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# PLEISTOCENE PALEOSOLS OF ITALY: PEDOSTRATIGRAPHY, GENESIS, PALEOCLIMATE AND GEOARCHAEOLOGY

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ABSTRACT: This paper provides the first comprehensive, critical review on Pleistocene paleosols of Italy over about the last for decades. We summarize methodological approaches and major scientific findings from case studies throughout Italy, in both natural environments and human-influenced (archaeological) contexts. Many researchers showed the relevance of paleosols as pedostratigraphic and chronostratigraphic markers, useful for cross-correlations, geological mapping and reconstruction of the geomorphological evolution of Quaternary landscapes. Considering the variety of Italian paleosols, scholars introduced, applied and discussed crucial concepts in soil science, such as pedostratigraphic level, geosol or pedocomplex to reconstruct paleotopographies over time and space. We also discuss the value of paleosols that received distal volcanic input from Pleistocene explosive eruptions as (crypto)tephrostratigraphic markers, along with the neogenesis of short-range order minerals and development of andic properties as paleoenvironmental proxies. Several authors explored the effect of time and duration of exposure of parent materials to pedogenesis on the degree and direction of soil development as observed in soil chronosequence studies. Several among these studies revealed the efficiency of pedogenic iron forms to compare stages of soil formation with age. Many studies emphasized the potential of paleosols for paleoclimatic and paleoenvironmental reconstructions, often achieved through combining different analytical techniques and natural archives, among which the role of micromorphology gained considerable importance. Prominent clay illuviation and rubification due to hematite formation were interpreted as diagnostic of warm and humid paleoclimates, typical of Pleistocene interglacials. Illuviation of coarser particles, platy, lenticular or cuboid pedogenic structures, banded fabric, ice wedge casts and other macro- and microscale features were considered as indicative of past seasonal freezing in colder environments during Pleistocene glacial stages, when also loess deposition took place in northern Italy. With respect to secondary carbonate accumulation, some papers invoked cold and dry climatic shifts during glacials or stadials, although this feature may reflect a wide range of paleoclimatic conditions. An interesting discussion arose on the complex genesis of fragipans, plinthite and petroplinthite. Many case studies focused on paleosols related to archaeological contexts, where paleopedological and geoarchaeological investigations offer the possibility to understand the relations between settlements distribution, human impact and adaptation to geological, geomorphological, paleoclimatic and paleoenvironmental dynamics. Worth mentioning are also the assessment of paleosol quality and their intrinsic pedodiversity as geoheritage, with respect to fertility for agricultural purposes and their pollution with potentially toxic elements, given the uniqueness and irreproducibility of specific pedogenic properties. Other novel aspects and applications concern geotechnical and construction purposes, such as the suitability of certain paleosols for building foundations and the evaluation of the response to seismic events in urban areas. We draw further attention on key issues regarding the paleopedological approach, addressed by various authors or still needing investigations. A common problem arises from the lack of some genetic horizons after erosion, overprinting by younger pedogenesis due to surface exposure or changes in soil properties after burial, poor resilience of paleosols with respect to natural and anthropogenic threats, because of the long time required for acquiring specific properties. Their multifaceted nature represents a valuable tool for predicting the potential responses of the Earth system to forthcoming scenarios and providing best-suited strategies for sustainable land planning, adaptation and mitigation of geological hazards.

Keywords: Soil chronosequences; soil micromorphology; paleoenvironmental reconstruction; volcanic input; human settlements and artifacts.

## 1. INTRODUCTION

The specific geographic location of Italy as a peninsula bridging continental Europe to the Mediterranean and its variety of geomorphological units from the Alps across the Apennines to the large plains, from volcanos to shorelines, allowed the formation of a plethora of environmental niches with specific pedoclimatic conditions, thus supporting the evolution of many different soils during the Pleistocene. Paleopedological studies in Italy and the international debate on the genesis, classification, rates of development and paleoclimatic record of paleosols in this country have been missing until the last two decades of the 20$^{th}$ century. Since then, some papers started dealing with paleosols distributed along the Italian territory, especially in the north and central sectors of the peninsula. Therein, paleosols (i) were identified in sedimentary archives as markers of stages recording relative geomorphological stability (phyto/biostasy conditions vs. rhexistasy); (ii) were described in the field from a qualitative point of view; (iii) were assumed as paleoclimatic indicators by comparing their main morphological features in terms of past climatic conditions (especially of glacial/cold and interglacial/

warm, subtropical or tropical climates) considered either similar to or different from the present -day environment; (iv) were investigated in correspondence of archaeological evidence to support their dating and paleoclimatic recosntruction (Cremaschi et al., 1984; Cremaschi, 1987; Coltorti & Dramis, 1988; Cremaschi et al., 1990; Cremaschi & Van Vliet-Lanoë, 1990; Busacca & Cremaschi, 1998). Other papers published during the last two decades of the last century included the study of paleosols in the frame of a more comprehensive geomorphological evolution. Among these, Amato & Dimase (1997) applied soil micromorphology to investigate soil genesis and relate it to Quaternary paleoclimatic shifts. A few attempts aimed at quantifying the degree of paleosol development using a soil chronosequence approach (Arduino et al., 1984, 1986). Since the early 2000s to nowadays there has been a flourishing of studies focused on paleosols, from both natural landscapes and archaeological settings throughout Italy, as well as on stratigraphic markers, paleoclimatic/ paleoenvironmental proxies and indicators of different time spans. Several multiproxy, multidisciplinary and multianalytical methodological approaches contributed to this substantial knowledge gain. In this work, we provide some of the major research advances on Pleistocene paleosols of Italy (Fig. 1) from the aforementioned perspectives over more than the last four decades through a first comprehensive review on this topic.

Fig. 1 - Map of Italy showing regions and major geographic place names where the study sites reported in the cited literature are located. Base map: Eric Gaba and NordNordWest, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons.

This review occasionally includes Holocene soils as well, namely when a comparison of pedogenic features formed in the Pleistocene and Holocene enables a deeper understanding of the corresponding paleoenvironments, as well as in those cases when pedogenesis in certain paleosols started in the Pleistocene but continued diachronically into the Holocene, sometimes overprinting the Pleistocene features to some extent. Our critical analysis of the available literature also focuses on traditional and innovative techniques applied to paleopedological studies, often emphasizing several pedogenic features which are recurrent in different regions of Italy and are diagnostic of specific genetic processes and corresponding (paleo) environments (Table 1). In addition, we provide an overview of major applications, problems or open questions raised or addressed in the literature, including an overview on the application of paleopedology and related techniques to the study of archaeological soils. In fact, soil science is crucial in the reconstruction of processes involved in the formation and weathering of anthropogenic pedosedimentary sequences and in tracing evidence of human settlements on ancient topographic surfaces. A particular interest arises from the location of Italy in the central Mediterranean basin encompassing many different ecological settings (including paleosols related to human ecology), which makes it particularly sensitive to Pleistocene, current and future climatic changes and related natural hazards. The latter are enhanced by the tectonic activity at the boundary between the African and Eurasian plates, as well as by an increasing human impact, which threatens the pedodiversity of paleosols as heritage and georesource.

## 2. PEDOSTRATIGRAPHY, CHRONOSTRATIGRAPHY AND GEOMORPHOLOGICAL IMPLICATIONS

Field observation of paleosols is commonly used to separate phases of sedimentation from those characterized by absence of deposition, often coupled with prevalent weathering and soil formation processes, and possibly marked by episodes of erosion (Fig. 2). Where paleosols extend over wide areas, they may allow for correlating underlying and/or overlying sedimentary successions in space and time, even at regional scale (tens to hundreds $km^2$ at least), and tracing surfaces or buried paleotopographies. The North American Commission on Stratigraphic Nomenclature defined a geosol as the fundamental pedostratigraphic unit (NACSN, 1983, 2021; Catt, 1998). It consists of a laterally traceable, mappable, geological weathering profile or three-dimensional body of soil material comprising one or more differentiated pedogenic horizons, which has a consistent stratigraphic position and is buried by younger deposits at least in a reference site. Although the International Commission on Stratigraphy (ICS), which

| Pedogenic features | Responsible processes | Paleoenvironmental/ paleoclimatic conditions | Major periods of development | Main geographic location |
|---|---|---|---|---|
| Rubification (matrix reddening) | Diffuse release of Fe from mineral weathering and formation of ferrihydrite during moist winters, recrystallization into hematite during warm and dry summers | Warm and humid, seasonally contrasted | Pleistocene interglacials | Piedmont, Liguria, Lombardy, Emilia Romagna, Tuscany, Marche, Abruzzo, Molise, Basilicata, Calabria, Sardinia, Sicily |
| Illuvial clay coatings/ infillings and Bt horizon | Translocation of clay particles | Temperate to warm and humid, seasonally contrasted | Pleistocene interglacials/ interstadials | Piedmont, Liguria, Tuscany, Abruzzo, Marche, Molise, Basilicata, Calabria, Sardinia, Sicily |
| Fe/Mn mottles, coatings, concretions, nodules | Segregation of Fe/Mn oxides caused by reduction, redistribution and precipitation by re-oxidation | Temperate to warm and humid, seasonally contrasted; hydromorphic | Pleistocene interglacials and glacials; waterlogging throughout the Quaternary | Piedmont, Lombardy, Emilia Romagna, Marche, Abruzzo, Campania, Calabria, Sardinia |
| Carbonate coatings, concretions, nodules and Bk horizon | Dissolution, leaching and precipitation of carbonate | Arid/semiarid (cold and dry; warm and dry; subhumid (temperate to warm and humid) | Pleistocene glacials and interglacials; Holocene | Veneto, Abruzzo, Marche, Molise, Apulia, Basilicata, Calabria, Sardinia |
| Loess | Wind erosion, transport and deposition of mostly glacier- and meltwater- ground rock grains | Arid/semiarid; bare soil as sediment source; grass and low shrubs as sediment traps | Pleistocene glacials/stadials; Holocene dry spells | Piedmont, Lombardy, Veneto, Emilia Romagna, Tuscany |
| Platy, lenticular structure and banded fabric | Alternation of ice lense formation and melting | Cold, with diurnal and seasonal temperature contrast | Pleistocene glacials/stadials | Piedmont, Liguria, Campania |
| Illuvial silt coatings/ infillings | Freeze-thaw cycles and silt translocation with intense meltwater flushes; intense rainfall on bare soil; agricultural practices | Cold, with diurnal and seasonal temperature contrast; poorly vegetated soil; ploughed and/or irrigated soil | Pleistocene glacials/stadials; Holocene human-impacted soils | Piedmont, Lombardy, Liguria, Campania, Calabria, Sardinia |
| Degenerated clay coatings | Freeze-thaw cycles (cryoturbation); shrink -swell dynamics (argilloturbation); bioturbation; anthropogenic activities | Cold, with diurnal and seasonal temperature contrast; faunal activity and/or vegetation cover; human impact | Pleistocene glacials/stadials; Pleistocene inter-glacials/ interstadials; Holocene human-impacted soils | Tuscany, Abruzzo, Campania, Calabria, Sardinia |
| Cryoturbated horizons and wedge casts | Seasonal or permanent soil freezing and differential increase of ice volume | Cold, with diurnal and seasonal temperature contrast or permafrost | Pleistocene glacials/stadials | Piedmont, Lombardy, Liguria, Calabria |
| Volcanic input | Volcanic eruptions and tephra/ cryptotephra deposition | All | Throughout the Quaternary | Umbria, Abruzzo, Latium, Campania, Molise, Calabria, Sicily |
| Vitric properties | Poor degree of weathering of tephra | All | Throughout the Quaternary | Latium, Campania, Molise, Sicily |
| Andic properties | Neogenesis of short-range order minerals from the weathering of volcanic glass | Humid with udic soil moisture pedoclimate and free drainage | Pleistocene inter-glacials and milder glacial interstadials | Abruzzo, Latium, Campania, Molise, Calabria |
| Vertic properties and Bss horizon | Shrink-swell dynamics and expandable clays | Alternation of imbibition/ desiccation of clays | Pleistocene glacials and interglacials | Lombardy, Marche, Molise, Campania, Calabria, Sicily |
| Fragic properties and Bx horizon | Freeze-thaw cycles; shrink-swell cycles; hydro-consolidation; seismic shaking and liquefaction; bonding by precipitated Fe, Al, Si and/or clays | Cold, with diurnal and seasonal temperature contrast; all | Pleistocene glacials; throughout the Quaternary | Lombardy, Piedmont, Tuscany, Calabria |
| Plinthite, petroplinthite | Laterization processes and Fe oxide segregation | Warm and humid | Pleistocene interglacials | Liguria, Tuscany |
| Pedorelicts | Soil reworking | All; anthropogenic impact | Throughout the Quaternary | Lombardy, Abruzzo, Campania, Apulia, Calabria |

