Z. Geomorph. N. F.	45	2	145–158	Berlin · Stuttgart	Juni 2001

A Quaternary soil chronosequence of Southeastern Spain

by

LOTHAR SCHULTE and RAMÓN JULIÀ, Barcelona

with 4 figures and 1 table

Summary. A Quaternary soil chronosequence of the Aguas river terraces has been established, and it seems to be typical for the Vera basin. The chronology of the fluvial sequence of 15 geomorphological units was determined by geomorphologic and sedimentologic criteria, ^{14}C, ^{210}Pb, U/Th disequilibrium dating and artifacts. The data indicate that Rhodoxeralfs (Red Mediterranean soils) formed during early Pleistocene, Haploxeralfs (reddish Mediterranean soils) from the middle Pleistocene to isotopic stage 5, and weak developed soils (e. g. Haploxerolls) during late Pleistocene and Holocene. In particular, the Bt horizons of the Rhodoxeralfs are decalcified, show a redness rating of 15, have high Fe and Al contents and degraded cutans and overlie thick nodular and/or laminar Bk horizons. The younger soils are thinner, redness rating and the content of cutans in the Bt horizons less. The youngest Haploxeralfs are associated with the fluvial terrace T3 overlyed by travertine deposits dated at 148,000 ± 8000 yr B. P. (U/Th), and on the last interglacial marine terrace located at +9 m a. s. l. In adition to the 148,000 ± 8000 yr B. P. (U/Th) travertine phase, the main period of travertine formation have been detected between 94,000 ± 5000 and 54,000 ± 2000 yr B. P. (U/Th), and were drastically reduced during isotopic stage 2 and the Holocene. The environmental conditions seem to be too dry for an intense soil and travertine development during these latter periods.

Zusammenfassung. *Eine quartäre Boden-Chronosequenz aus Südostspanien.* – Die durchgeführten Untersuchungen richten sich auf die Erstellung einer quartären Paläoboden-Chronosequenz in Flußterrassen des Río Aguas im südlichen Becken von Vera (Südostspanien). Die zeitliche Gliederung der bis zu 15 morphologischen Niveaus stützt sich auf geomorphologische und sedimentologische Kriterien, U/Th-, ^{14}C-, ^{210}Pb-Datierungen, und Artefakte. Den pedostratigraphischen Befunden zufolge haben sich im Altpleistozän *Rhodoxeralfs* (rote Mediterranböden) und im Mittelpleistozän sowie während der Sauerstoffisotopenstufe 5 *Haploxeralfs* (rötlich braune Mediterranböden) als maximale Bodenentwicklungen gebildet. Das Jungpleistozän und Holozän zeichnen sich dagegen durch schwächere Bodenbildungen (z. B. *Calciorthids* und *Haploxerolls*) aus. Die Bt-Horizonte der *Rhodoxeralfs* sind entkalkt, weisen hohe Fe- und Al-Gehalte auf, enthalten häufig Tonbeläge und erreichen in der Regel einen Rotfärbungs-Index *(Redness rating)* von bis zu 15. An der Basis der Bt-Horizonte befinden sich häufig mächtige noduläre und z. T. auch laminare Kalkanreicherungshorizonte. Die bodenkundlichen Untersuchungen zeigen, daß mit geringerem Terrassenalter die Bodenmächtigkeit, der *Redness rating* und der Anteil an Tonbelägen abnehmen. Der jüngste *Haploxeralf* hat sich auf der Flußterrasse T3, die in der Nähe von Alfaix von einem mit 148,000 ± 8000 B. P. (U/Th) datierten Travertin überlagert wird, sowie auf der letztinterglazialen 9 m-Strandterrasse entwickelt. Abgesehen von der Travertinbildung um 148,000 B. P.

0372-8854/01/0145 $ 3.50

(U/Th) liegen die Hauptphasen der Travertingenese im Vera-Becken zwischen 94,000 ± 5,000 und 54,000 ± 2000 B. P. (U/Th). Die Sauerstoffisotopenstufen 2 und 1 (Holozän) verzeichnen weder nennenswerte Kalkausfällungen noch intensive Bodenbildungen. Die paläoklimatischen Bedingungen scheinen zu dieser Zeit zu trocken gewesen zu sein.

Résumé. *Une chronoséquence des sols Quaternaires pour le sudest de l'Espagne.* – Une chronoséquence des sols Quaternaires des terrasses de la rivière Aguas a été établi et elle semble être caractéristique de l'ensemble du basin de Vera. La chronologie des 15 unités géomorphologiques différenciés est basé sur des arguments géomorphologiques et sédimentologiques, sur des datations radiométriques ^{14}C, ^{210}Pb, U/Th et sur la présence d'artefacts. Les données montrent que des Rodoxeralfs se sont formés pendant le Pléistocène inférieur, des Haploxeralfs entre le Pléistocène moyen jusqu'au stade isotopique 5 et que des sols peu évolués (par exemple des Haploxerolls) sont présents pendant le Pléistocène supérieur et l'Holocène. En particulier, les horizons Bt des Rhodoxeralfs ont perdu les carbonates, montrent un index de rouge de 15, un élevé taux en Fe, des cutans dégradés et ils recouvrent des épais horizons Bk nodulaires ou laminaires. Les sols plus jeunes sont plus minces et l'index de rouge ainsi que la présence de cutans dans les horizons Bt moins développés. Les sols brun-rougeâtres plus jeunes (Haploxeralfs) sont en relation a une terrasse fluviatile recouverte par des travertins datés en 148,000 ± 8,000 ans B. P. (U/Th), et à la dernière terrasse marine interglaciaire située à +9 m sur le niveau de la mer. En plus de la phase de formation de travertins datée en 148,000 ans B. P., on a reconnue une autre période favorable aux dépôt de travertins entre 94,000 ± 5000 et 54,000 ± 2000 ans B. P.. La formation de travertins est drastiquement réduite pendant le stade isotopique 2 et l'Holocène. Il parait que les conditions de l'environnement furent trop arides pour une pédogenèse intense et la formation de travertins.

