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Soil genesis in a marine terrace sequence of Sicily, Italy

Stephen Wagner[1,*], Edoardo A.C. Costantini[2], Daniela Sauer[1], and Karl Stahr[1]

[1] *Institute of Soil Science and Land Evaluation, University of Hohenheim,*
Emil-Wolff-Str. 27, D-70599 Stuttgart, Germany.
[2] *Experimental Institute for Soil Study and Conservation, Ministry of Agricultural Policies,*
Piazza M. D'Azeglio 30, 50121 Firenze, Italy.
** stwagner@uni-hohenheim.de*

ABSTRACT

Knowledge about the rates of pedogenic processes is essential to understand landscape development and history. It can be attained by the quantitative investigation of soil chronosequences. In this work, the development of Chromic Luvisols in the Mediterranean is addressed. The soils investigated are located on five uplifted Pleistocene marine terraces in south-western Sicily, and have developed on calcareous marine and fluvial sediments. The soil on the highest terrace is a Ferri-Profondic Luvisol, while soils on the lower terraces represent a Chromi-Profondic Luvisol (Bathifragic), a Chromi-Profondic Luvisol and two Bathicalci-Chromic Luvisols. The soils on the 1st (lowest) and 2nd terrace are 100 cm thick, the one on the 3rd terrace, 160 cm and those on the 4th and 6th (highest) terrace more than 200 cm. All soils are decalcified, while greater $CaCO_3$ contents in the Ap horizons of the soils on the three lower terraces are due to deposition of younger calcareous fluvial sediments. Soil pH (water) drops from pH 7.7–8.9 in the soils on the three lower terraces to values below pH 7 in the soils on the two higher terraces. In general, the chemical alteration and the leaching of silicic acid increase with elevation, and are most pronounced on the 4th and 6th terrace. Clay illuviation and associated translocation of Fe, Al and K is pronounced in all soils. The clay minerals include kaolinite, illite and expandable three-layer silicates. Irregularly interstratified clay minerals are composed of illite, vermiculite, smectite and chlorite, and usually constitute 20–40 % of all clay minerals, indicating proceeding soil development. The comparatively more advanced weathering and the high kaolinite content on the most elevated terrace point to soil development under warmer and wetter climate, that is early Pleistocene or earlier. The soil on the 4th terrace is more developed than the soils on the less elevated terraces.

The 3rd terrace was exposed to local rejuvenation by sedimentation in a lagoon/lacustrine environment. Above the lacustrine layer, the Chromi-Profondic Luvisol on the 3rd terrace shows a similar development as the soils on the two lower terraces. Therefore, we assume that the marine terraces around Menfi in south-western Sicily emerged at least at three different time steps; the 6th terrace and the 4th terrace developed at different times, whereas the lower three terraces formed at similar times. The latter may have formed also at the same time, and later dislocated to different elevations by tectonics.

*Key words***:** *soil genesis, Chromic Luvisols, marine terraces, terrace sequence, weathering, Sicily.*

RESUMEN

El conocimiento sobre las tasas de procesos pedogenéticos es esencial para entender el desarrollo y la historia del paisaje. Este puede obtenerse a través de la investigación cuantitativa de cronosecuencias de suelos. En este trabajo analizamos el desarrollo de Luvisoles crómicos en el Mediterráneo, en una secuencia de cinco terrazas marinas pleistocénicas emergidas, localizada en el suroeste de Sicilia. Las terrazas se desarrollan a partir de sedimentos marinos y fluviales calcáreos. El suelo de la terraza más alta es un Luvisol Ferri-Profóndico, mientras que los suelos en las terrazas más bajas representan un Luvisol

Cromi-Profóndico (Bathifragic), un Luvisol Chromi-Profóndico y dos Luvisoles Bathicalci-Crómicos. Los suelos en la 1ª (más baja) y 2ª terraza tienen 100 cm de profundidad, el situado en la 3ª terraza tiene 160 cm y aquellos de la 4ª y 6ª (más alta) terraza tienen más de 200 cm de profundidad. Todos los suelos están descalcificados; el mayor contenido de $CaCO_3$ en los horizontes Ap de los suelos en las tres terrazas más bajas se debe a la deposición de sedimentos fluviales. El pH (en agua) disminuye de pH 7.7–8.9, en los suelos de las tres terrazas más bajas, a valores debajo de pH 7 en las dos terrazas más altas. De manera general, la alteración química y la lixiviación de ácido silícico aumentan con la elevación, y son más pronunciadas en la 4ª y 6ª terraza. La iluviación de arcilla y la translocación de Fe, Al y K asociada es evidente en todos los suelos. Las minerales arcillosos presentes incluyen a caolinita, illita, vermiculita y esmectita. Los minerales interestratificados irregulares se componen de illita, vermiculita, esmectita y clorita, y constituyen generalmente un 20–40 % de todos los minerales arcillosos, indicando que el desarrollo del suelo sigue en proceso. La meteorizacion comparativamente más avanzada y el alto contenido de caolinita en la terraza más alta indican que este suelo se ha desarrollado bajo un clima más cálido y más húmedo al actual, es decir en el Pleistoceno temprano o antes. El suelo en la 4ª terraza se encuentra más desarrollado que los de las terrazas menos elevadas.

La 3ª terraza estuvo sujeta a un rejuvenecimiento local por el aporte de sedimentos lacustres. Sobre la capa lacustre, el Luvisol Cromi-Profóndico de la 3ª terraza muestra un desarrollo similar al de los suelos en las dos terrazas más bajas. Por lo tanto, asumimos que las terrazas marinas alrededor de Menfi, al suroeste de Sicilia, se formaron en por lo menos tres períodos distintos de tiempo: la 6ª terraza y la 4ª terraza se formaron en dos períodos distintos, mientras que las tres terrazas más bajas se formaron en un tiempo posterior. Las últimas tres terrazas también pudieron haberse formado al mismo tiempo y haber sufrido posteriormente un levantamiento diferencial por tectonismo.

Palabras clave: pedogénesis, Luvisoles crómicos, terrazas marinas, secuencia de terrazas, meteorización, Sicilia.

INTRODUCTION

Knowledge on the rate of soil genesis is important for the reconstruction of landscape development. An estimation of the time of soil formation is also required to evaluate tolerable soil erosion rates for different environments. However, research on the time frame of pedogenic processes is limited, because soil chronosequence studies require constant parent material, topography, climate and vegetation within the time of soil formation for all pedons. In uplifted coastal environments, fresh material is successively raised above the water level, forming sequences of marine terraces of different ages, and allowing the observation of subsequent stages of soil genesis. Such conditions exist along the tectonically active coast in western Sicily. In this area, soils have developed from calcareous parent materials. Typical soils on such materials are Chromic Luvisols. Here we address the issue of the development of Chromic Luvisols in a sequence of Pleistocene marine terraces.

Merritts *et al.* (1991) determined relative soil age and degree of soil development on marine terraces in California by calculating clay mass accumulation, with the latter increasing by *ca.* 0.4 $g \cdot cm^{-2}$ per 1,000 years. Torrent *et al.* (1980) calculated redness rating (RR) by hue, chroma and value according to the Munsell soil colour charts and found a strong relationship between RR and hematite content for soils on river terraces in Spain. This correlation was confirmed for soils developed on calcarenites in southern Spain (Torrent and Cabedo, 1986). The degree of weathering for red tropical soils has been estimated by the silt/clay ratio, with prolonged weathering being characterised by a ratio of less than 0.2 (Fitzpatrick, 1971).

The dynamics of elements such as Fe, Al and Mn can be studied by different extractions, and may be used as proxy for soil age. While dithionite dissolves crystalline, amorphous and poorly crystallised oxides and hydroxides, oxalate dissolves only the amorphous and poorly crystalline minerals. Ratios of these reflect weathering stages and degree of soil development, as the Fe_d/Fe_t ratio increases and the Fe_o/Fe_d ratio decreases with terrace age. The Fe_o/Fe_d ratio characterises a progressive transformation of ferrihydrite into goethite and hematite (Muhs, 1982; Aniku and Singer, 1990). This behaviour is not found where volcanic ashes played a role in the chronosequence (Grez, 1977; Jahn, 1988).

An often neglected, nevertheless important aspect of soil genesis in the Mediterranean region is that most of the soils in this region contain considerable amounts of eolian material. Yaalon (1997) stated that dust derived from the Sahara continuously affects soil formation since around five million years ago, when the Sahara began to convert into a desert, with the accumulated dust being calcareous and supplying enough $CaCO_3$ over time to form calcic horizons.

