Soil development and time

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Introduction

Soil development refers to the state of a soil parameter relative to its state in the parent material (Harden, 1990). The degree of soil development is dependent on the different soil-forming factors (Jenny, 1941). Because the variables of climate, parent material, relief and time also govern geomorphic processes, landscape evolution is intimately related to soil development (McFadden and Kneupfer, 1990). Differences in soil properties have been used in the age determinations of soils (Levine and Ciolkosz, 1983; Harden, 1982; Harrison *et al.*, 1990) and thus, can be used for the approximate dating of the landforms (Semmel, 1989). This would be true if soil properties would increase constantly with time (Bockheim, 1980; Birkeland, 1990). Nevertheless, according to Morrison (1963) and Simón *et al.* (2000), the above theory may not be entirely true, and soils could have evolved during different pedogenic episodes alternating with erosion-deposition episodes. In each pedogenic episode, the soils could have approached or reached a steady state.

The aim of this work is to advance knowledge concerning soil evolution over time. With this objective, we have compared soil development on two different types of surface: 1) geomorphically stable surfaces with pedogenic overprinting; 2) unstable surfaces with successive erosion-deposition episodes alternating with pedogenic episodes. In the first case, the successive pedogenic stages are not spatially distinct as in the second case.

Materials and methods

In the Granada Basin (southern Spain), we have studied soils developed on three stable surfaces over time (DUR, LLP, COL) and an unstable surface formed by different erosion-deposition episodes alternating with pedogenic episodes (NIG) (Figure 1). Both the stable surfaces and the oldest deposit of the unstable surface (NIG-1) are dated from the transition Plio-Pleistocene or Pleistocene (Fernández and Soria, 1986-1987).

Field descriptions of the soils were based on procedures of the Soil Survey Staff (1990). In all soils, physical, chemical and physico-chemical properties were determined (Tables 1 and 2): particle-size, pH, electric conductivity, organic carbon, carbonate content, cation-exchange capacity (CEC), exchangeable bases, total iron (Fe_t), iron oxides (Fe_d) and the iron-oxide amorphous forms (Fe_o). For the estimation of the degree of development of each profile, a clay-accumulation index (CI) was calculated as follows: Σ (B-C)T, where B=B horizon clay content (%), C=C horizon clay content (%) and T= thickness of the B horizon in cm (Levine and Ciolkosz, 1983). Because, for any given intensity of weathering, the pedogenic iron oxides (Fe_d) should rise in proportion to the total iron content (Fe_t), an iron oxide-accumulation index (FeI) was calculated using the same equation as that for clay, where B=B horizon Fe_d:Fe_t ratio, C= C horizon Fe_d:Fe_t ratio.

