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EXTENDING WESTWARD THE LOESS BASIN BETWEEN THE ALPS AND THE MEDITERRANEAN REGION: MICROMORPHOLOGICAL AND MINERALOGICAL EVIDENCES FROM THE NORTHERN SLOPE OF THE LIGURIAN ALPS, NORTHERN ITALY (****)

ABSTRACT: RELLINI I., TROMBINO L., FIRPO M. & ROSSI P.M., *Extending westward the loess basin between the Alps and the Mediterranean region: micromorphological and mineralogical evidences from the northern slope of the Ligurian Alps, Northern Italy*. (IT ISSN 0391-9838, 2009).

A representative loess-paleosol sequence has been identified and studied by mineralogical and micromorphological analyses, in order to clarify its genesis, and to investigate its palaeoclimatic significance in relation to the Quaternary climatic fluctuations in the Ligurian Alps. The his analysis also establishes a chronological succession of pedological and sedimentary events in order to interpret the environmental significance of each phase. The micromorphological evidences and mineralogical analyses, suggest a polygenetic origin for the profile. The profile reflects the influence of different processes acting on distinct parent material under different environmental conditions. In fact the deeper unit was produced by a strong pedogenetic phase, involving the bedrock parent material and leading to the development of a pedogenetic body showing characteristics like present day strongly weathered subtropical to tropical area soils (i.e. fersiallitic to ferrallitic soil), while from the upper units it is clear that multiple erosion-deposition events of material developed from loess blankets has taken place. These materials show features that are comparable to Lateglacial interstadial soils of the middle Europe, which were not erased by the present day pedogenesis. This analysis of the loess-paleosol sequences along the slope of the Ligurian Alps allows to extend our knowledge of the history of the loess sedimentation basin in the area between the Alps and the Mediterranean coast.

KEY WORDS: Loess, Paleosols, Ligurian Alps, Micromorphology, Climate changes, Quaternary.

INTRODUCTION

Loess deposits in Northern and Central Italy are well represented along the margins of the Po plain and in the Pre-Alps (Cremaschi 1990a, 1990b). They have been subdivided according to the main areas of deposition as follows: (a) Loess on fluviatile terraces, that can be found all along the Appennine fringe; (b) Loess on moraines and fluvioglacial deposits, that can be found at the southern margin of the Pre-Alps; (c) Loess on karst-plateaux, or included in cave or shelter fills, that are wide-spread in the calcareous Pre-Alps. Moreover, some loess deposits has been identified on glacis and erosional surfaces at the Appennine fringe between the Liguria and Marche regions but previously no loess deposit has been described from the Ligurian Alps.

The present paper is focused on the detailed mineralogical and micromorphological study of an upper Pleistocene loess-paleosol sequence identified at Palo (SV), Northern Italy, in order to elucidate its genesis, and assess its palaeoclimatic significance in the framework of the Quaternary climatic fluctuations in the Ligurian Alps. The Quaternary history of this area of Liguria is almost unknown, except for information from the Holocene pollen record recorded in peat sites (Braggio Morucchio & *alii*, 1978). The existing paleoclimate reconstruction is uncertain and speculative. For the Late Tertiary/Lower Pleistocene boundary, no paleoclimatic evidence exist in the Ligurian Alps, whereas along the western ligurian coast Rellini & *alii* (2007) have described strong weathered pedogenetic bodies on preserved geomorphological surfaces connected to warm periods, similar to those that occurred in Italy before the glacial Pleistocene (Late Tertiary and Early Pleistocene). In contrast, Cortemiglia (1984) identified colluvial deposits with lateritic pedogenesis at the hight of the 200 m a.s.l on the northern slope of the Ligurian Alps dated to the Middle Pleistocene, similar to those

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described along the appennine slopes. Moreover, little paleoclimatic evidence related to the Late Pleistocene has been recorded in the study area: Ravazzi (2002) suggest that the area could have been covered by spruce forest since the Eemian Interglacial; according to Biancotti & Cortemiglia (1984), the area was loess-tundra zone during the Weichselian; Firpo & *alii* (2005) hypothesised that permafrost aggradation occurred during the last glacial period.

STUDY AREA

The study area was located in eastern sector of the Ligurian Alps, along the watershed between the Po and the Ligurian river basins, it contains the Beigua massif, comprising several summits over 1000 m a.s.l. with the highest one at 1287 m a.s.l. (fig. 1). The basement of the area is formed by the Voltri Group metaophyolite complex, composed of serpentinites, metabasites and metasediments. Moreover, part of the metasediments are unconformably overlapped by some marine late and post orogenic deposits, as Oligocene deposits of the Tertiary Piedmontese Basin.

From a geomorphological point of view the northern slope, dipping to the Po river basin, is characterized by several valleys rich in terraces and gently tilted surfaces that are deeply influenced by running water erosion processes, increased by human activities. The high part of the slope is characterized by the accumulation of large blocks with morphological features related to the creep and/or the gelifluction processes tentatively attributed to permafrost conditions during the Würm (blockfields and blockstreams, Firpo & *alii*, 2005).

The study area has a typical temperate oceanic climate; the data published from Regione Piemonte (weather stations of Bric Berton, 773 m a.s.l. and Marcarolo, 780 m a.s.l., fig. 1) showed mean annual precipitation ranges from 1000 to 1400 mm/years and mean annual temperatures from 9.1°C to 10.2°C. The ombrothermic diagram (fig. 2), calculated from the data of the nearest station (Piampaludo, 800 m a.s.l., fig. 1), shows two distinct rainy seasons with maxima in April and October and with a clear precipitation decrease between July and August, even if it is not possible to consider that period as a true dry season (the condition 2T > P does not occur). Accord-