In western Africa, the source area of dust outblown during the dry season is probably characterised by secondary carbonates, because calcite proportions increase with their distance to the source (Stahr and Herrmann, 2001). Dust deposition is generated by gravitational settling, rainfall or "catch-out". Consequently, the rate of dust deposition is largely influenced by the weather conditions and the processes involved (Stahr *et al.*, 1996). A less intense, continuous dust accumulation provides the condition of gradual incorporation by bioturbation which often impedes its identification (Jahn *et al.*, 1991). The provenience of sediments can be traced by heavy minerals, clay mineralogy and particle-size distribution, as well as by element ratios (*e.g.*, Herrmann *et al.*, 1996).The objective of this study was to characterise processes of soil development and weathering of parent materials by soil description and analysis of texture, clay mineralogy, total element contents and element ratios, composition of secondary amorphous and crystalline phases, and to verify if the state of pedogenesis varies according to the elevation of the marine terraces.

MATERIALS AND METHODS

General setting

The study area is located in the south-west of Sicily, close to Menfi (Figure 1). The climate at the nearby station of Trapani (15 m a.s.l.) is Mediterranean, with an average annual precipitation of 516 mm and a mean annual temperature of 18.2°C (Figure 2), and is classified as thermic-xeric, with moderate excess humidity in winter and an annual water deficit of 255 mm. The land in this area is typically cultivated by olive groves, vineyards, cereals and pastures (Guaitoli *et al.*, 1998). The geological map of the area shows a sequence of marine abrasion or sedimentary terraces of Pleistocene age underlain by marl deposits (Guaitoli *et al.*, 1998).

The soils investigated are located on five marine terraces that rise from 97 m to 361 m a.s.l.. The lowest and the 5th terrace (T5) were excluded from the study, because they are actively influenced by present fluvial deposition (lowest terrace), or limited in extension and only supporting strongly eroded soils (T5).

Recent studies carried out by local geologists, however, have recognised eight marine terraces in an adjacent area between Punta Granitola and Porto Palo (D'Angelo *et al.*, 2001), which can be correlated with the terraces studied by us as follows: terraces 1 to 5 (from 0 to about 80 m a.s.l.) correlate with our lowest excluded terrace, terraces 6 and 7 (from 90 to 114 m a.s.l.) with our T1, terrace 8 (from 115 to 214 m a.s.l.) with our T2, T3 and T4. They tentatively dated the terraces by means of regional correlation, and related them to oxygen isotope stages. The eight terraces were respectively attributed to stages 5e, 7, 9, 11 (both 4th and 5th), 13, 15, 17. That would mean that the terraces studied in this work should be middle Pleistocene in age,

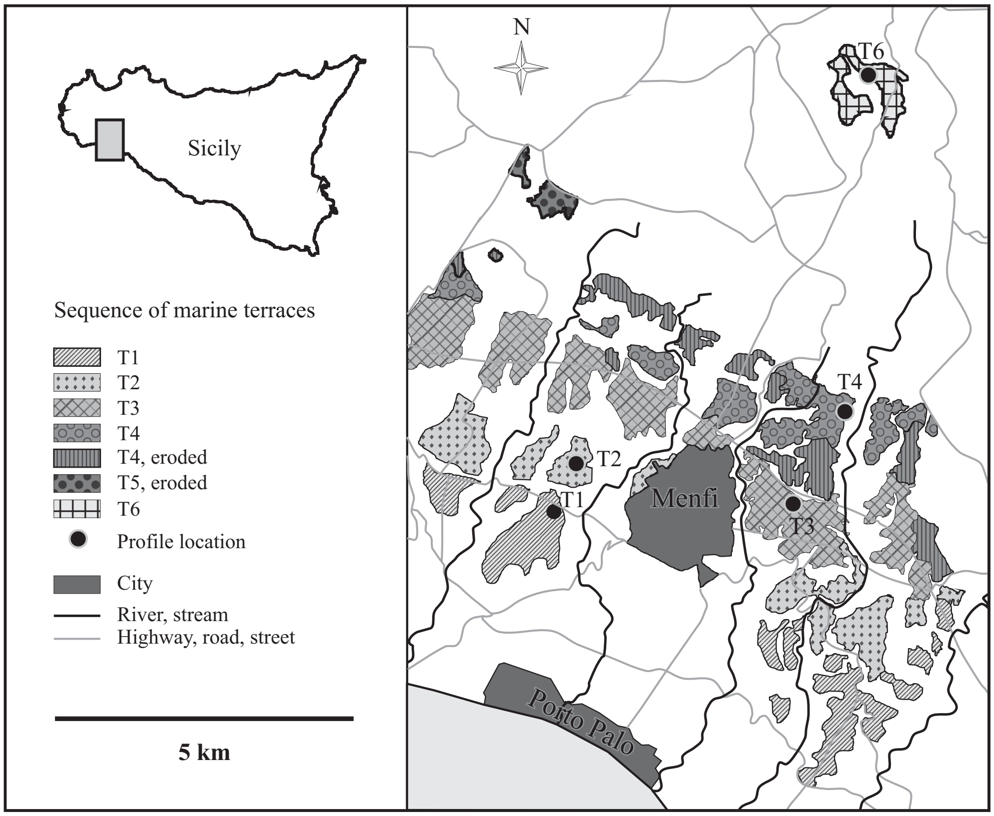

Figure 1. The sequence of marine terraces in the study area near Menfi, south-western Sicily, with the location of the soil sampling sites (modified after Guaitoli *et al.*, 1998).

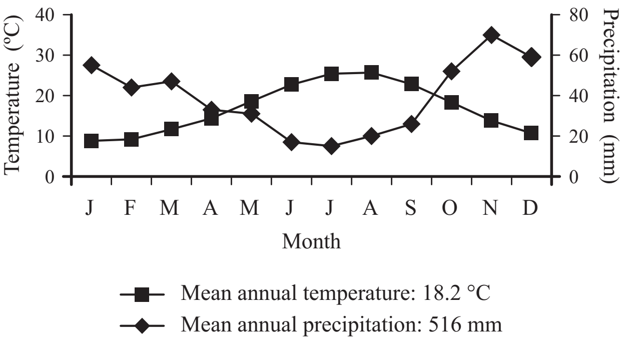

Figure 2. Climate diagram of Trapani, western Sicily, 15 m a.s.l., 28° N.

with the exception of our terraces T5 and T6, which could be older. D'Angelo *et al.* (2001), in fact, report the presence of sandy clays and calcarenite ("Calcarenite di Marsala") of early Pleistocene age (Santerniano-Siciliano) between marine terraces and pre-Quaternary marine deposits. They also indicate the occasional occurrence of a reddish paleosol at the top of the "Calcarenite di Marsala". The paleosol should have been formed during the so-called "regressione romana" (sea regression), which lasted from oxygen isotopic stage 21 to 17.

The studied soils have developed on calcarenite, locally covered by fluvial sediments. The fluvial sediments are akin to the calcarenite and can be individuated by the presence of unweathered rounded pebbles, mixed with the marine sandy material. The soils on the two most elevated terraces T4 and T6, which are assumed to be the oldest ones, are a Chromi-Profondic Luvisol (Bathifragic) and a Ferri-Profondic Luvisol, while the soils on the three lower terraces (T1, T2 and T3) represent Bathicalci-Chromic Luvisols.

Field and laboratory methods

The sequence of five soil profiles was described in the field and sampled for laboratory analyses. Bulk samples were air-dried and passed through a 2 mm mesh sieve to obtain the fine earth fraction. The Munsell soil colours were determined on moist samples. The pH values were measured in water at a soil:solution ratio of 1:2.5. The electrical conductivity was determined using a 1:5 soil:water extract. Carbonate-carbon (C_{carb}) and organic carbon (C_{org}) content were determined by a LECO RC 412 analyser. Particle-size analysis was performed after removal of carbonates and organic matter (OM) by treatment with HCl (pH 4.5) and H_2O_2 (10 %), and of excessive salts by repeated addition of deionised water, centrifugation and decantation until the electrical conductivity (EC) dropped below 40 µS cm^{-1}. After subsequent addition of NH_3 for water dispersion, overnight shaking and ultrasonic treatment, the sand fractions (63–2000 µm) were obtained by wet-sieving, while the silt and clay fractions were separated by pipette analysis. Clay mineralogy was determined by X-ray diffraction (XRD) of oriented clay specimens using a Siemens D-500 instrument with Cu Kα radiation. Different treatments of the clay samples included K and Mg saturation, heating to 110°C, 220°C, 400°C and 600°C of the K- and glycerol solvation of the Mg-saturated samples. The amounts of the different clay minerals were estimated on a semi-quantitative basis by using the computer package DIFFRAC AT V3.3 Siemens 1993. The cation exchange capacity (CEC) was measured by use of 1 M Na-acetate at pH 7.0. Exchangeable bases were extracted with 1 M NH_4-acetate at pH 7.0 and measured by flame photometry (Na, K and Ca) and atomic absorption spectroscopy (Mg). Element compositions were obtained by X-ray fluorescence spectrometry (Siemens SRS 200) of fused discs with $Li_2B_4O_7$. Loss on ignition (LOI) was derived from the weight loss of the soil sample after fusing. Dithionite-citrate-bicarbonate extractable Fe (Fe_d) was analysed by atomic absorption spectrometry (AAS). Oxalate extractable Fe (Fe_o) was measured by inductive coupled plasma – optical emission spectrometry (ICP-OES). Redness rating (RR) was calculated according to Torrent *et al.* (1980). All soils were classified according to the World Reference Base for Soil Resources (WRB) (FAO, 1998). Fifty two undisturbed soil samples were taken to prepare 80 × 50 mm thin sections for petrographic and micromorphological observation.