Tab. 1 - Summary of major paleopedological features, associated processes and their paleoclimatic interpretation .

oversees the matters relating to the world chronostratigraphic chart and the corresponding geological time scale within the International Union of Geological Sciences (IUGS), has never approved the use of pedostratigraphic units, several researchers have developed concepts around this topic and applied them to specific case studies. Cremaschi (1978) was one of the Italian scientists who first used lithostratigraphic and pedostratigraphic units to fix hypothetical chronological constraints and derive paleoclimatic shifts recorded in loess deposits with embedded paleosols on Quaternary terraces in the northern Apennines fringe. The author attributed major loess aggradation to the penultimate glacial period, whereas he ascribed fersiallitic pedogenesis and leaching/hydromorphic features to the penultimate and the last interglacial, respectively. Cremaschi (1987) also introduced the concept of vetusols (see section 3) based on a combined study of Quaternary geology and paleopedology of the Pleistocene terrace staircase along the Po River Plain (northern Italy). There, he identified relict paleosols, developed on alluvial, loessic and glacial deposits and, exposed at the present, stable topographic surfaces, which underwent the same set of soil formation processes (decarbonation, rubification and clay illuviation) over time, i.e. keeping the same direction of pedogenesis, though less intense moving from older to younger surfaces, across the terrace-soil chronosequence. Also, in the Campania region (southern Italy), Magliulo et al. (2006) were able to distinguish different stacked lithostratigraphic units, separated by erosive discontinuities, within the early Pleistocene, clastic alluvial fan succession of the Eboli conglomerates, based on the study of intercalated (buried) paleosols. Among these, the so-called paleosol of Eboli (along with some K/Ar-dated pyroclastic layers) permitted correlations between varying stratigraphic sections and proved to be a good pedostratigraphic marker in the area, also adding a potential climatic signature of warm and humid conditions of the MIS 25 interglacial. In the Sila Massif upland plateaus (Calabria, southern Italy), Scarciglia et al. (2008) defined an informal geosol in the surroundings of the Cecita Lake, which is an artificially dammed reservoir occupying a Pleistocene morphotectonic depression that once hosted an ancient, extinct lake. Soil charcoal content therein dated mostly to the Holocene and limitedly to the late Pleistocene, in line with the main pedological features (organic matter accumulation, clay illuviation, neogenesis of phyllosilicate and poorly crystalline clay minerals) and archaeological remains, the latter spanning from late Neolithic to Roman times (Pelle et al., 2013; Moser et al., 2017). Noteworthy in that area is the partial contribution of very fine (micrometric) volcanic ashes, sourced from the Aeolian Islands archipelago (southern Tyrrhenian Sea, NE of Sicily), to soil development, in addition to the in situ weathering of granitoid rocks and associated sediments. This finding permitted to use the Sila upland soil as a potential (crypto)tephrostratigraphic marker. However, repeated late Pleistocene and Holocene explosive eruptions dispersed their distal, pyroclastic products with similar (rhyolitic) composition in the Sila plateaus, thus not allowing the identification and dating of a single eruptive event and corresponding age (Scarciglia et al., 2008; Raab et al., 2017). The time-transgressive (diachronous) genesis of the ash-bearing Sila upland soil, which in this case formed in various substrates of different ages, and the dominant exposure at the surface of the Cecita Lake geosol, only in places buried by alluvial, colluvial and detrital slope deposits, imply that it cannot be considered a chronostratigraphic unit. Modern pedogenesis and anthropogenic disturbance may be partly superimposed on it, and partial truncation by surface erosion processes may cause a partial loss of "soil memory". Nonetheless, it still appears a reliable pedostratigraphic marker and record of the late Pleistocene to middle Holocene pedogenesis, indicating relatively stable geomorphic conditions, followed by late Holocene episodes of severe erosion/sedimentary aggradation. It is a useful tool to constrain both older and younger soils and deposits and morphodynamic processes for more extensive correlation.

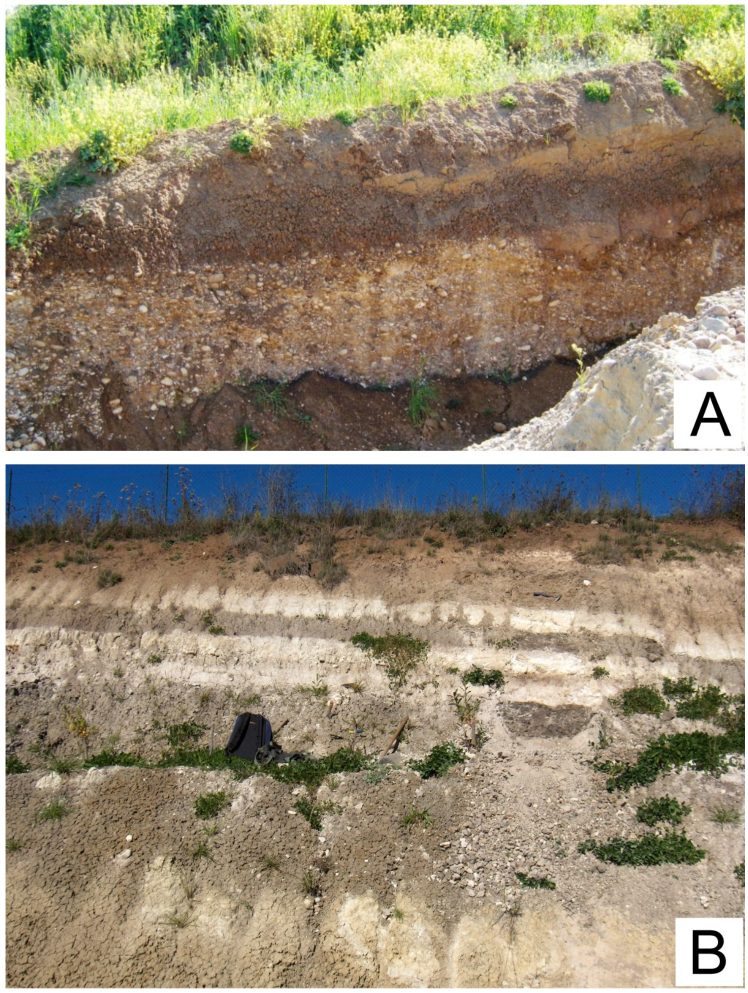

Fig. 2 - (A) Erosive and depositional unconformities marked by paleosols in a middle Pleistocene stratigraphic sequence in the Molise-Apulian Apennines between the Trigno and Fortore rivers (photo courtesy of V. Bracone). (B) Pleistocene pedostratigraphic succession alternating tephra and volcanic ash-bearing paleosols in the Sessano intramontane basin (Molise Apennines).