Introduction

Soil studies can contribute to the geomorphologic interpretation of a basin and allow the reconstruction of its chronostratigraphic evolution and modelling. Soil chronosequences developed on fluvial terraces have been used to identify regional pedogenic processes (Torrent et al. 1980, García Marcos & Santos Frances 1997). The aim of this paper is to gain a better understanding of Quaternary soil development in one of the driest regions in Europe. The question is whether the soil development on stable surfaces in Mediterranean regions has been dominated by the time factor as shown by Torrent et al. (1980), Harvey et al. (1995) and Bronger & Bruhn-Lobin (1997), or has been conditioned by the climate factor, as shown by Brunnacker & Lozek (1969), Carmona et al. (1993) and Courty et al. (1994). The present paper seeks to contribute to this question from the establishment of a pedo-stratigraphic model based on the detailed study of the Aguas river terrace soils.

2 *Site description*

The Vera basin formed as a result of Miocene extension and is located along the eastern margin of the Betic ranges, in southeastern Iberian peninsula (fig. 1). The Miocene deposits consist of interbedded marine marl, reef-limestone, calcareous sandstone, siltstone and conglomerate. During the late Pliocene marine regression and subsequent progradation of delta conglomerates of the Espíritu Santo Formation

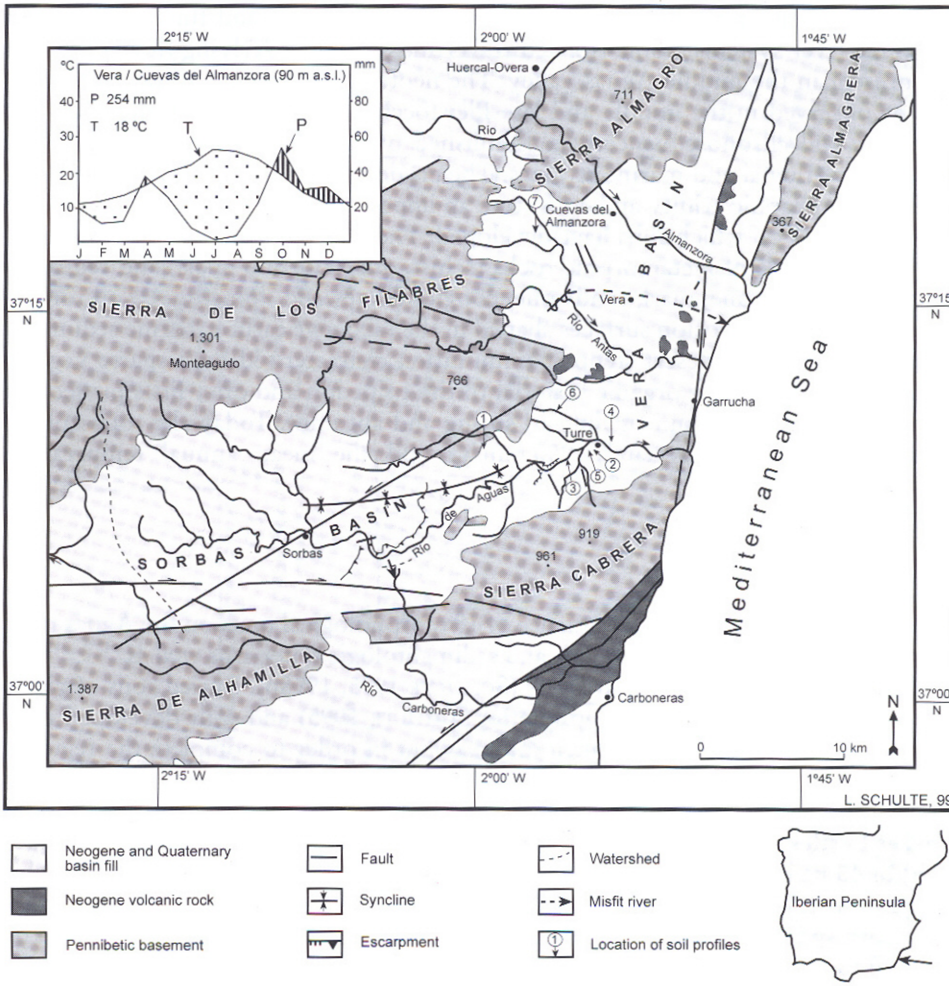

Fig. 1. Location of the study area. The geological cartography is based on the geological maps 1 : 50,000 (I. G. M. E.) and the reconstruction of the river captures and misfit rivers on the studies of HARVEY et al. (1995) and SCHULTE (1995, 1999).

the coastline moved eastward. At the end of the Pliocene, the basin was tectonically uplifted, ending the marine influence from the central part of the Vera basin. During this phase, pediments (P1 of SCHULTE 1998a) were cut and thick alluvial fans (S1 and S2 of SCHULTE 1998a), correlated with the Raña Formation of central Spain (WENZENS 1992), were deposited along the depression margins. Since the early Pleistocene the Vera basin was drained by three river systems: the Almanzora river in the north, the Antas river in the centre, and the Aguas river in the south. In addition, paleosols forming during this time have been well preserved in the southern Vera basin. Climate changes, tectonics, river capture (fig. 1) and eustatic oscillations of base level generated a staircase of alluvial fans, "glacis"[1] and fluvial terraces in the three river systems. Some isolated travertine deposits overlying fluvial terraces are present in the middle Aguas valley. The neotectonic activity of the Vera basin can be observed in the middle and late Pleistocene river and marine deposits. An extensive soil chronosequence was established on the stable land surfaces of the Quaternary fluvial and marine terraces. The erodeable Neogene marls of the basin fill increase edaphic aridity and constitute an important source of carbonates to the fluvial terraces on which soils have developed. These terraces are formed by cobles, gravels and sands of metamorphic rocks (schist, quartzite and gneis) and sedimentary rocks (limestone, marl, sandstone, conglomerates and dolostone). Soil formation on slopes and erosion surfaces shaped in the Neogene carbonate fine sediments is limited. The semi-desert steppe communities, characterised by a sparse vegetation cover, supply little organic material to the epipedon and offer little protection against thunderstorm rain (mainly in spring and autumn). Today the total annual precipitation is approximately 250 mm/yr and the mean annual temperature reaches 18 °C (fig. 1).

3 *Materials and methods*

The chronology of the fluvial sequence of 15 morphological units on the Aguas river was determined by geomorphologic and sedimentologic criteria, as well as ^{14}C, ^{210}Pb, U/Th radiometric dating and artifacts (SCHULTE 1995, 1998b). Buried soils of glacis G1 at the Antas valley (stratigraphy after SCHULTE 1995) and soils developed over marine terraces has been also taken into account in order to complete the regional pedostratigraphy.