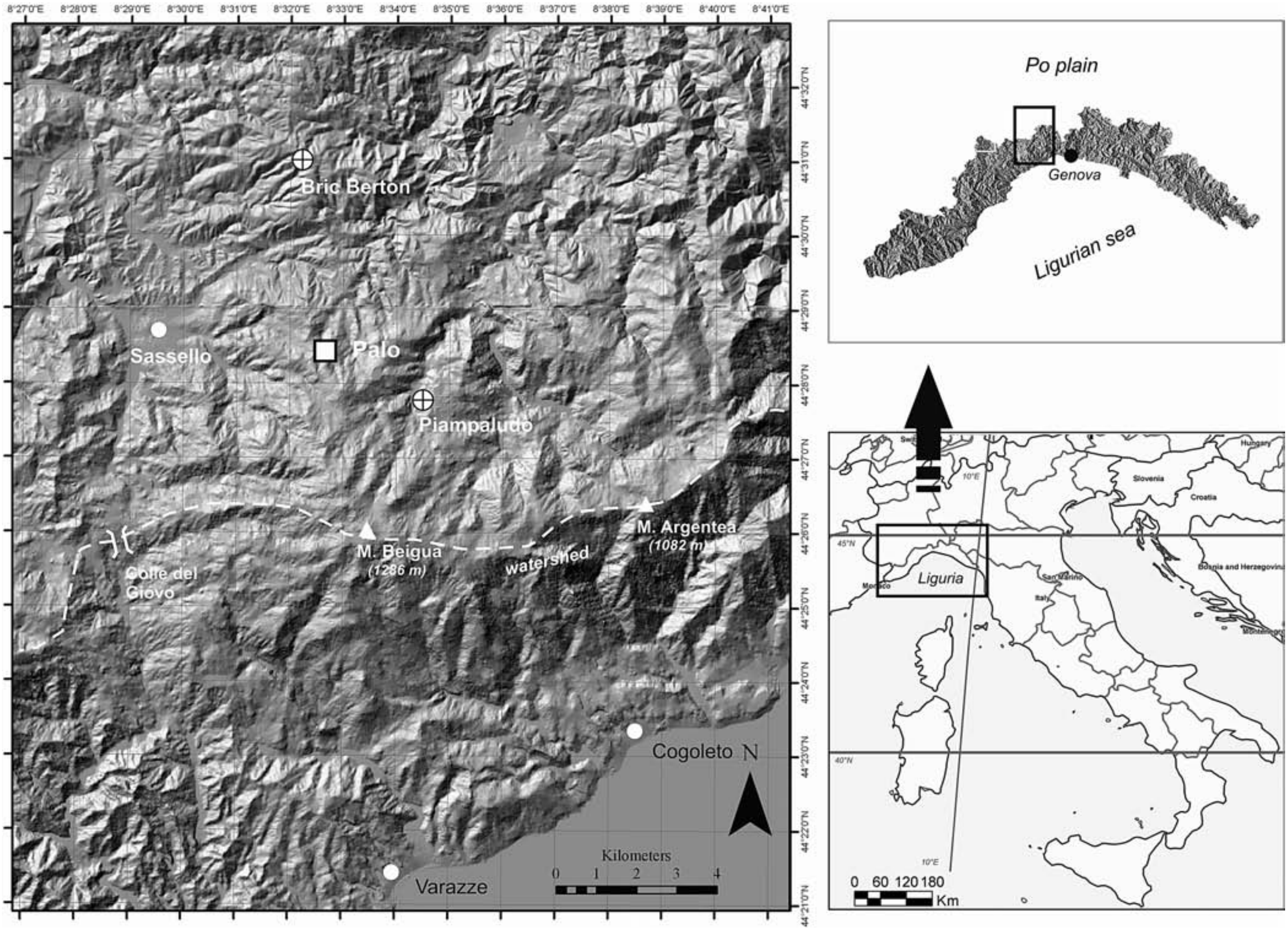

FIG. 1 - Location of the study area and the meteorological stations in the region of Liguria (north-western Italy). Hillshade map.

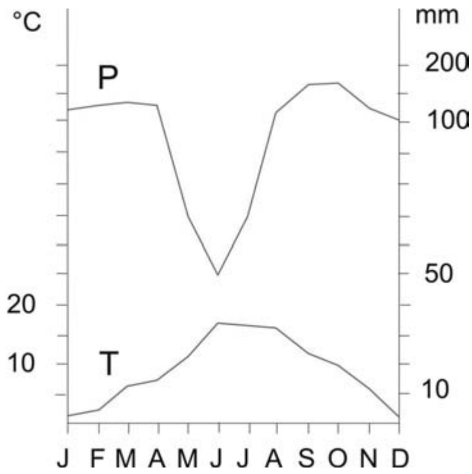

FIG. 2 - Ombrothermic diagram for the meteorological station of Piampaludo (800 m a.s.l.). T: temperature; P: precipitation.

ing to the Bagnouls and Gaussen (1957) climatic classification, the area is Ipomesaxeric-type with no dry season with air temperatures of the coldest month ranging from 0°C to 10°C. The present-day- pedoclimate (*sensu* USDA, 2003) is characterized by a udic soil moisture regime associated with a mesic soil temperature regime.

METHODS

Soil profiles were characterized by field description, bulk and undisturbed sampling, routine physical and chemical analyses, x-ray diffraction, micromorphology and heavy mineral analyses. Field description have been carried out according to the methods and terminology of ISSDS (2002) which is published in Italian language.

Soil samples were air dried, particle size distribution analysed by sieving for the fraction > 63 μ, while the composition of fine fraction (< 63 μ) was determined by the aerometer method (Gale & Hoare, 1991). Carbonate content was determined using a Dietrich Früling calcimeter.

Sampling for micromorphological analysis was performed using Kubiëna Boxes; soil thin sections were taken by technicians of «Servizi per la Geologia», Piombino, (LI) Italy. Thin sections were described using a polarizing microscope and an incident UV light microscope at magnifications ranging from 16 to 400 X, according to the terminology and methods of Stoops (2003); terms from Brewer (1976) were also employed in order to emphasize certain concepts or better interpret features.

For the mineralogical investigation of the clay fraction, a diffractometer equipped with Ni-filtered Cu radiation generated at 40 kW, 20mA (Philips Analytical PW3710) has been used; X-ray patterns were interpreted according to Brindley & Brown (1980). Clay samples for X-ray analysis were prepared according to the methods of Robert & Tessier (1974). Finer investigations were performed using different treatments: i.e. heating to 550°C and ethylene-glycol (EG) solvation.

Heavy minerals were separated (according to Gale & Hoare, 1991) by sieving from the fine sand fraction (63 μ - 125 μ), then the sands were treated with oxalic acid to remove iron coatings and with hydrochloric acid (18%) to remove carbonate coatings. Finally, the sands were floated using a natrium metawolframate [Na6O39W12 (H2O)] solution (2.9 g/cm^3 density). The separated heavy minerals were mounted on slides by means of Canada Balsam (refractive index n=1.55) and identified and counted, for a minimum of 250 grains, under the polarising microscope.

RESULTS

A – FIELD FEATURES

The described loess-paleosol sequence has been identified downslope of M.te Beigua, nearby Palo (SV) at about 790 m a.s.l. (geographic coordinates in WGS 84 system: 8°32’20’’ longitude, 44°28’34’’ latitude). The present day vegetation cover is mainly composed of chestnut and oak coppice woods. The profile chosen for detailed analyses was considered of particular significance because of the clear contact shown between the loess deposit and the deep rubificated paleosols (fig. 3); the macroscopic lack of evidence of reworking and colluviation typical of the other deposits along the same slope (fig. 4). The profile was located on a scarp bordering a flat crest, the latter gently inclined towards the valley floor (fig. 5).

The profile is comprised of following horizons (summarized in table 1):

A (0 - 15 cm): strong brown (7.5 YR 4/6), common medium weak red mottles (2.5 YR 4/2), silty clay loam, no rock fragments, weak fine granular structure, very friable, sticky and no-plastic, common fine pores, many fine and medium roots, clear smooth boundary.

B (15 - 25 cm): strong brown (7.5 YR 4/6), silty clay, very few and angular fine gravel, moderate medium subangular blocky structure, friable, sticky and plastic, few fine and medium pores, many fine and medium roots, gradual smooth boundary.

BC (25 - 45 cm): strong brown (7.5 YR 4/6), silty clay, common angular fine and medium gravel, moderate medium subangular blocky structure, firm, sticky and plastic, few fine and medium pores, many fine and medium roots, few charcoal fragments, clear wavy boundary.

2Bw (45 - 55 cm): dark yellowish brown (10YR 4/6), silty loam, no rock fragments, weak medium angular blocky structure, very friable, non-sticky and slightly plastic, few fine and medium pores, common fine roots, common charcoal fragments, gradual smooth boundary.

TABLE 1 - The main morphological, physical and chemical features.
Aggregation: AB: angular blocky; SB: subangular blocky; G: granular; m: medium; f: fine.
–, +, indicate increasing abundance of some soil features: absent, rare

Horizon	Depth (cm)	Colour	R.R.	Structure	Clay coatings	Particle size gravel	 sand	 silt	clay	% $CaCO_3$
A	0-15	7.5YR 4/6	3,75	fG	–	3,25	20,00	64,66	12,09	2,66
B	15-25	7.5YR 4/6	3,75	mSB	–	5,62	22,25	65,05	7,08	2,88
BC	25-45	7.5YR 4/6	3,75	mSB	–	5,01	19,08	65,62	10,29	1,76
2Bw	45-55	10YR 4/6	0	mAB	–	3,38	21,90	66,25	8,46	2,29
2BC	55-70	10YR 4/6	0	mAB	–	1,81	17,08	72,12	8,99	3,06
2Ct	70-85	7.5YR 4/6	3,75	fAB	–	9,75	24,39	56,09	9,77	3,77
3BtC	85-100	5YR 4/6	7,5	mAB	+	27,59	46,50	12,03	13,87	4,06
3BC	100 +	5YR 4/6	7,5	mAB	+	16,27	54,97	15,49	13,25	5,08