Paleosols have demonstrated to be very useful in Quaternary geology surveys and mapping. Napoli et al. (2006) and Costantini et al. (2007b) applied soil surveys and paleopedological studies to generate detailed maps of the Quaternary soil cover in a pilot area of Tuscany (central Italy) using geographic information system (GIS). They produced pedostratigraphic maps representing ancient buried surfaces from the early to the middle and late Pleistocene (and the Holocene), derived from the regolith thickness and the estimated soil ages. Different pedostratigraphic sequences were identified based on pedostratigraphic levels (PLs), defined as characteristic assemblages of soil genetic horizons, formed in parent materials exhibiting a similar degree of weathering and a maximum age estimated by means of correlation to benchmark soils (Costantini & Priori, 2007). This approach proved to be a useful tool to identify differential tectonic uplift across the study area, even where the soil cover may hide surface evidence of faults underneath. Further improvement of this approach came from geologists who identified stacks of unconformity-bounded stratigraphic units (UBSUs), marked by buried paleosols, thus using a Quaternary geology approach in paleopedology. These often allowed to distinguish different synthems (Capezzuoli et al., 2009; Zuffetti & Bersezio, 2021), together with their specific sedimentary facies associations, discontinuities and erosive boundaries (Andreucci et al., 2010; Giraudi et al., 2011; Pascucci et al., 2014; Di Celma et al., 2016; Bruno et al., 2017, 2020; Morelli et al., 2017). This approach contributed to reconstruct 2D to 3D geological/geomorphological and temporal evolution models from exposed outcrops and/or cores drilled in subsurface sedimentary successions of past marine and continental realms, especially where paleosols have large lateral continuity. In particular, Coltorti & Pieruccini (2006) studied in detail some pedocomplexes (compound geosols, i.e. sequences of overlapping paleosols of different ages formed on different lithologic units; NACSN, 1983) dating to the last interglacial from several sites in central Italy. The pedocomplexes consisted of three buried, truncated paleosols, separated by erosive surfaces and/or stone lines, marking the passage between the late middle Pleistocene (MIS 6) and late Pleistocene (MIS stages 4 and 2) UBSUs, developed on calcareous fluvial and moraine gravels with minor flints. Their main features are red colors, illuvial clays, secondary carbonate accumulation and bioturbation, which are consistent with the triplet of MIS 5e-5c-5a last interglacial stages. These allow detailed correlation with similar paleosols and pedocomplexes already observed in other sectors of the central Apennines, but conversely display dissimilar features and lesser degree of weathering than younger late Pleistocene and Holocene soils. Almost the same time period including the last two glacial cycles (and older stages) is recorded in thick, continental (glaciofluvial) and shallow marine sedimentary successions from the Venetian plain (NE Italy) (Marcolla et al., 2021). The authors provided detailed multiproxy data from deep cores on the stratigraphic architecture and landscape evolution. Integrated stratigraphic, palynological, micropalaeontological, geochronological and paleopedological results showed that alluvial aggradation phases correlate to glacial culminations in the Alps, which alternated with marine transgressions and/or soil formation during intervening interglacials. Paleosols therein contributed to correlate mutually different core sections, similarly to other works where they were interbedded in Pleistocene alluvial fan deposits and, although often truncated, served as pedostratigraphic markers and paleoclimatic proxies, from several sites of north, central and south Italy (Giaccio et al., 2004; Robustelli et al., 2005a; Carboni et al., 2006; Magliulo et al., 2006; Carnicelli et al., 2015; Marcolla et al., 2021). Other works worth mentioning are those of Villa et al. (2016b) and Amorosi et al. (2015), who coupled electrical resistivity tomography (ERT) surveys and pocket penetration tests to assess high-resolution pedostratigraphic records. Bracone et al. (2012) and Amorosi et al. (2014b) also integrated paleosol information with the principles of sequence stratigraphy to delineate systems tract equivalents even in non-marine successions and trace their Quaternary geomorphological, tectono-sedimentary evolution. In some cases, the constraints obtained from the reconstruction of the deep pedostratigraphic architecture of river or coastal plains permitted to estimate sedimentary aggradation rates and paleoclimatic changes (Fontana et al., 2014; Bruno et al., 2017) and to use paleosols as regional stratigraphic markers for long-distance correlations, also supported by key pedochemical fingerprints (Amorosi et al., 2021). Such an approach of long-distance correlations based on the visual identification of buried paleosols (or soil horizons) along deep cores offers a tool to accomplish paleogeographic reconstructions up to the scale of sedimentary basin, although a major methodological bias was suggested by Aghib et al. (in press). Considering a deep core of Pleistocene sediments from the northern Po Plain, they performed a micropedological investigation on layers visually interpreted as paleosols. Their findings highlighted that only a few of them were real paleosols, whereas some others were preweathered and pedogenized sediments consisting of reworked and eroded paleosol material (geological pedorelict), layers of accumulation of $CaCO_3$ related to the presence of groundwater (deep groundwater calcrete), or Fe-enrich layers interpreted as buried iron bogs. A noteworthy example of the study of paleosols along deep sequence is represented by the so called *caranto* paleosol, found in cores from the central sector of the Lagoon of Venice (NE Italy), outcropping in the fields during tillage, and referenced in ancient chronicles of local architects and builders (Mozzi et al. 2003; Donnici et al., 2011). This late Pleistocene to early Holocene paleosol is a compact layer (as expressed by the term *caranto* itself, which in the local dialect of peasants indicates hard, cemented horizons). According to Mozzi et al. (2003), it consists of white calcic and greyish gleyic (with yellowish Fe-hydroxide-rich mottles) pedogenic B and C horizons. It occurs at a depth of some meters from the topographic surface, often forming centimeter-thick crusts, on top of distal alluvial plain sediments and overlain by transitional marine, lagoon and continental deposits. It is well-correlated with spatial continuity to the Calcisols inland, and the alternation of oxidizing and reducing conditions, in response to groundwater fluctuations, are considered responsible of its pedogenic features. The time of pedogenesis of the *caranto* paleosol was estimated in a large range of 8,000-12,000 years and it marks a major stratigraphic uncomformity in the Venice lagoon area separating the Last Glacial Maximum from the Holocene. The role of paleosols as pedostratigraphic markers in the frame of Quaternary morphotectonic evolution (and paleoclimatic) reconstructions was also investigated by several researchers. Zembo (2010) and Zembo et al. (2011) focused on paleopedological characterization to unravel the interplay between tectonic activity, local base-level changes and climate in controlling alluvial dynamics in Quaternary alluvial sediments of the Val d'Agri Basin (southern Italy). Livio et al. (2009, 2014, 2020), Zerboni et al. (2015) and Perini et al. (2023) performed a detailed investigation of a loess-paleosol sequence on top of Monte Netto (Brescia, Lombardy region), which is one of the isolated hills of tectonic origin in the middle of the Po Plain (Desio, 1965). Their multidisciplinary investigation of paleosols allowed the reconstruction of the complex evolution of the hill and the identification of the tempo and mode of Pleistocene structural deformation of the area and related seismic hazard. The same approach was applied to reconstruct the tectonic evolution of the Monferrato Hills in Piedmont (Frigerio et al., 2017). Zuffetti et al. (2018) explored how relicts of eroded and reworked paleosols, occurring systematically in colluvial wedges close to the main faults and/or at the erosive bottom of paleovalleys, mark phases of tectonically-driven landscape instability triggered by late Pleistocene uplift and faulting, along with valley incision and drainage network diversion in a hilly sector of the Po River Plain (Lombardy region, northern Italy). Aucelli et al. (2011) used paleosols as auxiliary tools to acquire morphostratigraphic and chronological constraints for the assessment of the geomorphological and tectonic evolution of Quaternary paleosurfaces in the Molise Apennine (southern Italy), the genesis of which can be related to long-lasting periods of major tectonic stability alternating with episodes of uplift. Many of the aforementioned papers clearly showed that pedo- and chronostratigraphic correlations obviously benefited from varying dating techniques, such as radiocarbon, $^{40}K/^{40}Ar$ and $^{39}Ar/^{40}Ar$, electron-spin resonance (ESR) and optically stimulated luminescence (OSL), according to the available materials and the time ranges investigated. Despite the wide application of paleosols in reconstructing Quaternary environments and dynamics, their classification remains matter of discussion (Zerboni et al., 2015). In fact, many authors suggest that, due to their variability and the current soil nomenclature codes, paleosols can hardly be classified with accuracy without introducing specific pedologic parameters of classification (James et al., 1998; Nettleton et al., 1998, 2000; Krasilnikov & García Calderón, 2006). The classification of paeolsols thus requires the identification of those key attributes in modern soils that have preservation potential following burial, diagenesis, deformative, and erosion events. Unfortunately, most of the key soil attributes have a low probability of being preserved without major modification or destruction (James et al., 1998; Zerboni et al. 2011). In such contexts, it is preferable to find analogies between the described paleosols (or at least their remaining B horizons, Zerboni et al., 2011) and modern soils categories defined by the international nomenclature (IUSS Working Group WRB, 2022.

## 3. SOIL AGE AND CHRONOSEQUENCES

Soil chronosequences provide insight into the rates of soil-forming processes under defined combinations of climate, vegetation, parent material, and relief (Sauer, 2015). Over the last four decades, soil chronosequences have been studied all along the Italian peninsula and in Sicily. In the very northwest of Italy, in the Piedmont region, three studies on soil chronosequences formed in several series of Pleistocene river terraces were reported in the 1980s. Arduino et al. (1984, 1986) investigated redness rating according to Torrent et al. (1980), pedogenic iron ratios and clay mineralogical composition of soils formed in Pleistocene river terraces around and northeast of Torino, in between the rivers Elvo and Cervo. They found that redness, $Fe_d/Fe_t \times 100$ and $(Fe_d\text{-}Fe_o)/Fe_t \times 100$ were closely related to terrace age. Clay mineralogical composition was dominated by 2:1 clay minerals in soils on the younger terraces; kaolinite and gibbsite were identified only in a soil on the oldest terrace. Only a short time later, Ajmone Marsan et al. (1988) studied soils on three Pleistocene river terraces about 90 km northeast of Torino, estimated to 10-50 ka BP, 90-130 ka BP, and 500-750 ka BP. All soils showed clay illuviation, whereby the Bt horizons of the two younger soils had brown colors (10YR6/6 and 10YR6/8), whereas the Bt horizons of the oldest soil were more reddish (7.5YR5/6). Horizon thickness and clay contents increased with soil age. The ratio $(Fe_d\text{-}Fe_o)/Fe_t \times 100$ increased, while that of $Fe_o/Fe_d \times 100$ decreased with soil age. In the Emilia-Romagna region, Eppes et al. (2008) studied a soil chronosequence consisting of 19 soil profiles formed in late Pleistocene to Holocene fluvial terraces in the Reno River Valley near Bologna. They found consistently progressing differentiation of soil profile horizonation, particularly for soils on the Holocene and Late Würmian (ca. 12 ka) river terraces, whereas older soils reflected a more complex development affected by climatic changes, including periods of stronger carbonate leaching, and of variable input of calcareous dust and/or colluvium. Soils <2 ka were cumulic soils with weakly developed Bw horizons and no evidence of carbonate redistribution. Soils developed in about 5.46 ka old deposits showed a well-developed Bw horizon and weak carbonate accumulation below, in the form of filaments and minimal coatings on the bottom of clasts. Soils on about 12.5 ka old terrace bodies had Bt horizons with well-developed clay films, underlain by Bk horizons with 2-5 cm thick carbonate pendants on clast bottoms. In the Montagnola Senese mountain range in Tuscany, Costantini et al. (2002a, b) and Costantini & Damiani (2004) investigated early, middle to late Pleistocene and Holocene soils developed in acid rock and siliceous slope and alluvial deposits. With increasing soil age, they observed decreasing silt/clay ratios, decreasing cation exchange capacity of clay, increasing proportions of vermiculite and kaolinite in the clay mineral composition, as well as increasing $Fe_t$ and $Fe_d$ contents. Also, contents of other elements, particularly those of Cr, Pb, and Zn, increased with soil age. Magaldi & Tallini (2000) proposed a quantitative micromorphological index (MISODI) to assess the degree of weathering and pedogenesis of relict paleosols. Their aim was to provide a tool for extracting improved chronostratigraphic information from relict paleosols, in order to correlate them with ancient landforms, and thus contribute to the reconstruction of Quaternary landscape development based on pedostratigraphic successions. They tested this index on B horizons of relict paleosols in the L'Aquila-Scoppito Basin, within the Abruzzo region, central Italy, for which chronostratigraphic information was available. The index, which is based on microstructure, b fabric, thickness and abundance of coatings and nodules, and degree of alteration of mineral grains, showed an overall increase with soil age, amounting to 0 to 12 for Holocene relict paleosols, 7 to 17 for late Pleistocene relict paleosols, and 14 to 22 for middle Pleistocene relict paleosols. In the Molise region in the southern central Apennines, van Otterloo & Sevink (2021) observed a soil chronosequence in the upper Volturno Basin, ranging from Fluvisols in Holocene sediments of the Volturno River and tributaries, to Chromic Luvisols in late Pleistocene river terraces, and highly weathered, deeply developed Chromic Luvisols and Nitisols with reddish argic horizons formed in early middle Pleistocene fluvio-lacustrine sediments. Along the Tyrrhenian coast of northern Calabria, Scarciglia et al. (2006) studied two soil chronosequences on early to late Pleistocene marine terraces, in between the Noce River in the north and the Lao River in the south. The age of the I order terraces (the oldest ones, at 100-130/140 m a.s.l.) is assumed to be 0.8-1.3 Ma. The II order terraces (at 50-65 m a.s.l.) are estimated to 0.8-0.65 Ma, the III order terraces (at 30-45 m a.s.l.) to 0.6-0.5 Ma, the IV order terraces have been dated to 250 - >350 ka by U series dating of corals, pointing to their formation during MIS 7-9. The MIS 5 sea-level highstand created no comparable extensive terrace, but only a small wave-cut platform in this area. Each of the two soil chronosequences (a northern and a southern one) included four soil profiles. All soils had intensely rubified, clayey argic horizons with strongly developed blocky to prismatic structure and common to very abundant clay coatings on ped surfaces. Particularly the older soils showed iron-manganese mottles, coatings and concretions in their deeper argic horizons. The youngest soils (on the MIS 7 -9 terraces) show carbonate accumulation at some depth. The redness rating according to Torrent et al. (1980) yielded higher values for the northern chronosequence compared to the southern one, without showing any age trend. The clay-mineralogical composition of all soils was dominated by kaolinite and illite. Ratios of ($Fe_d$ -$Fe_o$)/$Fe_t$ and $Fe_d$/$Fe_t$ tended to be higher in soils on the I and II order terraces, compared to the III and IV order terraces, however, without exhibiting a strong relationship with terrace age. Along the Ionian coast of Basilicata, Sauer et al. (2010) studied a soil chronosequence on a staircase of marine terraces in an area framed by the rivers Basento in the north and Cavone in the south. Twelve soil profiles were investigated across the terrace

Fig. 3 - Late Pleistocene marine terrace T2 exposed in a gravel quarry about 8 km southwest of Metaponto, at the Ionian coast of Basilicata.