RESULTS AND DISCUSSION

General characterisation

Soil thickness is about 100 cm on the 1st terrace, it increases to 160 cm on the 2nd terrace and exceeds 200 cm on the three higher terraces (Table 1). The two lower terraces are covered by fluvial deposits (42 to 105 cm). At the location on the 3rd terrace, a deposit assumed to originate from a former lagoon environment covers the marine terrace. On the two highest terraces, the marine sediments were relocated by colluvial activity (Table 1). The boundaries between the different layers are generally sharp or distinct as result of differences in the hue of soil colour (Tables 1, 2). Soil structure is mostly subangular blocky in the Ap horizons and prismatic or angular blocky in the Bt horizons (Table 1).

In the solum of all soils, carbonate assembles 0–3 % (Table 2), indicating more or less complete decalcification in the soil sequence. Values of pH in water down to pH 6.8 and pH 6.4 indicate incipient acidification of the soils on the 4th and 6th terrace, respectively. On the lower terraces, the pH ranges between 7.7 and 8.9 (Table 2). The electrical conductivity (EC) is rather low. The soils on the three lower terraces show a greater EC than those on the two higher terraces (Table 2), because of their closer vicinity to the sea. OM contents range between 0.7 and 1.7 % in the Ap horizons and rapidly decline downwards (Table 2).

Table 1. Field description of the soils.

Site / Horizon	Depth [a] (cm)	Parent material	Type of rock fragments [b]	Lower boundary [c]	Structure [d]	Redoximorphic features [e]	Roots per dm^2
Terrace 1, Bonera, 97 m a.s.l., N 37°36.224' E 12°56.640' Bathicalci-Chromic Luvisol							
Ap1	20	fluvial sed. [f]	gravel, stones	diff.	cr, 2-5 mm		21-50
Ap2	42	fluvial sed.	gravel, stones	sharp, wavy	cr-sbk, 5-20 mm		21-50
2Bt1	75	calcarenite	gravel	diff.	pr (abk), 30-50 mm		21-50
2Bt2	95	calcarenite	gravel	dist., wavy	pr, 50 mm		16-20
2CBk	105	calcarenite	wth. remn.	sharp, wavy	coh		1-2
2Ckm	>110	calcarenite	—	—	—		0
Terrace 2, Torrazza, 121 m a.s.l., N 37°36.609' E 12°56.785' Bathicalci-Chromic Luvisol							
Ap1	12	fluvial sed. [f]	gravel	dist., flat	sbk, 5-20 mm		10-20
Ap2	57	fluvial sed.	gravel	sharp, v. wavy	sbk, 5-20 mm		10-20
2Bt1	85	calcarenite	gravel	diff., wavy	pr, 40-50 mm; abk, 20-30 mm		5-10
2Bt2	100	calcarenite	gravel	sharp, wavy	pr, 40-50 mm; abk, 20-30 mm		5-10
2BCk	118	calcarenite	gravel, wth. remn.	dist., wavy	coh	3% lime nodules	0
2Ck	155	calcarenite	gravel, wth. remn.	sharp, v. wavy	sig	3% lime nodules	0
2R/Ckm	>180	calcarenite	—	—	mas	5% lime nodules	0
Terrace 3, Cavarretto, 139 m a.s.l., N 37°36.332' E 12°59.206' Chromi-Profondic Luvisol							
Ap1	45	fluvial sed. [f]	gravel	diff.	cr, 2-5 mm		2-5
Ap2	65	fluvial sed.	gravel	dist., flat	sbk, 5-20 mm		2-5
2Bt1	105	calcarenite	gravel	indist., flat	pr, 40 mm; abk, 20 mm		2-5
2Bt2	120	calcarenite	gravel	diff., flat	pr, 50 mm		0-1
2Bt3	155	calcarenite	gravel	sharp, flat	abk, 5-20 mm	few Mn motl.	0-1
2Ckm	165	calcarenite	stones	sharp, flat	—		0-1
3Bkgb	240	lagoon sed.	—	—	abk, 2-5 mm		0
Terrace 4, Puporosso, 218 m a.s.l., N 37°37.145' E 12°59.941' Chromi-Profondic Luvisol (Bathifragic)							
Ap	22	colluvium [g]	gravel	dist., wavy	cr, 1-2 mm; cr, 2-5 mm		21-50
2BE	50	colluvium	gravel	diff., wavy	sbk, 5-20 mm		16-20
2Bt1	78	colluvium	gravel	diff., wavy	abk, 5-20 mm	Mn nodules	6-10
2Bt2	110	colluvium	gravel	indist., flat	abk, 5-20 mm	Mn nodules	3-5
2Bt3	165	colluvium	gravel	diff., wavy	pr, 15-40 mm (abk, 10-20 mm)	Mn motl. on aggr.sf.	3-5
2Btx	>205	colluvium	gravel	—	pr, 40 mm	Mn motl. on aggr.sf.	1-2
Terrace 6, Gorghi, 361 m a.s.l., N 37°40.098' E 12°59.916' Ferri-Profondic Luvisol							
Ap1	15	colluvium [g]	gravel, stones [h]	indist., wavy	sbk, 5-20 mm		11-15
Ap2	40	colluvium	gravel, stones [h]	dist., wavy	sbk, 5-20 mm		6-10
2Bt1	54	colluvium	—	indist., wavy	abk, 5-20 mm		1-2
2Bt2	100	colluvium	—	dist., very wavy	abk, 5-20 mm	7% Fe motl.	1-2
2Bcm	105	colluvium	—	dist., very wavy	mas		0
3BEtb1	120	marine sed. [f]	—	indist., wavy	coh – mas	15% Fe motl.	0
3BEtb2	150	marine sed.	—	dist., wavy	coh		0
3Btb	+200	marine sed.	—	—	coh	5% Fe motl.	0

[a] depth is the depth of lower horizon boundary; [b] wth. remn.: weathering remnants; [c] diff.: diffuse, dist.: distinct, ind.: indistinct, sh: sharp, v.: very; [d] abk: angular blocky, coh: coherent, cr: crumby, gr: granular, mas: massive, pr: prismatic, sbk: subangular blocky, sig: single grain; [e] motl.: mottles, aggr. sf.: aggregate surfaces; [f] sed.: sediment; [g] the colluvium consists of resedimented marine sediment of the same terrace., [h] pieces of ironstone.

Soil colour

Across the soil sequence under study, the hue of the soil colour is generally brown and ranges between (dark) reddish and bright yellowish brown in the soils on the 1st and 2nd terrace, brown and reddish brown in the soils on the 3rd terrace, dark to bright brown on T4, and brown to orange on T6. Reddish colours support advanced weathering in the soils on T1 and T2, while higher RR values (Table 2) suggest comparatively greater contents of hematite relative to the soils on T3 and on T6 (Torrent and Cabedo, 1986). The lower RR of the latter reflects the specific redoximorphic environment for the soils on T3 and T6 (Table 1).

Soil texture

Clay coatings and a concomitant increase of pedogenic iron oxides (Fe_d) in the Bt horizons in all soils of the sequence indicate co-illuviation of clay and iron oxides (Mirabella *et al.*, 1992). This is confirmed by a fairly constant Fe_d/clay ratio and a significant correlation between

Table 2. Main properties of the soils.

