7.5 YR 5/6	m	0.0	15.0	29.9	55.1	43.3	29.7
AM47	Ap	0-32	10 YR 4/3	m2cr	16.8	57.0	31.2	11.8	16.2	5.5
	Bt1	32-50	2.5 YR 4/8	c3abk	12.1	30.0	13.4	56.6	39.9	24.3
			5 YR 4/5							
	Bt2	50-106	2.5 YR 3/6	c3pr	33.1	21.1	6.7	72.2	43.2	29.9
			7.5 YR 4.5/3							
	CBtk1	106-180	10 YR 6/8, 2.5 Y 7/4	m	62.5	58.2	12.9	28.9	21.8	12.3
	2CBtk2	180-215	yellowish white		74.8	50.7	17.5	31.8	26.4	15.2
	3CBtk3	215-240	7.5 YR 6/8	m	54.3	66.9	3.8	29.3	21.9	13.8
			10 YR 6/8							
	4CBtk4	240->280	10 YR 6/6	m	19.8	50.0	20.1	29.9	24.2	12.3
AM64	Ap	0-25	7.5 YR 5/4	m2cr	27.0	52.2	21.6	26.2	21.5	10.7
	2Bt1	25-45	2.5 YR 4/6	c2abk	4.8	31.4	18.9	56.3	38.5	21.8
			5 YR 5/6							
	2Bt2	45-100	5 YR 3/4	c3pr	5.4	22.3	11.5	70.6	44.2	29.0
	2Btk	100-110	7.5 YR 5/4	m3pr	8.0	29.1	16.5	54.4	37.9	23.6
	2BCtk1	110-140	10 YR 5/4	m	16.0	44.8	19.0	42.2	32.4	19.5
			2.5 Y 6/4							
			2.5 Y 6/4							
	2BCtk2	140->200	10 YR 5/4	m	4.9	32.0	14.1	53.9	40.5	22.1
			10 YR 5/6							
Parent materials			10 YR 6/5	m	42.0	96	2.2	2.8	4.0	2.0

† vf = very fine, f = fine, m = medium, c = coarse, 0 = structureless, 1 = weak, 2 = moderate, 3 = strong, cr = crumb, sbk = subangular blocky, abk = angular blocky, pr = prismatic. Abbreviations from Soil Survey Staff (1951, p. 139-140).

‡ Variations of horizon boundaries.

Table 3. Selected chemical and mineralogical properties of the soils studied.

Profile code	Horizon	Organic C	N	pH (paste)	Cation-exchange capacity (NH_4OAc)	Base saturation	$CaCO_3$	Minerals: Quartz	Minerals: Feldspar
		g kg^{-1}	g kg^{-1}		cmol$_c$ kg^{-1}	%	g kg^{-1}	g kg^{-1}	g kg^{-1}
AM4	Ap1	4.1		4.7	2.8	100	0.0	350	600
	Ap2	2.7		5.4	3.6	100	0.0	190	810
	2C1	0.9		6.9	2.5	100	0.0	270	600
	2C2	0.7		7.8	2.2	100	0.0	300	560
	2C3	0.9		8.0	4.5	100	0.0	220	720
AM7	Ap	7.8	0.5	6.0	5.3	100	0.0	370	580
	Bt	4.9	0.3	6.2	23.1	100	0.0	310	640
	BCt	2.3	0.2	6.1	20.2	100	0.0	380	650
	CBt	2.0	0.1	6.8	25.0	100	0.0	340	310
AM14	Ap	8.5	0.5	5.1	4.2	95	0.0	460	540
	Bt	7.4	0.6	5.3	17.8	100	0.0	500	490
	Btg	4.3	0.4	7.1	32.6	100	0.0	510	480
	2Btk	3.6	0.2	7.6	39.6	100	71	300	600
	2CBtk1	2.0	0.2	7.6	32.8	100	38	260	440
	2CBtk2	1.5	0.2	7.5	28.8	100	24	470	300
AM18a	Ap	7.1	0.4	4.7	2.9	82	0.0	390	510
	2Bt1	8.5	0.6	5.0	22.0	100	0.0	430	500
	2Bt2	6.2	0.3	6.7	42.1	100	0.0	360	630
	3BCt	4.5	0.2	7.4	43.5	100	0.0	300	630
	3Ck1	2.8	0.2	7.4	45.5	100	56	240	750
	4Ck2	2.6	0.2	7.6	48.7	100	188	260	690
	5Ck3	2.2	0.2	7.5	46.5	100	115	330	490
AM18b	Ap	5.8	0.5	5.6	5.3	100	0.0	590	410
	Bt	4.1	0.4	5.7	21.0	100	0.0	430	560
	2Btg	2.3	0.3	6.3	24.6	100	0.0	360	630
	2BCtk	1.8	0.2	7.6	34.1	100	187	240	750
	2CBt	0.7	0.1	6.6	16.2	100	0.0	330	490
AM36	Ap	6.5	0.6	5.3	4.4	87	0.0	370	600
	Bt1	5.0	0.5	5.5	18.7	100	0.0	480	470
	Bt2	3.5	0.4	6.9	33.9	100	0.0	550	430
	CBtk1	0.8	0.2	7.4	33.1	100	15	480	440
	CBtk2	0.6	0.2	7.6	35.4	100	47	510	420
	CBtk3	0.4	0.1	7.6	18.1	100	14	280	600
	2Ck	1.1	0.2	7.5	49.1	100	14	300	610
AM47	Ap	4.8	0.4	5.1	4.4	91	0.0	450	540
	Bt1	5.5	0.5	6.0	25.5	100	0.0	660	340
	Bt2	3.5	0.4	6.7	31.1	100	0.0	550	460
	CBtk1	1.1	0.2	7.6	27.6	100	175	470	410
	2CBtk2	1.5	0.2	7.7	26.8	100	67	330	670
	3CBtk3	0.2	0.2	7.6	20.7	100	24	470	530
	4CBtk4	0.6	0.1	7.5	27.8	100	19	240	660
AM64	Ap	11.0	0.8	6.3	14.6	100	0.0	810	190
	2Bt1	6.5	0.6	6.9	23.5	100	0.0	730	270
	2Bt2	5.9	0.5	6.8	40.0	100	0.0	600	400
	2Btk	4.5	0.4	7.5	49.9	100	61	470	530
	2BCtk1	2.2	0.3	7.6	44.0	100	91	310	690
	2BCtk2	3.3	0.4	7.7	45.5	100	251	220	780
Parent materials		1.0	0.0	7.6	1.4	100	0.0	270	720

indices and the other refers to the degree of differentiation among the horizons of each soil.

A marked increase with age is observed in regard to the global values of these indices. The floodplain soils are outstanding due to their very low values. In the soils of Upper Pleistocene age, the indices corresponding to the mineral alterations continue to be spectacularly low, while those corresponding to MI and AI have moderate values. In the soils of the Middle Pleistocene age, all the indices increase as the age of the soils advances.

In regard to the degree of differentiation of the horizons of each soil, the following trend was observed: the soils of the present floodplains show very underdeveloped profiles. The soils of the Upper Pleistocene surfaces have a pronounced horizoning; these soils show a horizon of maximum differentiation situated at about 100-cm depth. In the soils of the Middle Pleistocene age, the most developed horizons increase in their absolute values and become broader towards horizons above and below. Very similar distributions have been reported for the MI of California soils by Harden (1982, Fig. 7) and Busacca (1987, Fig. 3).