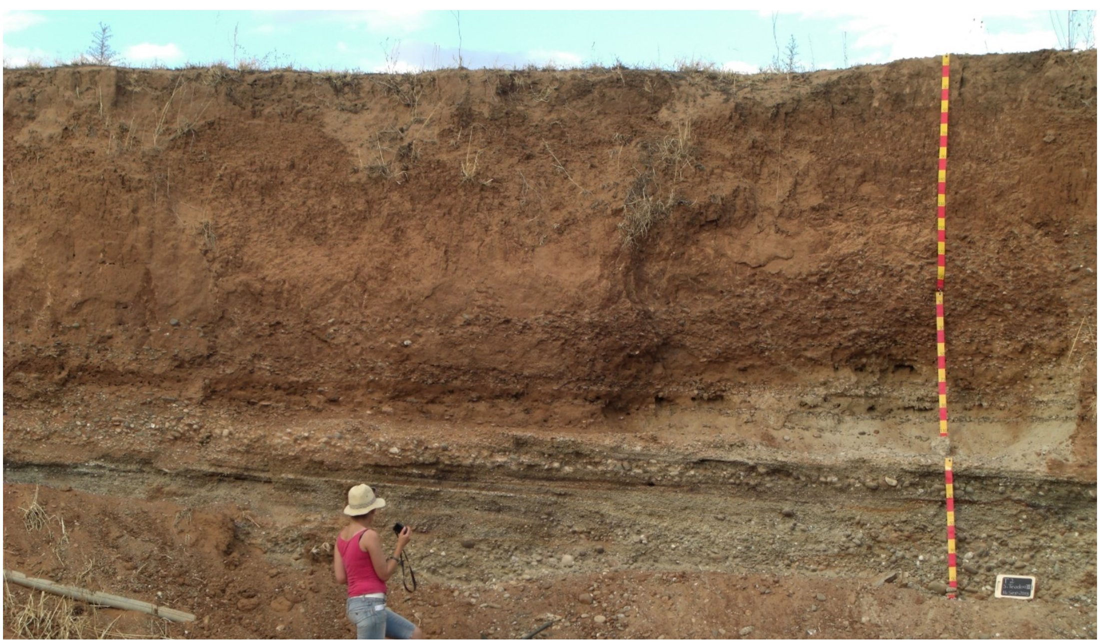

Fig. 4 - Chromic Luvisol developed in terrace T2 near Metaponto, attributed to MIS 5c.

staircase between Lido di Metaponto, located on Holocene alluvial deposits (terrace T0), and Pisticci, located on the oldest terrace body that accumulated already during the Brunhes epoch (terrace T10). The terraces (Fig. 3) were attributed to MIS 1, 5a, 5c, 5e, 7, 9, 11, 13, 15, 17, and 19, respectively. Later, the number of soil profiles was increased to 22 profiles (Sauer et al., 2015).

Soils developed towards Chromic Luvisols and Alisols (Fig. 4), whereby clay/silt ratios tended to increase with soil age. The increase in the $Fe_d/Fe_t$ ratio with soil age could be best described by a logarithmic function. The authors used the weathering index based on the molar element ratio of (Ca+Mg+K+Na)/Al (excluding Ca in calcium carbonate), $WI_{MER}$ (Sauer, 2017), to trace progressive silicate weathering and leaching of the released base cations. The $WI_{MER}$ showed a logarithmic decrease with soil age. Soil thickness increased over the first ca. 400 ka, while erosion prevented a further increase in soil thickness thereafter. This trend could be best described by a logarithmic equation. However, soil thickness increase was probably not continuous but took place only during interglacial periods, whereas pedogenesis under drier, more continental conditions and a corresponding forest-steppe landscape during glacial periods affected only the upper parts of the already deeply developed interglacial soils (Sauer, 2015). Corresponding steppe soils have been found embedded within last-glacial alluvial fans in Calabria (Fig. 5 in Sauer, 2010).

Robustelli et al. (2009) investigated a soil chronosequence at the Ionian coast of northern Calabria, on five stacked river terraces along the rivers Colognati and Coserie, that are running next to each other into the Ionian Sea. The oldest terrace T1, which was attributed to MIS 11-9, is at 218-154 m a.s.l., the second oldest terrace T2, which accumulated during MIS 7, reaches an elevation of 120 m a.s.l., and the three youngest terraces T3, T4, and T5, which were attributed to MIS 5e, MIS 5c, and MIS 5a, are at about 80 m, 60 m, and 45 m a.s.l., respectively. All soils had well-developed reddish argic horizons with clay coatings on ped surfaces and Fe-Mn concentrations. Redness rating according to Torrent et al. (1980) was highest in the soils on the oldest terrace. Also, the ratio $(Fe_d-Fe_o)/Fe_t$ (Arduino et al., 1984) was highest in the soils on the oldest terrace and highly variable in the soils on the younger terraces. The weighted chemical index of alteration (CIA) by Nesbitt & Young (1982) was high in all profiles, ranging between 0.8 and 0.95. Later, Scarciglia et al. (2015) also compared this soil chronosequence to the two soil chronosequences that had earlier been investigated by Scarciglia et al. (2006) along the Tyrrhenian coast of Calabria and proved the efficiency of weighting pedogenic iron indices on the basis of single horizon and total soil profile thicknesses to minimize the effects of soil truncation by erosion. Wagner et al. (2007) analyzed a soil chronosequence on a series of five middle Pleistocene marine terraces around Menfi in western Sicily, ca. 50 km east of Marsala. All soils were Chromic Luvisols having well-developed argic horizons with blocky to prismatic structure and clay films coating the ped surfaces. The oldest soil had ferric properties at some depth. Soil thickness increased with soil age. The clay mineral composition included a mixture of illite, smectite, and kaolinite in all soils. $Fe_d/Fe_t$ ratios generally ranged between 0.5 and 0.6; only the oldest soil had $Fe_d/Fe_t$ ratios of 0.73- 0.88.

As time is crucial in the formation, development and preservation of soils, it is noteworthy reporting on the concept of vetusol proposed by Cremaschi (1987) after reconsidering the paleosols formed in the Po Plain since the beginning of the Pleistocene. Cremaschi investigated many pedostratigraphic sequences distributed in the region including paleosols embedded in complex sedimentary sequences, remains of dismantled paleosols, and soil bodies at the ground surface. The latter category includes several highly developed red paleosols, traditionally called *ferretto* soil (Billard & Orombelli, 1986), which can be classified as a *sol fersiallitique* (following Duchafour, 1983) or Oxisol, meaning a soil with huge kaolinite neogenesis, decarbonation, clay and Fe translocation, and development of red color (see also section 4.1). Comaparing the soil forming processes required for the development of such soils and the soils formed under interglacial conditions in the Pleistocene, Cremaschi (1987) concluded that the *ferretto* soil is not the result of a single pedogenic event under warm and humid conditions during a single time window of the Pleistocene. Conversely, its formation presumably started at the end of the early Pleistocene and never stopped until today. Such soil is the product of continuous pedogenesis occurred on stable surfaces under Mediterranean climatic conditions. Glacial conditions only slowed down the process. Moreover, erosion only limitedly removed the topsoil and windblown sediments never buried the *ferretto* because thin sedimentary layers were involved into the pedogenesis.

## 4. PALEOSOL GENESIS, PALEOENVIRONMENTAL AND PALEOCLIMATIC RECONSTRUCTIONS

### 4.1. Rubified, clay illuviated paleosols

Among major distinctive features of Pleistocene paleosols across the Italian territory is the common coexistence of rubification (i.e. a diffuse matrix reddening caused by intense Fe staining due to the high pigmenting power of hematite among iron-oxyhydroxides; Torrent et al., 1980, 1983), extensive in situ clay neogenesis, and abundant illuvial clay coatings/infillings forming one or more Bt (argic) horizons (Fig. 5).

Such types of paleosols largely represent Acrisols, Alisols and Luvisols (IUSS Working Group WRB, 2022) or Alfisols (USDA Soil Taxonomy; Soil Survey Staff, 2014) and fall within the so-called *Terrae rossae*, *Terra Rossa* or red Mediterranean soils (Fig. 6).

Several researchers have interpreted the above cited set of features (especially the pair rubification-clay illuviation) as developed under warm/temperate and humid, seasonally contrasted climatic conditions, diagnostic of Pleistocene interglacial periods, both in Italian sites (Carboni et al., 2006; Coltorti & Pieruccini, 2006; Scarciglia et al., 2006, 2009, 2011; Robustelli et al., 2009; Bracone et al., 2012; Di Celma et al., 2015) and in other circum-Mediterranean (Fedoroff, 1997; Cremaschi & Trombino, 1998b) and mid-latitude environments


Fig. 5 - Truncated reddish paleosol in the Trionto River basin (Calabria) showing the upper argic horizon exposed at the ground surface in response to severe erosion (A). A subangular blocky aggregate partly covered by dark brown clay coatings of illuvial origin (B) from marine sands in the Pizzo Calabro area (Calabria).