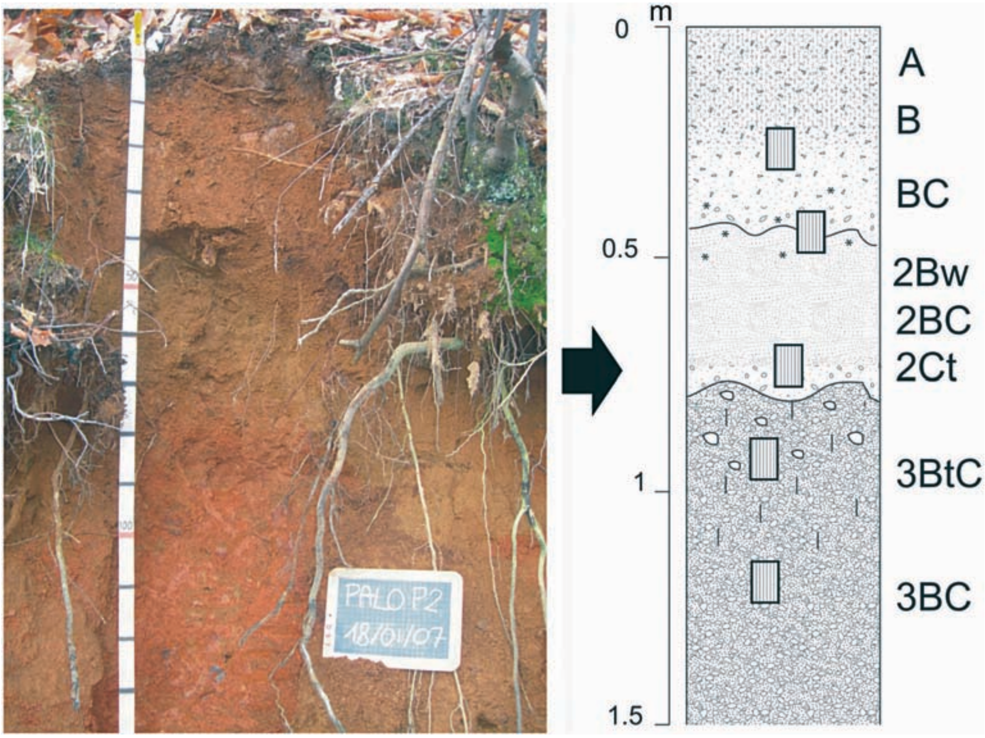

FIG. 3 - Soil profile reconstructed type-section and the position of the undisturbed samples (Kubiëna Boxes).

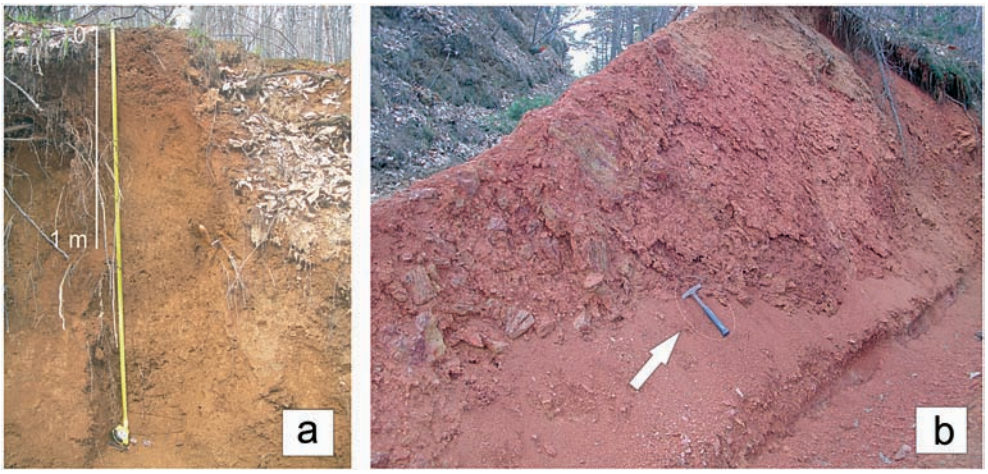

FIG. 4 - Photographs of the different deposits along the slope. a: reworked loess deposit on upper sideslope. Note the considerable thickness; b: thick saprolite outcrop (from calcschist) on middle sideslope.

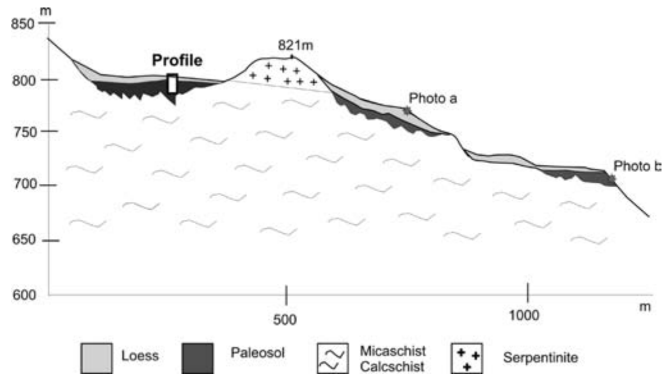

FIG. 5 - Schematic cross section of the study area with the location of the photographs (fig. 4). The thickness of the deposits is not in scale.

2BC (55 - 70 cm):	dark yellowish brown (10YR 4/6), silty loam, abundant subangular fine and medium gravel, weak medium angular blocky structure, friable, sticky and plastic, few fine and medium pores, common fine roots, few charcoal fragments, very few clay coatings, clear smooth boundary.
2Ct (70 - 85cm):	strong brown (7.5 YR 4/6), silty loam, abundant angular fine and medium gravel (weathered, calcschist), weak fine angular blocky structure, firm, sticky and slightly plastic, few fine and medium pores, few fine roots, very few clay coatings, clear wavy boundary.
3BtC (85 - 100cm):	yellowish red (5 YR 4/6), few fine mottles brownish yellow (10 YR 6/8), clay loam, common angular fine and medium gravel (strongly weathered, calcschist), moderate medium angular blocky structure, friable, sticky and plastic, few medium and frequent fine pores, very few fine roots, few clay coatings, diffuse smooth boundary.
3BC (100 cm +):	yellowish red (5 YR 4/6), few fine mottles brownish yellow (10 YR 6/8), clay loam, abundant angular fine and medium gravel (strongly weathered, calcschist), moderate medium angular blocky structure, friable, sticky and plastic, few medium and frequent fine pores, very few fine roots, few clay coatings, not exposed boundary.

The field description identified three different units: (1) The upper unit composed of A, B and BC brownish horizons with a scarce to common skeletal fraction and evidence of present biological activity. (2) An intermediate unit composed of 2Bw, 2BC, 2Ct yellowish horizons, with a sandy-silty loam to silty clay texture typical of loess soil (powdery when dry and friable and fluffy consistency). (3) The deeper unit composed of 3BtC, 3BC horizons was separated from the units one and two by a sharp erosional discontinuity; it was intensely rubificated and also includes abundant rock fragments strongly weathered in a claysh matrix.

Finally, the Redness Index (R.I.) calculated on the basis of the Munsell notation of matrix color (Torrent & *alii*, 1980) shows higher values for the deeper unit (R.I.: 7.5), than the upper ones, where only the superficial horizons have values different from zero (R.I.: 3.75).

These features indicate the sequence was composed of a buried relict soil (unit 3) overlain by at least two loess-like blankets (unit 1 and 2).

B – PARTICLE SIZE DATA

The coarse fraction (fig. 6) was particularly important only at the base of the sequence (3BC, 3BtC) where it is mainly composed by micaschist fragments. On the contrary, in the two upper units, it displayed only two small peaks, corresponding to the horizons BC and 2Ct. In this light, the particle size trends, shown in figure 6, correspond to the three identified units.

