Ivano RELLINI (*), Luca TROMBINO (**,***), Pietro Mario ROSSI (**)
& Marco FIRPO (*)

FROST ACTIVITY AND ICE SEGREGATION IN A PALAEOSOL IN THE LIGURIAN ALPS (BEIGUA MASSIF, ITALY): EVIDENCE OF PAST PERMAFROST?

ABSTRACT: RELLINI I., TROMBINO L., ROSSI P.M. & FIRPO M., *Frost activity and ice segregation in a palaeosol of the Ligurian Alps (Beigua Massif, Italy): Evidence of past permafrost?* (IT ISSN 0391-9838, 2014).

This research is a part of a broader paleopedological investigation aimed at characterising and verifying the extent of the permafrost zone during the Last Glacial Maximum (LGM) in the Ligurian Alps. The paper presents the results of a micromorphological study of a palaeosol located at an elevation of 650 m a.s.l., near a blockstream deposit on Beigua Massif in northwestern Italy. We examined a profile exposing sandy sediments characterised by macroscopic structures that are clearly cryogenic in origin. These features were interpreted with their micromorphological characteristics, and we found that during the LGM, this unglaciated area of the Ligurian Alps was characterised by a periglacial environment with discontinuous permafrost even at low elevations.

KEY WORDS: Micromorphology, Periglacial processes, Last Glacial Maximum, Cryogenic structures, Ice lensing, Permafrost, Beigua Massif (Liguria, Italy).

RIASSUNTO: RELLINI I., TROMBINO L., ROSSI P.M. & FIRPO M., *Effetti del gelo e segregazione del ghiaccio in un paleosuolo nelle Alpi Liguri (Massiccio del Beigua, Italia). Evidenze di permafrost antico?* (IT ISSN 0391-9838, 2014).

Il presente lavoro è parte di un più ampio progetto paleopedologico finalizzato a verificare l'estensione del permafrost durante l'Ultimo Massimo Glaciale nelle Alpi Liguri. L'articolo presenta i risultati di un'indagine micromorfologica svolta su un paleosuolo ubicato a quota di 650 m s.l.m., molto vicino ad un blockstream, sul Massiccio del Beigua in Italia

nord-occidentale. È stato esaminato e descritto un profilo impostato su sedimenti sabbiosi e caratterizzato da evidenti macrostrutture criogeniche. Queste strutture, anche alla luce delle loro caratteristiche micromorfologiche hanno permesso di ipotizzare che, durante l'Ultimo Massimo Glaciale, quest'area delle Alpi Liguri non modellata dall'azione dei ghiacciai, era caratterizzata da un ambiente periglaciale, con presenza di permafrost discontinuo anche a bassa quota.

TERMINI CHIAVE: Micromorfologia, Periglaciale, Ultimo Massimo Glaciale, Strutture criogeniche, ice-lencing, Permafrost, Beigua Massif (Liguria).

INTRODUCTION

The term «past permafrost» refers to permafrost (presumably of the Pleistocene age) that does not exist today (French, 2008). Knowledge of the extent of the past permafrost in northern Italy during the Last Glacial Maximum (LGM) is poor. Existing palaeoclimatic reconstructions are uncertain and speculative. The first reconstruction based on selected pollen, charcoal, and macrofossils suggested that spruce forests occasionally covered this area during the Eemian Interglacial (Riss-Würm Interglacial in Alpine Europe) and the early Weichselian (Würm glacial stage in Alpine Europe). During the LGM, however, a maximum reduction phase of the spruce range began, and its extinction occurred across many districts (Ravazzi, 2002). In fact, Büdel (1959) argued that the area was located in a loess-tundra zone during the Weichselian.

The European distribution of past permafrost during the various stages of the LGM is relatively well known, and certain relict features (ice wedge casts, sand wedges, and pingo remnants) associated with permafrost are well preserved (French, 2008). Various authors (e.g., Velichko, 1982; Poser, 1948; Van Vliet-Lanoe, 1989; Vandenberghe & Pissart, 1993) performed extensive inventories of the known relict permafrost features in Europe during that

(*) *Dipartimento di Scienze della Terra, Ambiente e Vita (DISTAV), University of Genova, corso Europa 26, 16132 Genova* (rellini.ivano@dipteris.unige.it)

(**) *Istituto per la Dinamica dei Processi Ambientali, Consiglio Nazionale delle Ricerche, via Mario Bianco 9 - 20131 Milano.*

(***) *Dipartimento di Scienze della Terra, University of Milano, Via Mangiagalli 34 - 20133 Milano.*

period. Based on their maps, permafrost (continuous or discontinuous) clearly extended throughout northwest and central Europe (France, Germany, and Belgium) but did not extend south of the Alps or to the Mediterranean Sea, even during the LGM (i.e., the time of the largest permafrost extent). Kaiser (1960) hypothesised that permafrost aggradation affected the northern Italian plains during one of the earlier glacial periods. However, according to the micromorphological evidence found by Cremaschi & Van Vliet-Lanoë (1990), it is more likely that the permafrost never reached the Po plain and was present only as mountain or alpine permafrost (i.e., permafrost of an altitudinal character; Dobinski, 2011) at elevations higher than 800 m. Mountain permafrost is presently widespread in Italy. The lower limit of the discontinuous mountain permafrost is 2500-2800 m a.s.l. in the Alps and Apennines (Dramis & Kotarba, 1994; Ribolini & Fabre, 2006; Baroni & *alii*, 2004).

Most authors have used the criteria developed in the present-day Arctic to characterise fossil permafrost, although the present-day climatic requirements for permafrost cannot be directly applied to the past (i.e., the LGM, Van Vliet-Lanoë, 1989), and an adequate genetic correlation between periglacial forms of the Pleistocene and those of the present is not always evident (Vandenberghe & Pissart, 1993).

The investigations of LGM palaeo-permafrost and the reconstruction of the permafrost degradation in the Alps have generally relied on geomorphic-geological features such as relict rock glaciers (Dramis & *alii*, 2003; Seppi & *alii*, 2010) or blockstreams/blockfields (Firpo & *alii*, 2005; 2006). The elevation of the terminus of a rock glacier is generally regarded as an indicator of the lower limit of discontinuous permafrost, whereas blockfield and blockstream deposits indicate of permafrost conditions in mountain areas (Harris, 1994). In particular, blockstreams are the consequence of several processes acting in combination or succession (Wilson, 2013). Harris & *alii* (1998) found that the blocks in an active blockstream were derived by the frost shattering (macrogelivation) of rock outcrops. The downslope movement of active blocks has been attributed to the creeping and sliding of blocks in association with voidspace ice. Harris (1994) assessed the relationship between key climatic parameters and active blockstreams in China, Siberia, and North America. These authors showed that they are associated with cold, dry climates (mean annual air temperature, MAAT, range, –6°C to –20°C; mean annual precipitation, MAP, range, 50 mm to 500 mm) and occupy a discrete climatic zone that has limited overlap with zones characterised by active rock glaciers and active gelifluction landforms.

Firpo & *alii* (2006; 2005) recently surveyed several relict blockstreams associated with permafrost expansion during the LGM in the Beigua Massif (1,287 m a.s.l., Liguria, northwest Mediterranean). Only a few studies have characterised the palaeopedological record extending back to the LGM in this area. These investigations have reported the presence of loess-palaeosol sequences along the slopes of the Beigua Massif (Rellini & *alii*, 2009) and microcryo-

genic features in cave deposits along the west coast of Liguria (Rellini & *alii*, 2013). Conversely, numerous palaeopedological studies have been performed in southern Italy (e.g., Scarciglia & *alii*, 2003a; 2003b; Scarciglia & *alii*, 2005; Dimase, 2006). These studies have reported periglacial features (micro and macrogenic) in soils near the coast as well as in the mountain range between the Sila Massif and the west coast of Calabria, indicating the presence of periglacial environmental conditions in southern Italy during the LGM. Thus, cryogenic fabrics inherited from ice-lensing in sediments (platy fabric or ice wedge casts) are the most commonly recorded features in the soil, thereby allowing for the precise identification of the location of a former permafrost table (Van Vliet-Lanoë, 1976; 1985). Moreover, soil micromorphology is frequently used to infer cryogenic and pedogenetic processes occurring in frozen ground (Van Vliet-Lanoe, 1998; 2010).