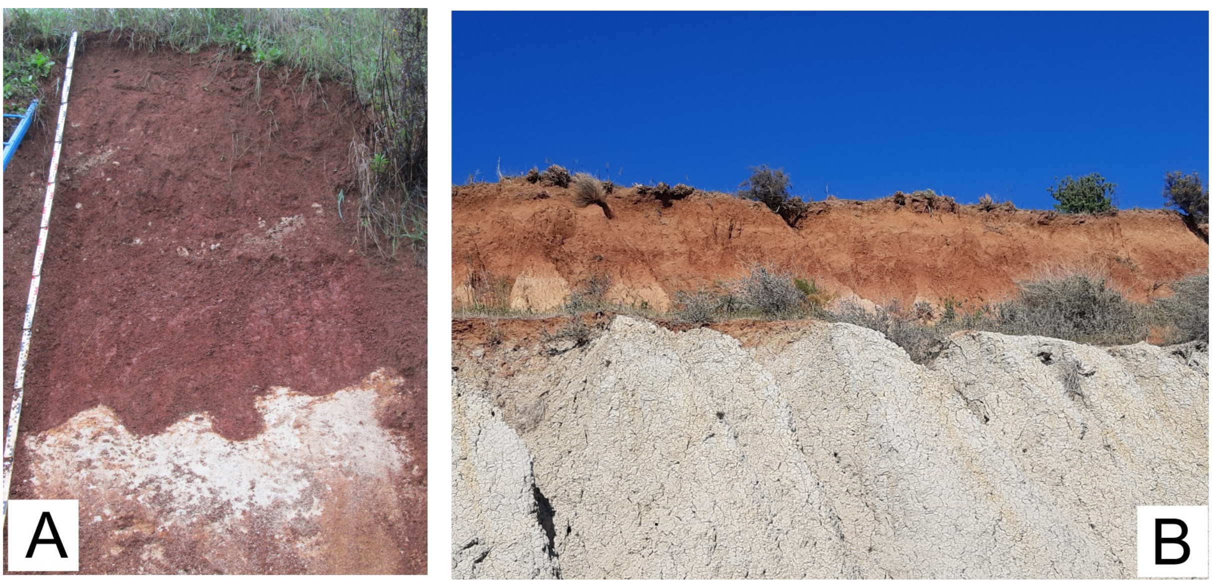


Fig. 6 - Examples of typical Pleistocene red Mediterranean soils in Tuscany (Valdelsa basin) (A) and Calabria (Vrica site) (B). Their substrates consist of lacustrine limestone shaped by karst dissolution (A) and terraced marine marly clays affected by concentrated water erosion and badlands (B).

(Catt, 1989; Bronger & Sedov, 2003). High moisture availability and seasonality promoted water infiltration and downprofile migration of clay-enriched water suspensions, followed by capillary water rise and evaporation, leading to water deficit and stacking of clay particles in the soil macro/micropores. Also, water uptake by plant roots and evapotranspiration could have contributed to their emplacement, especially under a stable and dense (forest) vegetation cover. Recurrent cycles of clay illuviation often lead to (polycyclic) microlaminated/crescent coatings/infillings, in some cases distinguishable in more than one generation based on changes in color and/or texture (Fig. 7).

Multiple generations of orange to yellow, limpid to dusty clay coatings were detected also in loess-paleosols sequence from the Po Plain and formed during MIS 4 to 3, thus suggesting that interstadials occurred during cold phases were warm enough to break (or slow) wind sedimentation and allow the onset of soil forming processes (Zerboni et al., 2015). The same pedoclimatic conditions are suitable to chemical weathering processes affecting primary rock components and neogenesis of clay minerals. In particular, they could have favored an intense iron staining responsible of rubification, with iron released from Fe-bearing primary minerals as the mobile $Fe^{2+}$, followed by its precipitation as $Fe^{3+}$ in neoformed oxyhydroxides (Schwertmann & Taylor, 1989; Huang & Wang, 1997). Such conditions

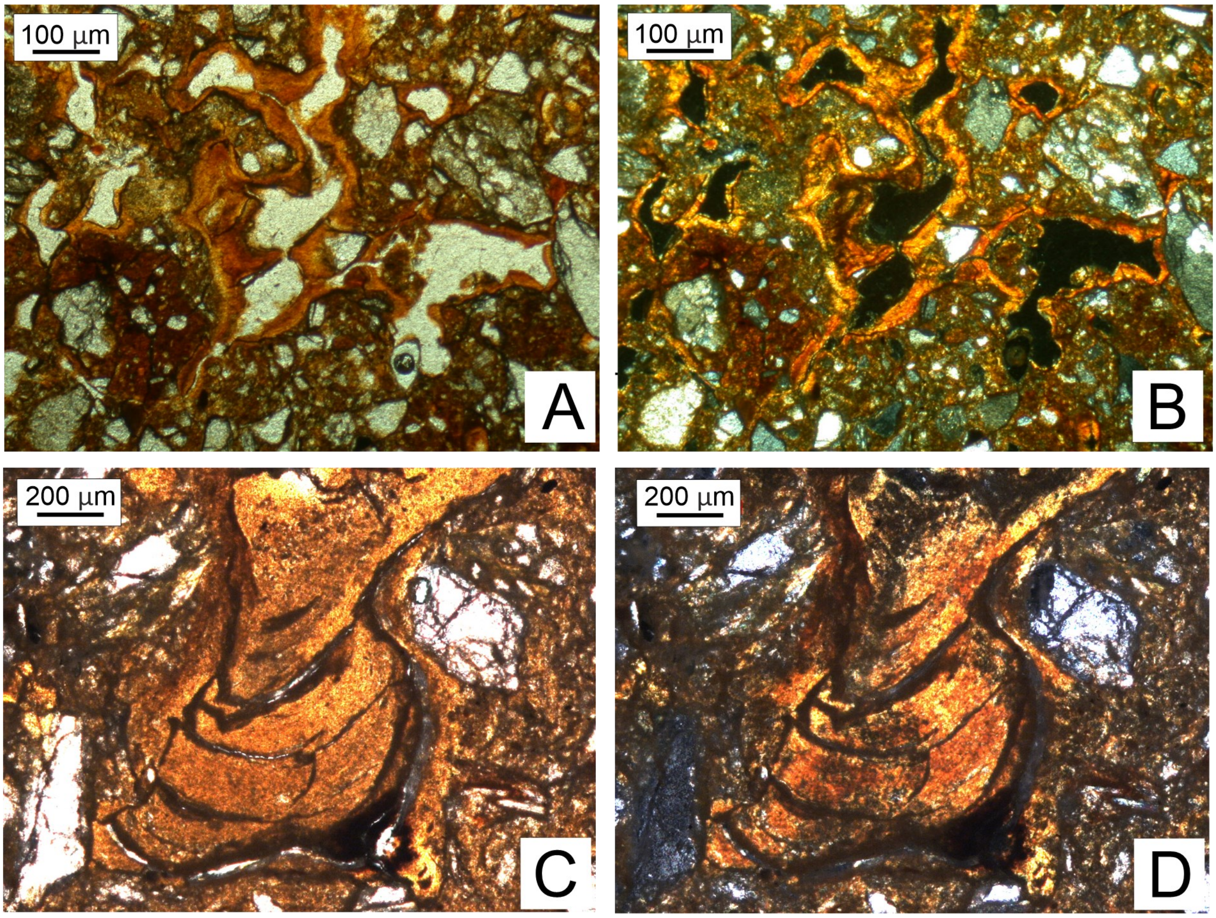


Fig. 7 - Microphotographs of clay coatings observed in thin sections in plane polarized light (A, C) and crossed polarized light (B, D). Smooth-banded to grainy extinction patterns observed between crossed polarizers and cracks indicate their relict significance. Photos are from argic horizons developed on terraced fluvial gravel deposits including plutonic, metamorphic and sedimentary rock clasts in NE Calabria (Trionto River catchment) (A, B) and on detrital metarenite slope deposits in SE Sardinia (S'Acqua Callenti stream catchment) (C, D). In C and D a laminated clay infilling exhibits an alternation of silt and silty-clay coatings.

may lead to the development of other common pedofeatures of this and other types of paleosols, such as reddish-brown/yellow to blackish Fe-Mn mottles, coatings, soft concentrations and concretions (Fig. 8) (Scarciglia et al. 2003a, 2006; Coltorti & Pieruccini, 2006; Robustelli et al., 2009; Di Celma et al., 2015; Cremaschi et al., 2015; Boretto et al., 2017). Among these, rounded nodules, which often exhibit a typical concentric internal fabric identified in thin section under an optical microscope, are common. This layered pattern testifies to a progressive outward growth from an initial accumulation of iron and manganese oxides around an inner "nucleus". Fe and Mn contents vary largely across the accretionary layering (White and Dixon, 1996; Liu et al., 2002; Scarciglia et al. 2003a). The nodules may display redder Fe-rich alternating with blackish Mn-rich layers, in response to cyclical changes in moisture availability from humid to dry soil state and slightly changing redox conditions (Taylor et al., 1964; McKenzie, 1989). Worth mentioning is that the intense tectonic activity, coupled with glacio-eustatic sea-level oscillations during the Pleistocene, in places led to the burial of paleosols, obviously developed under exposed continental conditions, by marine sediments emplaced during a transgressive depositional cycle (Fig. 8A). It is the case of a middle Pleistocene paleosol in the Cilento area (Campania region, southern Italy). It formed from aeolian deposits, was partially truncated and covered by 4-6 m of younger biocalcarenites reaching an altitude of about 35 m a.s.l., although nowadays it is not located along the coastline (Scarciglia et al., 2003a, b). Its burial modified the geochemistry of the pedogenic matrix, leading to a strong increase of sodium in the exchangeable complex despite its high solubility and mobility in the pedoenvironment, and especially to chlorine trapping in the iron-rich layers of the concentric nodules, as nicely shown in SEM-EDS (scanning electron microscopy coupled with energy dispersive X-ray spectrometry) compositional maps (Fig. 8C). Based on size, shape, outer rim outline and geometric relationships with the surrounding groundmass observed in thin sections, some case studies found that not always Fe-Mn nodules formed in situ (anorthic), but were eroded and redeposited from other adjacent paleosols, sometimes coexisting with in situ nodules (Cremaschi et al., 2015; Di Celma et al., 2015; Boretto et al., 2017; Frigerio et al., 2017).