Site / Horizon	Depth (cm)	pH (H_2O)	EC ($mS{\cdot}cm^{-1}$)	CEC ($cmol_{c+}\ kg^{-1}$)	Base sat. (%)	$CaCO_3$ (%)	Corg (%)	SOM (%)	Colour moist	RR moist
Terrace 1, Bonera, 97 m a.s.l., N 37°36.224' E 12°56.640' Bathicalci-Chromic Luvisol										
Ap1	20	7.7	0.18	7.3	100	0.39	0.62	1.08	5YR 3/4	6.7
Ap2	42	8.1	0.26	9.2	100	0.29	0.49	0.85	5YR 3/4	6.7
2Bt1	75	8.1	0.06	16.3	100	0.01	0.32	0.57	2.5YR 3/6	15.0
2Bt2	95	7.8	0.09	14.4	100	0.13	0.27	0.47	2.5YR 4/8	15.0
2CBk	105	8.3	0.14	5.8	100	19.17	0.25	0.44	7.5YR 5/8	4.0
2Ckm	>110	—	—	21.5	—	—	—	—	10YR 8/3	0.0
Terrace 2, Torrazza, 121 m a.s.l., N 37°36.609' E 12°56.785' Bathicalci-Chromic Luvisol										
Ap1	12	8.1	0.25	14.0	100	1.40	0.86	1.51	5YR 3/4	6.7
Ap2	57	8.1	0.20	12.4	100	1.06	0.66	1.16	5YR 3/4	6.7
2Bt1	85	8.5	0.13	13.1	100	0.04	0.21	0.37	2.5YR 4/6	11.3
2Bt2	100	8.5	0.09	7.3	100	0.32	0.19	0.33	2.5YR 4/6	11.3
2BCk	118	8.7	0.11	5.3	100	23.38	0.17	0.30	7.5YR 6/8	3.3
2Ck	155	8.9	0.09	5.2	(100)	25.83	0.11	0.19	10YR 6/6	0.0
2R/Ckm	>180	—	—	—	—	—	—	—	10YR 6/6	0.0
Terrace 3, Cavarretto, 139 m a.s.l., N 37°36.332' E 12°59.206' Chromi-Profondic Luvisol										
Ap1	45	7.8	0.22	20.7	100	2.57	0.91	1.59	7.5YR 4/3	1.9
Ap2	65	7.9	0.24	21.0	100	2.99	0.95	1.67	7.5YR 4/3	1.9
2Bt1	105	8.0	0.15	21.1	100	2.10	0.72	1.26	5YR 3/2	3.3
2Bt2	120	8.1	0.16	19.2	100	0.85	0.40	0.71	5YR 4/3	3.8
2Bt3	155	8.0	0.21	22.6	100	0.76	0.30	0.52	5YR 3/4	6.7
2Ckm	165	—	—	—	—	—	—	—	—	—
3Bkgb	240	8.1	0.33	21.5	100	34.29	0.24	0.42	2.5Y 7/4	0.0
Terrace 4, Puporosso, 218 m a.s.l., N 37°37.145' E 12°59.941' Chromi-Profondic Luvisol (Bathifragic)										
Ap	22	7.2	0.13	5.0	100	0.18	0.70	1.22	7.5YR 3/3	2.5
2BE	50	7.5	0.06	10.3	100	0.14	0.46	0.80	7.5YR 3/2	1.7
2Bt1	78	7.7	0.04	10.5	100	0.72	0.25	0.43	7.5YR 3/4	3.3
2Bt2	110	7.6	0.04	17.6	100	0.10	0.22	0.39	5YR 4/4	5.0
2Bt3	165	7.0	0.10	18.9	100	0.61	0.16	0.27	7.5YR 5/6	3.0
2Btx	>205	6.8	0.12	16.3	79	—	—	—	7.5YR 5/6	3.0
Terrace 6, Gorghi, 361 m a.s.l., N 37°40.098' E 12°59.916' Ferri-Profondic Luvisol										
Ap1	15	8.0	0.09	6.5	100	0.47	0.53	0.93	7.5YR 4/4	2.5
Ap2	40	8.0	0.08	6.2	100	0.20	0.39	0.69	7.5YR 4/4	2.5
2Bt1	54	6.9	0.06	15.6	72	1.22	0.41	0.72	7.5YR 5/6	3.0
2Bt2	100	6.4	0.05	18.9	75	1.18	0.29	0.50	10YR 6/8	0.0
2Bcm	105	6.8	0.04	9.5	58	—	—	—	10R 3/2	6.7
3BEtb1	120	6.8	0.03	5.0	60	0.89	0.08	0.13	7.5YR 5/8	4.0
3BEtb2	150	6.9	0.02	4.1	75	0.79	0.14	0.24	7.5YR 6/8	3.3
3Btb	+200	6.9	0.02	6.5	81	0.72	0.11	0.18	5YR 5/8	8.0

EC: Electrical conductivity; CEC: Cation exchange capacity; Base sat.: Base saturation; Corg: Organic carbon; SOM: Soil organic matter; RR: Redness rating. Depth is the depth of lower horizon boundary.

Fe_d and clay ($r^2 = 0.99$). Higher carbonate contents in the Ap horizons of the soils on the 2nd and 3rd terrace and in the Bt horizons of the Ferri-Profondic Luvisol on the 6th terrace (Table 2) indicate that after carbonate leaching and clay illuviation, allochthonous calcareous material was deposited and carbonates infiltrated. Apart from the soil on the 4th terrace, no increase of silt content towards the surface can be observed, so we assume that eolian deposition is not substantial in most soils in this area, or has been removed by earlier erosion.

Although the textural differences between the Ap and the Bt horizons in the soils on the 1st and 2nd terrace (Figures 3a, 3b) are primary due to the change in parent material (Table 1), moderate to prominent clay illuviation features are present in both soils, and were also found in thin sections. On the 3rd terrace, fluvial sediments are underlain by a 10 cm thick petrocalcic layer followed by lagoon sediment (Table 1). The textural differences clearly show the boundaries of the different sediments (Figure 3c). In the soil on the 4th terrace, the solum exceeds the profile depth of 200 cm. The greater sand content in the Ap horizon (Figure 3d) indicates recent deposition related to slope transport. A distinct decrease of the silt content to a depth of 110 cm indicates different layers of marine sediments. The soil on