The fine fraction grain size analysis produced two different types of cumulative curves (fig. 7): (a) unsorted curves (3Bt, 3BtC), rich in sand and clay (median lower than phi 3.5), which have to be regarded as resulting from the weathering of the calcschist parent material; (b) moderately sorted curves (B, BC, 2Bw, 2BC, 2Ct), with weak sandy tail, clearly unimodal, whose median showed values of coarse and medium silt (between phi 5.4 and phi 5.7), and with a marked positive asymmetry. The soil horizons of the upper units showed a clay content ranging from 10% to 15% that increased with depth, probably due to accumulation of illuvial clay (see field and micromorpho-

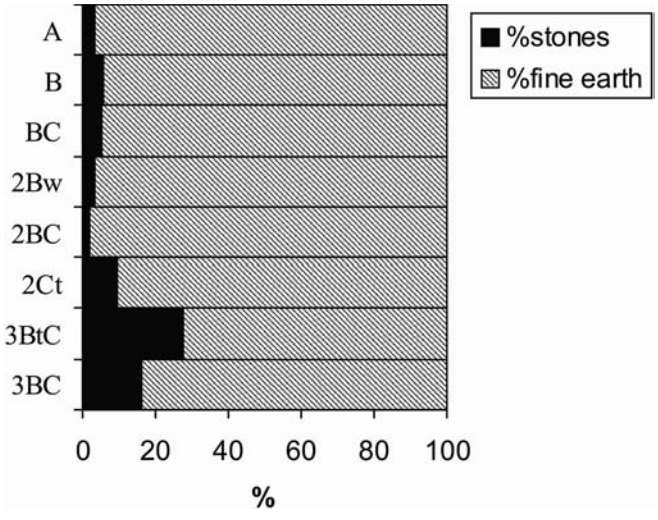

FIG. 6 - Distribution of stones with depth in the soil profile.

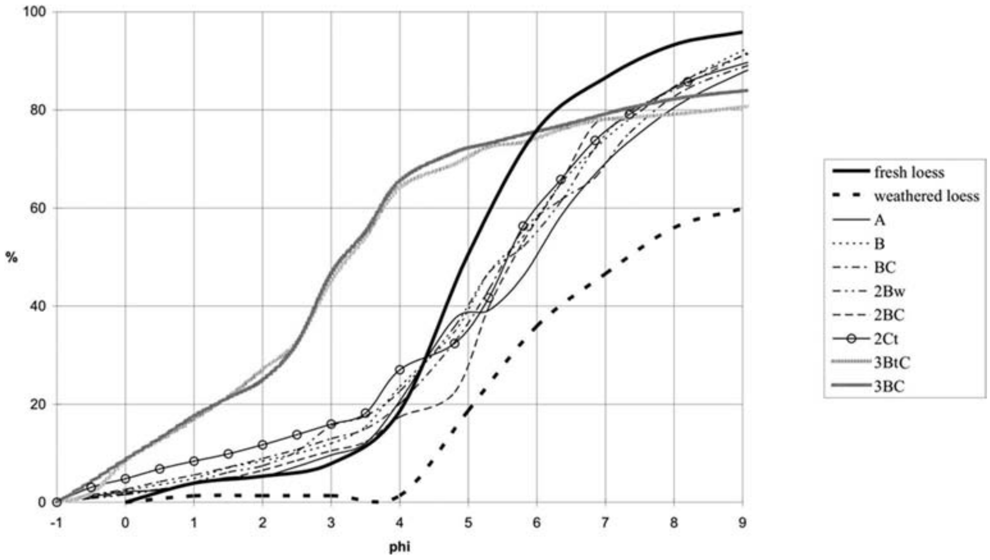

FIG. 7 - Grain size cumulative curves of the profile horizons in comparison with the fresh loess and weathered loess curves (modified from Cremaschi, 1987).

logical descriptions). These curves compared to the cumulative curves obtained for Po Plain aeolian loess (Cremaschi, 1990a, 1990b) showed trends comparable to fresh or slightly weathered loess (fig. 7), with an increase in sand probably due to the colluvial nature of the materials.

C – MINERALOGICAL DATA

The heavy mineral assemblage of the fine sandy fraction (tab. 2) was composed of both transparent and opaque minerals, although the opaque minerals dominate only in the deeper horizon (3BtC). Among the transparent minerals, amphiboles, pyroxenes, epidotes and zoisites were prevalent, together with the garnets they represent minerals mostly of metamorphic paragenesis in the deeper unit. Ultrastable minerals were also well represented and consisted of tourmaline (typical of metamorphic limestone) and titanium oxides such as rutile and, in few cases, titanite.

TABLE 2 - Heavy minerals assemblage of selected horizons (expressed in %)

	B	2Bw	2Ct	3BtC	3BC
Opaque	39	32	31	28	51
Trasparent	61	68	69	72	49
Amphibole	24.4	15.2	39.7	8.9	8,5
Glaucophane	1.1	0	2.8	0	0
Pyroxene	17.6	28.2	15.6	26.8	26.7
Micas	0.5	2.7	3.4	0.7	0
Staurotide	1.7	0.5	0	0	0
Chloritoid	0.5	0	0	0	1,9
Epidote	22.7	11.4	12.8	17	8,6
Garnet	2.3	2.7	8.3	2	0
Zoïsite	7.4	12.5	8.3	2	3,8
Rutile	1.1	3.2	3.4	0	0,9
Tourmaline	19.8	20.6	8.9	41.8	49,5
Spinelles	0.5	0	0	0	0
Sphene	0	0	2.2	0	0
W.I.	0,7	0,4	0,2	1,2	1,4

With regards to the heavy minerals assemblage of the whole profile we observed:

- Mica muscovite, glaucophane and staurolite largely prevailed in the upper unit deposits;
- Amphiboles and tourmaline showed opposite trends, the first increasing considerably in the upper units;
- The pyroxenes mainly consisted of augite series and increase in correspondence to the lower unit;
- The weathering index (Brewer 1976), reached its maximum in the lower unit of the sequence (3BtC, 3BC), decreased markedly in the overlying loess unit (2Bw, 2Ct) and then increases again in the upper loess unit (B).

The XRD analysis of the fine clay fraction (< 0.2 µm) taken from the intermediate and deeper units showed a mineralogy dominated by illite, kaolinite, chlorite and gibbsite. The X-ray diffraction patterns of the ethylene-glycol treated samples confirmed the absence of smectite minerals. The remaining small reflection at 14 Å, in 2BC and 2Ct samples after heating at 550°, suggests the presence of non-weathered trioctahedral chlorite. Another diagnostic reflection was observed in the studied horizons, with one peak typical of talc.

A semi-quantitative estimation of clay fraction mineral composition was made on the basis of relative height and area of the X-ray diffraction peaks of each mineral (Shaw & *alii*, 1971). The semi-quantitative mineralogical composition of the clay fraction is given in table 3. Illite predominantly occur in the loess horizons (2BC, 2Ct) and markedly decreases towards the bottom of the profile. Indeed the amount of gibbsite in the clay fraction increased with depth and reached a maximum in the 3BC horizon, where in contrast, the relative amount of kaolinite is reduced. Small amounts of quartz and talc were observed especially in the intermediate loess unit.

TABLE 3 - semi-quantitative mineralogical composition of the clay fraction of the selected horizons.
Ill: illite; Kln: kaolinite; Gbs: gibbsite; Chl: chlorite; Tlc: talco; Qtz: quartz. . , –, +, ++, +++ indicate increasing abundance of some minerals: absent, rare, frequent, common, abundant

Horizon	Minerals					
	Qtz	Tlc	Ill	Chl	Kln	Gbs
2BC	–	–	++	+++	++	+
2Ct	–	+	+	+++	++	++
3BtC	.	+	–	+++	++	++
3BC	.	.	–	+++	+	+++

D – Soil micromorphology

Soil thin section micromorphological descriptions are presented in appendix I and are summarized in table 4.

Going from the base to the top of the profile, the main micromorphological features of the three units are:

Unit 3: common limpid reddish clay coatings and dense infillings, locally fragmented and progressively assimilated into soil matrix (argilloturbation) (fig. 8 - microphotograph f). Reddish clay coatings and infillings sometimes occurred in surface pittings of the weathered mineral grains and can be covered by more recent thin yellowish clay coatings. The reddish fine fraction, mainly composed of clay, showed stipple-speckled b-fabric, locally undifferentiated, and a dotted limpidity due the presence of Fe oxides. The coarse sandy and fine gravel fraction was abundant (porphyric single-spaced c/f relative distribution) and it mainly consisted of angular quartz aggregates (metamorphic), with irregular linear and intermineral weathering, and mica flakes with parallel linear weathering. In some planar intramineral areas (mica) and alteromorph (Delvigne, 1998), we have identified a relative strong fluorescence (fig. 8 - microphotograph e), partially reduced by the presence of dark brown iron oxyhydroxides, due to the Al accumulation, which is present in a stage intermediate between Al ions and large hydroxipolymers (Van Vliet-Lanoë, 1980). Some large quartz grains (fig. 8 - micrograph g) with hematite-filled fissure, described as runiquartz by Eswaran & *alii* (1975) were observed, together with weathered grains (fig. 8 - microphotograph h) showed textures completely obliterated by neoformed minerals (alterorelic, Delvigne, 1998). Therefore, all the mineral grains showed dominant physical breaking patterns and a wide range of chemical weathering features. The weathering degree of primary minerals varied from moderate to very strong. The few planar voids produced a moderately developed and weakly separated primary angular blocky microstructure with intrapedal vughy microstructure. Finally, typic blackish disorthic Mn nodules strongly impregnated, with sharp boundaries, were observed.