Profile	Horizon	Depth (cm)	Colour dry	Structure (type, size, grade)	Gravel (%)	Clay (%)	Coarse Silt (%)	Fine Silt (%)	Sand (%)
NIG-4	Bt1	0-17	5YR 4/6	abk,m,2	19.5	35.7	7.1	15.1	42.1
	Bt2	17-34	2,5YR 4/4	abk,m,2	17.1	27.0	11.6	15.1	46.3
	BC	34-48	7,5YR 5/6	sbk,m,1	36.6	18.0	11.6	18.2	52.2
	CB	48-60	10YR 6/4	sbk,f,1	33.7	12.2	11.3	18.7	57.8
	C	60-105	10YR 6/2	m,-,0	47.0	15.2	12.2	26.4	46.2
	2Ck1	105-120	2,5Y 6/2	m,-,0	45.3	8.5	14.6	26.8	50.1
	2Ck2	120-150	2,5Y 5/2	m,-,0	58.4	8.3	14.2	26.7	50.8
	2Ck3	150-190	2,5Y 6/2	m,-,0	51.1	6.1	14.2	29.5	50.2
NIG-3	Bt	190-280	10R 4/6	abk,m,3	42.0	55.1	5.2	9.2	30.5
	C	280-310	10YR 6/3	sg,-,0	49.3	5.8	13.9	15.5	64.8
NIG-2	Bt1	310-345	10R 4/6	abk,m,2	36.3	45.2	5.6	12.1	37.1
	Bt2	345-388	10R 4/6	sbk,m,2	39.1	28.5	10.4	19.2	41.9
	C	388-428	10YR 6/3	sg,-,0	37.6	10.0	13.2	19.3	57.5
NIG-1	Bt	428-508	2,5YR 4/6	abk,m,2	38.7	35.6	6.4	16.3	41.7
	BC	508-538	7,5YR 6/6	abk,f,1	73.3	12.0	7.4	15.1	65.5
	C	538-563	10YR 6/3	sg,-,0	49.3	10.9	11.3	19.4	58.4
DUR	Bt1	0-80	2,5YR 3/4	pr,c,3	6.8	72.4	4.5	5.8	17.3
	Bt2	80-104	2,5YR 3/4	abk,m,2	26.8	56.9	6.4	10.6	26.1
	Ckm	>104	10YR 6/3	m,-,0	80.9	8.8	10.2	16.0	65.0
LLP	A	0-2	7,5YR 4/6	cr,f,1	12.7	11.1	7.7	6.7	74.4
	E	2-18	7,5YR 6/6	gr/sbk,m,2	28.0	12.5	10.8	10.5	66.2
	Bt1	18-50	10R 4/6	abk,m,2	21.7	54.2	4.9	8.4	32.5
	Bt2	50-85	2,5YR 4/6	abk,c,2	35.0	39.1	5.2	10.4	45.3
	Bt3g	85-121	2,5YR 4/6	abk,c,2	46.4	31.3	6.8	8.7	53.2
	BCg	121-176	2,5YR 4/6	abk,m,2	48.8	22.1	6.8	11.2	59.9
	Ck	>176	7,5YR 8/4	m,-,0	73.4	7.1	6.6	11.9	74.4
COL	Ap1	0-6	2,5YR 3/6	abk,m/gr,f,2	12.9	57.6	5.2	15.8	21.3
	Ap2	6-20	2,5YR 3/6	pr,c,3	6.3	58.7	5.6	13.3	22.4
	Bt	20-50	2,5YR 3/6	pr,m,3	0.18	91.6	0.6	2.8	5.0
	BCtk	50-90	2,5YR 4/6	abk,f,2	15.1	44.7	6.2	36.4	12.7
	BCkt	90-120	2,5YR 7/4	abk,f,1	9.0	21.7	8.3	54.6	15.4
	2Ck	>120	10YR 8/2	sg,0	64.3	14.9	5.4	33.4	46.3

Table 1. Field soil dataand particle- size distribution of the soils.