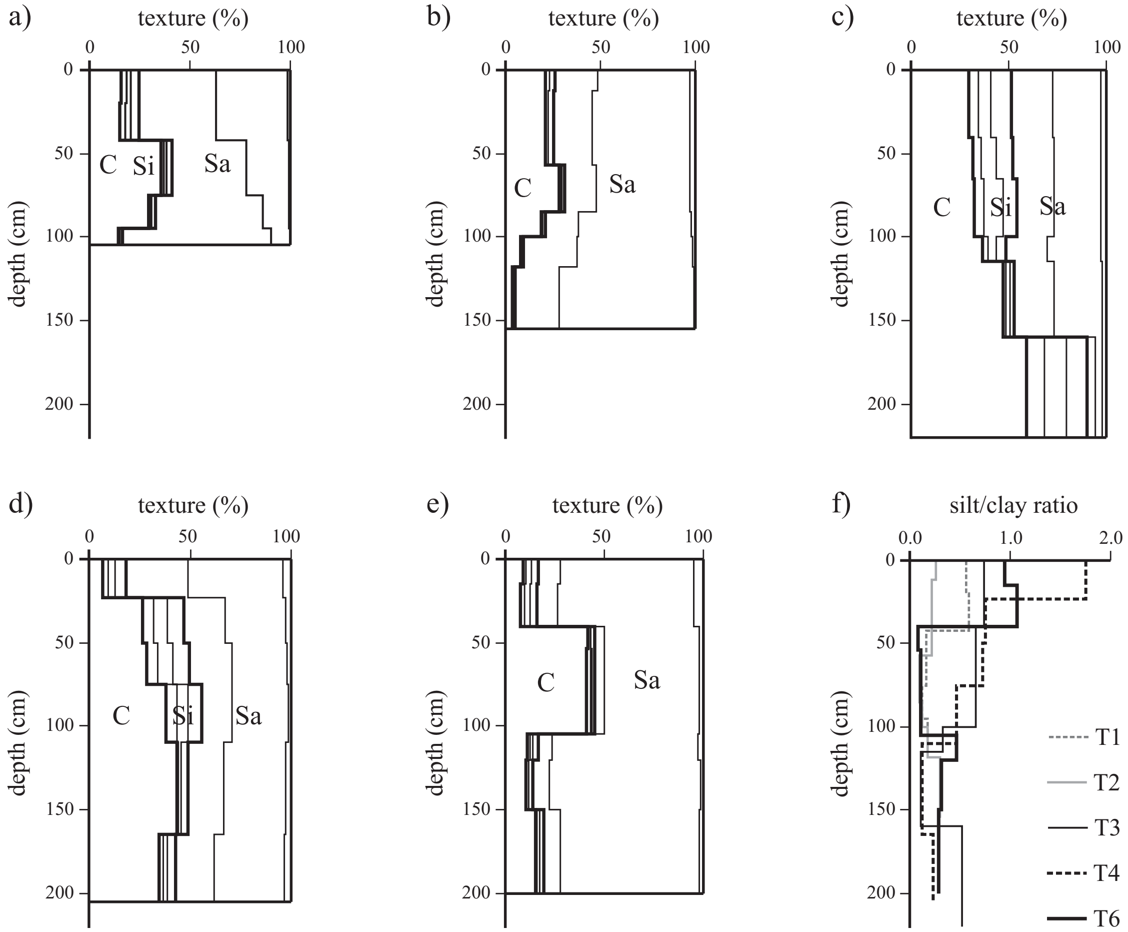

Figure 3. Particle-size distribution and silt/clay ratios of the soils at sampling sites near Menfi. a: Bonera, 1st terrace (T1); b: Torrazza, 2nd terrace (T2); c: Cavarretto, 3rd terrace (T3); d: Puporosso, 4th terrace (T4); e: Gorghi, 6th terrace (T6). C: clay, Si: silt, Sa: sand. Broad lines represent fraction change, thin lines represent change in fine, medium and coarse fractions (for silt and sand). f: silt/clay ratios in all profiles.

the highest terrace is characterised by a 5 cm thick massive iron crust at about 100 cm depth. The Bt horizons above are characterised by high contents of Fe and Al (Table 3), and particularly by large proportions of the dithionite-soluble fractions of these elements. The texture is conspicuously uniform in all horizons, except for 2Bt1 and 2Bt2. The latter, however, have the same distribution of sand fractions (Figure 3e). Clay illuviation is less pronounced than in the other soils, as shown by comparatively thin clay coatings.

The silt/clay ratio is often used as a measure of the degree of weathering. However, abrupt changes in the silt/clay ratio between layers reflect the major influence of the parent material. The silt/clay ratios in the fluvial sediments on T1, T2 and T3 are noticeably higher when compared with the underlying calcarenitic material (Figure 3f), because in the younger and coarser-textured fluvial sediments, clay formation is less pronounced (Durn, 2003). The highest silt/clay ratios are found in the colluvial layers on T4 and T6 (Figure 3f). In all soils where colluvium occurs, the material transport is accompanied by clay loss and subsequent deposition of coarser material.

Clay mineralogy

On all marine terraces, the clay fractions of the Luvisols contain mixtures of kaolinite, illite, smectite and interstratifications of clay minerals. It is obvious, however, that the clay mineralogical composition of the soils on the three lower terraces is characterised by distinctly higher proportions of smectites, compared to the soils on the two more elevated terraces (Figures 4a-e). Interstratified clay minerals constitute conspicuously higher proportions in the soil on T1 than on T2 and T3, which is related to a more intense weathering. Kaolinite is also, albeit only slightly, increased in the soil on the 1st terrace. This is concordant with Churchman *et al.* (1994), who found discrete kaolinites occurring parallel to interstratified kaolinite-smectites in Australian soils and Herbillon *et al.* (1981), who found increased change of smectite to kaolinite not only towards the more intensively weathered soil surface, but also in a sequence from black to red soils of Burundi. The smectite of the soils on the 1st and 2nd terrace is presumably inherited from the calcarenite and gradually transformed into interstratified forms during

Table 3. Chemical composition of the soils (by X-ray fluorescence analysis).

Site / Horizon	Depth (cm)	SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	ZrO_2 (%)	LOI (%)
Terrace 1, Bonera, 97 m a.s.l., N 37°36.224’ E 12°56.640’ Bathicalci-Chromic Luvisol													
Ap1	20	89.0	0.34	4.7	2.2	0.046	0.28	0.48	0.27	0.77	0.092	0.049	1.9
Ap2	42	88.9	0.32	4.4	2.0	0.046	0.23	0.41	0.26	0.73	0.063	0.054	2.6
2Bt1	75	78.0	0.37	9.2	4.6	0.045	0.38	0.41	0.07	1.03	0.052	0.040	5.8
2Bt2	95	84.3	0.29	7.7	4.2	0.056	0.35	0.35	0.27	0.97	0.047	0.032	1.5
2CBk	105	69.5	0.16	3.1	1.8	0.037	0.40	22.92	0.24	0.56	0.048	0.023	1.3
2Ckm	>110	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Terrace 2, Torrazza, 121 m a.s.l., N 37°36.609’ E 12°56.785’ Bathicalci-Chromic Luvisol													
Ap1	12	87.0	0.31	5.6	2.7	0.034	0.33	1.30	0.57	0.95	0.140	0.045	1.1
Ap2	57	89.0	0.28	5.5	2.6	0.031	0.32	0.86	0.12	0.80	0.068	0.042	0.4
2Bt1	85	85.0	0.30	7.5	3.6	0.027	0.34	0.41	0.56	0.95	0.043	0.030	1.3
2Bt2	100	90.3	0.21	4.6	2.2	0.029	0.26	0.42	0.44	0.66	0.031	0.031	0.9
2BCk	118	69.6	0.10	1.5	0.9	0.024	0.41	25.91	0.10	0.34	0.031	0.018	1.1
2Ck	155	67.2	0.08	1.2	0.5	0.022	0.39	26.75	0.20	0.27	0.048	0.016	3.3
2R/Ckm	>180	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Terrace 3, Cavarretto, 139 m a.s.l., N 37°36.332’ E 12°59.206’ Chromi-Profondic Luvisol													
Ap1	40	82.4	0.51	8.5	3.5	0.060	0.45	2.20	0.34	1.30	0.069	0.047	0.6
Ap2	65	82.1	0.53	8.2	3.6	0.050	0.50	2.70	0.16	1.19	0.074	0.047	0.8
2Bt1	100	81.7	0.53	8.5	3.7	0.055	0.49	1.84	0.31	1.15	0.051	0.045	1.7
2Bt2	115	81.9	0.50	9.9	4.4	0.053	0.47	0.67	0.22	1.28	0.036	0.039	0.4
2Bt3	160	76.5	0.43	12.5	5.9	0.061	0.60	0.61	0.43	1.51	0.046	0.029	1.4
2Ckm	165	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
3Bkgb	220	39.3	0.55	11.0	4.6	0.036	0.89	39.71	0.23	1.02	0.060	0.018	2.5
Terrace 4, Puporosso, 218 m a.s.l., N 37°37.145’ E 12°59.941’ Chromi-Profondic Luvisol (Bathifragic)													
Ap	23	90.5	0.28	2.6	1.1	0.053	0.16	0.29	0.24	0.56	0.073	0.054	4.0
2BE	50	84.5	0.55	7.8	3.5	0.139	0.31	0.38	0.23	1.15	0.048	0.054	1.3
2Bt1	78	83.6	0.64	8.3	3.7	0.154	0.36	0.38	0.30	1.32	0.046	0.054	1.1
2Bt2	110	78.5	0.62	10.9	4.8	0.095	0.47	0.35	0.27	1.51	0.049	0.045	2.4
2Bt3	165	79.9	0.45	11.4	5.1	0.044	0.49	0.35	0.10	1.31	0.041	0.049	0.7
2Btx	>205	82.5	0.45	9.5	4.3	0.052	0.41	0.34	0.21	1.20	0.042	0.055	0.9
Terrace 6, Gorghi, 361 m a.s.l., N 37°40.098’ E 12°59.916’ Ferri-Profondic Luvisol													
Ap1	15	93.3	0.22	2.4	1.8	0.043	0.17	0.44	0.20	0.41	0.052	0.031	0.8
Ap2	40	93.0	0.21	2.3	1.7	0.042	0.14	0.27	0.17	0.39	0.050	0.029	1.7
2Bt1	54	78.2	0.32	11.2	7.3	0.020	0.36	0.39	0.14	0.86	0.047	0.019	1.1
2Bt2	100	78.7	0.32	11.4	6.9	0.014	0.36	0.33	0.14	0.82	0.043	0.020	1.0
2Bcm	105	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
3BEtb1	120	92.2	0.23	3.0	2.9	0.023	0.14	0.09	0.11	0.33	0.026	0.030	0.9
3BEtb2	150	92.7	0.21	2.4	2.4	0.010	0.13	0.08	0.13	0.29	0.025	0.034	1.6
3Btb	+200	86.2	0.23	3.8	2.9	0.010	0.14	0.10	0.13	0.34	0.027	0.031	6.1

n.d.: not determined. Depth is the depth of lower horizon boundary.

weathering (Allen and Hajek, 1989). Increased kaolinite proportions in the fluvial sediments of T1 and T2 (Table 1, Figures 4a–b) possibly reflect higher weathering rates and leaching environment (*e.g.*, Kantor and Schwertmann, 1974) where this material was once formed. Similar smectite distributions in the soil formed in fluvial and lagoon sediments of T3 suggest inheritance from the underlying material. Although illite and interstratifications are present in all layers, they are more common in the calcarenite between the fluvial and lacustrine sediments (Figure 4c). On the two most elevated terraces, smectite constitutes less than 15 % of all clay minerals. Originally, smectite, vermiculite and kaolinite are formed from biotite. While smectite and vermiculite are formed under more temperate climates, biotite tends to weather directly to kaolinite in the humid tropics. Thus, the abundance of kaolinite, the absence of vermiculite, and the scarcity of smectite in the soils of the two highest terraces (Figures 4d, 4e) reflect a more humid climate than at present or longer time of formation.