Soils from Aguas valley were described and magnetic susceptibility was measured at 11 sites. Furthermore, the redness rating, the ratio of soil reddening (rubefaction) of 40 Bt horizons were calculated after TORRENT et al. (1980) and modified by HARVEY et al. (1995). Multiple samples were collected for laboratory analysis at six sites, corresponding to different fluvial terraces (table 1). The determination of nitrogen and total and organic carbon was performed by chromatography and the major elements (Al_2O_3, P_2O_5, K_2O, CaO, SiO_2, TiO_2, MnO, Fe_2O_3, MgO, Na_2O) by X-ray fluorescence. The micromorphology of the soil samples was studied in petrographic thin sections.

4 *Results*

Up to 15 morphological units (pediments P, alluvial fans S, glacis G, Pleistocene terrace levels T and Holocene terraces H), and covering the whole Quaternary, bear different soils in the middle and lower Aguas valley (SCHULTE 1998a). The soil sequence extends from the older (early Pleistocene) well developed Rhodoxeralfs (Red Mediterranean soils) with argillic Bt horizons to the less developed Holocene Haploxerolls (fig. 2).

[1] We use the term "glacis" for piedmont slopes developed on non-resistent rocks. In the Vera basin the distal end of the "glacis" is often covered by thick fluvial deposits.

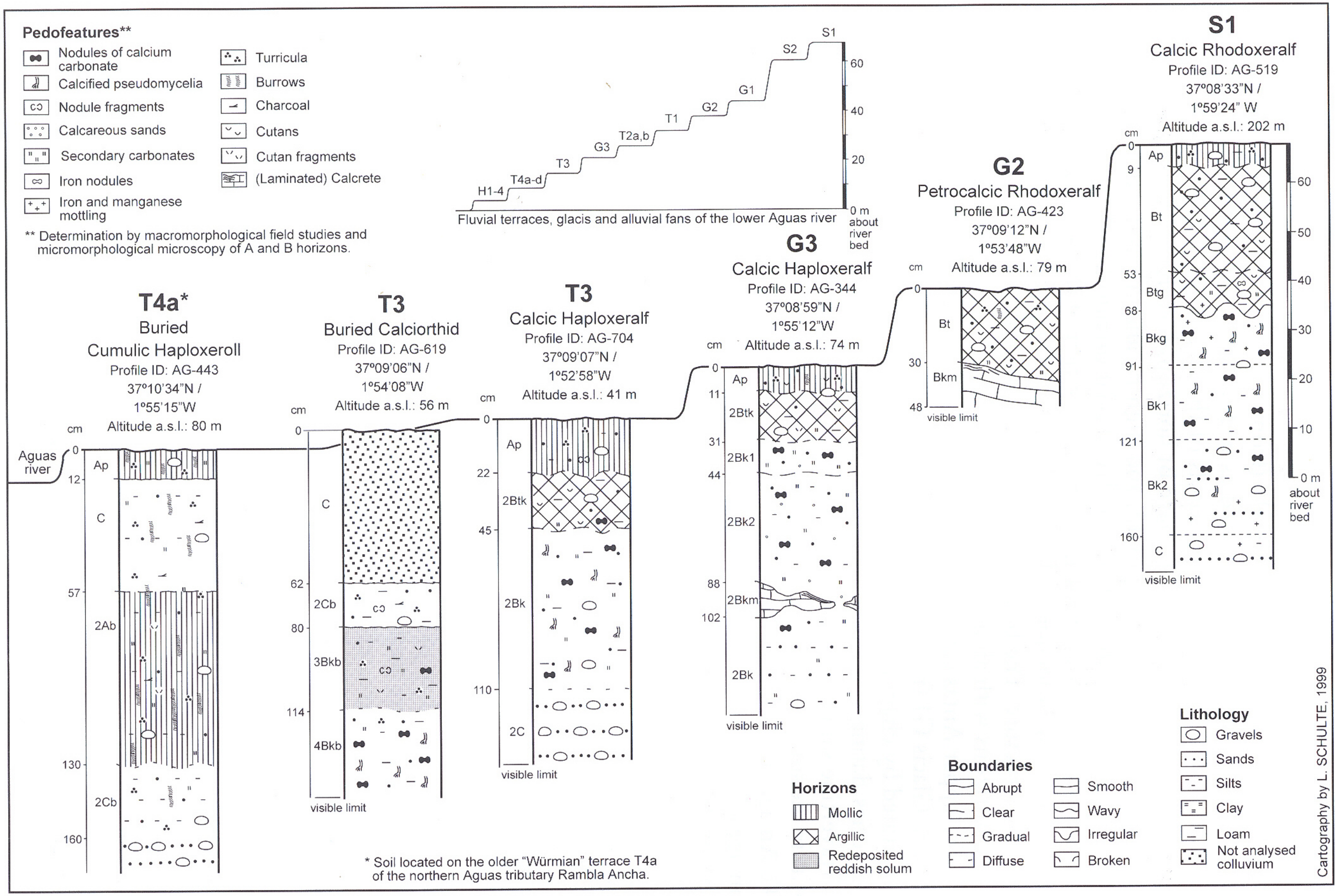

Fig. 2. Analysed soil profiles and their morphostratigraphical location on the Aguas river terraces.

4.1 *Early Pleistocene soils*

The red Rhodoxeralfs of profiles Ag-519 (from alluvial fan S1; refered as n°1 in fig. 1) and Ag-423 (from Glacis G2; refered as n° 2 in fig. 1) are described in fig. 2 and table 1. These soils as well as the paleosols of the alluvial fan S2 and glacis G1 (see stratigraphical order in fig. 2 and 4), have Bt horizons less than 60 cm thick, they are decalcified, have a redness rating of 15, and high Fe and Al contents (table 1). Frequent clay coatings provide evidence of clay illuviation into Bt. Micromorphological analyses show that the higher the ground mass content of the Bt horizons, the older the surface. This phenomenon is also evidenced by the presence of an angular blocky or prismatic structure. The Bt horizons always overlie thick nodular Bk and/or laminar Bkm horizons with abundant vertical to subvertical calcified structures.

In the upper Antas catchment, a sequence of four buried paleosols of the early Pleistocene Glacis G1 (refered as n° 7 in fig. 1) includes Rhodoxeralfs and Haploxeralfs separated by channel and floodplain deposits.