The MineI disclose the very low degree of alteration shown by soils of the Holocene and Upper Pleistocene ages (AM7, AM14, and AM18) whereas for the other indices—MI and AI—these soils are already clearly developed. The main process responsible for the development of these soils is clay illuviation; this process begins in the initial phase of soil development, long before mineral alteration is developed. We believe that this is due to the special characteristics of the fluvial deposits over which the soils have been formed.

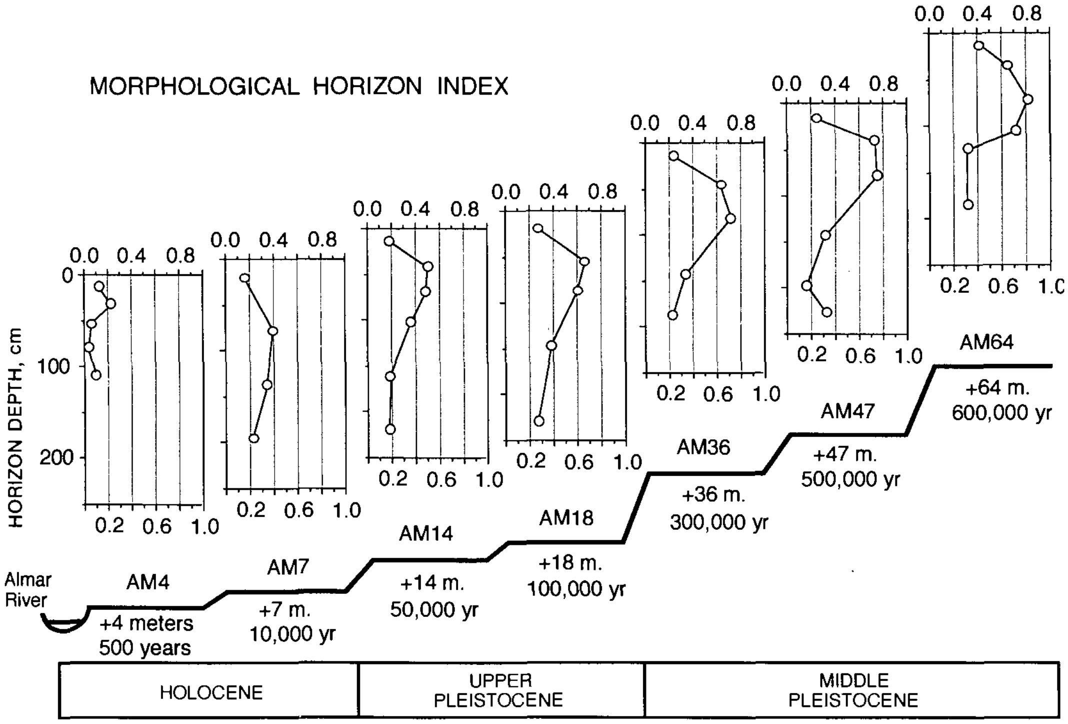

Fig. 2. Distribution of general morphological horizon indices by depth and soil age.

First, the deposits of fluvial sands display a certain mineral stability since, on the one hand, due to their size the mineral fragments are fairly well protected from weathering and, on the other, these fluvial deposits contain reasonably stable minerals, since the unstable ones would have decomposed during previous phases of erosion and river transport.

Secondly, the fluvial deposits are mostly formed of loose grains of sand and are therefore very porous, thereby enormously facilitating the infiltration of rain-

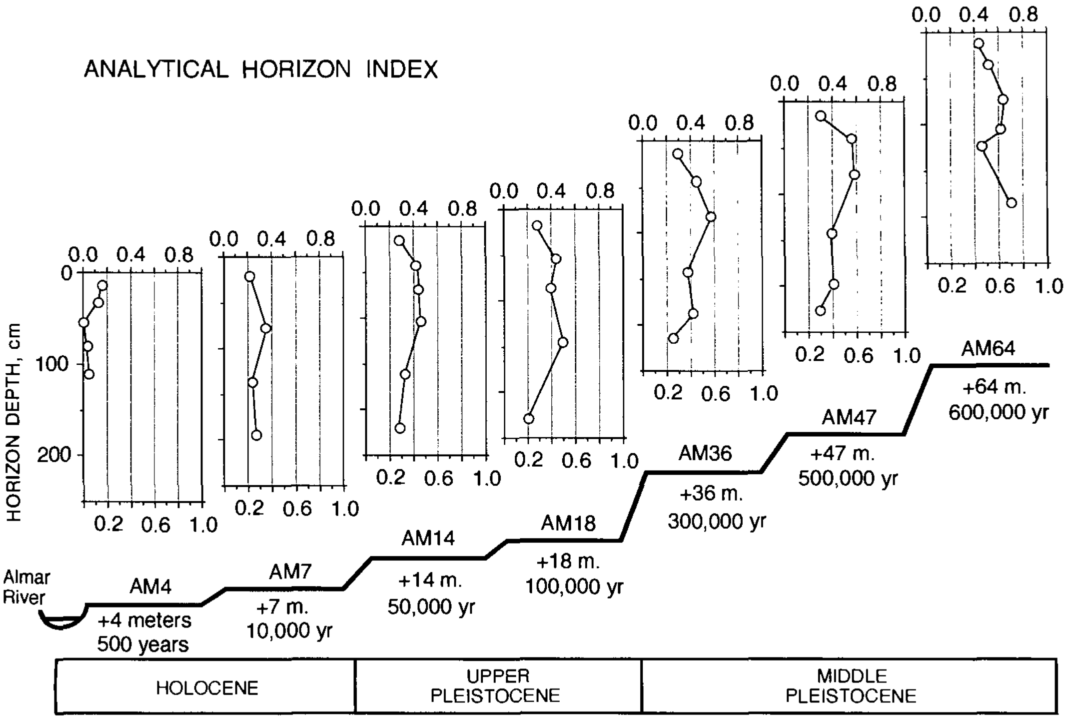

Fig. 3. Distribution of general analytical horizon indices by depth and soil age.

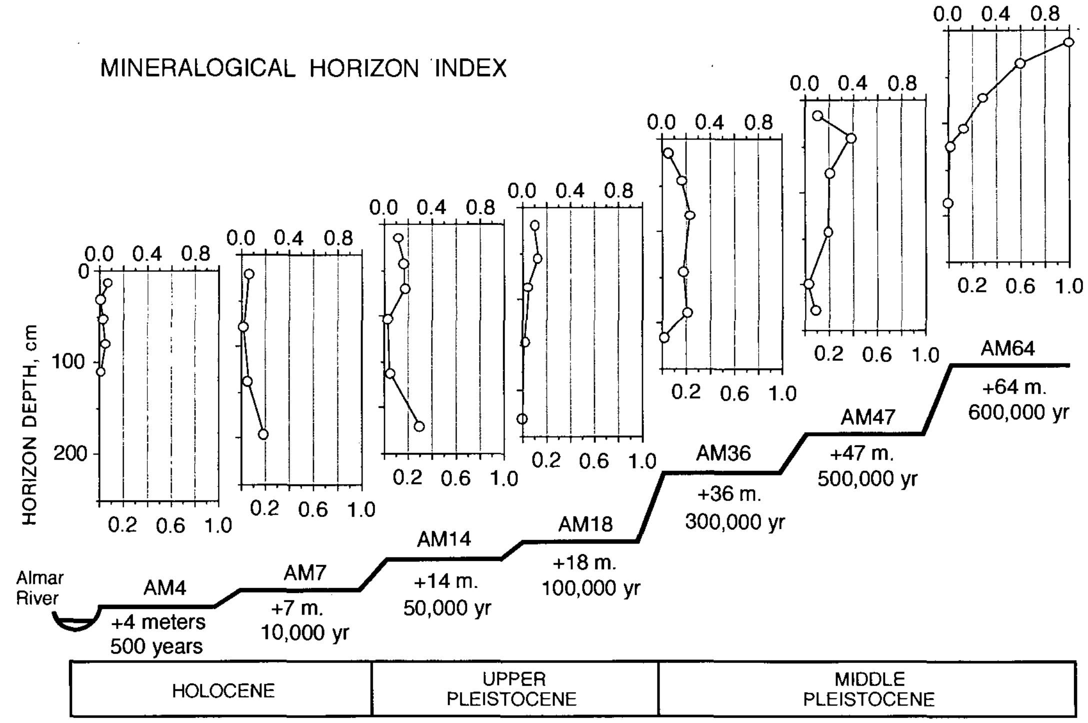

Fig. 4. Distribution of general mineralogical horizon indices by depth and soil age.