The current paper focuses on the morphogenetic characterisation of the cryogenic structures of a buried palaeosol observed close to a blockstream downslope of Mt. Beigua (northwest Italy). This paper seeks to comprehensively describe the morphological, chemical, and physical properties of the buried soil; furthermore, it discusses the palaeopedological features of the soil to document various soil processes and better understand the extent of the permafrost zones in the Ligurian Alps during the LGM.

STUDY AREA

Geology and geomorphology

The Beigua Massif is located in the highlands of western Liguria, northwest Italy, bordering the Tyrrhenian Basin in the eastern Ligurian Alps (fig. 1). The study area contains several summits higher than 1000 m a.s.l., with the highest at 1287 m a.s.l. (Mt. Beigua). The geological basement in the area consists of the Voltri Group metaophiolite complex (Vanossi & *alii*, 1984), which is composed of serpentinites, metabasites, and metasediments (fig. 2). Oligocene marine conglomerates and sandstones belonging to the Tertiary Piedmontese Basin unconformably overlap a portion of the metaophiolite (Gelati & Gnaccolini, 1998).

From a geomorphological standpoint, the northern slope of the Beigua Massif, which slopes toward the Po River basin, is characterised by several wide valleys that contain abundant terraces.

The levels of these terraces, which were uplifted by tectonism, are at various elevations. However, the lack of data regarding these geomorphic markers and the Quaternary uplift rates in the Ligurian Alps (Ferraris & *alii*, 2012) encumbers their precise dating and characterisation.

Erosion due to running water is particularly enhanced along the steepest slopes of serpentinite rocks where the erosion exceeds the rate of soil formation, especially in areas affected by intense forest clearance (coppice). Well-developed soils one to several metres thick are preserved on protected planar landforms and slopes.
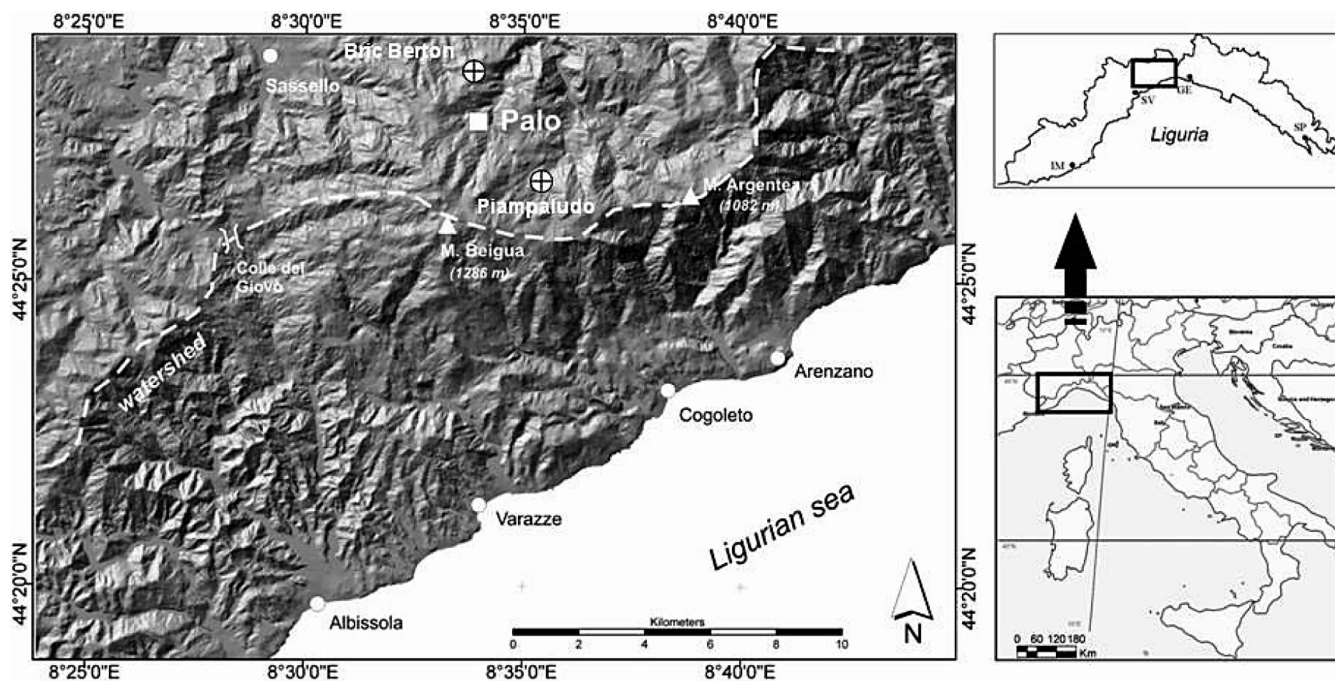
Fig. 1 - The study location (relief-shaded map) and the meteorological stations in the Liguria region (northwestern Italy).

Wind-blown silt deposits (loess) are widespread on flat crests or along gentle northeast-facing footslopes (fig. 2), which are the windward sides with higher rates of loess sedimentation (Rellini, 2012) where the intense reworking and accumulation of colluvial loess material was also observed (see fig. 3a, for the doubling of surface A horizons in soil development). The loess deposits are frequently affected by deep gullies produced by concentrated runoff. The highest portion of the slope is characterised by relict block accumulations (blockstreams, fig. 3b) several hundred metres long, which are mostly confined to valley axes (fig. 2; Firpo & *alii*, 2005).

In certain flat depressions north of Mt. Beigua Massif (e.g., Laione peat bog) where seasonal waterlogging occurs (which is often enhanced by snow/ice melting), hummocky fields of soil and grass are the dominant morphology.

Climate and soil

The topography, vertical relief (hilly or mountainous), and proximity to the sea of the Ligurian region primarily determine its climatic features. This area has a typically temperate marine climate; published data from Regione Piemonte (Bric Berton weather stations, 773 m a.s.l., fig. 1) indicate a mean annual precipitation ranging from 1000 mm/year to 1400 mm/year and mean annual temperatures ranging from 9.1°C to 10.2°C. An ombrothermic diagram calculated using the data from the weather station at the highest elevation in the area (Piampaludo, 800 m a.s.l., fig. 1) shows two distinct rainy seasons with maxima in April and October as well as a clear decrease in precipitation between July and August (the condition 2T>P does not oc-

cur; therefore, it is not possible to consider this period a true dry season) According to Bagnouls & Gaussen's (1957) climatic classification, the area is of an ipomesaxeric type with no dry season, and the air temperatures during the coldest month ranges from 0°C to 10°C. The present-day pedoclimate (sensu USDA, 2003) is characterised by a mesic, locally cryic soil temperature regime associated with an udic soil moisture regime (Costantini & *alii*, 2004). According to the WRB (2006), soils of this landscape are primarily of Humic, Skeletic Regosol, and Hypereutric or Dystric Cambisol types (Scopesi, 2009). Therefore, the pedoclimatic conditions favourable for cryosol formation are no longer present in this area, even if the topsoil frequently freezes during the coldest months (vertical ice needles are occasionally observed; fig. 4) and subsequently becomes hydrated and plastic due to the melting of ice during the spring.