U-series dating was undertaken to determine the age of the early Pleistocene soils. Travertine samples extracted from the base of Glacis G1 and from Glacis G2 deposits in the southern margin of the Vera basin yield ages older than 350,000 yr B. P. (fig. 4). An age of 2.358 myr B. P. was obtained for the base of the oldest alluvial fan and an age of 1.624 myr B. P. for the Glacis G1, by ESR-dating in the northeastern Vera basin (WENZENS 1992).

4.2 *Middle and late Pleistocene soils*

The reddish brown to yellowish red Haploxeralfs on the middle Pleistocene terraces are less developed than the Rhodoxeralfs on the early Pleistocene alluvial fans and glacis. Their redness rating ranges between 3.5 and 11.25 and the Al_2O_3 contents are lower (table 1). Clay coatings were also observed in thin sections, although with less frequency than in the Rhodoxeralfs. The calcic and petrocalcic horizons of the Haploxeralfs are well developed and have $CaCO_3$ contents between 30 and 40 % and sometimes greater (Profile Ag-344 and Profile Ag-704, table 1 and refered as n° 3 and n° 4 in fig. 1).

The youngest reddish brown soils (e. g. Calcic Haploxeralfs, Ag-704, fig. 4) are located on the fluvial terrace T3. In the middle Aguas valley, this fluvial terrace is overlyed by a 9 m thick travertine deposit dated between 148,000 ± 8000 yr B. P. (U/Th) and 54,700 ± 1800 yr B. P. (U/Th) and on the top of the travertine deposits a reddish soil was not found. Nevertheless some Bk horizons interfinger the travertine lithosome suggesting a discontinuous travertine formation.

In the littoral zone, the youngest reddish soil occurs over the last interglacial marine terrace defined by several datings (e. g. 100,000 ± 6500 yr B. P. (U/Th) by GOY & ZAZO 1986; > 100,000 yr B. P. (IRSL) by COURTY et al. 1994).

The middle and late Pleistocene soils are frequently affected by down-slope colluvium aggradation and by subsequent recalcification. For example, Profile Ag-619 (refered as n° 5 in fig. 1), located on terrace T3, shows up to four aggradation phases and their micromorphological features, such as subrounded cutans and calcrete fragments, reveal the polycyclic origin of this profile, suggesting that soil

Table 1. Morphological and analytical characteristics of the studied soil profiles.

Terrace*	Horizon	Depth (cm)	Sample	Structure	Colour dry	RR dry	$CaCO_3$ (%)	Fe_2O_3 (%)	Al_2O3 (%)	SiO_2 (%)	CaO (%)	C org. (%)	Other characteristics
Profile: Ag-519, Calcic Rhodoxeralf, altitude a.s.l.: 202 m													
S1, + 67 m	Ap	0-9	519.6	wk suanbl	2.5YR 4/6	11.25	0	6.8	16.9	60.6	2.2	n.d.	Bt and Btg: Frequent cutans. Btg: iron nodules and secondary micrite. Bkg - Bk2: Chalky nodules, vertical calcified pseudomycelia. Bkg: Iron and manganese mottling.
	Bt	9-53	519.7	md anbl	2.5YR 3/6	15	0	6.5	17.3	63.7	0.9	n.d.	
	Btg	53-68	519.8	st pr	5YR 5/6	6	0	6.2	16.3	62.7	1.2	n.d.	
	Bgk	68-91	519.9	*n.d.*	7.5YR 6/8	3.33	64.4	1.7	4.5	14.2	43.2	n.d.	
	Bk1	91-121	519.10	*n.d.*	10YR 7/4	0.57	60	1.5	4.1	17.1	42.1	n.d.	
	Bk2	121-160	519.11	*n.d.*	7.5YR 6/4	1.66	27	3.1	9.6	45.5	19.3	n.d.	
	C	160-174	519.12	*n.d.*	7.5YR 6/4	1.66	14.8	3.9	11.7	54.9	11.3	n.d.	
Profile: Ag-423, Petrocalcic Rhodoxeralf, altitude a.s.l.: 79 m													
G2, + 37 m	Bt	0-30	423.6	st anbl	2.5YR 3/6	15	0	8.2	18.6	57.2	1.7	n.d.	Bt: Few potential weathering-minerals preserved, degraded and broken cutans. Bkm: Polycyclic, laminar hard pan and calcareous silts.
	Bkm	>30	-	*n.d.*	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	
Profile: Ag-344, Calcic Haploxeralf, altitude a.s.l.: 74 m													
G3, + 26 m	Ap	0-11	344.7	wk gr	7.5YR 5/4	2	26.2	5.3	10.6	73.0	1.1	n.d.	2Btk: Degraded and broken cutans, secondary micritic calcite. 2Bk1 - 2Bk: Calcium carbonate nodules, calcareous sands, subsurface micrite stringers.
	2Btk	11-31	344.8	md suanbl	5YR 4/4	5	14.5	4.7	10.6	45.6	15.4	n.d.	
	2Bk1	31-44	344.9	*n.d.*	7.5YR 6/6	2.5	31.1	3.5	7.5	44.2	22.3	n.d.	
	2Bk2	44-88	344.10	*n.d.*	10YR 7/4	0.57	22	2.8	5.6	40.8	26.1	n.d.	
	2Bkm	88-102	-	*n.d.*	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	
	2Bk	102->142	344.12	*n.d.*	10YR 7/3	0.43	23.8	3.3	6.5	56.4	16.4	n.d.	
Profile: Ag-704, Calcic Haploxeralf, altitude a.s.l.: 41 m													
T3, + 14 m	Ap	0-22	704.4	wk suanbl	10YR 5/6	1.2	18.36	5.3	10.5	69.6	3.4	n.d.	2Btk: Degraded cutans, secondary micrite covering cutans in voids, iron nodules. 2Bk: Calcium carbonate nodules, calcified pseudomycelia.
	2Btk	22-45	704.3	md suanbl	5YR 4/4	5	19.15	7.1	12.7	65.5	2.6	n.d.	
	2Bk	45-110	704.6	md suanbl	7.5YR 7/6	2.14	47.08	4.5	10.0	50.3	15.3	n.d.	
	2C	>110	704.7	stle	10YR 7/3	0.43	41.45	3.6	7.8	58.7	13.3	n.d.	
Profile: Ag-619, buried Calciorthid, altitude a.s.l.: 56 m													
T3, + 14 m	2Cb	62-80	619.2	stle	10YR 5/4	0.6	8.3	4.0	9.1	59.9	10.6	n.d.	3Bkb: Primary and secondary calcite, rounded fragments of cutans. 4Bk: Calcareous nodules, calcified pseudomycelia.
	3Bkb	80-114	619.3	st anbl	5YR 6/6	5	16.9	4.3	10.5	47.8	15.8	n.d.	
	4Bkb	114->149	619.4	wk suanbl	7.5YR 5/6	1.43	41.7	2.7	6.9	33.3	29.1	n.d.	
Profile: Ag-443, buried Cumulic Haploxeroll, altitude a.s.l.: 80 m													
T4, + 8 m	Ap	10	443.16	wk gr	10YR 6/3	0.5	23.1	3.9	9.1	43.6	19.0	1,2	2Ab: Secondary calcite, turricula, rounded fragments of cutans, abundant burrows, few soft nodules of calcium carbonate.
	C	20	443.15	wk gr	10YR 7-6/3	0.42	25	4.0	9.3	42.5	19.5	1,4	
		30	443.14	wk gr	10YR 7-6/3	0.42	25.8	4.3	9.7	43.2	19.1	1,1	
		40	443.13	wk gr	10YR 7-6/3	0.42	28.1	4.2	9.1	46.9	17.3	1,4	
		50	443.12	wk gr	10YR 5/3	0.6	19.4	4.5	9.8	46.2	16.7	1,2	
	2Ab	60	443.11	md suanbl	10YR 5/3	0.6	24.2	4.3	10.4	45.1	17.2	1,5	
		70	443.10	md suanbl	10YR 5/3	0.6	20.3	4.3	10.5	45.5	16.0	1,8	
		80	443.9	md suanbl	10YR 5/3	0.6	20.3	4.5	10.6	46.3	15.8	1,8	
		90	443.8	md suanbl	10YR 5/3	0.6	21.3	5.0	10.7	63.3	6.0	1,5	
		100	443.7	md suanbl	10YR 5/3	0.6	22.2	4.3	10.5	47.3	15.5	1,5	
		110	443.6	md suanbl	10YR 5/3	0.6	23.3	4.4	10.7	48.6	15.1	1,2	
		120	443.5	md suanbl	10YR 5/3	0.6	19.7	4.4	10.2	49.6	14.6	1,2	
		130	443.4	md suanbl	10YR 7/2-3	0.42	16.9	4.2	10.0	48.1	16.1	1,1	
	2Cb	140	443.3	*n.d.*	10YR 7/2-3	0.42	20.3	4.1	9.4	47.7	17.2	1,1	
		150	443.2	*n.d.*	10YR 7/2-3	0.42	21.3	4.2	9.5	46.0	17.7	1,2	