water and hence the vertical transport of clay suspensions. Since they are present in small amounts, the clays are weakly retained in the soils and migrate with ease. Indeed, micromorphological study clearly shows that, at the present time, clay illuviation has already developed on the floodplain. Rapid clay translocation at an early stage seems to explain the absence of Inceptisols in this developmental sequence.

Soil Development Age Trends

Soil Properties

Particular types of behavior of different soil properties can be grouped in three broad categories, according to whether the value of the property tends to increase with age, decrease, or whether there is no relationship with age at all. For the first two groups, a series of subgroups can be established as a function of the intensity and constancy of the change.

Properties that increase with age. Many properties show a direct dependence with age. According to the evolution of the property with age, the following groups can be differentiated:

1. Constant and regular increase throughout the chronosequence depending strongly on age: the available water and COLE of the Bt horizon (Fig. 5).

2. Strong increase only during the first phases. Another group of properties shows strong increase with age for the Holocene and Upper Pleistocene soils, thereafter undergoing a change in their development in the final stages, corresponding to the Middle Pleistocene. This change may follow different trends: (i) some properties continue to increase with age but more moderately (Fig. 6): water retention at 0.03 and 1.5MPa and cation-exchange capacity of the Ap horizon (also in Dickson and Crocker, 1953; Torrent, 1976; Ahmad et al., 1977; Jongmans et al., 1991), Fe_d of the Bt horizon (Hendershot et al., 1979; Torrent et al., 1980; Alexander and Holo-

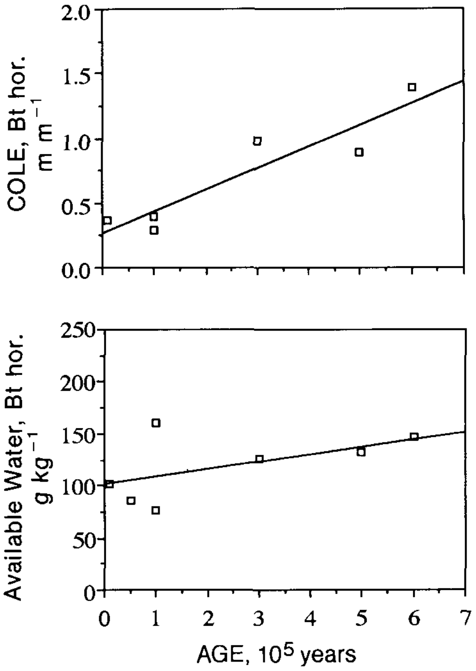

Fig. 5. Profile properties vs. soil age for properties that increase constantly and regularly throughout the chronosequence. For curve fittings, see Table 5.

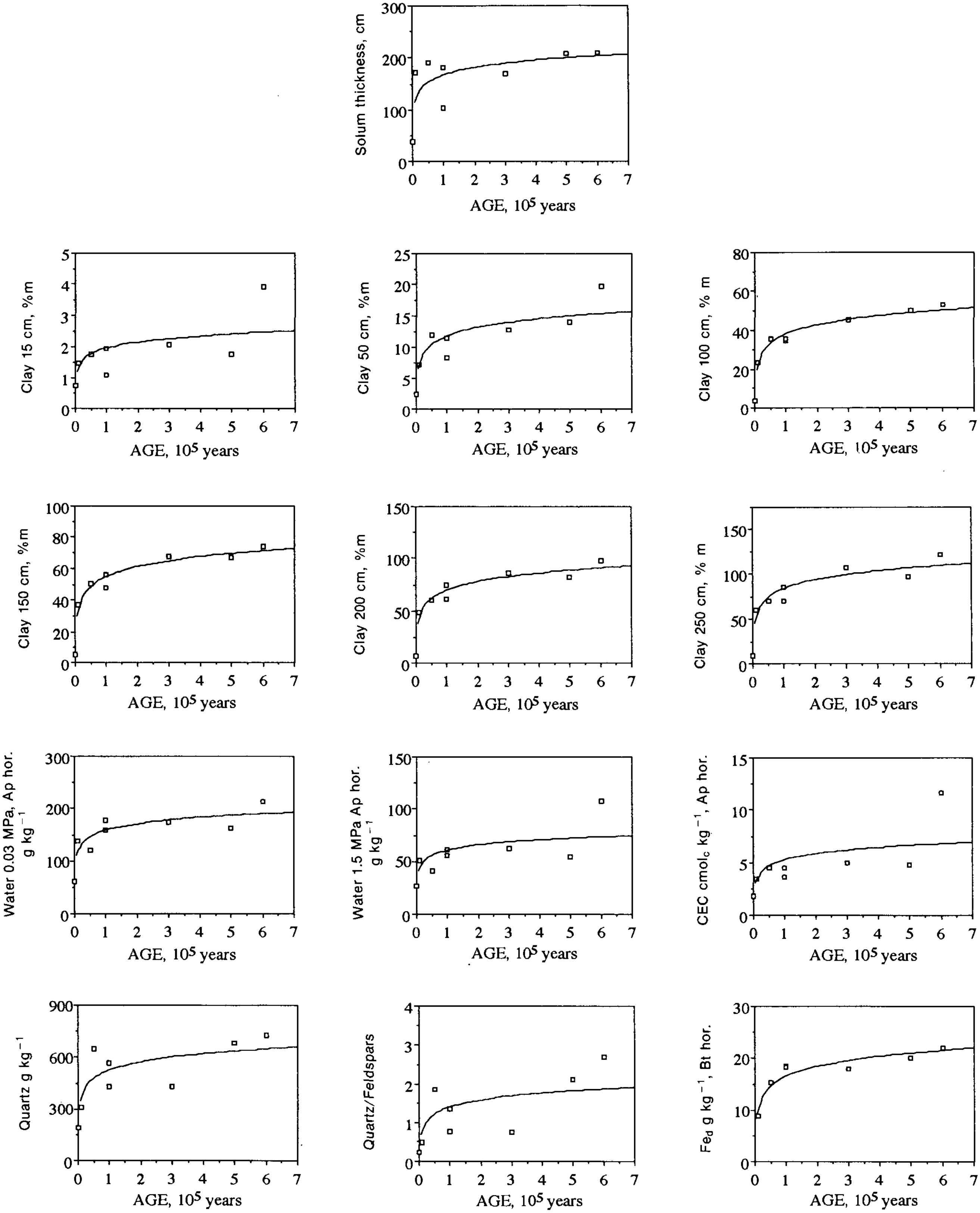

Fig. 6. Profile properties vs. soil age for properties that increase with age with strong increase only during the first phases. Clay at 15, 50, 100, 150, 200, and 250 cm are cumulative values of the percentage of clay particles by horizon thickness in meters; Fe$_d$ is dithionite-citrate-extractable Fe; CEC is cation-exchange capacity. For curve fittings, see Table 5.