METHODS

Field descriptions were developed in accordance with the methods and terminology of CRA-ABP (Costantini, 2007). Soil profile was characterised using physical and chemical analyses. Laboratory analyses were performed in compliance with the proposed Italian official methods (MiPAF, 1999). The soil samples were air dried; particle size distribution analysis was performed via wet sieving for the fraction >50 µm; the composition of the fine fraction (<50 µm) was determined using the pipette procedure after sample dispersion using sodium hexametaphosphate ([NaPO3]6); pH was measured using the potentiometric method in a 1:2.5 soil:water suspension; and the total car-

Legend:
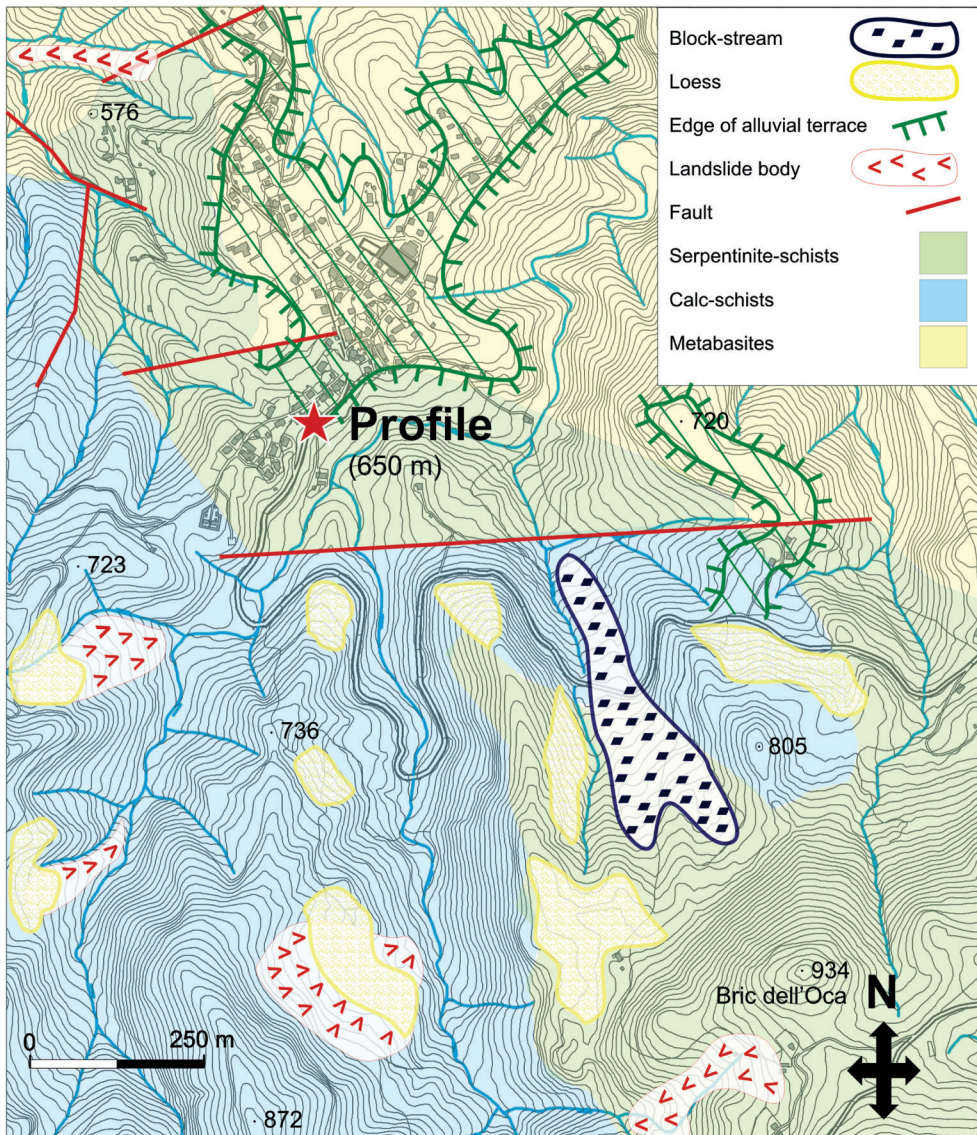- Block-stream
- Loess
- Edge of alluvial terrace
- Landslide body
- Fault
- Serpentinite-schists
- Calc-schists
- Metabasites

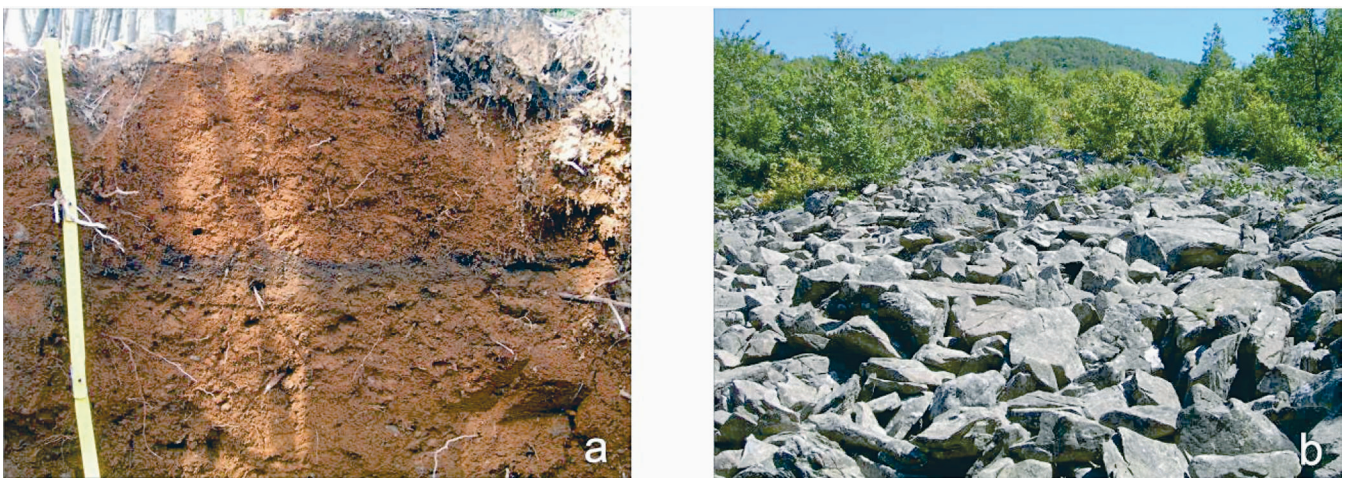Profile (650 m)

Bric dell'Oca

0   250 m

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FIG. 3 - a) colluvial loess deposit showing a buried A horizon; b) general view of the blockstream deposit near Palo.
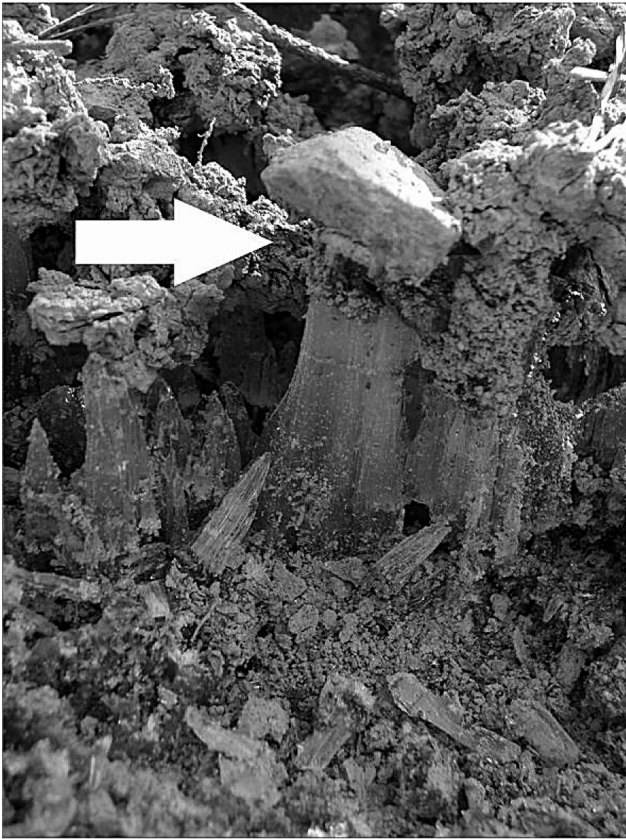
Fig. 4 - Vertical ice needles. Note that in some cases ice emerged from the soil and lifted the pebbles (white arrow).