Abreviations: stle = structurless, wk = weak, md = moderate, st = strong; pl = platy, pr = prismatic, co = columnar, anbl = angular blocky, suanbl = subangular blocky, gr = granular, cr = crumb; n.d. = not determined; RR = redness rating. * altitude about riverbed.

development is mainly triggered by slope erosion. COURTY et al. (1994) assign an age of 83,000 ± 20,000 yr B. P. (IRSL) to one of these phases.

4.3 *Holocene soils*

Reddish soils were not observed on subsequent stages 2 and 1 fluvial terraces. Bk horizons are also absent in stage 2 and in Holocene deposits. Haploxerolls were detected on the surfaces where soils were not excessively transformed by human activity. Figure 2 shows the profile of a buried Cumulic Haploxeroll (Ag-443, refered as nº 6 in fig. 1) situated on the older stage 2 terrace (T4a) of the Rambla de Mofar, a tributary of the Aguas river. Organic carbon reaches maximum values of 1.8 % in the buried 2A horizon. The most remarkable pedofeature of this profile is the abundant worm casts with diameters of up to 1.7 cm and frequent turricula. The intensive biological activity seems to be related to a more humid climate during early Holocene wich agree with the palynological data (BURJACHS et al. 1997).

4.4 *Correspondence analysis as an enhanced tool for chronostratigraphic criterium*

A chronological argument can also be supported by multivariate analysis. The data matrix is defined by the chemical composition ($CaCO_3$, Al_2O_3, P_2O5, K_2O, CaO, SiO_2, TiO_2, MnO, Fe_2O_3, MgO, Na_2O) and the redness rating as variables (columns), and by the 35 samples taken in the pedological horizons as individuals (rows). Correspondence ordination analysis (COA) shows (fig. 3) that the first axis, which accounts for 80 % of the total variability, is controlled at one end by the $CaCO_3$ and Ca contents and at the other end by the Fe, Si, Al, K and Ti contents. This analysis, as well as the correlation matrix itself, shows the opposite role between the insoluble elements (iron oxides and silicates) and the calcium and carbonate content. Thus,

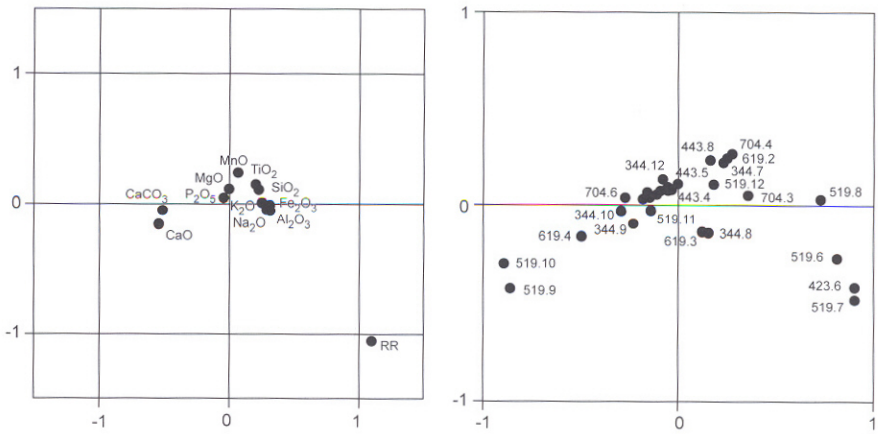

Fig. 3. Correspondence ordination analysis (COA) of the chemical composition of soil horizons.

the samples plotted in the plane defined by the first two axes of the COA are distributed in accordance with their age: in the centre the horizons of the most recent soils and at the extremes ends the well differentiated Bk and Bt horizons of the oldest soils.