waychuck, 1983; Peña and Torrent, 1984; Arduino et al., 1984, 1986; Aniku and Singer, 1990), solum thickness (Ahmad et al., 1977; Meixner and Singer, 1981; Little and Ward, 1981; Harden, 1982; Muhs, 1982; Alexander and Holowaychuck, 1983; Arduino et al., 1984, 1986; Chittleborough et al., 1984; Busacca, 1987; Ajmone et al., 1988; Reheis et al., 1989), clay accumulations at depths of 15, 50, 100, 150, 200, and 250 cm, quartz content, and quartz/feldspar ratio (also in Ruhe, 1956; Barshad, 1955; Muhs, 1982); (ii) other properties cease to increase for the soils from the Middle Pleistocene: silt and clay contents, and available water of the Ap horizon, and available water at 0.03 and 1.5MPa and cation-exchange capacity of the Bt horizons (Fig. 7). A highly representative property of this type of study is the concentration of clay accumulated in the B horizon of the soils. Logically, as age increases, a progressive increase in the amount of clay present would also be expected to occur. This kind of behavior has been observed both in our soils and in many others studied (Ruhe, 1956; Franzmeier and Whiteside, 1963; Janda and Croft, 1967; Torrent, 1976; Ahmad et al., 1977; Pastor and Bockheim, 1980; Meixner and Singer, 1981; Dorronsoro et al., 1988; Fine et al., 1989; Reheis et al., 1989; Aniku and Singer, 1990). All of these chronofunctions can be adapted to power and logarithmic models without a value of maximum enrichment being reached after which the values remain constant, although this does occur in some cases (Peña and Torrent, 1984) and also in this study for the total enrichments in clay at defined depths (clay [%] × thickness) of 50, 100, 150, and 200 cm.

3. Strong increase only during the last phases. Another group of properties shows strong increases with age for the Middle Pleistocene soils. In this situation are the clay and N content of the Ap horizon, the thickness of the Bt horizons, and carbonate accumulations (Fig. 8). Some of these properties are not strongly age dependent and could be included with the group of properties that are not age related.

Properties that decrease with age. These show the opposite behavior to that of the previous group; that is, the increase in these properties diminishes as the soil ages.

The properties belonging to this group are minor. All of these properties (Fig. 9) show strong decreases up to the Upper Pleistocene soils, thereafter decreasing very moderately (feldspar content), or else they cease to increase for the soils from the Middle Pleistocene (sand content of the Ap and Bt horizons) or show increase during the last phases (bulk density of the Bt horizon).

Properties that are not age related. Finally, for one group of properties it is not possible to establish any logical relationships between their degree of manifestation and the age of the soil (pH and base saturation of the Ap horizon, and silt content of the Bt horizon) (Fig. 10).

The organic matter contents were expected to increase with age (Dickson and Crocker, 1953; Ruhe, 1956; Viereck, 1966; Leisman, 1957; Olson, 1958; Syers et al., 1970) although, in our soils, an increase was observed only for the very young soils; after the Upper Pleistocene, the soils display a chaotic behavior, possibly due to the intense anthropogenic activity to which they have been subjected.

The absence of a dependence between base saturation and age could also be the result of land practices.

In other chronosequences, the pH of the soils clearly reflects the progressive acidification that atmospheric precipitation tends to produce on the surface horizon

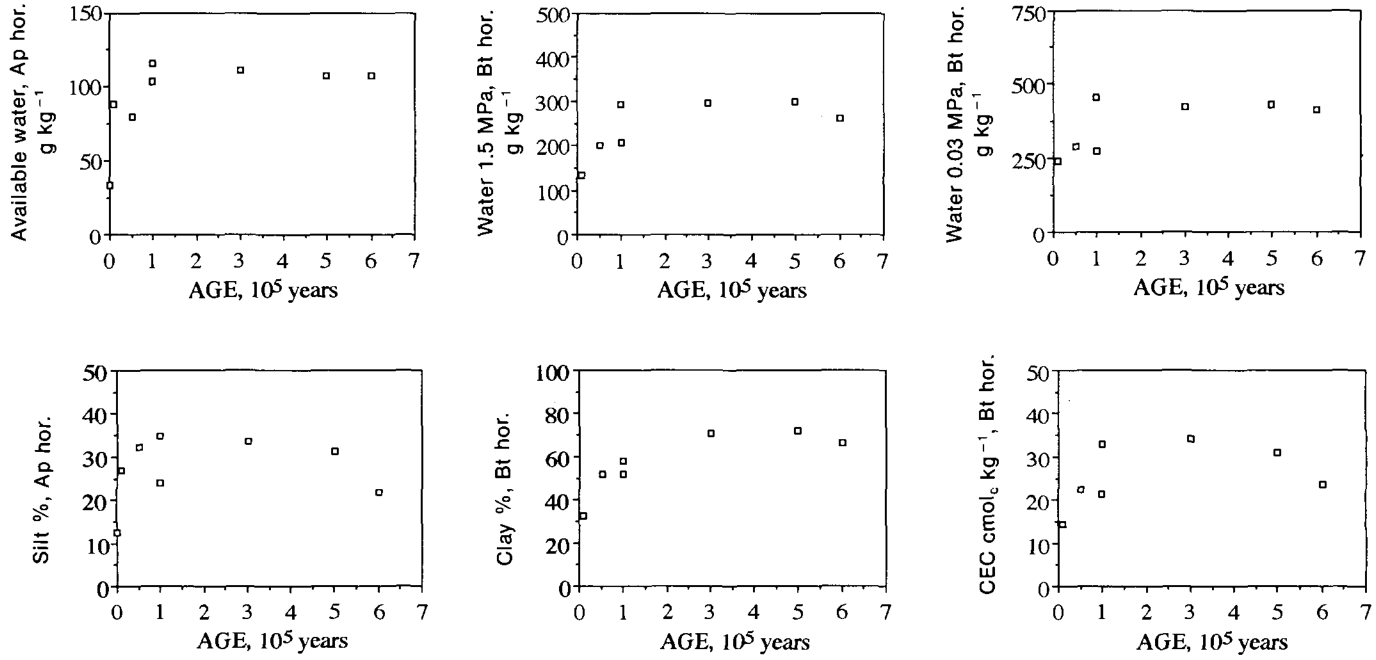

Fig. 7. Profile properties vs. soil age for properties that cease to increase for the soils from the Middle Pleistocene.