bonate content was determined using a Dietrich Früling calcimeter. Total organic C was determined using an elemental analyser based on Dumas (1831). For the micromorphological study, undisturbed, oriented samples were taken from all described soil horizons (except the AC horizon) using Kubiena boxes; thin sections (100x60 mm) were prepared after impregnation with polystyrene and dilution with acetone in a vacuum (Benyarku & Stoops, 2005). The thin sections were examined using a polarising microscope. The thin sections were described using the terms and methods of Stoops (2003) and Bullock & *alii* (1985). The micromorphological features were interpreted in accordance with Stoops & *alii* (2010). In addition, the back-scattered images were examined, and an elemental analysis was performed on the areas of interest in the soil aggregates from the same micromorphological samples using a Vega3_ TESCAN scanning electron microscope (SEM) equipped with BSE-LVSTD detectors and an EDS Link operating system (Apollo XSDD with software TEAM EDS).

RESULTS

Site characteristics

A palaeosol profile was found downslope of Mt. Beigua on the north side of the range near Palo at approximately 650 m a.s.l. (WGS 84 44°29'10.72" N latitude, 8°32'52.91" E longitude). The present-day vegetation cover is primarily composed of continuous chestnut and oak coppice forests. The profile was observed near the edge of a dissected and relatively flat fluvial terrace surface (which was tentatively assigned to the Late Pleistocene) and a blockstream deposit (fig. 2).

In general, the profile consisted of a buried relict palaeosol developed on fluvial sediments (sand and gravel, Unit 1), overlain by a recent fine colluvial layer (including occasional coarse, angular rock fragments, Unit 2), which was composed of reworked material from the area upslope.

Soil morphology

The soil profile was composed of the following horizons (table 1, fig. 5):

– AC (0-20 cm): olive brown (2.5Y 4/4), no mottles, sandy loam, common subangular fine and medium gravel and scarce coarse gravel (weakly weathered, calcschist), moderate medium granular structure, soft, slightly sticky and non plastic, abundant fine pores, many fine and very few medium roots, common biological activity (coprolites), abrupt smooth boundary.

TABLE 1 - Some selected physical and chemical soil features. Structure: G = granular; P = platy; L = lenticular; M = massive; vc = very coarse; m = medium - CaCO3: total carbonate; O.C.: organic carbon content

Horizon	Depth (cm)	Colour	Struct	Particle size			pH (H2O)	% CaCO3	% O.C.
				Sand	Silt	Clay			
AC	0-20	2.5Y 4/4	Gm	48.6	46.3	5.1	7.2	2.9	2.9
2BCg1	20-50	10YR 4/6	Pvc	76.4	21.9	2.7	7.5	4.7	0.2
2BCg2	50-80	10YR 4/6	Lvc	84	13.3	2.7	7.7	6.9	0.2
2BCg3	80-100	10YR 4/6	Pvc	84.6	14	1.4	7.6	5.9	0.2
2C	100+	–	M	–	–	–	–	–	–

– 2BCg1 (20-50 cm): yellowish brown (10YR 5/4), common coarse distinct red and grey mottles (2.5YR 4/6 and 5Y 6/7), loamy sand, common rounded fine and medium gravel (moderately weathered, calcschist, and serpentinite), moderate coarse platy structure, hard, non sticky, and non plastic, scarce fine pores, scarce medium roots, few manganese coatings on coarse fraction, clear smooth boundary.

– 2BCg2 (50-80 cm): yellowish brown (10YR 5/4), many coarse distinct red and grey mottles (2.5YR 4/6 and 5Y 6/7), loamy sand, common rounded fine and medium gravel (moderately weathered, calcschist, and serpentinite), strong coarse lenticular structure, hard, non sticky, and non plastic, scarce fine pores, scarce medi-um roots, few manganese coatings on coarse fraction, clear smooth boundary.

– 2BCg3 (80-100 cm): yellowish brown (10YR 5/4), few fine distinct red and grey mottles (2.5YR 4/6 and 5Y 6/7), loamy sand, common rounded fine and medium gravel (moderately weathered, calcschist, and serpentinite), strong coarse platy structure, hard, non sticky, and non plastic, scarce fine pores, scarce medium roots, abundant manganese coatings on coarse fraction and ped faces, abrupt smooth boundary.

– 2C (100+ cm): stratified gravel and pebbles with massive structures, abundant manganese coatings on coarse fraction.

The field description identified two units: (1) an upper unit composed of a brownish AC horizon with characteristics of colluvial material and evidence of present biological activity; and (2) a deeper unit composed of 2BCg1, 2BCg2, 2BCg3, and 2C horizons separated from the upper unit by a sharp erosional discontinuity (fig. 5). This deeper unit exhibited a prominent soil structure of hard lenticular and platy aggregates whose sizes progressively increased with depth (fig. 6). The aggregate shapes in the surficial horizon (2BC1) were distinctly foliated and displayed interpedal fissures discretely open and clearly parallel to the ground surface (fig. 7). Bleached areas were distributed along the
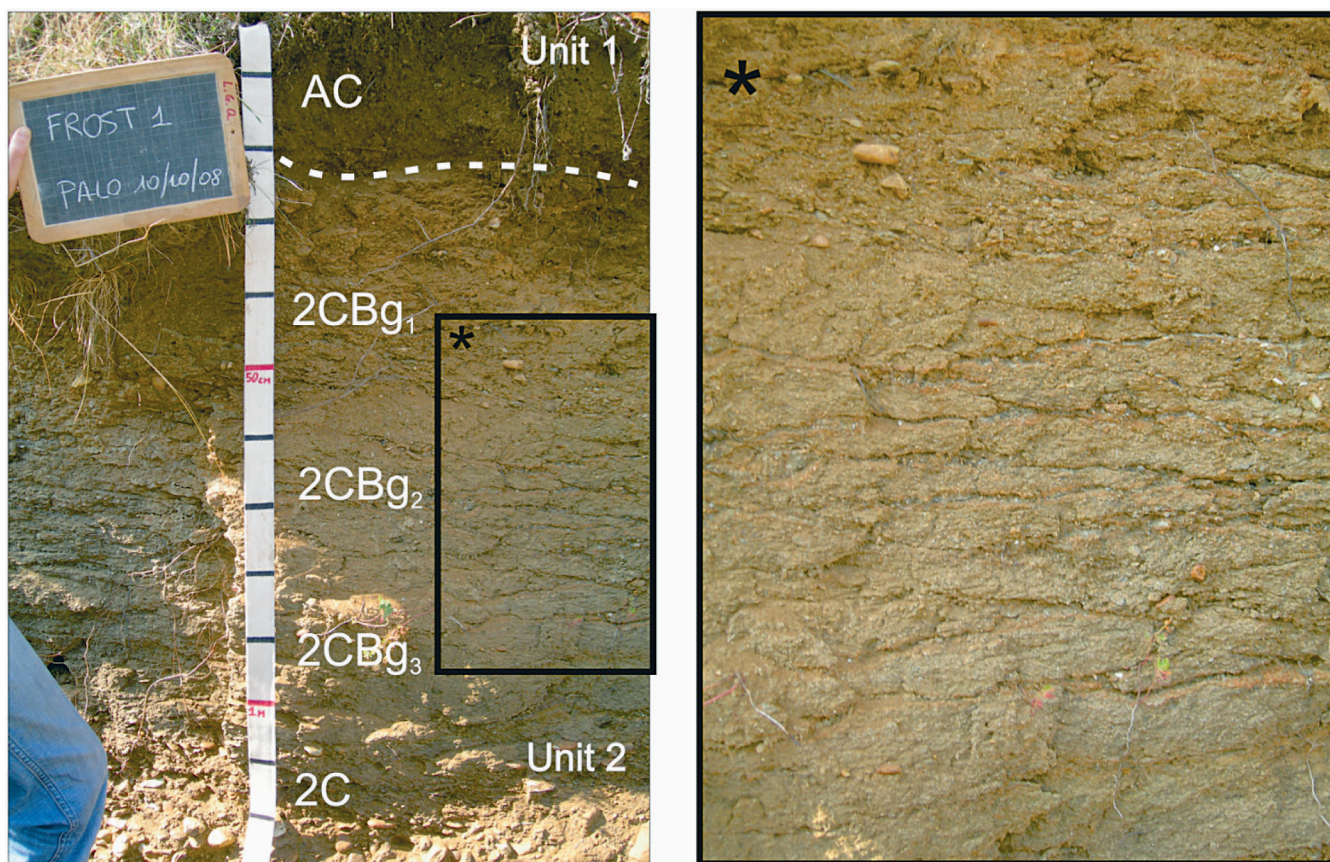