5 *Discussion*

5.1 *Palaeoclimate discussion*

5.1.1 *Early Pleistocene*

Soils bear a more or less close relationship to climatic change and permit a reconstruction of the Quaternary environment of the Vera basin. Although the intensive development of the older paleosols can be attributed to the greater length of pedogenic processes since terrace accumulation, it can also be ascribed to more favourable climatic conditions (seasonal hot/dry and more humid) during the early Pleistocene, as shown by Mediterranean ^{18}O isotope records (VERGNAUD GRAZZINI et al. 1990; fig. 4). Paleoecologic studies of a Plio-Pleistocene lacustrine sequence of the near Baza basin (800–1000 m a.s.l.) record several alternating phases of dry/cold and humid/temperate conditions (ANADÓN et al. 1994).

The palaeoclimatic interpretation of the red paleosols analysed agrees with the results of COURTY et al. (1994), who studied a Red Mediterranean soil on a middle terrace of the Almanzora river in the northern part of the Vera basin. On the basis of microlaminated clay coatings and intensive rubification of the Bt horizon these authors suggested a climate which was humid enough to favour dense vegetation cover, in spite of hot and dry summers. They attributed this soil to an interglacial period during the Pleistocene. The morphostratigraphic mapping shows that the middle terrace corresponds laterally to the glacis G3 of the Antas river (SCHULTE 1995, 1999), which is approximately an early/middle Pleistocene boundary age.

In the upper Antas catchment a sequence of four buried paleosols of the early Pleistocene glacis G1 includes Rhodoxeralfs, which have not been found related to the middle Pleistocene terraces. The repeated change from soil formation and buring indicates the relatively short time necessary for the development of Red Mediterranean soils (Rhodoxeralfs) under certain environmental conditions.

5.1.2 *Middle Pleistocene*

The relict soils of the study area undergo a gradual decline in the redness rating from the lower to late Pleistocene (fig. 4). Soil development on the middle Pleistocene terraces was less efficient, probably because of lower temperatures and drier conditions during the middle and late Pleistocene, which were evidenced by loess-like deposits (BRUNNACKER & LOZEK 1969) and pollen records (PONS & REILLE 1988). However, the middle Pleistocene Haploxeralfs also show reddish Bt horizons with clay illuviation and Bk horizons. These data coincide with the pedological results of other studies from Southern Spain. The existence of better developed red soils on early Quaternary surfaces of the nearby Sorbas basin has also been reported by HARVEY et al. (1995). In addition, recent paleopedological studies of paleosols of alluvial fans from the Granada basin (S-Spain), undertaken by GÜNSTER & SKOWronek (1998), report more intensive pedogenesis (red and brown soils) during early Pleistocene and less intensive soil formation (reddish yellow and brown soils) during middle and late Pleistocene. In western Spain García Marcos & Santos Frances (1997) observed a similar pedostratigraphical sequence on the Tormes river terraces.

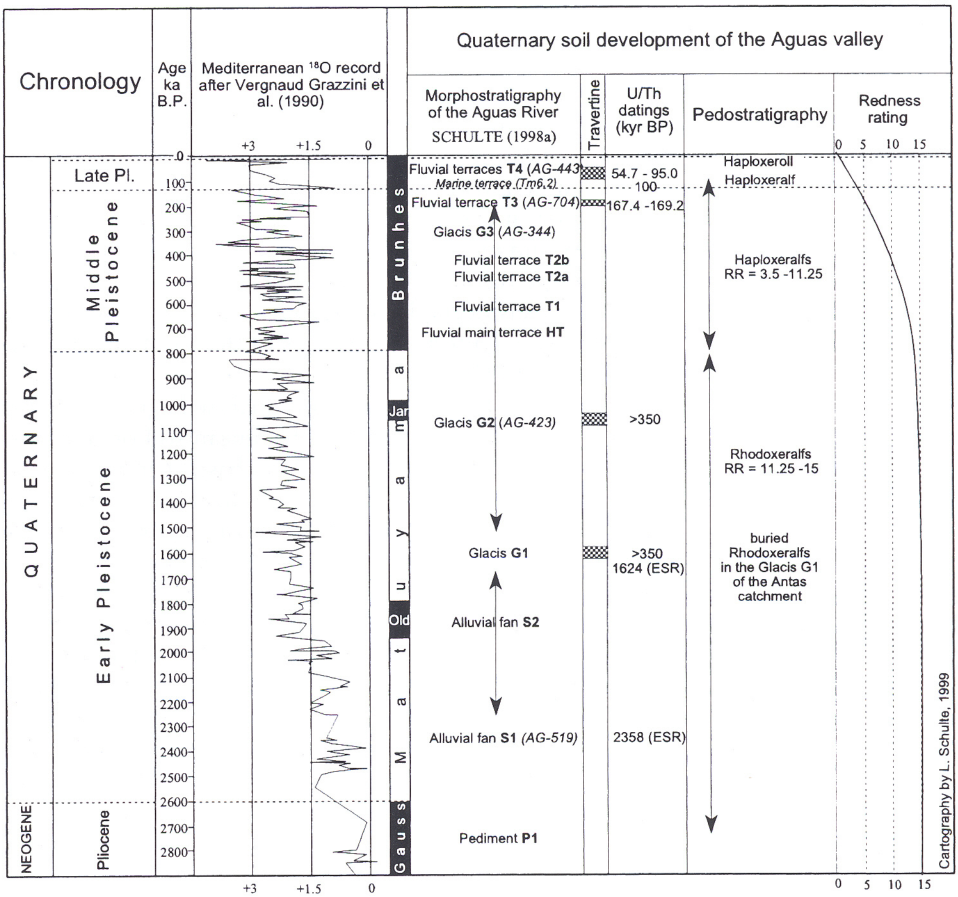

Fig. 4. The pediment P1 is regarded as upper Pliocene. In the northeastern part of the Vera basin an age of 2.358 myr B. P. was obtained for the base of the oldest alluvial fan and an age of 1.624 myr B. P. (ESR) for the "glacis G1" (Wenzens 1992). The alluvial fan S2 is located morphostratigraphically between these two geomorphologic units. The U-series dating method gives ages of 169,000 ± 9000, 167,000 ± 7000 and 148,000 ± 8000 yr B. P. for the fluvial terrace T3. The morphological levels differentiated between G2 and G3 developed from latest early Pleistocene to middle Pleistocene. An age of 100,000 yr B. P. (U/Th) was reported by Goy & Zazo (1986) for the 9 m marine terrace. The Würm terraces T4 were accumulated after 54,700 ± 2000 yr B. P. The arrows of the morphostratigraphic column represents the chronostratigraphic range of the terrace levels which were not radiometrically dated. Their order in the column corresponds to the relative morphostratigraphic sequence. (AG-519) = Location of the analysed soil profiles.