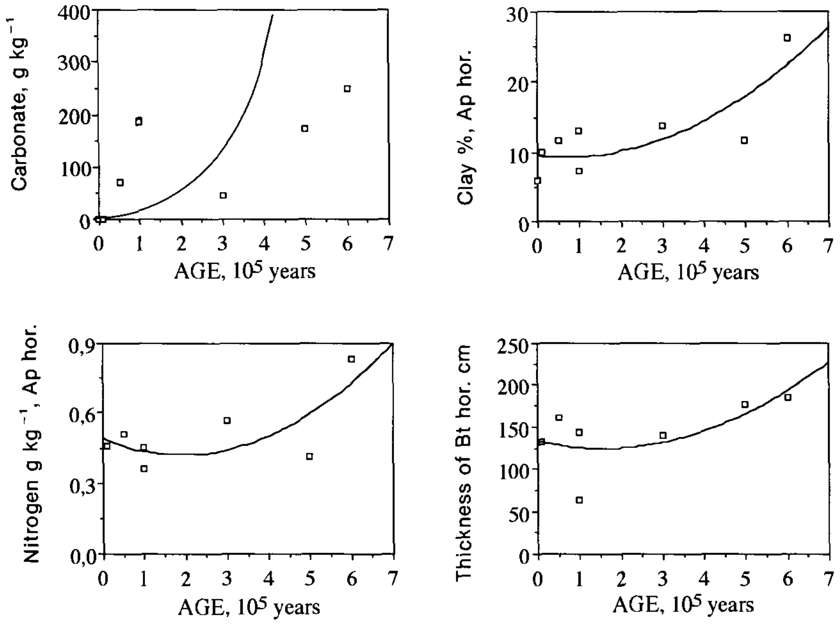

Fig. 8. Profile properties vs. soil age for properties that show a strong increase only during the last phase. For curve fittings, see Table 5.

(Dickson and Crocker, 1954; Crocker and Dickson, 1957; Wilson, 1960; Cowie, 1968; Ugolini, 1968; Viereck, 1970; Bockheim, 1979; Alexander and Holowaychuck, 1983; Arduino et al., 1984; Chittleborough et al., 1984; Peña and Torrent, 1984; Aniku and Singer, 1990).

Soil Indices

Morphological Indices. As shown in Fig. 11, all of the MI show strong increases during the initial phases of soil formation; as for the Upper Pleistocene soils, these increases are reduced to the minimum (MI of texture, dry consistency, and the general one for all the properties together) or may even remain constant (moist consistency and rubification MI). A similar kind of behavior, with continuous increases and mostly in the early phases of the development of the soils, has been reported for these MI by Harden (1982), Birkeland (1984b), Busacca (1987), and Reheis et al. (1989).

Analytical Indices. As occurs with the MI, the AI show a very dominant type of behavior. The values of most of the AI increase throughout the chronosequence but only do so very intensively in the case of the soils

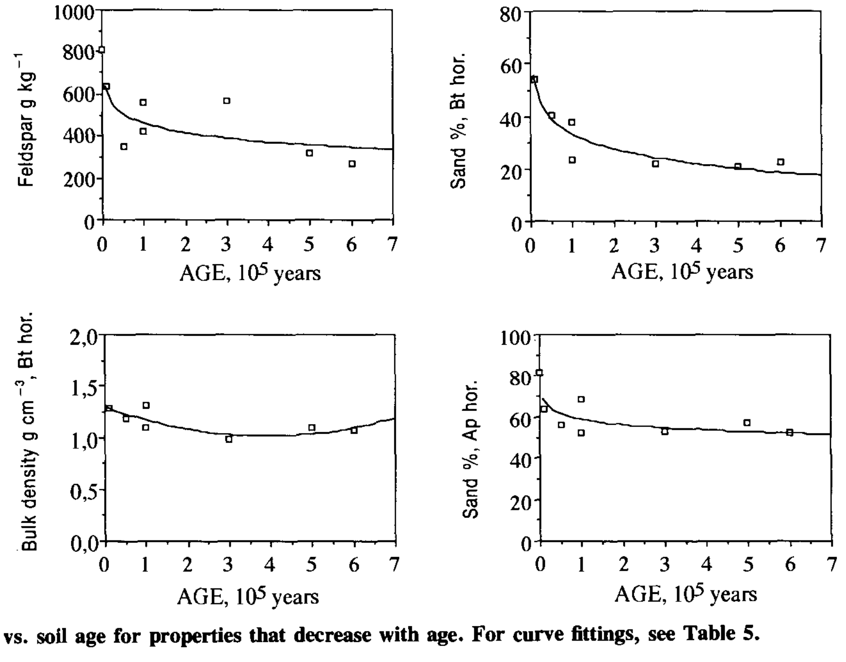

Fig. 9. Profile properties vs. soil age for properties that decrease with age. For curve fittings, see Table 5.

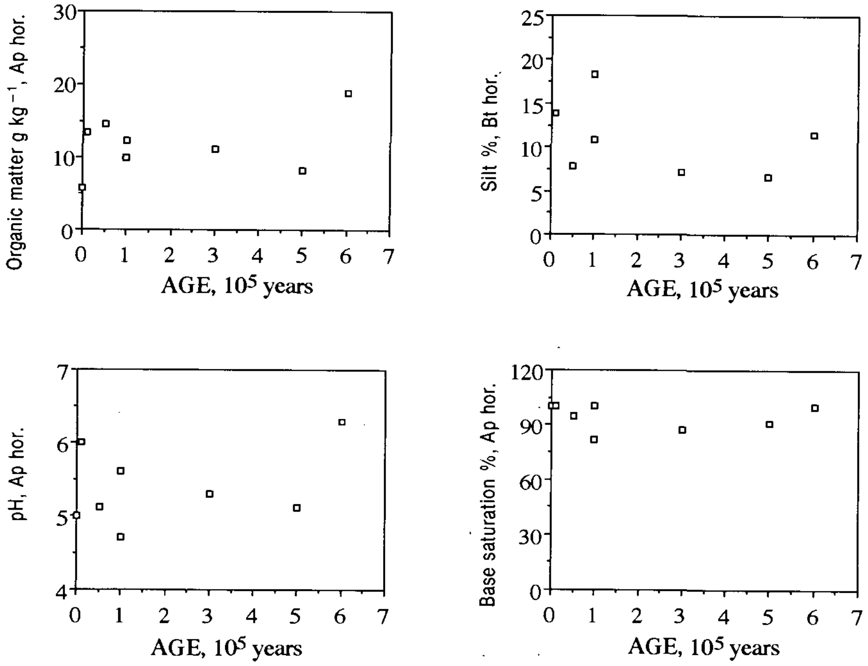

Fig. 10. Profile properties vs. soil age for properties that are not age related.