FIG. 5 - Soil profile (left) and magnification of the soil structures (right).

FIG. 6 - Lenticular aggregates showing bleached areas on their surfaces (2BCg2). For scale, the knife is 3 cm thick.

FIG. 7 - Foliated structure characterised by fissures discretely open and clearly parallel to the ground surface. Vertical orientation of the tabular stones are described in this horizon (white arrow, 2BCg1). For scale, the knife is 3 cm thick.

fissures between the aggregates (fig. 6), with evident disjoined manganese accumulations in the deeper coarse, massive sediments (i.e., pebbles and C horizon).

Primary physical and chemical properties

The primary physical and chemical characteristics of the horizons are summarised in table 1.

Samples from the cryogenic horizons were subjected to immersion for two hours in water to determine the persistence of aggregates. The slaking of aggregates in water is the most common field test to identify the effect of frost on ag-

gregate stability (Hodgson, 1976). The aggregate stability analyses indicated that the consolidation of the samples was primarily due to the closely packed arrangement of the particles, whereas the inorganic cements most likely played a secondary role, although certain aggregates persisted.

The results of the particle-size analysis matched the field description. Stones (Ø>2 mm) were scarce in the AC of the profile, whereas increases in the sand and stones percentages were observed with depth, which reflect the presence of old fluvial gravel layers. The pH (H2O) values were alkaline, increasing from 7.2 at the surface to 7.6 at the bottom of the profile. All horizons exhibited incomplete carbonate leaching, whereas organic matter was concentrated only along the surface horizon, where leaves and twigs accumulated and were subsequently mixed with the soil via biological activity

Soil micromorphology and SEM observations

The micromorphological observations of individual aggregates indicated both a massive microstructure characterised by a lack of separated peds and a compact/pellicular grain microstructure (*sensu* Bullock & *alii,* 1985; figs. 8a and 8b) with interpedal porosity due to only a few thin planar voids of zigzag or circular shape (figs. 8c and 8d), rare vugs, and small channels.

With regard to the groundmass in the horizons, the coarse:fine (c/f) ratio-related distribution pattern was close porphyric. The c/f at 10 μm was 6:1. The coarse fraction of the groundmass was essentially composed of polycrystalline quartz, mica schist, and serpentinite fragments as well as quartz, muscovite olivine, amphibole, and pyroxene grains in order of decreasing abundance. The compositions of the horizons were similar. Polycrystalline quartz comprised the largest grains (medium/coarse sand), which were subangular to subrounded, whereas mica schist grains exhibited more angular and elongated (tabular) shapes. All mineral grains exhibited predominantly physical breaking patterns and clear chemical weathering features (linear and pellicular alteration; figs. 8e and 8f), and only the most weatherable mineral grains (e.g., olivine) were completely replaced by secondary minerals (fig. 9i). Vertical and oblique orientations of coarse tabular grains were observed in the groundmass (figs. 9g and 9h), whereas certain elongated grains were distributed parallel to the planar void surfaces (fig. 9n).

The fine fraction was rare and displayed an undifferentiated b-fabric and a brownish colour (due to amorphous Fe gels and hydroxides) or a speckled/granostriated b-fabric, due to the presence of clay domains, slightly prolate or oriented parallel to the surfaces of the grains, and characterised by interference colours comparable to 2:1 clay (Stoops, 2003; fig. 9l). A minor component of organic material (i.e., root remnants) was present in the primary planar voids.