Unit 2: the deeper part (2Ct) showed a primary subangular blocky microstructure with intrapedal porous material (fig. 8 - microphotograph a) with highly interconnected vughs (spongy secondary microstructure) and rounded vesicles that sometime were irregular to mammillated. In contrast the top of the unit (2Bw) was mainly characterized by a weakly developed primary subangular blocky microstructure with clear crumbs to granular intrapedal aggregates. In this horizon (2Bw), the voids often contained ellipsoidal excrements and the groundmass was rich in organic components (roots remnants, tissue residues and amorphous material), all characteristics indicative of strong biological

TABLE 4 - Main micromorphological properties.
P: primary microstructure; S: secondary microstructure; Qtz: quartz grains; M: mica flecks; A: amphibole grains; MRG: metamorphic rocks fragments. +, ++, +++, indicate increasing abundance of some soil features: scarce, frequent, abundant; f.g.: fine gravel size, c.s.: coarse sand size, m.s.: medium sand size, f.s.: fine sand size, s.s.: silt size

	Morphological unit and horizons					
	UNIT 1: A-B-BC		UNIT 2: 2Bw-2BC-2Ct		UNIT 3: 3BtC-3BC	
	B (15-25 cm)	BC (25-45 cm)	2Bw (45-55 cm)	2Ct (70-85 cm)	3BtC (85-100 cm)	3BC (100 cm +)
Microstructure	P:Crumby S:Granular	P: Angular blocky S: Crumby	P: Subangular blocky S: Granular	P: Subangular blocky S: Spongy/Vescicular	Angular blocky	Angular blocky
Groundmass						
- c/f limit, ratio and related distribution	10µ; 1/2 or 1/3; single/double space porphyric	10µ; 1/2 or 1/3; single/double space porphyric	10µ; 1/2 or 1/3; single/double space porphyric	10µ; 1/2 or 1/3; single/double space porphyric	10µ; 1/2; single space porphyric	10µ ratio: 1/2 or 1/3; single/double space porphyric
- mineral coarse material	Qtz::+++; (f.s.,s.s.); M: ++; (m.s., f.s., s.s.) A: + (f.s.,s.s.) MRG: + (c.s.,f.g.)	Qtz: +++; (f.s.,s.s.); M: ++; (m.s., f.s., s.s.) A: + (f.s.,s.s.) MRG: + (c.s.,f.g.)	Qtz: +++; (f.s.,s.s.) M: ++; (m.s., f.s.,s.s.) MRG: + (c.s.,f.g.)	Qtz: +++; (f.s.,s.s.) M: ++; (m.s., f.s., s.s.) MRG: + (c.s.,f.g.)	Qtz: +++; (f.s., s.s.) M: ++; (f.s., s.s.) MRG: +; (c.s., f.g.)	Qtz: +++; (f.s., s.s.) M: ++; (f.s., s.s.) MRG: +; (c.s., f.g.)
- micromass b-fabric	stipple-speckled	stipple-speckled	stipple-speckled	stipple-speckled	weakly speckled or undifferentiated	weakly speckled or undifferentiated
Pedofeatures	orthic Fe-nodules	orthic-typic Fe-nodules anorthic-nucleic Fe-nodules	orthic Fe-nodules passage features	Mn hypocoatings clay infillings	two generations of clay coatings, fragmented clay coatings	two generations of clay coatings, runiquartz, alteromorphs

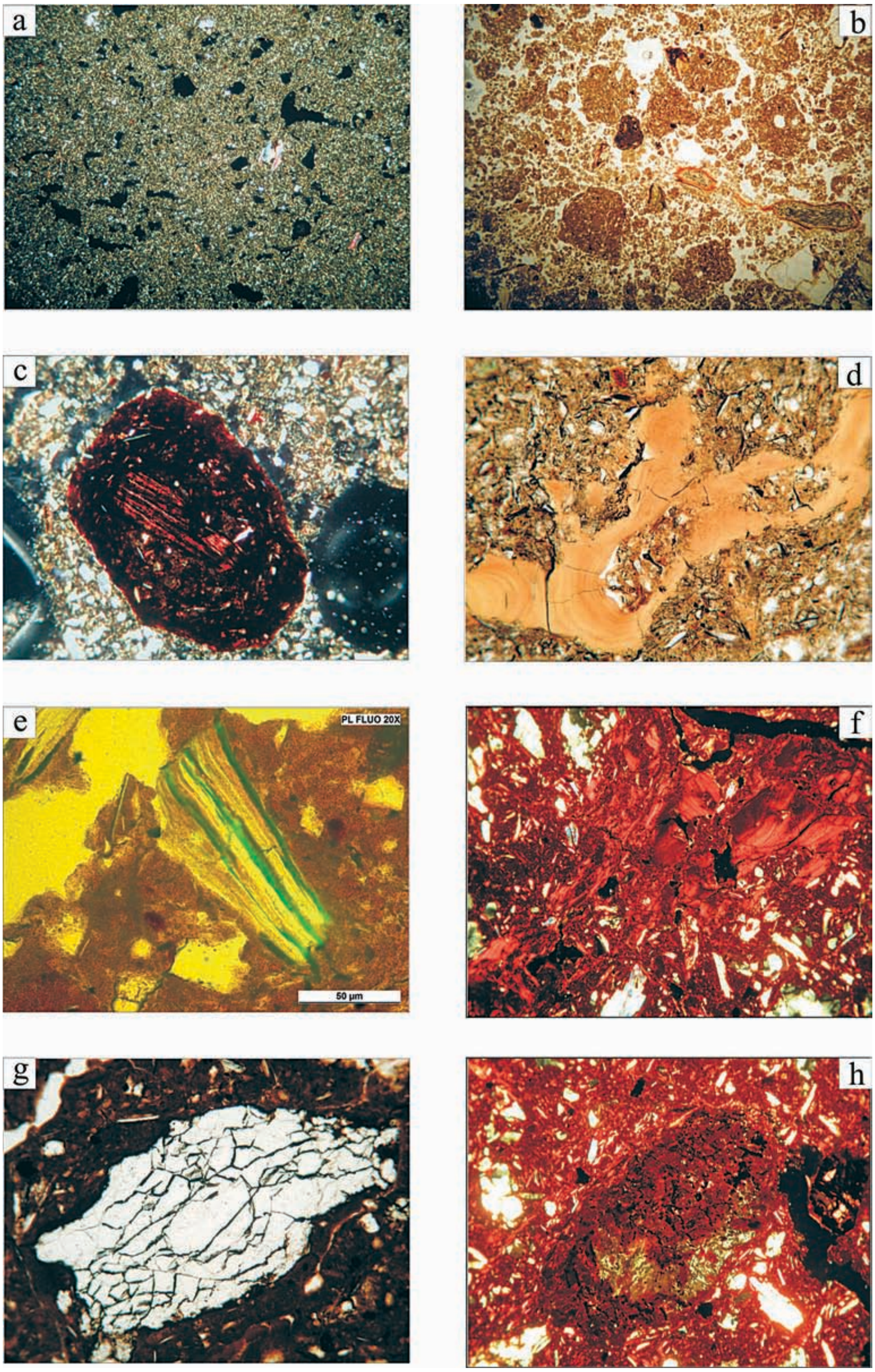

FIG. 8 - Microphotographs: (a) general view of groundmass. Note the spongy microstructure and the silty material (2Ct, 16x - XPL); (b) highly separated granular and crumb microstructure with fresh root residues (B-BC, 16x - PPL); (c) disorthic and nucleic Fe nodule built around muscovite alteromorph (*sensu* Delvigne, 1994) (BC/2Bw, 100x - XPL); (d) yellowish infilling of limpid illuvial clay in pore (2Ct, 100x - PPL); (e) Parallel linear alteration of muscovite grain. Note the strong fluorescence due to Al accumulation (3BtC, 20x - blue exciting filter, 420-490 nm); (f) fragmented reddish clay coatings partially assimilated in soil matrix (3BtC, 100x - XPL); (g) Splitting of metamorphic quartz grain with precipitation of Fe components in the cracks (runiquarts, *sensu* Eswaran & *alii*, 1975) (3BC, 100x - PPL); (f) weathered grain with development of secondary products (alterorelic, *sensu* Delvigne, 1998) (3BC, 100x - XPL).