Irregular interstratifications of illite, vermiculite, smectite and chlorite are common in most of the soil horizons in this soil sequence, with a proportion of 20–35 % of irregularly interstratified clay minerals in 23 out of 30 horizons (Figures 4a-e). Such interstratifications are caused by

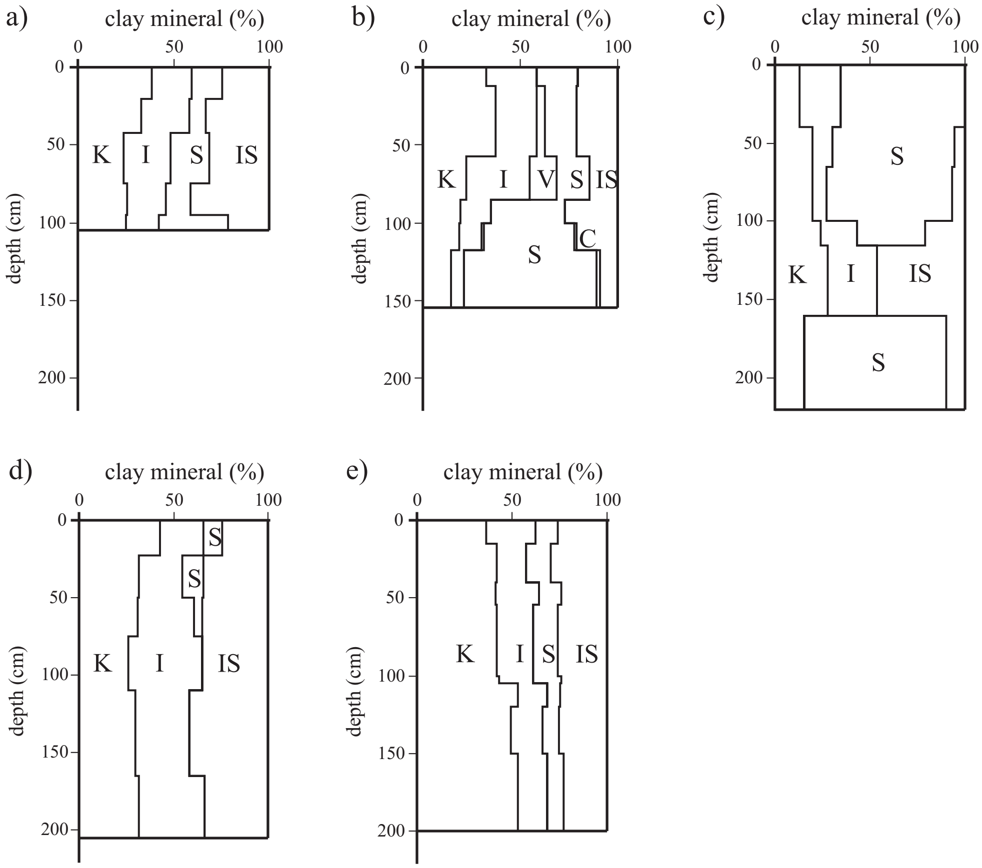

Figure 4. The relative distribution of clay minerals. a: Bonera, 1st terrace (T1); b: Torrazza, 2nd terrace (T2); c: Cavarretto, 3rd terrace (T3); d: Puporosso, 4th terrace (T4); e: Gorghi, 6th terrace (T6). K: kaolinites, I: illites, S: smectites, V: vermiculites, C: chlorites, IS: interstratification of illites, smectites, vermiculites and chlorites.

weathering under transitional conditions (Sawhney, 1989) and demonstrate ongoing soil genesis. The proportion of interstratification is rather weak in the soils on the 2nd and 3rd terrace (Figures 4b, 4c). Kaolinite is widespread and generally comprises more than 20 % of all clay minerals. On T6, kaolinite comprises between 36 % and 54 % of all clay minerals (Figure 4e), indicating soil genesis under strong leaching conditions.

Geochemistry

Clay neogenesis and illuviation seem to induce relocation of Al, Fe, and K, when comparing the chemical composition of the soils. This assumption is confirmed by significant correlations between clay content and Al ($r^2 = 0.99$), Fe ($r^2 = 0.86$), and K ($r^2 = 0.73$), which is valid for all soils. In the Chromi-Profondic Luvisol on T3, however, 3Bkgb was excluded, because the lacustrine material contained distinctly less K than the Bt horizons above, while clay contents were noticeably higher (59.3 %, Figure 3c). This demonstrates the distinguishing character of the lacustrine sediments in this soil. The noticeably higher concentration of Mn oxides in the soil on T4 compared to the soils on the other terraces (Table 3) is due to stagnic properties. In this soil, Mn oxide nodules reach diameters of 2 mm, while mottles on aggregate surfaces are up to 20 mm in diameter. Such mottling is typical for periodic wetness, *i.e.*, seasonal wetting and drying with accompanied mobilisation, translocation and immobilisation of Mn (Allen and Hajek, 1989). In the soils on the other terraces, mottling is less pronounced or absent (Table 4).

The composition and stratification of parent material is well reflected by the ratios of Ti/Zr and Zr/Si (*e.g.*, Stahr *et al.*, 2000). On the three lower terraces, the boundaries between calcarenite and fluvial sediments are expressed by higher Zr/Si ratios in the fluvial sediments. The sediment on the 4th terrace is fairly uniform, except for the Ap horizon. Distinctly higher Zr/Si ratios in the 2Bt horizons relative to the horizons above and below may suggest a lithological discontinuity in the soil on the highest terrace (Figures 5a, 5b). Silica leaching in the soil on T6 was accompanied by oxidation of and enrichment with Fe_2O_3 and Al_2O_3 (Table 3). Associated lateral water flow enhanced weathering and subsequently caused the cementation of the marine sediment by iron, as suggested by Igwe *et al.*

(2005), who observed this process in coarse sand fractions of highly weathered but Holocene floodplain soils on alluvial sands of the river Niger. The decalcification of soils reduces the ratio of (CaO+MgO)/Al_2O_3 (Retallack, 1997). CaO contents of less than 1 % in all soils (Table 3) suggest almost complete decalcification.

An abrupt boundary between the weathering front with clay coatings stained by iron and the unweathered calcarenite underneath was observed by micromorphological studies (Figure 6) in the soils of the three lower terraces, while in the soils on T4 and T6, the parent material could not be sampled. Field and micromorphological observations, *e.g.*, thin $CaCO_3$ coatings and recrystallisation of calcite nodules indicate secondary carbonate enrichment in some horizons, reflecting seasonal wetting and drying typical for a Mediterranean environment (Figure 5c). Higher ratios of (CaO+MgO)/Al_2O_3 in all Ap horizons (Figure 5c) are likely due to accretion of calcareous dust and subsequent enrichment of secondary carbonates (Yaalon, 1997), while higher concentrations of CaO and MgO in the soil on the 3rd terrace (Figure 5c) reflect the dolomitic character of the parent material on this terrace.