Among the textural pedofeatures, no particular layering was observed, and particle translocation was only represented by the limpid, thin clay coatings in planes and rare small channels (figs. 9m and 9n). The clay coatings generally exhibited a sharp extinction band with few signs
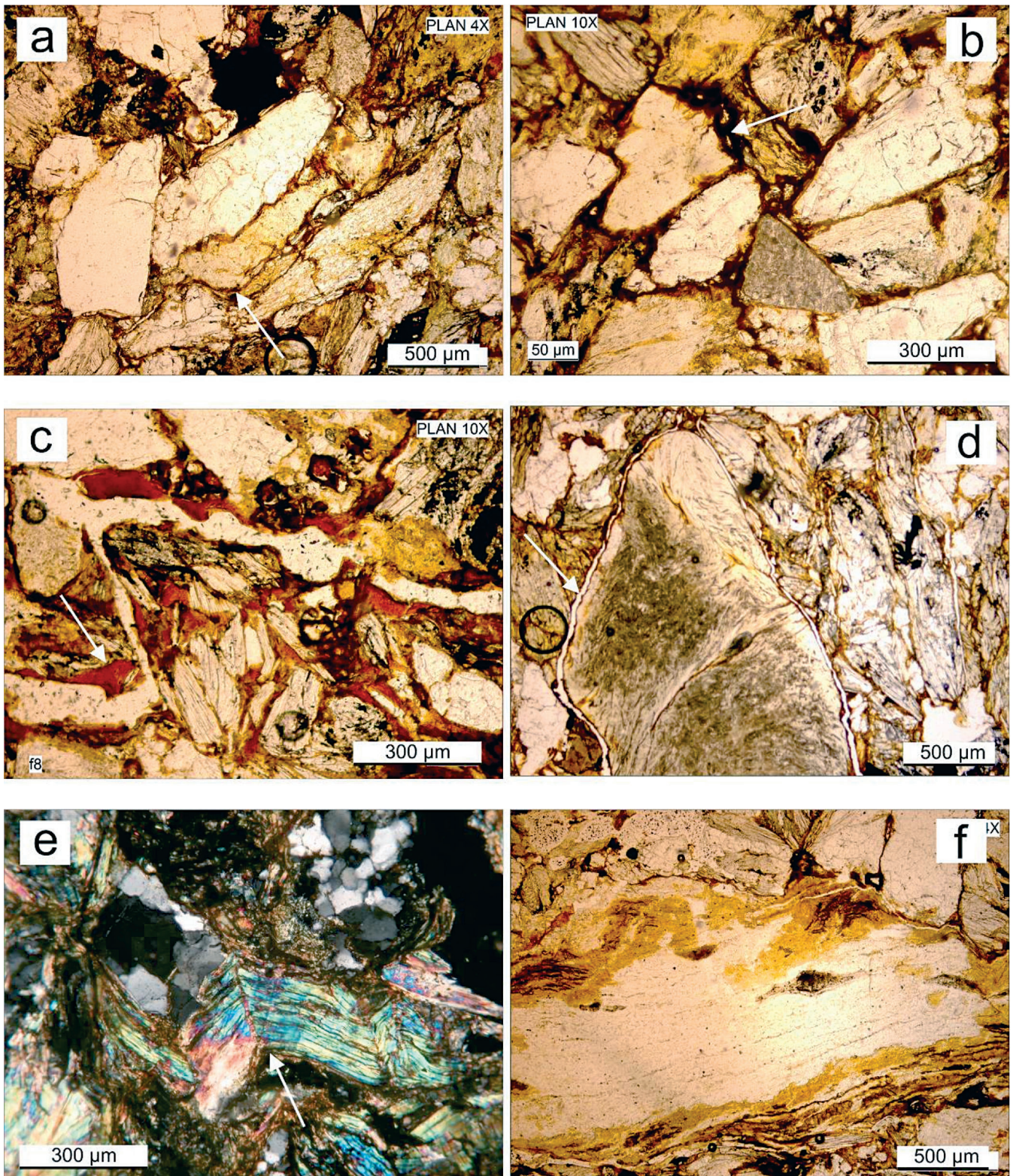
FIG. 8 - Photomicrographs: (a) a general view of the groundmass showing a massive microstructure and the sandy grain size (2BCg3, PPL); (b) Fe-hydroxide coatings in the voids between mineral grains (white arrow, 2BCg3, PPL); (c) zigzag planar void with clay coatings, (white arrow, 2BCg3, PPL); (d) circular voids around a coarse grain (white arrow, 2BCg2, PPL); (e) fragmented and deformed mica flake showing parallel linear weathering (2BCg2, XPL); (f) olivine grain showing pellicular weathering to a yellowish smectitic clay (2BCg2, PPL).
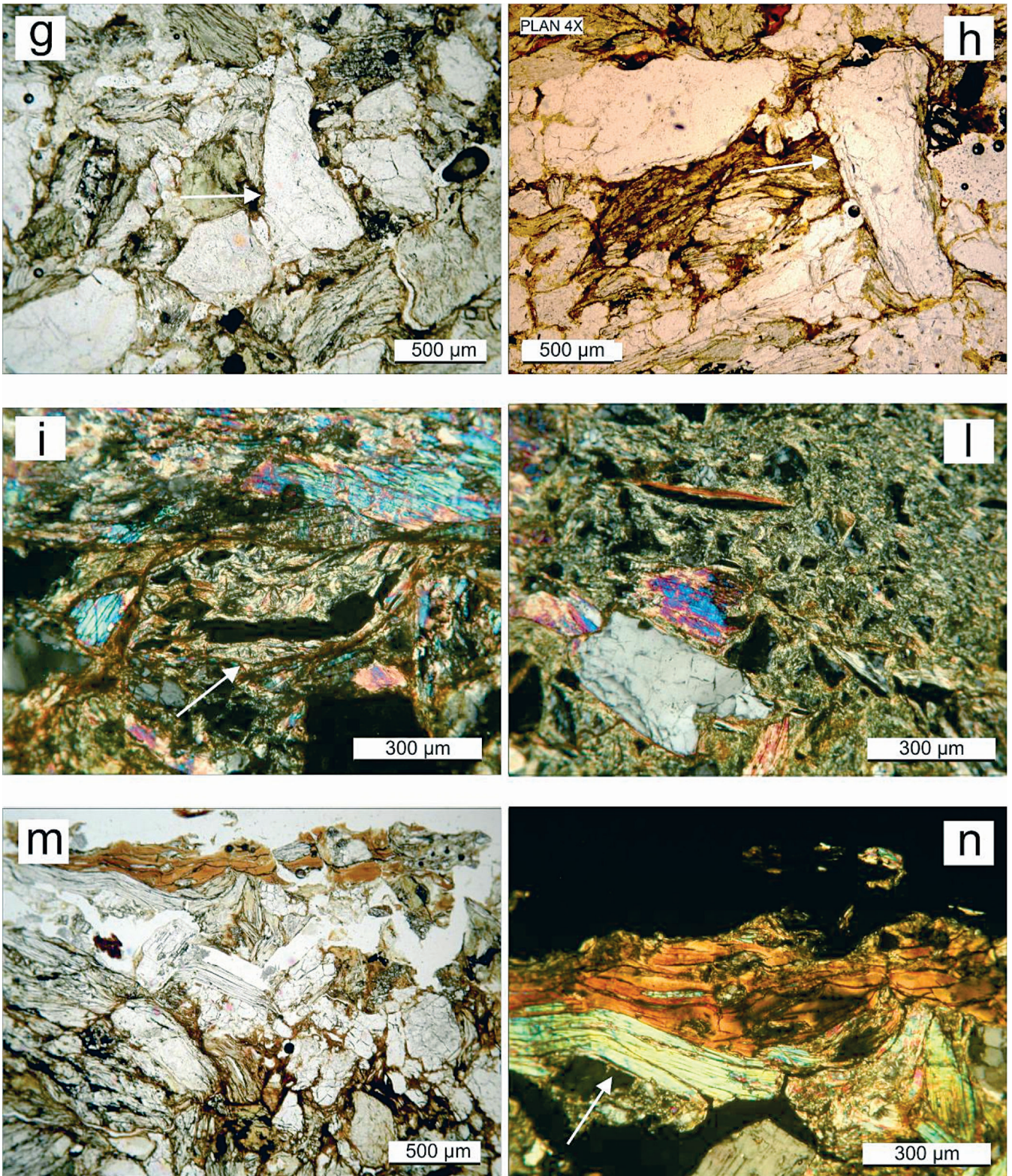
FIG. 9 - Photomicrographs: (g) and (h) vertical orientation of elongated grains (white arrow, 2BCg2, PPL); (i) olivine grain completely weathered to greenish smectitic clay (white arrow, 2BCg3, XPL); (l) micromass primarily consisting of yellowish grey clay showing granostriated and stipple-speckled b-fabric (2BCg2, XPL); (m) Fe-hydroxide quasi-coatings along the primary planar void (2BCg2, PPL); (n) limpid clay coating in plane. Note the tabular grain of muscovite (white arrow) showing a distribution parallel to the plane surface (2BCg2, XPL).

of deformation and fragmentation (fig. 9n). The amorphous pedogenic features consisted of local amorphous Fe-hydroxide coatings on mineral grains (fig. 8b). Redox depletion zones and Fe quasicoatings were present along all primary planes (fig. 9m).

SEM observations and microchemical determinations via energy-dispersive X-ray spectroscopy (EDS) in LVSTD/BSE mode were performed to more fully characterise the micromass observed under the optical microscope and better describe the primary minerals.

The results confirmed the diffuse presence of mica flakes and amphibole in the groundmass (fig. 10a). In particular, the grains were completely coated with clay minerals and iron oxides in many cases (fig. 10b). The morphology of certain grains remained visible, and the SEM images showed spaces between the grains (i.e., simple packing voids). Moreover, clay was also present within the micropores (i.e., small channels) related to biological activity (fig. 10a).