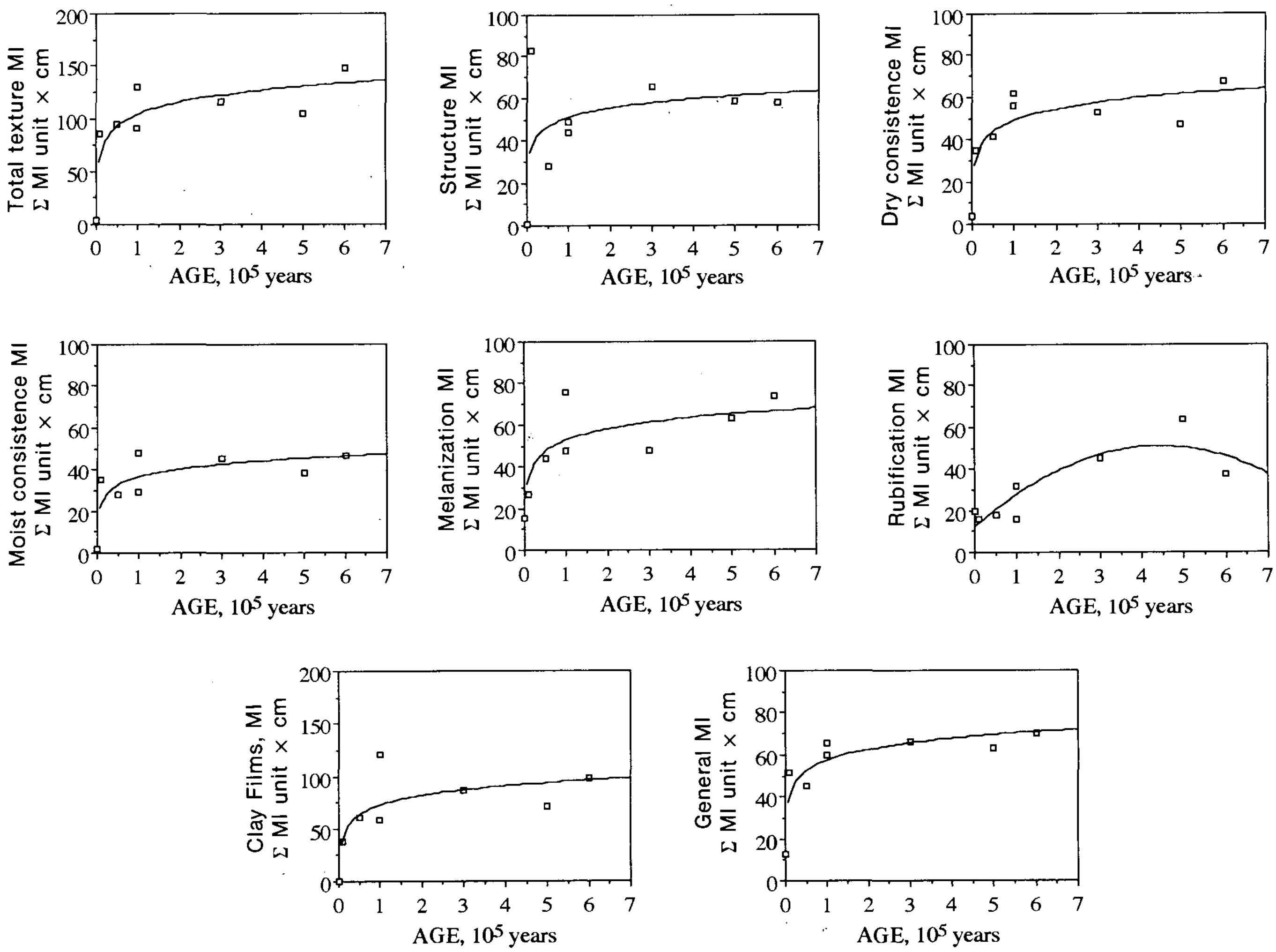

Fig. 11. Morphological indices vs. soil age.

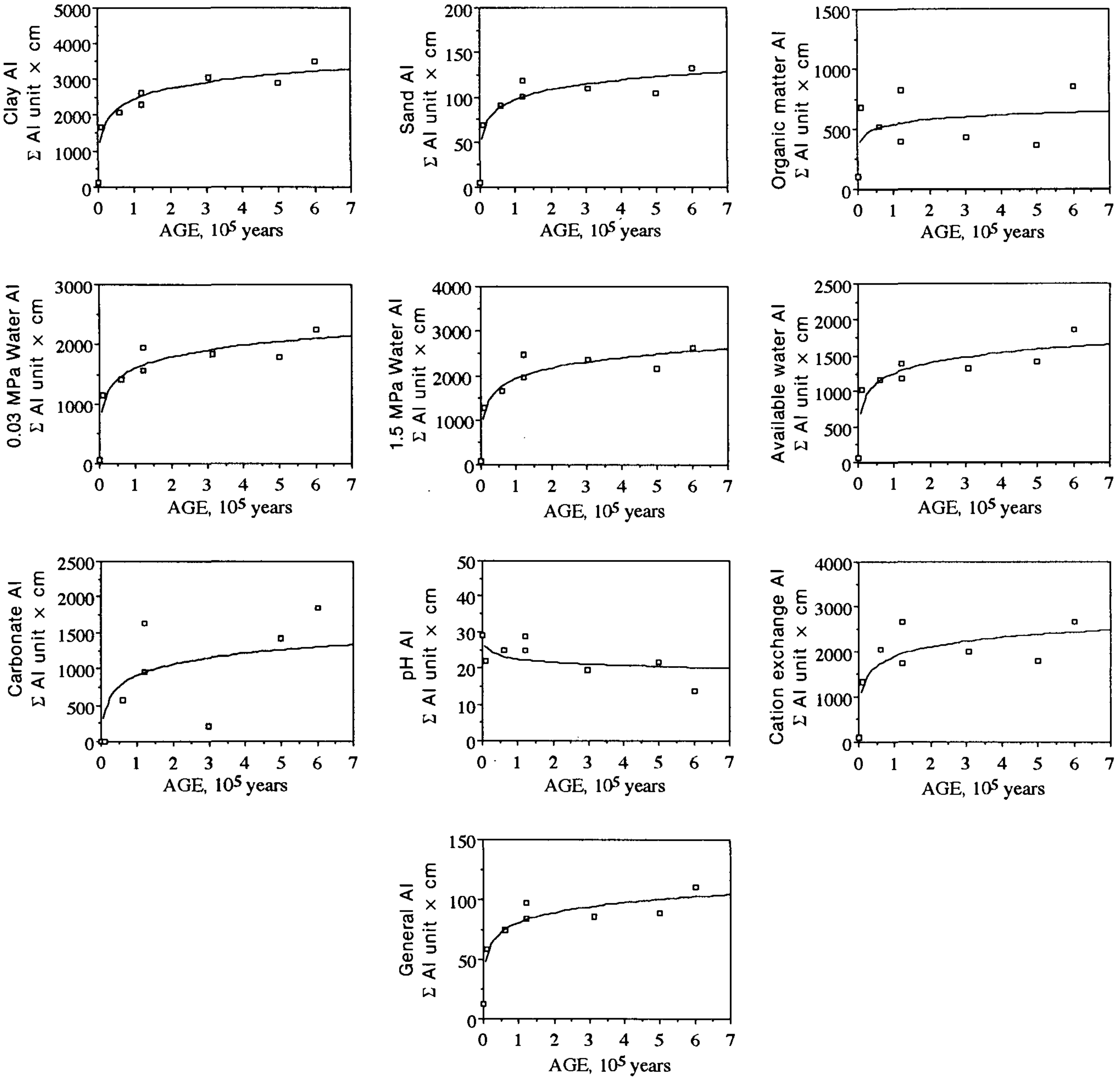

Fig. 12. Analytical indices vs. soil age.

of the Holocene and Upper Pleistocene age (Fig. 12). Similar increases as for these AI have been described by Birkeland (1984b) for soils of the Holocene age in New Zealand. Some of these AI are not strongly age dependent, such as organic C and carbonate.

Mineralogical Indices. The MineI are also well related with age. These MineI point to a constant and intense increase with age (Fig. 13).

Chronofunctions

Five models of regression equations were assayed for the chronofunctions of these soils: linear ($Y = a + bX$), second-degree polynomial ($Y = a + bX + cX^2$), power ($Y = aX^b$), logarithmic ($Y = a + b\log X$), and exponential ($Y = ab^X$). In each equation Y is a soil property and X is the geomorphic age of the soil surface. Of all these models, the power, second-degree polynomial, and logarithmic equations proved to be the ones best represented: almost all the regressions defined for the MI and AI and also for many of the properties corresponded to these equations (Tables 4 and 5). The linear model was the best fit in very few cases; the exponential equations had no representativity at all for these soils. In previous studies (Birkeland, 1984a,b; Yaalon, 1975; Bockheim, 1980, 1990; Little and Ward, 1981; Harden, 1982; Muhs, 1982), the equations most frequently found have been the logarithmic and power models.