The weathering progress has been evaluated by the "Chemical Index of Alteration" (CIA) of Nesbitt and Young (1984), which is calculated by Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O). On all terraces, weathering is more advanced in the Bt horizons compared to the Ap (Figure 5d). The largest indices were calculated for the

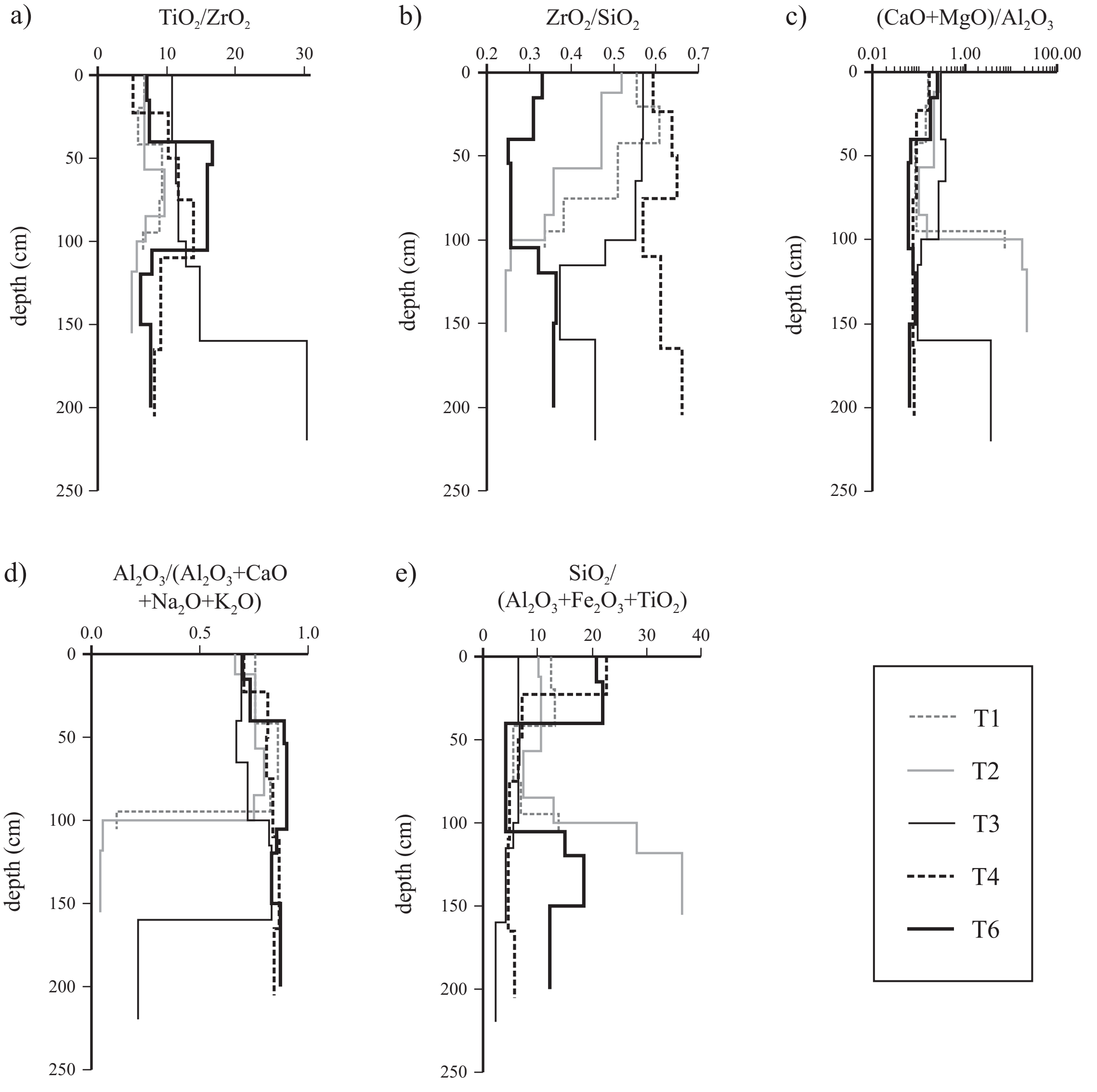

Figure 5. The geochemistry of soils in the terrace sequence. TiO_2/ZrO_2 (a) and ZrO_2/SiO_2 (b) ratios as indicators for stratification of parent material after Chartres *et al.* (1988) and Stahr *et al.* (2000). c: (CaO+MgO)/Al_2O_3 ratio for degree of calcification after Retallack (1997); d: Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O) as Chemical Index of Alteration (CIA) after Nesbitt and Young (1984); e: SiO_2/(Al_2O_3+Fe_2O_3+TiO_2) as index for silicate weathering and Si leaching after Colman (1982). Numbers on abscissa indicate ratios.

soils on T4 and T6, while the soil on the 2nd and parts of the soil on the 3rd terrace seem to be less developed than the soil on the 1st terrace. This is due to a more intense clay mineral alteration with noticeably higher amounts of interstratifications and kaolinite in the soil on the 1st terrace. Effects of *in situ* weathering were acquired by calculation of $SiO_2/(Al_2O_3+Fe_2O_3+TiO_2)$. This ratio characterises the degree of silicate destruction and Si removal in a leaching environment. Colman (1982) suggested that this ratio should decrease during weathering, because of the greater stability of Al, Fe, and Ti relative to Si. In most of the soils, the ratio decreases in the B horizons and increases below, which testifies the *in situ* weathering of the parent materials of the B and C horizons. Only the soils on the 3rd and 4th terrace do not show this pattern, where an increase of $SiO_2/(Al_2O_3+Fe_2O_3+TiO_2)$ in the Ap horizons (Figure 5e) is possibly due to the human influence. A slight decrease of this ratio below the Ap horizons with time also testifies silicate weathering within the terrace sequence (Figure 5e). A comparison of the most developed horizons of each terrace (generally Bt) shows that this ratio clearly decreases from T1 to T6, testifying the assumed progressive silicate weathering in the terrace sequence.

Weathering dynamics

The degree of weathering and formation of pedogenic iron oxides and hydroxides is expressed by the ratio of Fe_d/Fe_t. In the Ferri-Profondic Luvisol on T6, the release of 73–88 % of iron (Figure 7a) substantiates strong soil development. The Fe_d/Fe_t ratio generally ranges between 50–60 % in the soils on T1, T2 and T4 (Figure 7a) and reflects enhanced weathering, whereas lower ratios in the soil on T3 are due to little release of iron in the younger fluvial sediment. For appropriate estimation of the degree of weathering, Bronger *et al.* (1984) stress the necessity to compare solum and parent material. In fact, this could be done only in the soil on T2, whereas in the soils on T4 and T6, solum thickness exceeds 200 cm, and the parent material could not be sampled.

The Fe_o/Fe_d ratio characterises the degree of iron oxide and hydroxide crystallisation, where in general, lower ratios reflect more advanced stages of soil development (Alexander, 1974; Arduino *et al.*, 1986). Hence the Fe_o/Fe_d ratio tends to decrease with soil age (Moody and Graham, 1995; Bronger and Bruhn-Lobin, 1997). The lowest Fe_o/Fe_d ratios were found in the soil on the 6th terrace (ranging