DISCUSSION

Evidence of cryogenic processes

The described profile was composed of a buried palaeosol (Unit 2) characterised by the presence of layered and lenticular structures, including foliation. These fea-
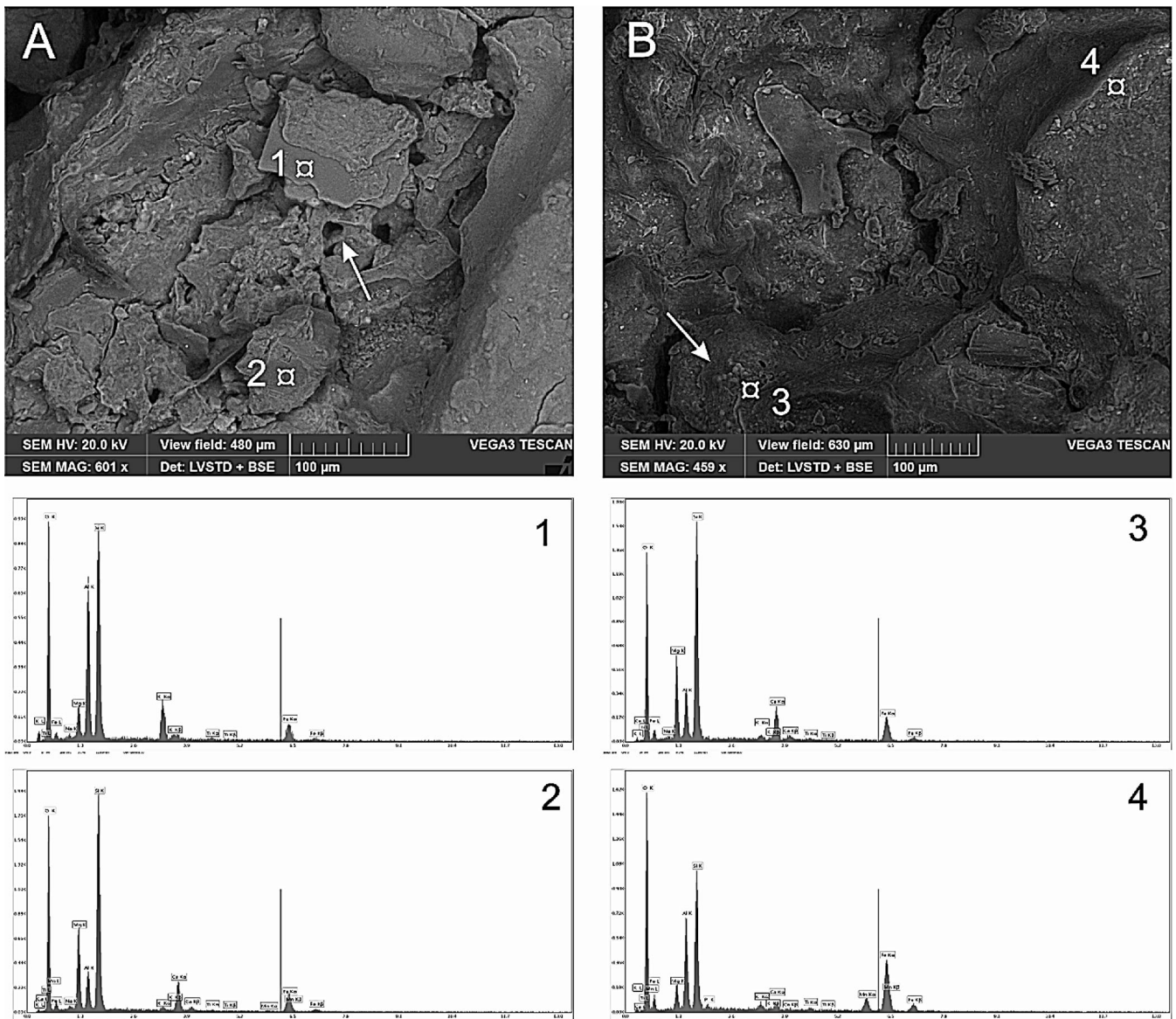

FIG. 10 - (A) An SEM image of groundmass: (1) flat, flaky muscovite crystals and (2) amphibole grain. Note that they both the crystals and grains are partially coated with clay material. The same coating is present in the small voids (white arrow). (B) An SEM image of the coating around the mineral grains with its EDS spectral images. The relative abundances of Si, O, Mg, and Al were attributed to a clay mineral phase (3). The more Fe-Mn-rich clay coating (4) was associated with Fe-oxide globular crystals (white arrow).

tures have typically been interpreted as structural patterns of ice segregation in the form of lenses or veins within fissures formed by desiccation (ice lensing; Van Vliet-Lanoë, 1976; Van Vliet-Lanoë & Langohr, 1981; French & Shur, 2010). As stated earlier, these structures are well developed in the lower sedimentary Unit 2, which was characterised by sandy materials: The morphology of the grains, the sedimentary structures (planar bedding), and grain size characteristics suggest a fluvial origin.

Usually, texture controls frost dynamics in the soil (Van Vliet-Lanoë, 1985), and the sandy soils for the their high permeability are considered non-frost susceptible; nonetheless, the presence of the mineral colloidal fraction in the micromass (e.g., 2:1 clay mineral) identified by the micromorphological observations might have promoted the formation of segregation ice (Popov, 1981), thereby increasing the water-retention capability of the soil. Moreover, the presence of oblique oriented rock fragments might have enhanced the development of frost-induced microstructures (Van Vliet-Lanoë, 1985).

Many field studies have indicated that this variety of cryostructures is diagnostic of permafrost formation (Van Vliet-Lanoë, 1976; 1985; Van Vliet-Lanoë & Langohr, 1981). In particular, these structures are usually associated with an ice-rich transition layer between the active layer and permafrost (French & Shur, 2010) where ice occurs as segregation lenses. Specifically, the lenses or veins of ice open parallel to and below the freezing front due to desiccation: Cryogenic suction induces water movement toward the freezing front, thereby resulting in a coarsening of cryogenic aggregates with depth along the contact with the permafrost table (Van Vliet-Lanoë, 1985). Moreover, the observed aggregate coarsening ends with an abrupt transition to a massive structure at the bottom of Unit 2 where abundant manganese coatings were also present on the coarse fraction due to waterlogging. These features might also be caused by the permafrost table.

In addition, the presence of a permafrost table and massive ice may explains the absence of well-preserved root remains and biological voids in the lower unit.

The results of the micromorphological analyses of thin sections from the profile confirm that the soil was affected at depth by ice lensing and permafrost. These lines of evidence include the following:

1. The massive microstructure due to the growth of successive ice lenses with compaction and decreases in internal porosity;

2. The reorientation of elongated coarse particles into a vertical position, resulting from the traction exerted by the growing ice lenses on rigid fragments in a frost-susceptible matrix (Pissart, 1969);

3. The reorientation of the particles along the planar voids (i.e., planes), resulting from the pressure exerted by growing ice lenses in the interpedal fissures;

4. The absence of sorting of soil materials; this is in strong contrast to seasonally frozen and thawed ground and, on the contrary, is characteristic of permafrost (Van Vliet-Lanoë & Langohr, 1981);

5. Zigzag and circular planes around the grains resulting from ultra-desiccation processes.

Moreover, micromorphological feature characteristics of the active layer (i.e., seasonal frozen ground) and the upper portion of permafrost (reported as lenticular and granular microfabric, sorted grain accumulation, vesicular voids, and silt cappings on coarse grains; Van Vliet-Lanoë, 1998) were not observed. The explanation for this absence might be the truncated palaeosol profile: the expected active portion might have been eroded away and replaced with the surficial sedimentary unit (i.e., the AC horizon).

Soil formation and environmental reconstruction

The soil development in the studied profile appears to be incipient and confined to organic matter accumulation, weak weathering, and moderate clay illuviation. The soils did not display distinct genetic horizons, either morphologically or chemically. Moreover, the absence of interglacial pedogenesis relict features (see Rellini & *alii*, 2007), the moderate degree of alteration, the abundance of weatherable minerals (e.g., amphibole and olivine), and the incomplete leaching of carbonate in the horizons demonstrates that these horizons were not subjected to a long period or intense degree of pedogenesis. Thus, these soil horizons likely developed after the LGM, and the weak soil development was likely due to the severe climate during this period, the short time for soil formation, erosion, and the constant input of colluvial material.