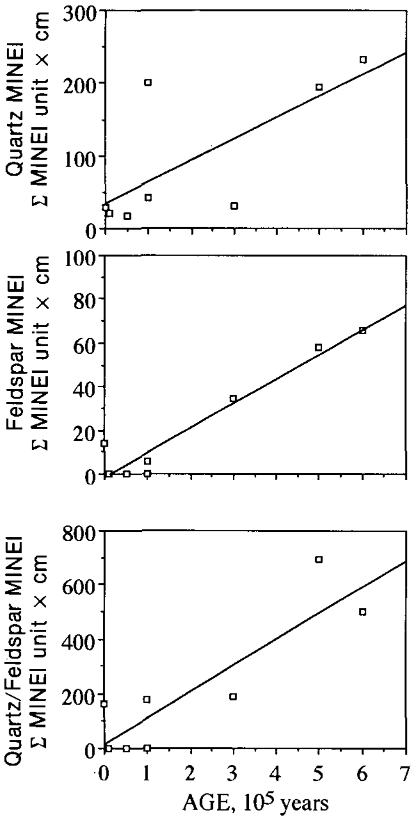

Fig. 13. Mineralogical indices vs. soil age.

In general, the correlation coefficients obtained had high values. The regression equations with the best fits for each chronofunction are shown in Table 5.

Steady State?

It is interesting to note that very few properties of the soils studied here seem to reach steady state during their development. All of them, except for sand content, continue to undergo changes even in the oldest soils of the chronosequence. For a large number of properties, however, development manifests only during the first period, corresponding to the Holocene and Upper Pleistocene soils (up to about 100 000 yr), with the rate of development slowing thereafter.

The paucity of results confirming the steady-state theory seems to be quite patent in most chronosequences investigated in different studies. Bockheim (1980) indicates that "the trends shown in this study cast some doubt as to whether soils reach a steady state (dynamic equilibrium) with their environment. Most of the properties investigated continue to change despite the passage of as many as 10^6 yr." Similar conclusions were reached by Muhs (1982) for the soils of marine terraces in California of up to 10^6 yr old. Also, Busacca (1987), studying a chronosequence of river terraces of the Sacramento Valley (California) of up to 10^6 yr, concluded, "Apparently none of the soils in the sequence has reached a steady state of development."

In light of this, it seems clear that most soil properties continue to develop with time and that no final stage of development is reached. Despite this, it is necessary to take into account that, during the development of a chronosequence, not only are there changes with time but also modifications due to climatic factors and the subordinate factor of organisms; these may have led to important variations in the final behavior of the soils of the chronosequence (in fact in most studies investigators should be using the term *climobiochronosequences*).

CONCLUSIONS

The following conclusions can be drawn from the results. First, the soil properties show several types of behavior.

1. As age progresses, some properties increase regularly throughout the chronosequence. This is strongly dependent on the age, COLE, and the available water of the Bt horizon.
2. Some properties continue to increase with age but more moderately during the last phases: for example, water retention at 0.03 and 1.5MPa and cation-exchange capacity of the Ap horizon, Fe_d of the Bt horizon, solum thickness, clay accumulations at depths of 15, 50, 100, 150, 200, and 250 cm, quartz content, and quartz/feldspar ratio.
3. Other properties cease to change in the soils from the Middle Pleistocene. In this situation are the silt and available water of the Ap horizon and the clay content, water retention at 0.03 and 1.5MPa, and cation-exchange capacity of the Bt horizons.
4. Still other properties show a strong increase only during the last phases (Middle Pleistocene and older soils). In this situation are the clay and N contents of the Ap horizon, the thickness of the Bt horizons, and carbonate accumulation.
5. Other properties decrease with age, with strong decreases up to the Upper Pleistocene soils, thereafter decreasing very moderately (feldspar contents), or they cease to increase for the soils from the Middle Pleistocene (the Ap and Bt horizon sand contents) or show an increase during the last phases (Bt horizon bulk density).
6. Other properties are not age related. Within this group there are two subgroups. One includes those properties that remain constant (Ap horizon base saturation) and the other those that vary chaotically (Ap horizon organic matter and pH and Bt horizon silt).

The second conclusion is that the horizon development indices show marked increases in their values with the advancing age of the soils and also show a progressive differentiation with time for the horizons of the soil profile.

Third, the soil development indices show very good correlations with age. In the vast majority of cases, the tendency to increase falls off strongly for the oldest soils of the Middle Pleistocene age.

Finally, in most cases, the properties and development indices continue to evolve constantly throughout the chronosequence without steady state being reached; however,

Table 4. Correlation coefficients for regression equations† relating to properties and indices with soil age.

	Linear	Polynomial	Power	Exponential	Logarithmic
		Properties			
Solum thickness	0.35	0.36	*0.67*‡	0.27	0.61
Bt horizon thickness	0.33	*0.44*	0.28	0.24	0.14
Sand, Ap horizon	0.34	0.45	*0.71*	0.35	0.49
Sand, Bt horizon	0.59	0.82	0.85	0.64	*0.87*
Silt, Ap horizon	0.03	*0.50*	*0.50*	0.04	0.42
Silt, Bt horizon	0.16	*0.23*	0.18	0.16	0.16
Clay, Ap horizon	0.59	*0.67*	0.55	0.58	0.40
Clay, Bt horizon	0.67	0.92	*0.94*	0.59	0.93
Clay accumulation to 15 cm	0.60	*0.66*	0.61	0.56	0.43
Clay accumulation to 50 cm	0.73	0.73	*0.90*	0.51	0.78
Clay accumulation to 100 cm	0.70	0.80	0.92	0.38	*0.97*
Clay accumulation to 150 cm	0.63	0.77	0.90	0.35	*0.97*
Clay accumulation to 200 cm	0.64	0.75	0.90	0.36	*0.95*
Clay accumulation to 250 cm	0.67	0.76	0.90	0.38	*0.92*
Water retention at 0.03 MPa, Ap horizon	0.50	0.52	*0.81*	0.40	0.76
Water retention at 0.03 MPa, Bt horizon	0.46	0.63	*0.67*	0.48	0.62
Water retention at 1.5 MPa, Ap horizon	0.47	0.62	*0.64*	0.53	0.57
Water retention at 1.5 MPa, Bt horizon	0.43	0.74	*0.79*	0.43	0.74
Available water, Ap horizon	0.28	0.47	*0.77*	0.25	*0.77*
Available water, Bt horizon	0.30	0.31	0.25	*0.33*	0.25
Organic matter, Ap horizon	0.12	0.21	*0.31*	0.10	0.23
N, Ap horizon	0.37	*0.56*	0.14	0.32	0.18
pH, Ap horizon	0.12	*0.37*	0.04	0.12	0.04
Cation-exchange capacity, Ap horizon	0.64	*0.72*	0.71	0.64	0.43
Cation-exchange capacity, Bt horizon	0.20	*0.77*	0.59	0.23	0.50
Dithionite-citrate-extractable Fe, Bt horizon	0.57	0.67	0.86	0.48	*0.90*
$CaCO_3$	0.42	0.42	*0.79*	0.36	0.53
Quartz	0.47	0.47	*0.79*	0.42	0.67
Feldspar	0.45	0.45	0.58	0.50	*0.67*
Quartz/feldspar ratio	0.55	0.50	*0.71*	0.46	0.59
		Indices			
Structure, morphological index	0.15	0.18	*0.66*	0.18	0.34
Texture, morphological index	0.41	0.48	0.77	0.22	*0.82*
Dry consistence, morphological index	0.34	0.48	0.81	0.24	*0.83*
Moist consistence, morphological index	0.34	0.48	*0.76*	0.22	0.73
Clay films, morphological index	0.29	0.48	*0.79*	0.22	0.69
Melanization, morphological index	0.46	0.53	*0.86*	0.44	0.73
Rubification, morphological index	0.66	*0.75*	0.41	0.69	0.40
General morphological index	0.49	0.65	0.83	0.28	*0.92*
Sand, analytical index	0.42	0.57	0.83	0.24	*0.92*
Clay, analytical index	0.62	0.75	0.86	0.30	*0.97*
Water retention at 0.03 MPa, analytical index	0.49	0.62	0.81	0.25	*0.93*
Water retention at 1.5 MPa, analytical index	0.45	0.65	0.83	0.25	*0.93*
Available water, analytical index	0.53	0.57	0.81	0.26	*0.89*
Organic matter, analytical index	0.07	0.09	*0.45*	0.10	0.25
$CaCO_3$ analytical index	0.42	0.42	*0.77*	0.36	0.49
pH, analytical index	0.63	*0.68*	0.35	0.65	0.39
Cation-exchange capacity (sum of bases), analytical index	0.27	0.37	*0.77*	0.21	0.75
General analytical index	0.46	0.57	0.86	0.30	*0.92*
Quartz mineralogical index	0.50	*0.52*	0.32	0.49	0.32
Feldspar mineralogical index	0.91	*0.94*	0.08	0.51	0.30
General mineralogical index	0.73	*0.76*	0.05	0.40	0.24