The increase in climatic and geomorphic contrast since the middle Pleistocene in the Vera basin is evidenced by a sequence of several fluvial terraces, including periods of accumulation and incision of the Aguas river. Sedimentological studies of the fluvial sediments of the Aguas river, undertaken by SCHULTE (1998b, 1999), show different depositional styles related to fluvial dynamics. Braided and torrential river structures in gravel reflect violent fluvial dynamics and increased sediment discharge. These dynamics probably occur as a result of precipitation concentration and less vegetation cover which produce an increase in the overland flow.

5.1.3 *Late Pleistocene and Holocene*

The environmental reconstruction for late Pleistocene and Holocene of the Vera basin is more precise. The youngest Haploxeralf was formed on the fluvial terrace T3 in the Aguas valley, which corresponds to isotopic stage 6 (SCHULTE 1998b). This soil probably developed during isotopic stage 5 (fig. 4). Likewise, Haploxeralfs were formed on the 9 m a. s. l. marine terrace, where an age of 100,000 ± 6500 yr B. P. was reported by GOY & ZAZO (1986). Given its morphostratigraphic position, the soil dates are subsequent to stage 5c. Reddish soils clearly younger than stage 5a were not found in the Vera basin, neither over colluvium of the stage 4 nor over the travertine deposits of stage 3.

The thick travertine deposit in the middle Aguas valley could provide some paleoclimatic data. The travertine formation suggests more humid climate conditions also favorable for soil development. In spite of sedimentary discontinuities, the main period of travertine formation falls within 94,000 ± 5000 (stage 5a) to 54,000 ± 2000 yr B. P. (beginning of stage 3), and were drastically reduced during stage 2 and the Holocene (fig. 4). Even palynological studies of selected travertine samples point to a more humid climate during stage 5a and at the beginning of stage 3. The soil formation probably correlates with the first of these two periods. Nevertheless, the few pollen records indicate generally dry steppe environments during stages 6, 5, 4 and 3 for the Vera basin (F. BURJACHS, pers. comm. 1999). Before isotope stage 2, leaching of carbonates occurred during the last glacial cycle (profile AG-619), whereas no calcic horizons were found in stages 2 and 1 sediments. The following reasons, amongst others, could account for the restriction of these pedological dynamics: the general lack of sufficient precipitation and the intervention of morphological (accumulation/erosion) processes. However, the aggradation of four lower terraces indicates important morphological processes related to climate fluctuations during isotope stage 2 (SCHULTE 1999).

The maximum soil development from stage 3 is represented by a late Glacial – early Holocene Haploxeroll, with abundant biological pedofeatures but without carbonate removal. Pollen records (BURJACHS et al. 1997) from the Mediterranean catchments of the Iberian Peninsula indicate a more humid climate at the beginning of Holocene. Nevertheless, the environmental conditions seem to have been too dry for an intense soil and travertine development during the last 10,000 years.

5.2 *Discussion regarding the youngest Haploxeralf*

The stratigraphy and paleoclimatological interpretation of Mediterranean soils seem to be complex and controversial. According to the pedostratigraphy of CARMONA et al. (1993), based on TL-dating, the development of reddish soils with clay illuviation in the nearby semiarid Valencia area corresponds to isotope stages 5e, 5c and to the beginning of stage 3. These authors detect a correlation between soil development and sea level highstands without specifying the direct influence of climate on soils. Even Bronger & Bruhn-Lobin (1997) report periods of soil formation from NW Morocco during the last glacial cycle. Rubified Bw horizons in fossil dunes date between 105,000 ± 12,000 and 71,000 ± 12,000 yr B. P. and 71,000 ± 12,000 and 36,000 ± 5000 yr B. P. (TL). Nevertheless, these authors assume that the formation of relict polygenetic *Terrae rossae* extends over most of the Brunhes epoch and was interrupted only by short periods of local eolian activity. On the basis of micromorphological studies undertaken on Moroccan soils Fedoroff (1997) concludes that the youngest typic clay illuviation occurred during the last interglacial period. From soil studies on Mediterranean loess deposits Brunnacker & Lozek (1969) propose that the last interglacial soil formation period of the central Europe pedostratigraphy probably shifted towards the end of the last interglaciation in the northern Mediterranean region and towards the beginning of the early Würm in the southern Mediterranean region. In the upper Aguas valley (fig. 1) Harvey et al. (1995) found the youngest Bt horizon on a terrace which was estimated as early Würm but they presented no absolute dating. Morphological mapping and longitudinal profiles of fluvial terraces undertaken by Schulte (1998a, 1998b) suggest that this terrace unit is much older.

Our results in the Aguas valley evidence that the youngest Haploxeralf was formed during the isotope stage 5.

6 *Conclusion*

The Quaternary soil chronosequence observed on the Aguas river terraces shows an increasing soil development with older terrace age. In accordance with the pedostratigraphic data, Rhodoxeralfs were formed on early Pleistocene alluvial fans and glacis, Haploxeralfs on middle and late Pleistocene terraces and weak developed soils (e. g. Haploxerolls) on Holocene terraces. The younger the terrace, the less the soil thickness, redness rating and content of argillians in the Bt horizons.

Regarding the occurrence of buried Rhodoxeralfs in glacis and fluvial terrace deposits from the Antas valley we conclude that their pedogenesis is related to climate fluctuations with increased precipitation and higher temperatures during the early Pleistocene.

The lack of Rhodoxeralfs on middle and late Pleistocene deposits of the Vera basin suggests that the climate conditions tends to be drier and colder, although warmer and more humid climate cycles are still recorded. The youngest Haploxeralf correlates, in the Vera basin, to isotopic stage 5, perhaps to stage 5a. Pollen records of Southeastern Spain define this stage as a relative humid period.