From a diachronic point of view, the initial weathering stages of the most weatherable primary minerals in a temperate, well-drained, and desaturated system were apparently the first processes to affect the fluvial sediments after their sedimentation (Unit 2). The soil formation started with stable conditions suitable for forming a moderately weathered soil. The abundant alteromorphs and the accumulation of 2:1 clay minerals and iron oxides in the micromass indicated the chemical weathering of the primary minerals (fig. 11A). This soil was subsequently transformed during a cold period, inducing a cryogenic phase via platy and lenticular ice segregation. The mechanical stress induced by the growth of ice lenses or blades parallel to the ground surface strongly compacted the aggregates (fig. 11B). The reoccupation of ice enhanced this compaction during every freeze-thaw cycle, and it remained after thawing while paths of preferential flow were created around the aggregates. Although the time control was tentative, the formation of well-developed cryogenic structures related to permafrost in these materials might be correlated with the significant cooling phase that occurred during the LGM. The presence of aeolian deposits in several locations on the Mt. Beigua Massif strongly indicates arid conditions during the LGM (Rellini & *alii*, 2009). Moreover, Firpo & *alii* (2006) hypothesised that permafrost aggradation occurred during the LGM. New evidence from the Palaeolithic deposits of the Arene Candide (SV) in the Liguria region, where Rellini & *alii* (2013) found traces of
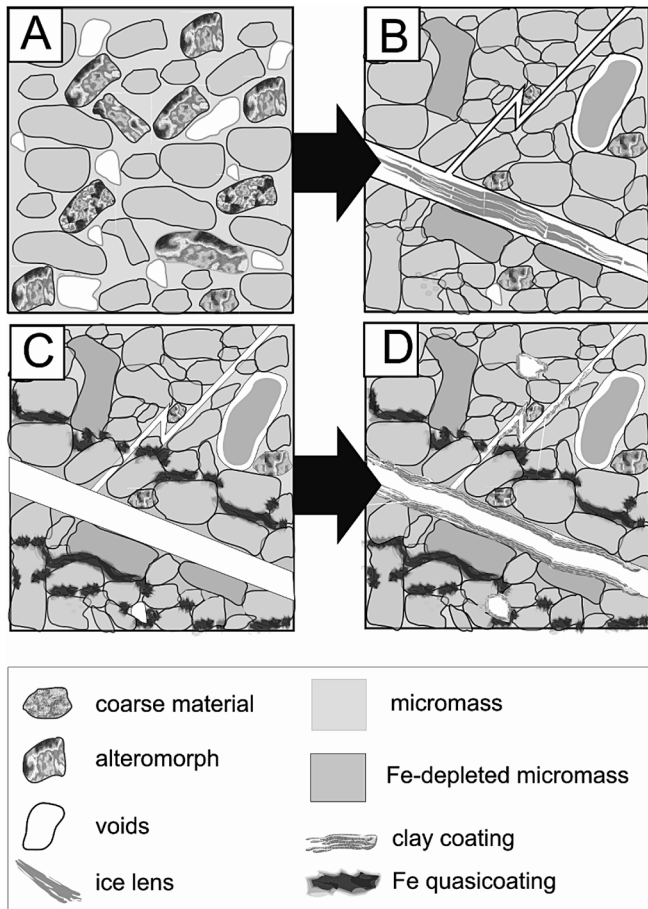
FIG. 11 - Schematic representation of the soil formation stages and related micromorphological pedofeatures.

ice segregation in a cave dating to the beginning of the last Pleniglacial, support this hypothesis.

The periglacial soil developed on sedimentary Unit 2 was also truncated given its lack of upper horizons. The deposition of the superficial Unit 1 most likely occurred during the deglaciation phase, together with the hydromorphic processes, following the LGM.

In fact, strong reduction might have occurred before the soil burials: Unit 1 does not display a clear indication of waterlogging, and the mottles were present immediately below the erosional surface along the primary frost cracks in Unit 2, which was also indicated by the micromorphology (quasi coatings). Therefore, water saturation due to snow melting and segregated ice is the responsible for reducing conditions in the soils prior to burial, although the climatic conditions remained relatively dry (fig. 11C). However, rubification and bleaching along the relict frost cracks (which constituted pathways of preferential flow) might have continued during the subsequent period of soil formation under wetter conditions. The next successive pedogenic phase included the formation of an accretionary soil under warmer and wetter climate condition (i.e., the Holocene). This soil developed from the new parent mate-

rial (colluvium) deposited on the truncated periglacial soil (Unit 2), and its genesis partially involved the top horizons of the buried periglacial soil (Unit 1). In fact, the upper horizons of Unit 2 do not display increases in the total clay content (tab. 1), although rare clay coatings were observed in thin section, indicating that illuviation occurred. Moreover, the micromorphological analysis indicated that most of the clay coatings characterising the deeper portion of cryogenic Unit 2 were found primarily in structural pores and were not Fe-depleted or broken. Therefore, these clay coatings must have originated from a weak phase of illuviaton in a later stage during the formation of the pedocomplex after the ice segregation and waterlogging (fig. 11D). This later stage of clay translocation might have occurred during the wet Holocene pedogenetic phases (Kühn, 2003). As Van Vliet-Lanoë (1990) observed, this stage might have occurred during a transitional period (e.g., the Boreal).

CONCLUSIONS

The macro- and micromorphological cross characterisation of cryogenic features performed on the palaeosol of the Beigua Massif allows for an accurate reconstruction of the soil evolution with respect to climate change and therefore a detailed palaeoenvironmental reconstruction of the study area. This approach is extremely useful for developing a detailed understanding of palaeosol genesis in general and the various processes induced by frost action in the soils and their interactions with the present day «temperate» soil-forming processes in particular. This study showed that the profile was affected, in various stages, by silicate weathering, cryogenic processes, redox-conditions, illuviation, and organic matter accumulation.

The palaeosol developed from sediments belonging to two sedimentary units separated by a clear erosional surface. The data supported the hypothesis of various soil formation stages under varying climatic conditions. The moderate alteration degree of the lower unit demonstrates that it was not subjected to a long period or intense degree of pedogenesis. Some of its relict features were associated with a short period of pedogenesis under drier and colder climatic conditions than those of today, which were presumably related to a periglacial environment at low elevations during the LGM and the presence of discontinuous permafrost. Later, strong reduction affected this periglacial soil, which was truncated during the deglaciation phase following the LGM. Afterward, an accretionary humiferous soil developed, which represented the last episode of soil formation during more stable climatic conditions that also favoured clay translocation. The presence of undisrupted clay coatings in the frost cracks strongly indicated that the illuviation was younger than the cryogenic processes.

The hypothesis regarding the presence of discontinuous permafrost was also supported by the geomorphological context of the site (Washburn, 1980), which was characterised by flat, poorly drained, and wind-exposed surfaces (as indicated by the presence of loess; Rellini & alii, 2009; Rellini, 2012) as well as the proximity to other indi-

cators of permafrost conditions in the mountainous areas, such as blockstreams (Harris, 1994). According to the climate model proposed by Firpo & *alii* (2006), which was based on Harris's (1994) model of active blockstreams, the MAAT in this area might have ranged from –1°C to –6°C; thus, cryotic conditions prevailed in the Beigua Massif. Based on our observations, we propose the presence of an altitudinal zonation and lower boundary of discontinuous permafrost on the Beigua Massif during the LGM, and this boundary likely exists at approximately the 600-m a.s.l. contour.

Finally, the micromorphologic features might be an important tool for reconstructing past permafrost distributions in regions characterised by climatic conditions that alternate between periglacial and temperate. The current study is one of a few cases in the literature documenting cryogenic structures in sandy soil where the presence of layered and streaky textures associated with segregation ice is the exception rather than the rule (Popov, 1981). Additional investigations are required to identify other well-expressed macro, micro, or both types of cryogenic features (e.g., ice wedge casts and sand wedges) and confirm the past permafrost limit during the LGM.

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