activity (soil mesofauna, etc.). The coarse fraction of groundmass (fig. 8 - microphotograph a) was essentially composed of quartz grains (fine sand) and mica flakes (fine sand and silt) but also angular metamorphic rock grains that were strongly weathered (lithorelicts, *sensu* Brewer, 1976) close to the boundary with Unit 3. The yellowish clay micromass had a dotted limpidity and stipple-speckled b-fabric and it may contain very fine muscovite flakes partially weathered. Furthermore the 2Ct horizon showed a variety of illuvial pedofeatures: microlaminated yellowish clay coatings and infillings (fig. 8 - microphotograph d), with sharp extinction bands between cross polar, occur in pores. Other features comprise common Mn hypocoatings on planar voids (peds surface) indicating moderate hydromorphism.

Unit 1: the fabric of these horizons (B, BC) was comparable to the Unit 2 horizons, both show a groundmass constituted by yellowish clay micromass with a stipple-speckled b-fabric and the silt and fine sand fraction composed mainly by quartz grains and mica flakes, while the coarse sand to gravel fraction is largely composed of weathered metamorphic rock fragments (lithorelics) and some nucleic disorthic Fe nodules (fig. 8 - microphotograph c). Their abundance testifies the intensity of reworking and colluvionation processes. The microstructure mainly ranged from crumb to granular (fig. 8 - microphotograph b). The most striking pedofeature was the presence of brown orthic Fe-hydroxides nodules (200/500 µm) with clear boundaries and of Fe-hydroxides hypocoatings along the planes surface, indicating conditions of temporary hydromorphism. Moreover coarse charcoal fragments were present as results of repeated burns or anthropic activity

DISCUSSION

The described profile was the result of multiple weathering processes acting on different parent materials under a variety of environmental condition. Allochthonous material inputs also contributed to the profile. Field observations, grain size distribution, thin section description and, above all, heavy minerals assemblage point out the presence of at least two distinct parent materials: the deeper unit (3) developed from metamorphic bedrock (see for instance the augite trend, typical of serpentinite basic rocks, tab. 2) and the upper units (1-2) developed from allochthonous material (as discussed below).

Going into detail, the deeper unit was produced by a strong pedogenetic phase, involving the bedrock parent material and leading to the development of pedogenetic body showing characteristics like present day strongly weathered subtropical to tropical area soils (i.e. geochemical type, fersiallitic to ferrallitic weathering *sensu* Duchaufour, 1977), as for instance:

- The sand fraction consisting of least weatherable minerals (e.g. tourmaline).
- Fe-Al oxide rich groundmass together with the presence of kaolinite-type phyllosilicates.
- Presence of runiquartz (Eswaran & *alii*, 1975), probably inherited from a lateritic environment.
- Presence of coatings and infillings of limpid fine clay with some color layering.

The development of this kind of soil needs specific climatic and environmental conditions on stable, forest-covered landscapes which can be connected to past warm-temperate, humid periods with alternating rainy and dry seasons like the ones occurred in Italy before the glacial Pleistocene (Late Tertiary and Early Pleistocene) or during the Middle Pleistocene interglacials. Similar evidence is also found in Europe during Late Tertiary and Early Pleistocene (Chartres, 1980; Bronger & Heinkele, 1989) or Late Pleistocene (Semmel, 1989). These conditions, coupled with a well-drained soil environment, promote intense weathering of primary minerals, growing in the intensity with the time span of pedogenesis.

Kaolinite and gibbsite is commonly formed in warm, moist environments where intense chemical weathering can take place (Dixon & Weed, 1989); similar conditions are favourable to quartz weathering. Moreover, the higher accumulations of gibbsite can be related to the age of soil development and the specific relief conditions as well as the climatic effects of the elevation, that lead to a temperature decrease and a rainfall increase (Hermann & *alii*, 2007). The parent material is also important, with the presence of a mafic as well as felsic parent material (Schaefer & *alii*, 2008). A coarse grained saprolite and good internal drainage might favour the gibbsite compared to kaolinite formation (Driessen & *alii*, 2001).

The basal unit is mineralogically more mature than the overlaying deposits; its pedogenesis occurred before aeolian inputs in the area and, successively this unit was affected by degradation processes during cold climatic phases in which a protective vegetational cover was absent. In fact the illuviation features show evidence of destruction (fragmented clay coatings) even in the absence of expandable clay minerals (smectite) that can be explained by either differential movements in the soil or frost disturbance (Van Vliet-Lanoë, 1998). Different authors have also considered such a sequence in terms of climatic oscillation between glacials, the majority of these ‘paleoargillic’ features are usually regarded as markers of change from interglacial to cold stage environments (Simòn & *alii*, 2000) and they can be interpreted as resulting from the disruption of clay coatings and infillings formed in previous temperate climate and successive incorporation of the fragments into soil matrix as microscopic frost features (Fedoroff & *alii*, 1990; Catt, 1991; Van Vliet-Lanoe, 1998).

Multiple erosional events have taken place in the upper units, interspersed with the deposition of material developed from loess blankets. The loessic nature of the upper units was supported by field observations, grain size analyses and the finding of muscovite mica and minerals of metamorphic paragenesis (glaucophane, staurotide), that are typical characteristics of Italian loesses (Cremaschi, 1990a). Moreover, micromorphological observations confirmed that these deposits mainly consist of reworked material of aeolian origin: the grain size of this material ranges from silt to fine sand, indicating a provenance from nearby source area, and they are also highly porous. However, differences between the two upper units have been detected. First, there are differences between the superficial and the deeper horizons in heavy minerals: the first contained smaller amount of micas, and showed an increase in opaque minerals and a slight rise in weathering index. These distinctive attributes were due both to the rearrangement of the aeolian cover and remixing by colluvionation of slope detritus, and to the effects of recent pedogenesis. Moreover, the high amount of unweathered minerals of these upper units implies that weathering under the present day condition has been active for only a short time. This is supported by the presence of primary chlorite, a relatively unstable mineral that is easily destroyed during periods of intense precipitation (Dixon & Weed, 1989). Furthermore, the illite content of the horizons can be related to dust fall in the area (detrital origin), as already described in Italian loess (Cremaschi, 1990a). Gibbsite, according to Macìas Vasquez (1981), could be interpreted also as a product of initial stages of weathering of aluminosilicates in present day temperate, well drained and desaturated system, not only as a feature inherited from warm and humid climates.

Finally, weak to moderately-developed granular microstructures were also common in these horizons, and both field and experimental evidence demonstrates that such features form in periglacial or seasonally frozen climates (Van Vliet-Lanoë, 1998; Cremaschi, 1990b). But granular microstructures are not unique to periglacial environments. For example, in organic A horizons of soils of mid-latitude steppes and steppe-forest transitions, soil fauna also have an important role in creating granular microstructures and also the crumb microstructure can be related to loss of textural B morphology (from blocky to crumbly) due to pedoturbation. Moreover, well preserved vesicle voids with no evidence of material accumulation on their wall have been identified in the illuvial horizon of the Unit 2 (2Ct), they can be interpreted as gaseous bubbles formed annually during freezing of the soil (seasonal frost; Van Vliet-Lanoë & Coutard, 1984). The enrichment of coarse material must be a result of colluviation, even if in thin section sedimentary structures allowing a more precise identification of the colluvial or slope processes (solifluction), were not observed. Probably they were obliterated by strong bioturbation processes or splash-action. The latter is supported by the presence of large vughs, which can be the result of soil aggregates collapsing under splash effect and upon wetting (Mücher & *alii*, 1990).