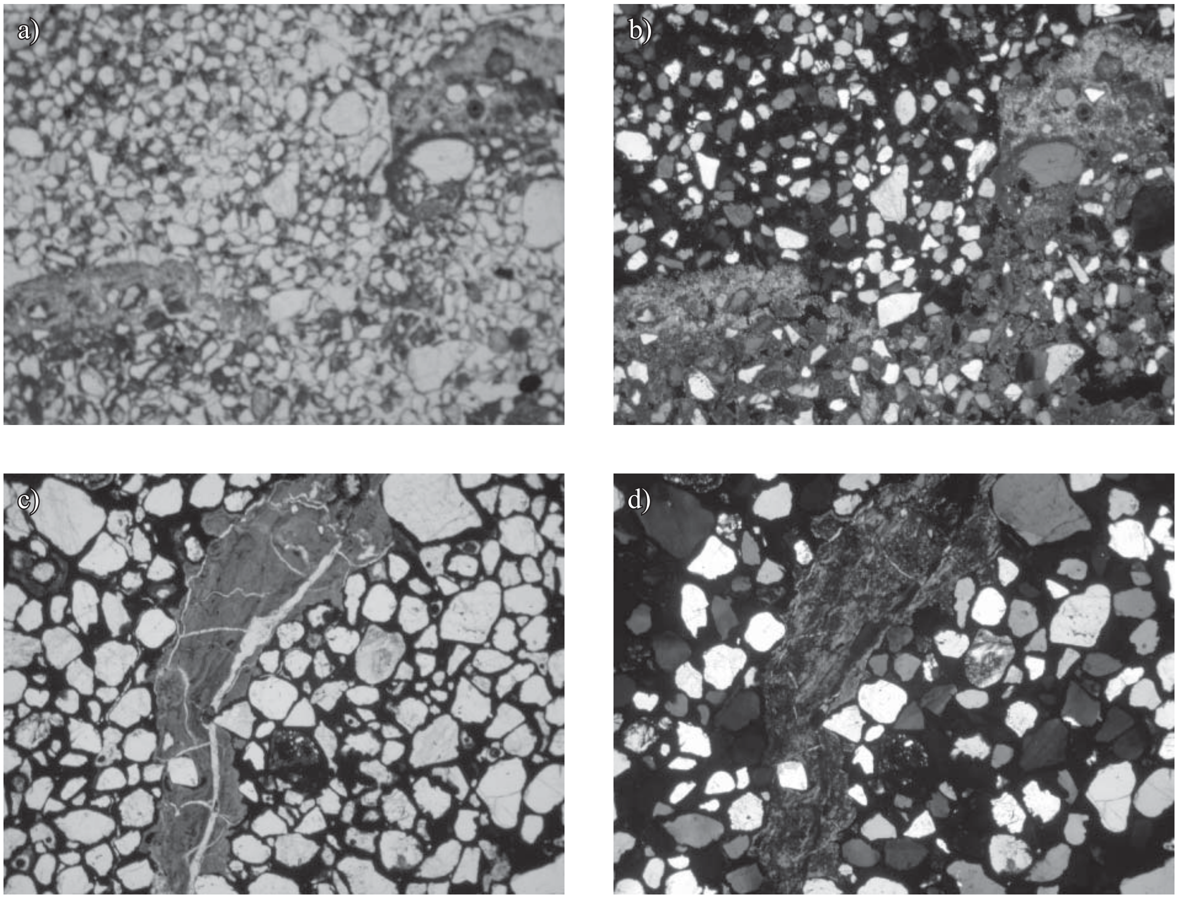

Figure 6. Micromorphological images. Top: Calci-Chromic Luvisol on 1st terrace (T1), 2Bt2 (83–91 cm), limestone. Bottom: Ferri-Profondic Luvisol on 6th terrace (T6), 2Bt1 (46–54 cm), infillings in cemented concretion fragments. Left: Plain-polarised light. Right: Cross-polarised light. Frame width is 4 mm for all images.

from 0.00 to 0.04, Figure 7b). In the Bt horizons of the soil on T4, the Fe_o/Fe_d ratio ranged from 0.03–0.07 compared to 0.02–0.04 in the Bt horizons on T1 and T2, reflecting a higher crystallinity in the latter (Figure 7b), and indicating rejuvenation of the soil on T4. Irrespective of the wide range of quantities, the average values of the Fe_o/Fe_d ratio in the soils of this terrace sequence account for mainly crystalline iron oxides (Torrent *et al.*, 1980). Comparatively higher Fe_o/Fe_d ratios of 0.10–0.37 in the soil on the 3rd terrace attest a correspondingly less developed solum and an accordingly younger soil, whereas a ratio of 0.02 in the 3Bkgb at depth reflects gleyic features. Across all soils, abrupt changes in the Fe_o/Fe_d ratio follow lithological discontinuities (Bech *et al.*, 1997).

The gradual transformation of ferrihydrite into more crystalline forms of iron oxide during pedogenesis can be expressed by Fe_d–Fe_o (Torrent *et al.*, 1980; Aniku and Singer, 1990; Costantini *et al.,* 1996). In the soils investigated, the largest difference was found within the Bt horizons, especially in that of the 6th terrace (Figure 7c). Smaller differences were calculated for the parent material on T2, the alluvial layer on T3 and the soil on T4.

CONCLUSIONS

The soil sequence investigated generally shows a time-progressive soil development with terrace elevation expressed by increasing solum depths. The soils on the two lower terraces represent Bathicalci-Chromic Luvisols and on the 3rd terrace, a Chromi-Profondic Luvisol has developed, whereas on the two highest terraces prolonged soil formation has led to a Chromi-Profondic Luvisol (Bathifragic) and a Ferri-Profondic Luvisol. The rather individual pattern of soil texture is due to the varying provenance of the overlying materials.

The degree of weathering and the degree of iron oxide crystallisation generally increase with terrace elevation, but local differences such as rejuvenation by fluvial sediments on the three lower terraces, which is most distinct on T3, and periodic wetness resulting in mottling on the 3rd, 4th and 6th terrace contribute to a certain variability of soil properties within the terrace sequence. Acidification is more advanced in the soil on T6 than on T4, but has not started in the soils on the three lower terraces. Greater amounts of kaolinite in the soils on the 4th and 6th terrace and interstratifications in the whole sequence suggest proceeding soil development. The trends of increasing chemical alteration and silica leaching with terrace elevation also support the assumption of progressive weathering with terrace elevation.

The presence of a horizon with cemented iron concretions, high contents of kaolinite, the geochemistry and the form of iron transformation suggest that the soil on the highest terrace might have been exposed to a warmer and wetter climate than at present. Hence, soil genesis on this terrace is consistent with that which occurred in the Mediterranean environment during early Pleistocene or earlier (Costantini *et al.,* 2002). Because of the rather minor amount of silt in the soil, we assume that eolian depositions play a minor role in this area.

The assumption of a soil chronosequence is supported by the tendency of increased weathering with higher terrace elevations. These data suggest that the 4th and 6th terrace have formed at different times, whereas the less elevated

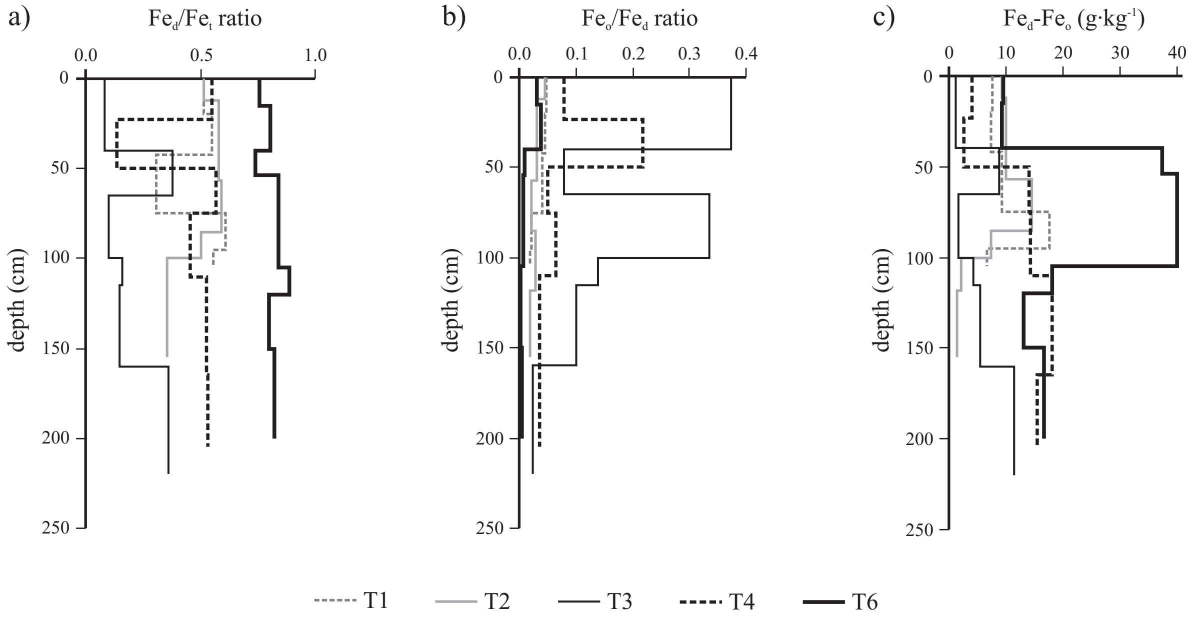

Figure 7. Weathering dynamics as calculated by relationships of various forms of iron. a: The Fe_d/Fe_t ratio as degree of weathering (*e.g.*, Bronger *et al.*, 1984); b: The Fe_o/Fe_d ratio as index of crystallisation after Alexander (1974); c: Fe_d–Fe_o (g kg^{-1}) as indicator for ferrihydrite transformation after Torrent *et al.* (1980).

terraces presumably arose in shorter time intervals. Further studies are required to confirm whether each of the three lower terraces has formed individually at similar times or whether these terraces arose as a single body and were later dissected by tectonic activity. Moreover, the causes for the difference in numbers of terraces between the Menfi area and the nearby area where D'Angelo *et al.* (2001) distinguished eight marine terraces still need to be identified. These differences may be caused by different tectonics in the two areas or by the presence of some unconspicious terraces which may have been overlooked and might be detected in a re-investigation of both areas.

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