Acknowledgements

These studies were financially supported by the CIRIT, Generalitat de Catalunya (Grant FI/96-1.255). We thank F. Burjachs, Institute of Earth Science, Barcelona, for the pollen analysis of the travertine samples. We express our gratitude to A. Bronger, Universität Kiel and S. Sedov, Lomonosow University, Moscow, for their help in the micromorphologic analysis and to A. Gómez, Universitat de Barcelona for his helpful suggestions. We also thank B. J. Buck from the University of Nevada, P. W. Birkeland from the University of Colorado and B. Harrison from the University of New Mexico for reviewing the entire manuscript and their helpful comments. Geochemical analysis was carried out at the Serveis Científico-Tècnics, Universitat de Barcelona.

References

ANADÓN, P., USTRILLA, R. & JULIÀ, R. (1994): Palaeoenvironmental reconstruction of a Pleistocene lacustrine sequence from faunal assemblages and ostracode shell geochemistry, Baza Basin, SE Spain. – Palaeogeography, Palaeoclimatology, Palaeoecology **111**: 191–205.

BRONGER, A. & BRUHN-LOBIN, N. (1997): Paleopedology of Terrae rossae-Rhodoxeralfs from Quaternary calcarenites in NW Morocco. – Catena **28**: 279–295.

BRUNNACKER, K. & LOZEK, V. (1969): Löss-Vorkommen in Südostspanien. – Z. Geomorph. N. F. **13**: 297–316.

BURJACHS, F., GIRALT, S., ROCA, J. R., SERET, G. & JULIÀ (1997): Palinología holocénica y desertización en el Mediterráneo occidental. – In: IBÁÑEZ, J. J., VALERO GARCÉS, B. L. & MACHADO, C. (eds.): El paisaje mediterráneo a través del espacio y del tiempo. Implicaciones en la desertificación: 379–394; Geoforma, Logroño.

CARMONA, P., FUMANAL, M. P., JULIÀ, R., PROSZYNSKA-BORDAS, H., SOLÉ, A., STANSKA-PROSZYNSKA, W. & VIÑALS, M. J. (1993): Contexto geomorfológico y cronoestratigráfico de algunos paleosuelos valencianos. – In: El Cuaternario en España y Portugal: 533–543; ITGE, Madrid.

COURTY, M.-A., FODOROFF, N., JONES, M. K. & MCGLADE, J. (1994): Environmental dynamics. – In: CASTRO, P. et al. (eds.): Temporalities and desertification in the Vera Basin, south east Spain. Archaeomedes Project **2**: 19–84; European Commission, Luxembourg.

FEDOROFF, N. (1997): Clay illuviation in Red Mediterranean soils. – Catena **28**: 171–189.

GARCÍA MARCOS, J. M. & SANTOS FRANCES, F. (1997): Relationship between the characteristics of Mediterranean Red soils and the age of the geomorphological surfaces in central-western Spain. – Catena **28**: 231–245.

GOY, J. L. & ZAZO, C. (1986): Synthesis of the Quaternary in the Almería littoral. Neotectonic activity and its morphologic features, western Betics, Spain. – Tectonophysics **130**: 259–270.

GÜNSTER, N. & SKOWRONEK, A. (1998): La posición geomorfológica y clima-genética de los paleosuelos fósiles en la depresión de Granada. – In: GÓMEZ ORTIZ, A. & SALVADOR FRANCH, F. (eds.): Investigaciones recientes de la Geomorfología española. V Reunión Nacional de Geomorfología, Granada: 367–374; Geoforma, Logroño.

HARVEY, A. M., MILLER, S. Y. & WELLS, S. G. (1995): Quaternary soil and river terrace sequences in the Aguas/Feos river systems: Sorbas basin, Southeast Spain. – In: LEWIN, J., MACKLIN, M. G. & WOODWARD, J. C. (eds.): Mediterranean Quaternary River Environments: 263–281; Balkema, Rotterdam.

PONS, A. & REILLE, M. (1988): The Holocene and Upper Pleistocene Record from Padul (Granada, Spain): A new study. – Palaeography, Palaeoclimatology, Palaeoecology **66**: 243–263.

SCHULTE, L. (1995): Jungquartäre Flussdynamik des Río Antas im zentralen Vera-Becken (SE-Spanien). – Geoökodynamik **16**: 173–196.

Schulte, L. (1998a): Quaternary morphodynamic and climate changes in the middle and lower Antas Valley. – In: Castro, P. V. et al. (eds.): Aguas Project. Paleoclimatic reconstruction and the dynamics of human settlement and land-use in the area of the middle Aguas (Almería), in the Southeast of the Iberian Peninsula: 38–42; European Commission, Luxembourg.

– (1998b): Respuesta de la dinámica fluvial a los cambios climáticos en el sureste peninsular. – In: Gómez Ortiz, A. & Salvador Franch, F. (eds.): Investigaciones recientes de la Geomorfología española. V Reunión Nacional de Geomorfología. Granada: 433–443; Geoforma, Logroño.

– (1999): Evolución cuaternaria de la depresión de Vera y de Sorbas oriental (SE-Península Ibérica). Reconstrucción de las fluctuaciones paleoclimáticas a partir de estudios morfológicos y edafológicos. – Ph. D. Thesis, University of Barcelona, 267 pp.

Torrent, J., Schwertmann, U. & Schulze, D. G. (1980): Iron oxide mineralogy of some soils of two river terrace sequences in Spain. – Geoderma **23**: 191–208.

Vergnaud Grazzini, C., Saliège, J. F., Urrutiaguer, M. J. & Iannace, A. (1990): Oxygen and carbon isotope stratigraphy of ODP Hole 653a and Site 654: The Pliocene-Pleistocene glacial history recorded in the Tyrrenian Basin (West Mediterranean). – In: Kasten, K. A. et al. (eds.): Proceedings of the Ocean Drilling Program, Scientific Results, vol. **107**: 361–384; Texas University.

Wenzens, G. (1992): Mittelquartäre Klimaverhältnisse und Reliefentwicklung im semiariden Becken von Vera (Südostspanien). – Eiszeitalter und Gegenwart **42**: 121–133.

Addresses of authors: Dr. Lothar Schulte, Departament de Geografia Física i Servei del Paisatge (Department of Physical Geography and Institute of Geoecology), Universidad de Barcelona, Baldiri Reixac s/n, E-08028 Barcelona, Spain. schulte@trivium.gh.ub.es – Prof. Dr. Ramón Julià, Institut de les Ciències de la Terra (Institute of Earth Science, CSIC), Lluis Solé Sabaris, s/n, E-08028 Barcelona, Spain. rjulia@ija.csic.es