Based on multiple pedogenetic phases, related to soil formation, erosion and deposition, identified by thin section examination and interpreted from sedimentological and mineralogical analyses, an evolutionary model can be created (fig. 9). The old pedogenetic phase that took place in a warm humid climate with bedrock weathering in situ was affected by a severe erosion phase. Comparison of pedoclimatic conditions typical of the Early Pleistocene with those occurring later in Pleistocene, characterized by climates of a more Mediterranean type and frequently alternating with glacial periods, leads to the conclusion that somewhere in the Early Pleistocene (probably end of the Early Pleistocene), a break in the paleoenviromental evolution occurred. The following phases were characterized by the deposition of loess alternating with erosion and redeposition of sediments, and weakly developed pedogenesis of the surface soil.

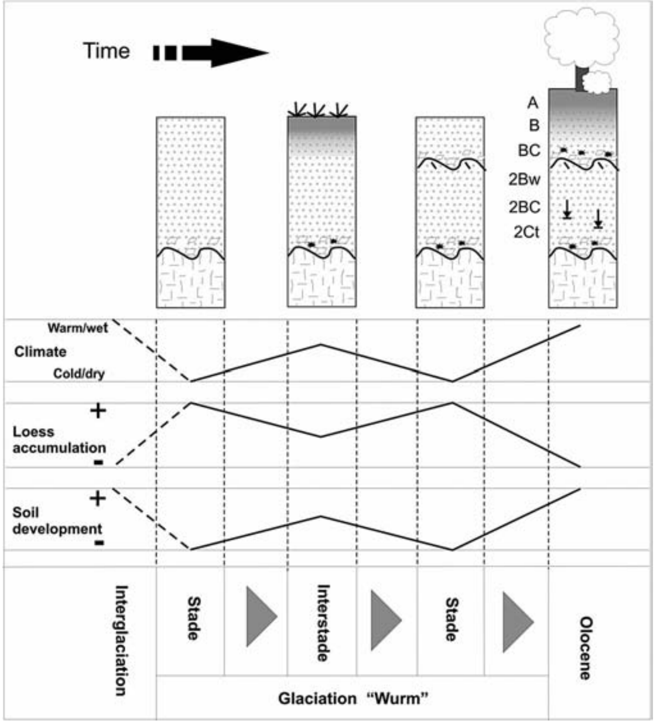

Fig. 9 - The interpretation model regarding the landscape evolution and the pedosedimentary events. * = hydromorphic features; **,** = illuvial features; **\ =** charcoal fragments.

On the base of an archaeological finding of upper Palaeolithic artefacts (Mounsterian) discovered in the loess units, they have be attributed to the Upper Pleistocene (Pleniglacial/Last Glacial, OIS 2: Cremaschi, Pian Castagna, personal communication). In fact, European loess MARs (mass accumulation rates) during the last glacial period (OIS 2) are higher than almost all eolian MARs calculated for the world's oceans (Frechen & *alii*, 2003). That can be correlated with the probable enhancement of fluvio-glacial recycling of silt-rich material in Po Plain during the LGM.

Therefore, the first pedogenetic cycle began with extreme aridity phase given rise to dominant eolian processes and thick accumulation of loess. Probably the soil developed over a stepped pedogenic episode with little chemical weathering and water logging during an interstadial. The occurrence of the traces of frost activity (rounded aggregates and vesicles), even if considerably affected by biological activity, besides indicating peaks of severe climate, so much so as to freeze the soil, is evidence of a certain degree of wetness in this environmental.

A second cycle probably started from the late Würm and continued during the Holocene. It was characterized by the partial erosion of the older soil and the colluviation of a reworked loess, also containing eroded material from the dismantling of the older surfaces (i.e. disorthic Fe-nodules and lithorelicts in the superficial layers), with development of a leached soil and development of hydromorphic features. Likely, the truncation of the Unit 2, and the deposition at its top of the reworked loess, then constituting the «surface soil», took place also thanks to human activity. The charcoal fragments observed between Units 1 and 2 indicate forest fires that can give rise to slope erosion processes. Indeed, the phase of clay illuviation (yellowish clay coatings) took place during a transitional period (e.g. Boreal), as already observed by Van Vliet-Lanoë (1990), who suggested that illuvial clay coatings in many argillic soils at the current land surface in western Europe are relict features that mainly accumulated under Late-glacial interstadial. This illuvial phase extend down into superficial horizons of Unit 3, where the yellowish coatings are superimposed upon the reddish clay coatings. This deposit is subjected to present day pedogenesis and it is affected by the biochemical brunification process (Duchaufour, 1977) leading to the organic matter oxidization and the $CaCO_3$ leaching. Each loess colluviation/solifluction phase has to be connected to a rhexistasy period, in which the protective vegetative cover is reduced or eliminated and rainfall efficiency is higher, inducing erosion and accumulation phenomena. The rhexistasy periods are separated by biostasy phases when climatic conditions are favourable to the development of a vegetal cover that protects the soil from physical erosion and in which pedogenesis can play a major role, leading to the chemical weathering of the parent material and the intensifying eluviation and illuviation phenomena. In the present study case the biostasy periods appear to be favourable both to geochemical and to biochemical pedogenesis (Duchaufour, 1977).

CONCLUSIONS

Pedogenesis of the Palo profile showed characteristics induced by multiple genetic phases. A strong pedogenetic phase is recorded in the deepest unit, leading to the development of a fersiallitic to ferrallitic paleosol (Duchaufour, 1977). A break in the pedogenesis, induced by a climatic deterioration, gives rise to the erosion of the profile and to sedimentation of new pedogenetic material, developed from loess blankets. At least two phases of deposition took place, over a significant time interval, during which less intense pedogenetic phases were recorded (i.e. weak translocation of clay, hydromorphic processes).

This study case emphasises the importance of using soils and paleosols as a tool in the palaeoenvironmental reconstructions of the recent past. The study has shown that many loess units are themselves the product of post or syndepositional reworking of wind-blown dust, supporting the findings of previous studies (Kemp, 2001). Different transport mechanisms (rain-splash) and cryopedogenic processes have been recognized from diagnostic macro- and micromorphological structures and fabrics. In this light, the described loess-paleosol sequence testifies to long-term fluctuating environmental conditions with phases of soil erosion after dry dust fallout, clearly separated by warm and wet phases of pedogenesis. This situation, described along the slopes of the Beigua Massif is to some extent comparable to those described for the same time span at the Alpine and Apennine fringe by Cremaschi (1987). Moreover, the significance of present work on the Palo's loess-paleosol sequence is relevant because it extends the North Italian aeolian sedimententation basin between the Alps and the Mediterranean region (Cremaschi, 1990a, 1990b) toward the Ligurian Alps, where this evidences weren't yet described because of their reworked nature: this work represents one of the first studies concerning Quaternary climatic evolution of this Alpine sector.

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APPENDIX

Profile: Palo P2 Horizon: **B** Thin section: palo P2 B-BC Size: medium

Abbreviations - f.g.: fine gravel size, c.s.: coarse sand size, m.s.: medium sand size, f.s.: fine sand size, s.s.: silt size.

Microstructure e porosity - Weakly developed crumb (c.s) to moderately developed granular (m.s., f.s.) microstructure, with compound packing voids between unaccomadating aggregates. Intrapedal vughs (f.s.; ± 2%) and channels (m.s., f.s.; ± 1%).

Groundmass - c/f $_{10\mu}$ ratio: 1/2 or 1/3; c/f related distribution pattern: single/double space porphyric.

Coarse material: dominant subangular quartz grains (f.s., s.s.); frequent muscovites flakes (m.s., f.s., s.s.); few angular metamorphic rock grains (c.s., f.g.) with intermineral and pellicular weathering; (lithorelicts), few prismatic grains of amphibole, few angular charcoal fragments (f.g.) and few root sections.