† Linear, $y = a + bx$; polynomial, $y = a + bx + cx^2$; power, $y = ax^b$; logarithmic, $y = a + b \log x$; exponential, $y = ab^x$.

‡ Maximum correlation coefficients are in italics.

the soils of the Middle Pleistocene age do reach a state of evident maturity from which development progresses very slowly.

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Table 5. Parameters included in each regression equation, and best fits for each correlation.

	Model	*a*	*b*	*c*	R^2	*P*
	Dependent variable					
Solum thickness, cm	Power	154.210	0.199		0.67	0.050
Bt horizon thickness, cm	polynomial	136.469	−15.865	4.260	0.44	
Sand, Ap horizon, %	Power	58.579	−0.055		0.71	0.010
Sand, Bt horizon, %	Logarithmic	34.118	−18.929		0.87	0.005
Silt, Ap horizon, %	polynomial	20.681	9.932	−1.623	0.50	0.050
Silt, Bt horizon, %	polynomial	14.205	−2.845	0.351	0.23	
Clay, Ap horizon, %	polynomial	9.556	−0.964	0.521	0.67	0.050
Clay, Bt horizon, %	Power	52.664	0.187		0.94	0.001
Clay accumulation to 15 cm, % m	polynomial	1.377	−0.103	0.072	0.66	0.050
Clay accumulation to 50 cm, % m	Power	10.503	0.256		0.90	0.001
Clay accumulation to 100 cm, % m	Logarithmic	37.683	15.166		0.97	0.001
Clay accumulation to 150 cm, % m	Logarithmic	54.139	20.746		0.97	0.001
Clay accumulation to 200 cm, % m	Logarithmic	69.212	26.321		0.95	0.001
Clay accumulation to 250 cm, % m	Logarithmic	83.222	31.812		0.92	0.001
Water retention at 0.03 MPa, Ap horiz., g kg^{-1}	Power	15.033	0.145		0.81	0.005
Water retention at 0.03 MPa, Bt horiz., g kg^{-1}	Power	33.258	0.152		0.67	0.050
Water retention at 1.5 MPa, Ap horiz., g kg^{-1}	Power	5.656	0.130		0.64	0.050
Water retention at 1.5 MPa, Bt horiz., g kg^{-1}	Power	22.032	0.182		0.79	0.010
Available water, Ap horiz., g kg^{-1}	Power	9.329	0.151		0.77	0.005
Available water, Bt horiz., g kg^{-1}	Exponential	9.673	0.029		0.33	
Organic matter, Ap horiz., g kg^{-1}	Power	1.533	0.084		0.31	
N, Ap horiz., g kg^{-1}	polynomial	0.050	−0.008	0.002	0.56	0.050
pH, Ap horizon	polynomial	5.485	−0.417	0.085	0.37	
Cation-exchange capacity, Ap horizon, $cmol_c$ kg^{-1}	polynomial	3.579	−0.568	0.269	0.72	0.010
Cation-exchange capacity, Bt horizon, $cmol_c$ kg^{-1}	polynomial	14.621	11.977	−1.175	0.77	0.010
Extractable Fe_d, Bt horizon, g kg^{-1}	Logarithmic	1.637	0.644		0.90	0.005
$CaCO_3$, g kg^{-1}	Power	2.317	1.643		0.79	0.005
Quartz, g kg^{-1}	Power	49.137	0.170		0.79	0.005
Feldspar, g kg^{-1}	Logarithmic	46.798	−14.604		0.67	0.050
Quartz/feldspar ratio	Power	1.109	0.295		0.71	0.010
	Indices					
Structure, morphological index (MI) (ΣMIunit × cm)	Power	36.749	0.570		0.66	0.050
Texture, MI (ΣMI unit × cm)	Logarithmic	102.870	37.757		0.82	0.005
Dry consistence, MI (ΣMIunit × cm)	Logarithmic	48.663	17.536		0.83	0.005
Moist consistence, MI (ΣMIunit × cm)	Power	30.280	0.391		0.76	0.005
Clay films, MI (ΣMIunit × cm)	Power	50.250	0.671		0.79	0.005
Melanization, MI (ΣMIunit × cm)	Power	48.108	0.211		0.86	0.001
Rubification, MI (ΣMIunit × cm)	polynomial	12.645	15.044	−1.550	0.75	0.010
General MI (ΣMIunit × cm)	Logarithmic	56.854	20.555		0.92	0.001
Sand, analytical index (AI) (ΣAIunit × cm)	Logarithmic	97.523	36.611		0.92	0.001
Clay, AI (ΣAIunit × cm)	Logarithmic	2445.400	999.380		0.97	0.001
Water retention at 0.03 MPa, AI (ΣAIunit × cm)	Logarithmic	1611.500	628.230		0.93	0.001
Water retention at 1.5 MPa, AI (ΣAIunit × cm)	logarithmic	1951.600	770.220		0.93	0.001
Available water, AI (ΣAIunit × cm)	Logarithmic	1257.000	472.500		0.89	0.001
Organic matter, AI (ΣAIunit × cm)	Power	478.861	0.192		0.45	
$CaCO_3$, AI (ΣAIunit × cm)	Power	97.994	2.087		0.77	0.005
pH, AI (ΣAIunit × cm)	polynomial	25.673	0.363	−0.357	0.68	0.050
Cation-exchange capacity (sum of bases) AI (ΣAIunit × cm)	Power	1581.713	0.404		0.77	0.005
General AI (ΣAIunit × cm)	Logarithmic	81.193	27.951		0.92	0.001
Quartz mineralogical index (MineI) (ΣMineIunit × cm)	polynomial	46.003	4.690	4.165	0.52	0.050
Feldspar MineI (ΣMineIunit × cm)	polynomial	2.598	2.473	1.481	0.94	0.001
General MineI (ΣMineIunit × cm)	polynomial	46.532	26.271	11.550	0.76	0.005

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