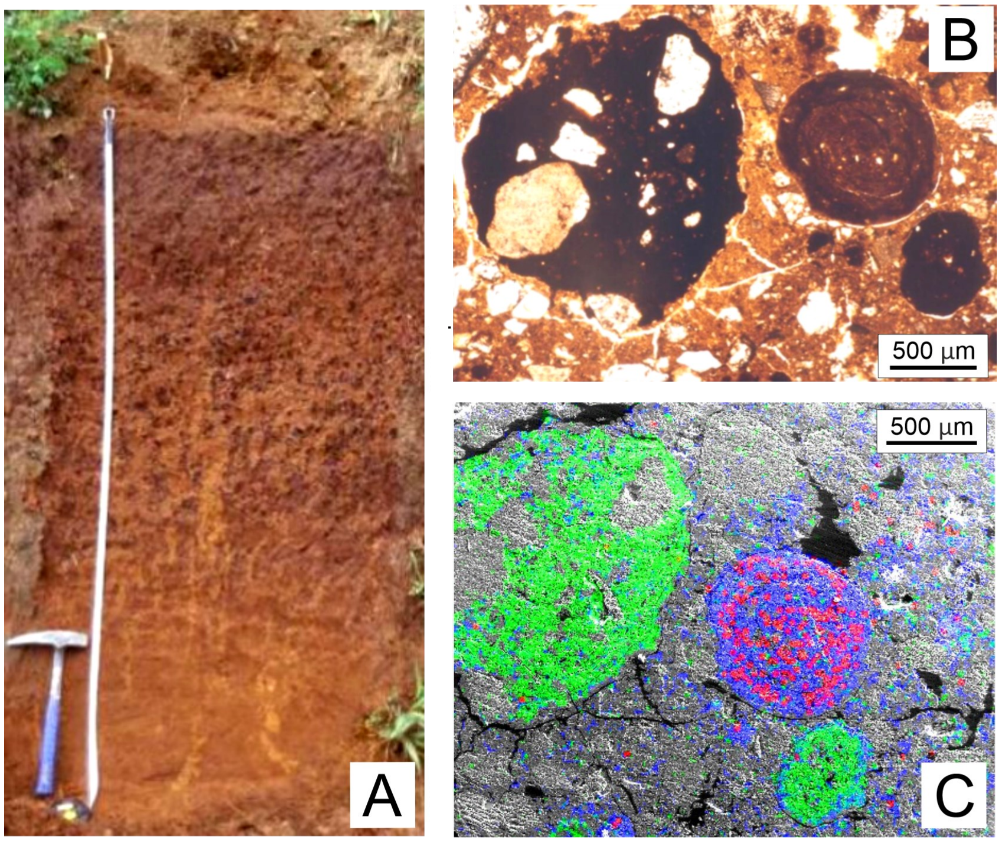


Fig. 8 - Partially truncated middle Pleistocene paleosol buried by marine bioclastic arenites in the Mt. Licosa promontory (Cilento, Campania) (A). Microphotograph of massive and concentric Fe-Mn nodules in the same paleosol (B) and corresponding EDS compositional maps of Mn (green), Fe (blue) and Cl (red) (C).

Both rubification and clay illuviation appear to be relict features. Actually, (late) glacial and Holocene (interglacial-like) soils do not display extensive red but rather (yellowish-)brown colors, and illuvial clay coatings have been usually attributed to glacial interstadials (with relatively milder climatic conditions than stadials), and/or to the late early to middle Holocene climatic optimum (sensu Rossignol-Strick, 1999), while scarcely present in Roman soils (Scarciglia et al., 2008; Aucelli et al., 2011; Pelle et al., 2013; Zucca et al., 2014a; Boretto et al., 2017). Similarly, based on pollen records from a karst cave in Apulia (SE Italy), Russo Ermolli et al. (2022) constrained reddish paleosols to the last interglacial, during which *Olea* was widespread in the Mediterranean area, and ascribed the overlying brownish soils to the Lateglacial, characterized by open, steppe-dominated environments with rare tree and shrub species. These finding are consistent with a comparison of soil-chronosequences from Mediterranean areas in Europe and California, which showed that matrix rubification can be found in soils >100,000 years (Sauer, 2010). Also, Fedoroff (1997) suggested that clay illuviation in red soils can only occur at present in humid/sub-humid margins of the Mediterranean basin. Based on these considerations, the Italian paleosols exhibiting the aforementioned features might have formed even under warmer and/or more humid climate conditions (tropical/subtropical) than modern (pre-industrial) times, able to enhance seasonal contrast and the speed/intensity of process response. This is in line with global-scale paleotemperature and stable isotope records (Lisiecki & Raymo, 2005; Hoffman et al., 2017) and paleoclimatic proxies from Italian marine and coastal environments, where Pleistocene interglacials (and the last interglacial in particular) are marked by higher sea-level stands and appearance of typical warm-water “Senegalese” fauna (e.g., *Persististrombus latus*, *Cladocora coespitosa*, *Globigerinoides ruber*) (Capraro et al., 2005; Ferranti et al., 2006; Amorosi et al., 2014a; Cerrone et al., 2021). The relict nature of the clay coatings in many Italian paleosols dating to the Pleistocene is proved by the frequent identification of post-emplacement degeneration/disruption features under the optical microscope in thin sections (Fig. 7) (Scarciglia et al., 2003a, b, 2006, 2009, 2011; Coltorti & Pieruccini, 2006). The main micromorphological evidence of their now inactive formation processes can be the one or more of the following: (1) smooth-banded to grainy extinction patterns observed between crossed polarizers, due to loss of the initial anisotropy (conversely showing sharp extinction bands derived from the parallel settlement of platy clay particles during illuviation onto pore surfaces); (2), fragmentation; (3) cross-cutting by subsequent pedofeatures; (4) deformation; (5) progressive disappearance

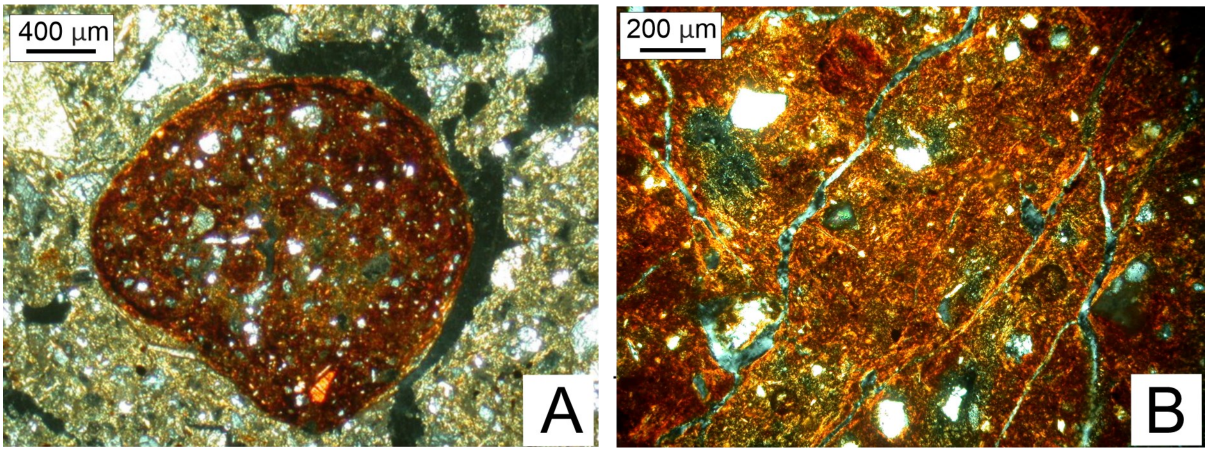


Fig. 9 - Microphotographs of: rounded iron-stained pedorelict reworked into a pedogenic matrix of a middle Pleistocene paleosol showing different color, fabric and skeletal grain size (Trionto River catchment, Calabria) (A); moderately anisotropic matrix showing parallel and crossed anisotropic domains in an argic horizon formed on an early middle Pleistocene marine terrace (north Tyrrhenian sea coast of Calabria, Torre Dino site) (B). Both frames are in crossed polarized light.

and assimilation into the surrounding pedogenic matrix; (6) (sub)rounded clayey papules (sensu Brewer, 1976) or pedorelicts (Fig. 9A), indicative of soil reworking processes. The spatial rearrangement of clay coatings and their internal fabric can be a result of shrink-swell (vertic) dynamics (argilloturbation), cryogenic processes triggered by freeze-thaw cycles, bioturbation by soil fauna or plant roots (Bronger, 1969/70; Brewer, 1976; Catt, 1989; FitzPatrick, 1984, Kemp, 1998; Verrecchia & Trombino, 2021, David Badía-Villas et al., 2022).

Based on the very diagnostic set of macro- and micromorphological features mentioned above, some researchers have tentatively used the red clay-illuviated paleosols (from north to south Italy) as rough indicators of possible Pleistocene interglacial-like climates, even when neither radiometric dating nor well-constrained chronostratigraphic information were available (e.g., Magaldi & Tallini, 2000; Cottignoli et al., 2002; Trombino & Ferraro, 2002; D'Amico et al., 2016).

Other interesting micromorphological features described in such types of Italian paleosols across peninsular and insular Italy are linear, crossed, curved or irregular anisotropic domains (speckled and striated b-fabric), observed in thin section under crossed polarized light (Fig. 9B) (Cremaschi & Van-Vliet Lanoë, 1990; Coltorti & Pieruccini, 2006; Scarciglia et al., 2006, 2011). They point to varying extents of iso-orientation of phyllosilicate clay platelets along cracks delimiting aggregates, around rock clasts, nodules, rounded pores or within the pedogenic matrix. They formed in response to cyclical shrink-and-swell dynamics of clay-bearing materials in turn caused by alternating soil desiccation/imbibition (vertic properties). This is consistent with cyclical changes in moisture, which also promoted clay translocation, iron-oxide staining and rubification. In places, the same authors found field evidence of this process in slickensides and/or shiny faces, although such features also occur in non-rubified soils and paleosols (e.g., Aucelli et al., 2011; Colombo et al., 2016).

Worthy of note are two innovative papers by Scarciglia et al. (2009, 2011), which for the first time applied laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to thin sections, associated with traditional micromorphological (optical and scanning electron microscopy) techniques, to investigate soil genesis in some pedons of SE Sardinia including a paleosol (Luvisol). Among the main results is the detection of a trend of increase in the contents of some trace elements, including rare earth elements (REEs), from the parent rock skeletal grains to the pedogenic matrix up to the illuvial clay coatings of the Bt horizons. This behavior highlights that element mobilization and fractionation was clearly controlled by pedogenesis, with trace elements released from the weathering of primary minerals, concentrated through illuviation processes and adsorption onto negatively charged surfaces of clay minerals (and iron oxyhydroxides) thanks to their cation exchange capacity.

#### 4.2. Paleosols with secondary carbonate accumulation

Case studies from several sites of Italy showed that commonly observed in Pleistocene paleosols formed on limestone/dolostone and other $CaCO_3$-bearing parent materials is decarbonation or decalcification (loss of carbonates by leaching), often coupled with recarbonation of deeper horizons. Secondary carbonate accumulation occurs in the form of soft concentrations, nodules or indurated concretions (sometimes including rhizoliths or impregnating the whole horizon) into Bk (calcic) and Bkm (petrocalcic) horizons (Fig. 10A) (Carboni et al., 2006; Coltorti & Pieruccini, 2006; Scarciglia et al., 2006; Sauer et al., 2010; Bracone et al., 2012; Di Celma et al., 2015).