Profile	Horizon	pH	CaCO3 (%)	OC (%)	EC (dSm^{-1})	Na^+	K^+	Ca^{2+}	Mg^{2+}	CEC	Base saturation (%)	Fe t (%)	Fe d (%)	Fe o (%)	Fed/Fe t x 100	Feo/Fed x 100
						Exchangeable bases ($cmol_c\ kg^{-1}$)										
NIG-4	Bt1	7.3	0.5	0.32	1.84	0.10	0.16	6.24	2.70	12.46	73.7	5.29	1.94	0.063	36.71	3.24
	Bt2	7.4	0.6	0.25	2.83	0.14	0.13	10.00	3.41	9.02	100.0	4.77	1.97	0.040	41.29	2.06
	BC	7.1	0.6	0.16	3.10	0.14	0.07	8.48	2.76	6.44	100.0	4.73	1.75	0.038	36.98	2.17
	CB	7.4	0.6	0.17	3.23	0.19	0.04	6.74	2.44	5.16	100.0	4.36	1.57	0.037	36.16	2.35
	C	8.0	0.7	0.20	2.74	0.41	0.04	7.49	3.00	6.87	100.0	4.38	1.60	0.022	36.58	1.37
	2Ck1	8.6	17.5	0.23	1.70	0.14	0.02	16.00	1.79	5.59	100.0	3.66	1.13	0.020	30.80	1.82
	2Ck2	8.5	14.7	0.24	1.99	0.07	0.02	16.00	1.54	5.16	100.0	3.69	1.10	0.021	29.91	1.90
	2Ck3	8.1	13.7	0.21	n.d.	0.27	0.02	11.00	4.55	4.30	100.0	3.76	1.13	0.014	30.06	1.24
NIG-3	Bt	8.3	0.4	0.14	0.67	0.12	0.39	10.23	4.95	14.18	100.0	6.69	2.39	0.039	35.68	1.65
	C	9.1	6.4	0.14	0.54	0.02	0.04	10.48	3.57	4.30	100.0	3.81	0.81	0.026	21.35	3.20
NIG-2	Bt1	8.6	2.2	0.16	0.46	0.09	0.26	7.24	9.18	14.18	100.0	6.00	2.55	0.036	42.41	1.43
	Bt2	8.3	2.8	0.21	2.60	0.07	0.18	6.24	7.31	10.31	100.0	5.73	2.26	0.047	39.39	2.10
	C	8.5	2.3	0.20	4.08	0.07	0.05	5.74	5.93	8.59	100.0	4.81	1.31	0.021	27.29	1.60
NIG-1	Bt	8.5	0.4	0.20	0.66	0.09	0.35	2.99	7.31	9.88	100.0	5.61	1.39	0.073	24.82	5.28
	BC	8.8	1.2	0.23	0.90	0.05	0.07	4.24	3.25	7.73	98.5	4.23	0.52	0.031	12.41	5.90
	C	8.9	0.7	0.25	0.85	0.02	0.07	4.24	2.68	4.73	100.0	4.70	0.37	0.030	7.82	8.16
DUR	Bt1	8.3	1.0	0.46	1.08	0.15	0.51	13.97	6.90	17.19	100.0	6.23	2.07	0.052	33.27	2.53
	Bt2	8.2	0.5	0.45	1.22	0.26	0.40	10.23	5.60	16.33	100.0	5.95	1.94	0.026	32.66	1.36
	Ckm	8.4	30.7	0.33	n.d.	0.03	0.15	12.23	1.22	3.44	100.0	2.92	0.26	0.024	9.00	9.14
LLP	A	7.4	1.1	3.77	0.51	0.06	0.26	14.00	2.25	24.12	68.7	2.86	0.71	0.038	24.76	5.43
	E	7.5	0.61	1.18	0.41	0.02	0.15	8.00	1.67	12.99	75.7	3.39	0.68	0.036	20.12	5.27
	Bt1	6.6	0.45	0.65	0.19	0.06	0.15	8.70	3.67	16.23	77.8	6.74	2.10	0.084	31.17	4.00
	Bt2	6.5	0.56	0.35	0.30	0.12	0.11	13.00	5.25	14.38	100.0	6.01	1.97	0.073	32.76	3.73
	Bt3g	6.7	0.68	0.26	0.94	0.15	0.11	9.70	4.42	12.99	100.0	5.93	1.81	0.084	30.56	4.64
	BCg	6.6	0.9	0.28	0.34	0.21	0.11	10.70	4.58	12.06	100.0	5.66	1.10	0.052	19.47	4.76
	Ck	8.7	36.0	0.31	0.83	0.21	0.04	27.50	0.78	6.03	100.0	3.25	0.52	0.009	16.17	1.71
COL	Ap1	8.0	1.9	0.10	0.55	0.11	1.85	29.00	1.25	24.33	100.0	5.41	2.39	0.100	44.15	4.19
	Ap2	8.2	2.0	0.10	0.37	0.09	1.66	27.70	1.00	29.34	100.0	5.33	2.49	0.100	46.82	4.01
	Bt	7.7	0.8	0.05	0.29	0.14	0.87	33.20	1.67	38.65	93.0	6.74	3.19	0.100	28.45	5.22
	BCtk	8.3	51.1	0.03	0.37	0.09	0.49	36.70	0.92	22.90	100.0	3.63	1.44	0.025	39.77	1.77
	BCkt	8.5	71.4	0.02	0.26	0.06	0.23	37.20	0.50	11.45	100.0	1.68	0.68	0.095	40.74	1.39
	2Ck	8.7	80.0	0.42	0.30	0.05	0.10	sat.	0.50	6.30	100.0	1.07	0.12	0.062	11.24	51.66

Table 2. Analytical soil data and iron forms of the soils.
OC=Organic carbon; EC=Electric conductivity; CEC=Cation exchange capacity

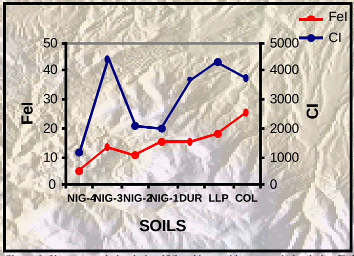

Figure 2. Clay-accumulation index (CI) and iron oxide-accumulation index (FeI) of the soils.