Micromass: yellowish brown, speckled and dotted clay with black, localized spots due to Fe oxihydrates or amorphous organic mater impregnations, with stipple-speckled b-fabric.

Pedofeatures. Very Few orthic Fe-nodules moderately impregnated (c.s. ± 1%).

Profile: Palo P2 Horizon: **BC** Thin section: palo P2 B-BC Size: medium

Abbreviations - f.g.: fine gravel size, c.s.: coarse sand size, m.s.: medium sand size, f.s.: fine sand size, s.s.: silt size.

Microstructure e porosity - primary highly separated and moderately developed angular blocky microstructure (1 cm) with partially accommodating planes, to secondary crumbs (c.s.); intra e interpedal channels with smoothed walls (m.s., 3% of the ped), intrapedal vughs (f.s.; ± 2% of the ped).

Groundmass - c/f $_{10\mu}$ ratio: 1/2 or 1/3; c/f related distribution pattern: single/double space porphyric.

Coarse material - dominant subangular quartz grains (f.s., s.s.); frequent muscovites flakes (m.s., f.s., s.s.); few angular metamorphic rock grains (calcschist, c.s., f.g.) with intermineral and pellicular weathering (Lithorelicts), very few angular charcoal fragments (f.g.) and very few root sections (m.s., c.s., ± 2%).

Micromass: yellowish brown, speckled and dotted clay with black, localized spots due to Fe oxihydrates or amorphous organic mater impregnations with stipple-speckled b-fabric.

Pedofeatures - Few orthic and typic Fe-nodules moderately impregnated (m.s. ± 5%), very few anorthic nucleic Fe-nodule, built around muscovite fragments; pores infilled with ellipsoidal yellowish brown excrements (s.f., s.m., ± 1%).

Profile: Palo P2 Horizon: **2Bw** Thin section: palo P2 BC-2B Size: medium

Abbreviations - f.g.: fine gravel size, c.s.: coarse sand size, m.s.: medium sand size, f.s.: fine sand size, s.s.: silt size.

Microstructure e porosity – highly separated and weakly developed primary subangular blocky microstructure (1 cm - 5mm) with partially accommodating planes, secondary crumbs to granular microstructure (c.s.). Intra e interpedal channels with smoothed walls (m.s., 3% of the ped), intrapedal vughs (f.s.; ± 2% of the ped).

Groundmass - c/f $_{10\mu}$ ratio: 1/2 or 1/3; c/f related distribution pattern: single/double space porphyric.

Coarse material: dominant subangular quartz grains (f.s., s.s.); frequent muscovites flakes (m.s., f.s., s.s.); few angular metamorphic rock grains (c.s., f.g.) with intermineral and pellicular weathering; (Lithorelicts), few angular charcoal fragments (f.g.) and few root sections.

Micromass: yellowish brown, speckled and dotted clay with black, localized spots due to Fe oxihydrates or amorphous organic mater impregnations, with stipple-speckled b-fabric.

Pedofeatures. Very Few orthic Fe-nodules moderately impregnated (m.s. ± 1%). Passage features. Pores infilled with ellipsoidal yellowish brown excrements (s.f., s.m., ± 1%).

Profile: Palo P2 Horizon: **2Ct** Thin section: palo P2 2C Size: medium

Abbreviations - f.g.: fine gravel size, c.s.: coarse sand size, m.s.: medium sand size, f.s.: fine sand size, s.s.: silt size.

Microstructure e porosity - primary highly separated and moderately developed subangular blocky structure with partially accommodated peds (± 4 cm); weakly separated and developed secondary subangular blocky structure; vughy or spongy intrapedal microstructure; irregular channels (m.s., 2% of the ped) e mammilated vughs (f.s., s.s., ± 5% of the ped).

Groundmass - c/f $_{10\mu}$ ratio: 1/2 or 1/3; c/f related distribution pattern: double space to open space porphyric.

Coarse material: dominant subangular quartz grains (f.s., s.s.); frequent muscovites flakes (f.s., s.s.); few angular metamorphic rock grains (c.s., f.g.) with intermineral weathering; few reddish brown tissue residues (m.s., ± 3%).

Micromass: yellowish brown, speckled and dotted clay with black, localized spots due to Mn oxihydrates impregnatios with stipple-speckled b-fabric.

Pedofeatures - yellow limpid and laminated clay infillings (f.s., ± 1%) in the pores and thin laminated clay coatings with sharp extinction lines, in the transpedal channels (<1%); Very few simple intercalations of coarse clay; very few orthic and tipic Fe nodules (m.s.); Common impregnative Mn hypocoatings on planar voids (peds surface). Few rounded and subrounded lithorelicts (alteromorphs) totally replaced by secondary products (oxides). Channels infilled with ellipsoidal yellowish brown excrements (f.s.); passage features.

Profile: Palo P2 Horizon: **3BC** Thin section: palo P2 3BB Size: medium

Abbreviations – f.g.: fine gravel size, c.s.: corse sand size, m.s.: medium sand size, f.s.: fine sand size, s.s.: silt size.

Microstructure e porosity - moderately separated and strongly developed angular blocky microstructure (3-5 mm) with partially accommodating or unaccomodating planes (s.f.); intra e interpedal channels with irregular walls (c.s., m.s., 3% of the ped), intrapedal vughs (m.s., f.s.; ± 5% of the ped).

Groundmass - c/f $_{10\mu}$ ratio: 1/2 or 1/3; c/f related distribution pattern: single/double space porphyric.

Coarse material - angular metamorphic rock grains (from some cm to f.g., c.s., ± 50%) with intermineral, linear and pellicular weathering, the intermineral fissures and pores are partially infiled by secondary products (hematite, clay) or illuvial clay; angular quartz grains (f.s. e m.s., ± 20%) and mica flakes (f.s., m.s., s.s. ± 30%). Very few quartz grains (m.s., c.s.) with Fe oxides -filled fissures (runiquartz).

Micromass: reddish brown speckled mixture of clay and Fe-Al hydroxides with weakly speckled or undifferentiated b-fabric.

Pedofeatures - two distinct generations of clay coatings (m.s) and infillings; the first is red and limpid, locally fragmented and partially incorporated in groundmass with sometime isotropic appearance in XPL (due to Fe-Al hydroxide) (<1%), the second is orange and well laminated with sharp extinction lines (2%). Common orthic Fe-Al nodules moderately impregnated (m.s. ± 5%), pores infilled with ellipsoidal yellowish brown excrements (s.f., s.m., ± 1%).

Profile: Palo P2 Horizon: **3Bt** Thin section: palo P2 3BA Size: medium

Abbreviations - f.g.: fine gravel size, c.s.: coarse sand size, m.s.: medium sand size, f.s.: fine sand size, s.s.: silt size.

Microstructure e porosity - primary (peds ± 3 cm) and secondary (peds ± 5 mm) moderately separated and strongly developed angular blocky structure with partially accommodated peds and planes (s.m., s.f.); common smooth channels (m.s., f.s., 5% of the ped) and vughs (f.s.; ± 2% of the ped).

Groundmass - c/f $_{10\mu}$ ratio: 1/2; c/f related distribution pattern: single space porphyric.

Coarse material: angular metamorphic rock grains (from some cm to f.g., c.s., ± 30%) with intermineral, linear and pellicular weathering and secondary products in the pores; angular quartz grains (f.s. e m.s., ± 20%) and mica flakes (f.s., m.s., s.s. ± 30%). Polycrystalline rock grains (micaschist) are decomposed to single crystals as quartz, tourmaline, mica, feldspar.

Micromass: reddish brown speckled mixture of clay and Fe-Al hydroxides with weakly speckled or undifferentiated b-fabric.

Pedofeatures – two distinct generations of clay coatings (m.s) and infillings, sometime juxtaposted; the first is red and limpid, locally fragmented and partially incorporated in groundmass with an isotropic appearance in XPL (due to Fe-Al hydroxide), the second is yellowish orange and well laminated with sharp extinction lines (2%). Channels infilled with ellipsoidal yellowish brown excrements (f.s. e m.s., ± 1%).