The specificity and diffusion of such features is traditionally acknowledged in the popular culture and buried calcic soil horizons are often defined with proper names, as the abovementioned *caranto* in the Veneto region (Donnici et al., 2011) or the *crusta* and *tufina* in the Apulia region (Magaldi, 1983; Carnicelli et al., 1989; Magaldi & Giammatteo, 2008; Mariani et al., 2020). The latter terms refer to a petrocalcic soil horizon (calcrete)


Fig. 10 - Thick petrocalcic horizon of late Pleistocene age with composite laminar fabric in a fluviokarstic valley close to Altamura town (Apulia region) (A). Laminar and lenticular structures in a buried palaeosol developed on calcschist and serpentinite fluvial gravels and sands located downslope of Mt. Beigua in Liguria (photo courtesy of I. Rellini) (B).

formed in the late Pleistocene or early Holocene onto Pleistocene fluvial sediments related to the uplift of the southern Apennines. $CaCO_3$ redistribution often occurs in reddish, clay-illuviated paleosols as well. Carbonate leaching is often assumed to necessarily occur before clay illuviation to allow dispersion of clay particles (inhibited by high amounts of $Ca^{2+}$ and other divalent ions) and their translocation downprofile (Quènard et al., 2011). However, some case studies on soil chronosequences in south Italy demonstrated that clay illuviation occurred even in paleosols where soil carbonates are occasionally still present and pH values are not always acidic (Scarciglia et al., 2006; Robustelli et al., 2009; Sauer et al., 2010). This evidence suggests that $Na^+$ content in the exchangeable complex might have played a major role as driver of clay dispersivity and mobilization in respect of anti-dispersive (flocculating) $Ca^{2+}$ (or $Mg^{2+}$) ions. Nonetheless, a relative low amount of the divalent cations is not always sufficient to hamper completely the dispersal of clay particles, based on pH values and types of clay minerals. In addition, a climate change towards more seasonally contrasted and possibly overall drier conditions might have favored carbonate dynamics after clay mobilization. Such a seasonality might have controlled carbonate dissolution and leaching first, followed by marked water deficit for its reprecipitation. A suitable soil environment could be tentatively related to climate shifts occurred during the same interglacials (e.g., Zucca et al., 2014b) or rather during intervening glacial stages (Aucelli et al., 2011). The latter interpretation is consistent with the cyclical alternation of Pleistocene carbonate-enriched layers and reddish iron-stained paleosols observed at low latitudes. This feature is interpreted as a response to cyclical changes from dry to wet climatic conditions (Scarciglia et al., 2018), and agrees with the main glacial/interglacial cycles recorded in the $\delta^{18}O$ isotopic signature at high latitudes (Tiedemann et al., 1994). Pollen data collected across the entire Italian peninsula show a typical alternation of *Artemisia*-dominated or wooded steppes and mesophilic/thermophilic forest cover as a proxy of the vegetation changes occurred during the Pleistocene from overall warm/temperate and humid interglacials to cold/dry glacials respectively, although more complex patterns can be found locally (Bertini, 2010; Bertini et al., 2015). The works of Boretto et al. (2017) and Zanchetta et al. (2017) on stable isotopes from pedogenic carbonates and terrestrial mollusk shells found in a middle Pleistocene paleosol and a late Pleistocene loess developed during glacial periods (MIS 14 and MIS 2) in central Italy, support these findings. Values of $\delta^{13}C$ and $\delta^{18}O$ clearly evidence drier climate conditions, with a sparse C3-dominated vegetation cover and temperature on average 3-5 °C lower than present. Based on these considerations, where Bk horizons are observed at shallower depth, drier (semiarid) climate could be invoked (unless severe erosion has rejuvenated the paleosol profile), whereas subhumid conditions could have favored deeper pedogenic carbonate accumulation (cf. Retallack, 2005).

### 4.3. Paleosols developed under cold climatic conditions

According to Fedoroff (1997), red Mediterranean paleosols developed during Pleistocene interglacials, often experienced other geomorphic and pedogenic processes during intervening glacial periods. They were affected by erosion (truncation), colluviation, aggradation/burial by wind-transported dust (often providing allochthonous carbonate input with subsequent lea-

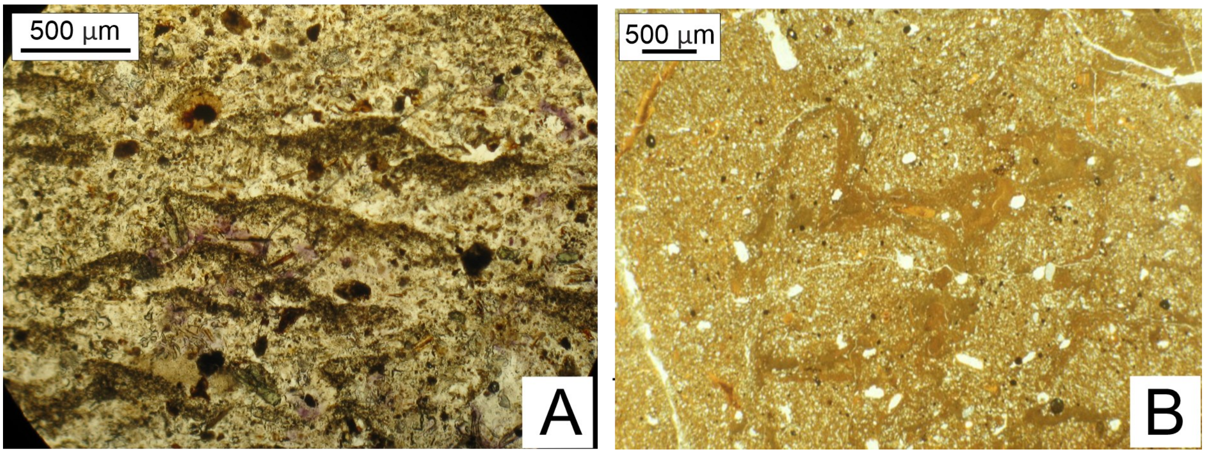


Fig. 11 - Microphotographs of: banded fabric developed in a weathered pyroclastic layer of late Pleistocene age (Agnano P.P. eruption, ~12 ka BP) sourced from the Phlegrean Fields in the Vesuvius piedmont, in Campania (photo courtesy of V. Zumpano) (A); cryoturbated silt and clay coatings and numerous vesicular pores in a Luvisol in the western Po River Plain, in Lombardy (B). Both frames are in plane polarized light.

ching/precipitation; see section 4.2) and/or local water logging (likely caused by wet conditions in response to slow seasonal ice thawing or prolonged melt during interstadials and partially impeded drainage). From northern to southern Italy, many researchers described soil features that clearly indicate the imprint of such a range of morphodynamic processes, also affecting other soil types (Cremaschi & Van-Vliet Lanoë, 1990; Coltorti & Pieruccini, 2006; Scarciglia et al., 2003b, 2015). There are many other morphological properties, observed at both field and microscale, attributed to Pleistocene glacial phases and considered diagnostic of seasonal soil freezing and thawing (periglacial conditions). These are platy, laminar, lenticular (Fig. 10B) or cuboid pedogenic structures, sand wedges and ice wedge casts, banded (micro)fabric (Fig. 11A), vesicular pores, cryoturbation (Fig. 11B) and rock clast orientation, in situ frost shattering of rocks, granulation or ped disaggregation, silt illuviation in the form of typical silt cappings (or caps), silt coatings/infillings (Fig. 7C, D) and sand coatings, degeneration/disruption of former illuvial clay coatings (Catt, 1989; FitzPatrick, 1997; Van Vliet-Lanoë, 1998; Van Vliet-Lanoë & Fox, 2018), discussed as follows.

Cremaschi & Van-Vliet Lanoë (1990) and Rellini et al. (2014) identified various horizontally elongated pedogenic structures in northern Italian paleosols of different Pleistocene ages located from Liguria to Lombardy even at low (non-mountain) altitudes on terraces, moraines, loess deposits and rock shelter fills at the margin of the Po Plain. Platy and foliated structures are typical features caused by seasonal ice segregation (freeze-thaw cycles) in the form of lenses or veins within fissures formed by cryodesiccation in response to a progressive propagation of soil cooling from the surface downwards (Van Vliet-Lanoë, 1998). In places, they may exhibit a banded fabric with internal textural changes (Fig. 11A) (Kemp, 1999).

Also, cubic structures formed by reticulate segregation patterns of ice were described from the Ligurian Alps (Rellini et al., 2014) to southern Tyrrhenian coastal sites (Scarciglia et al., 2003a, b), along with redoximorphic features and bleached tongues/zones, supposed to form under conditions of water stagnation or severely hampered drainage, enhanced by seasonal ice and snow melting. Scarciglia et al. (2003a, b) identified also vesicular pores, imprinted from air bubbles trapped during soil freezing, silt caps on skeletal grains and silt coatings in pores, derived from freeze-thaw cycles, in turn promoting aggregate disruption and granulation (see also Cremaschi & Van-Vliet Lanoë, 1990; Rellini et al., 2009), followed by melt water-driven migration of coarse particles downprofile. Degeneration features of clay coatings illuviated during Pleistocene interglacials (see section 4.1) were attributed to subsequent soil freezing and thawing under periglacial conditions. Although each of these pedogenic features has not always an univocal genesis, the coexistence of all of them in the same paleosols, coupled with other diagnostic geomorphological features observed in the study areas, support a past periglacial environment where (seasonal) frost action was prominent. This hypothesis is corroborated by the genesis of surface microrelief enhanced by frost action in swelling clay soils during the last glaciation, as well as by clear evidence of in situ frost shattering of cryogenic breccia (slope deposits) and a human-made flint artifact (Cremaschi & Van-Vliet Lanoë, 1990). In line with these finding, D'Amico et al. (2016, 2019) identified silt-illuviated horizons, lateral variations of coarse and fine particles, irregular depth patterns of organic matter, wedge casts and convoluted laminar microstructure in paleosols close to fossil periglacial landforms (blockfields/blockstreams, patterned ground and solifluction sheets) at elevations ≥600 m a.s.l. in the Ligurian Alps of Piedmont (NW Italy). All these features were explained by past cryoturbation and sorting during Pleistocene glacial periods. Also, typical stratified slope deposits (e.g., Coltorti & Dramis, 1988), emplaced by rockfalls and/or slope wash dynamics (Robustelli et al., 2005b), alternated to reddish (sometimes reworked) interglacial paleosols even in coastal zones of southern Italy (Esposito et al., 2003; Cottignoli et al., 2005; Scarciglia et al., 2006), support the past occurrence of periglacial conditions during Pleistocene glacial stages (Chelli et al., 2006). These led to cryoclastic and other cryonival processes, alternated and/or overprinted by varying surface dynamics and pedogenesis under milder conditions. Similarly, the main cryogenic features described by Rellini et al. (2014), located close to typical blockfields and blockstreams (Firpo et al., 2005, 2006), support the action of frost weathering (e.g., Ballantyne, 2010) and a combination of solifluction, gelifluction and/or frost creep, related to past glacial conditions and possibly a discontinuous permafrost. A recent work of Pintaldi et al. (2021) revealed the occurrence of well-developed paleosols hidden under the stony cover of periglacial blockstreams and blockfields in the NW Italian Alps, that likely record the major climatic changes and amelioration started since the end of the Last Glacial Maximum (LGM). In addition, the occurrence of reworked loess material on top of a polygenetic paleosol profile in the Ligurian Alps, displaying evidence of repeated phases of erosion and deposition, is consistent with an extension of windblown dust sedimentation during late Pleistocene cold dry stages in the north Italian region between the Alps and the Mediterranean (Rellini et al., 2014). Based on some of the aforementioned micropedological features (granular, platy, subangular blocky microstructures and silt cappings on coarse mineral grains), created by gelifluction and ice lensing, along with relative soil chronology obtained by comparing crystallinity ratios of free Fe oxides, and the analysis of paleoprecipitation/temperature derived from various proxies, Longhi et al. (2021) reconstructed late Pleistocene (and Holocene) podzolization phases and permafrost aggradation, the latter lowered more than 300 m than today, in the Central Italian Alps. To the last glacial period are referred a variety of soil morphological, micromorphological and sedimentological properties observed in two paleosols of mountain sites in the Sila Massif (Calabria), such as a sand wedge and an ice wedge cast, silt veins and lenses, reticulate silt veins and matrix lenses (Dimase, 2006). These features were interpreted as cryogenic and indicative of a periglacial environment possibly with former permafrost, and are in line with possible cirque landforms and moraine deposits reported by Boenzi & Palementola (1974, 1975) in close sites of the same massif. Ice wedge casts and other (micro- and macro-) pedofeatures related to the occurrence of permafrost were identified in loessic soils from northern Italy (Cremaschi, 1990; Zerboni et al., 2015, 2018; Negri et al., 2021), indicating the occurrence of phases of periglacial conditions at least at the northern margin of the Po Plain during the late Pleistocene. Ice wedge casts are good indicators of past permafrost conditions, but they are less common in the Italian loess record than in other loess basins of Europe, likely suggesting relatively less severe climatic settings.