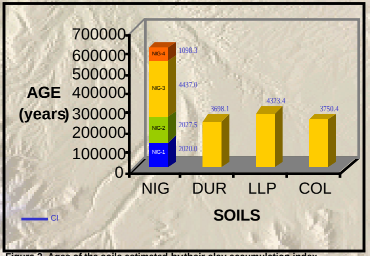

Figure 3. Ages of the soils estimated by their clay-accumulation index.

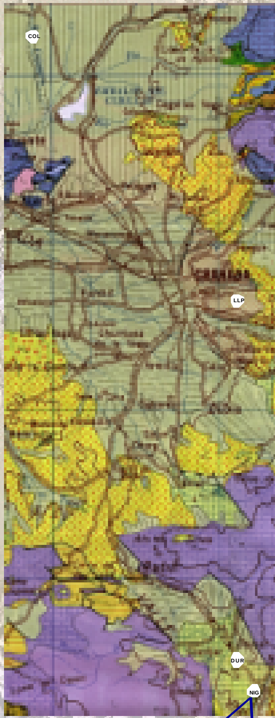
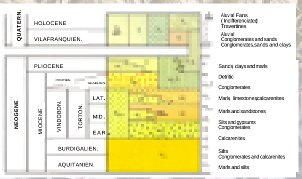
Figure 1. Geological map of the zone and situation of the studied profiles.


Scheme of the sequence of buried soils in Niguelas

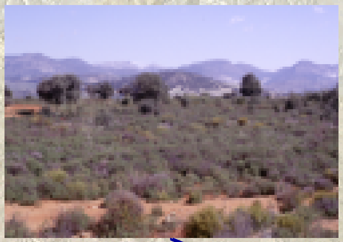

Figure 4. Landscape of the Llano de la Perdiz and characteristic profile.




Figure 5. Landscape of Nigüelas, sequence of buried soils and detail of the micromorphology.


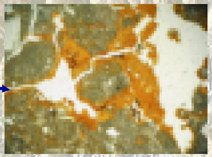
Figure 6. Profile COL and detail of the micromorphology of BCtk horizon.

Discussion

All soils have a Bt horizon, characterized by a red colour (2,5 YR-10R), a well-developed structure (angular blocky) and well-developed clay skins. The soils developed on stable surfaces have similar degrees of development, estimated by the increase in Fe_d and the clay content in the B horizon in relation to the C horizon. On the contrary, the soils developed on the ustable surface have different degrees of development. The oldest and deepest soils (NIG-1 and NIG-2) have similar intermediated development whereas NIG-3 is the most developed and NIG-4, close to the surface, the least developed (Figure 2).

By comparing our clay-accumulation indices with those of Levine and Ciolkosz, (1983) for soils of northeastern Pennsylvania, we estimate soils on the stable surfaces to be between 275,000 and 235,000 years old. In the unstable surface, the oldest and deepest soil (NIG-1) is around 130,000 years old. The second soil (NIG-2), above the former, is similar in age. The next soil (NIG-3) is around 280,000 years old and the top one (NIG-4) is around 70,000 years old (Figure 3).

This suggests that soils formed on the stable surfaces developed over a serie of stepped episodes and that they reached a maximum in their evolution in the episode more conducive to soil development. This episode would correspond to the NIG-3 pedogenic episode. Later processes less conducive to soil development that affected soil NIG-4 did not affect the soils developed on the stable surfaces; so that, these former soils should have reached a steady state. Thus, it is very difficult to estimate the age of a surface based on the degrees of development of their soils because soils with similar degrees of development can be different in age.