#### 4.4. Loess plaeosols and aeolian input

During the Pleistocene, wind sedimentation occurred in many parts of Italy and triggered the formation of loess bodies and sand dunes, as much as the input of dust and volcanic material to soils (see also sections 2 and 4.6). Windblown sediments underwent pedogenesis under warm (interglacial/interstadial) and cold (glacial/stadial) phases, thus preserving information on past climate change. Such soils were sometimes buried and are still preserved along complex pedosedimentary sequences, whereas elsewhere they were eroded or overprinted by Holocene soil-forming processes (Cremaschi, 1987). Loess - windblown silt - is widespread along the Italian peninsula and was recently classified into the


Fig. 12 - Loess-palsosols sequences at Monte Netto (Lombardy) (A) and Ghiardo (Emilia Romagna) (A). In A a multiple sequence of middle to late Pleistocene loess weathered into soil lays on top of a fluvial deposit. Huge hydromorphic features and Bc horizons (dark layers) formed in correspondence of the top of each buried soil. In B the stratigraphic sequence on the Ghiardo plateau (Cavriago site outcrop) exhibits the loess weathered into Bt horizons and at its bottom a Bc horizon is present, laying on a middle Pleistocene clay-rich fluvial sediments (photo courtesy of M. Cremaschi).

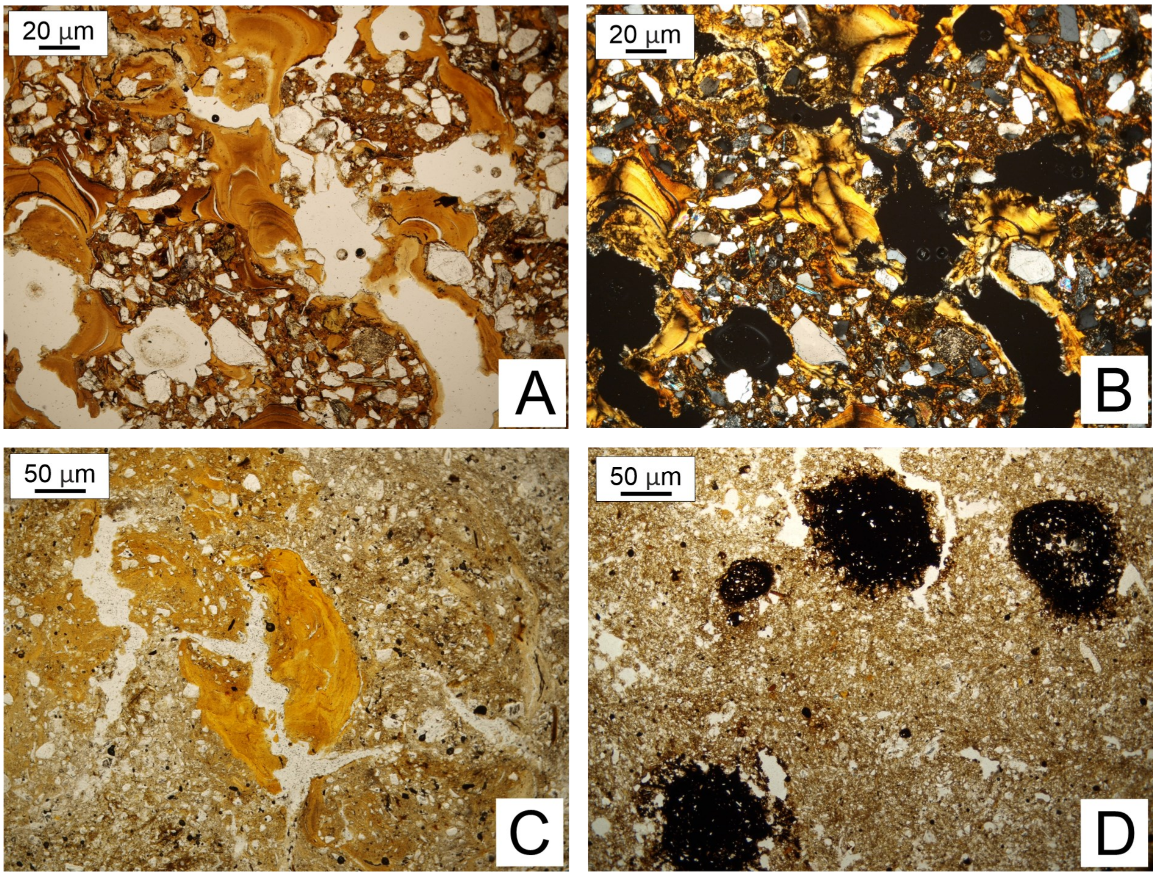


Fig. 13 - Microphotographs of: complex clay coatings in plane (A, C) and crossed polarized light (B) in a Bt horizon developed in a loess sequence from the central Po Plain (Monte Netto, Lombardy region); (D) A poorly weathered loess deposit from the central Po Plain (Ghiardo site, in Emilia Romagna) affectd by hydromophism (formation of Fe-Mn-rich nodules and discoloration of the groundmass) observed in plane polarized light. In all frames, the groundmass shows a dominance of silt grains.

Mediterranean loess domain of the loess landscapes of Europe (Lehmkuhl et al., 2021). In northern and central Italy, loess is widely recorded along the margins of the Po Plain (Fig. 12) and the coastline of the northern and eastern Adriatic Sea (Cremaschi et al., 1990; Cremaschi, 2004; Boretto et al., 2017; Costantini et al., 2018; Badino et al., 2020).

The main source for silt was the deflation of the middle/late Pleistocene fluvioglacial and fluvial deposits at the southern margin of the Alps and along the northern fringe of the Apennines and the exposed marine shelves. A further source of loess along the southern Adriatic and Tyrrhenian shorelines were reworked tephra sediments (Cremaschi & Ferraro, 2007; Hirniak et al., 2020). Italian loess is also often overprinted by pedogenesis (Costantini et al., 2018; Zerboni et al., 2018) and a variety of soils are interbedded within loess sequences, including Chernozems, Alfisols, Cambisols, and Luvisols. Occasionally, layers of reworked loess are also present. In many cases, polycyclic soils have been reported for loess sequences, suggesting the occurrence of subsequent pedogenic phases, marked by similar processes related to soil decarbonation, formation of iron oxides and clay translocation (Fig. 13) (Cremaschi, 1987; Cremaschi & Busacca, 1998; Zerboni et al., 2015; Negri et al., 2021). Some studies also highlight the relative role played by time and climate in the formation of loessic soils (Cremaschi & Busacca, 1998). Loessic soils commonly found along the northern fringe of the Apennines display evidence of strong clay neoformation and translocation as much as huge decarbonatation occurred in the Holocene (Cremaschi et al., 2015).

Periglacial processes were also reported from several loess/paleosols sequences from northern Italy. They are occasionally testified by the occurrence of pedofeatures related to soil freezing (e.g., ice lensing) (Cremaschi et al., 1990, 2015; Cremaschi & Van Vliet-Lanöe, 1990). The Val Sorda loess sequence, for instance, covers a truncated rubified soil dated to the last interglacial and includes at least three Chernozem-type buried paleosols (Ferraro, 2009), corresponding to phases of decreased wind sedimentation and accumulation of organics with low-rate of turnover in a steppe-like environment. At Monte Netto, several loessic soils are superimposed along a soil sequence formed since the middle Pleistocene and displaying a progressive reduction in intensity of soil forming processes during each phase of pedogenesis (Fig. 13A) (Zerboni et al., 2015). At the same site, the rate of pedogenesis informs on the tectonic evolution of the area and the rate of vertical uplift. Loess sediments accumulated on top of karst regions or of limestone plateaus were affected by stronger pedogenesis and were almost completed digested into soils (Trombino & Ferraro, 2002; Sauro et al., 2009; Peresani & Nicosia, 2015; D'Amico et al., 2021). Such evidence confirms that the paleopedological properties of Italian loess records soil-forming processes occurred under different climatic conditions encompassing the glacial/interglacial phases of the middle and late Pleistocene. Costantini et al. (2018) suggested that the identification of loess contribution to soil formation can be detected based on selected pedological parameters (particle size distribution and sorting, pedostratigraphic position, shape of the grains observed under optical and scanning electron microscopes, soil micromorphological features). Along the shorelines of Italy, several Pleistocene dunes deeply affected by pedogenesis can be found. Some of them were interpreted as eolianites. Along the shore of the Elba Island (Tyrrhenian Sea), late Pleistocene calcareous eolianites were affected by deep redistribution of calcium carbonate due to pedogenesis. Moreover, they display interlayered rubified soils that suggest the occurrence of phases of intense pedogenesis (Cremaschi & Trombino, 1998a; D'Orefice et al., 2007). Eolianites with interlayered rubified paleosols have been reported also from Sardinia (Coltorti et al., 2010). Zucca et al. (2014a) report on a complex sequence formed by the interplay between pedogenesis and wind sedimentation along the coastline of Sardinia, where a paleosol is buried by a coastal dune that experienced significant pedogenesis during the late Pleistocene interstadials, before being buried by aeolian sand.

The identification of aeolian inputs to soil formation is often difficult to assess, but several authors investigated Pleistocene paleosols form Italy and identified inputs from proximal or distal dust sources (Costantini et al., 2018). The input of Saharan dust is likely ubiquitous over Europe, but its identification in ancient soils need a careful characterization of the geochemical fingerprint and of the mineral constituents of soil horizons. Giraudi et al. (2013) identified the occurrence of hexogen quartz in soils from the Mount Matese in southern Italy, associated to dust sedimentation sustained by late Pleistocene phases of increased aridity and deflation over the Sahara Desert. Andreucci et al. (2012) investigated a reworked paleosol from NW Sardinia and using SEM observation and XRD analyses identified the occurrence of abundant allochthonous dust that represents a Saharan input to the island, which continued for large part of the late Pleistocene.

### 4.5. Fragipan, plinthite and petroplinthite-bearing paleosols

Other interesting field features described in Pleistocene paleosols of Italy are fragipans (Fig. 14), plinthite and petroplinthite, all of which characterized by important enrichment in iron oxides and phyllosilicate clays. The genesis of fragipans is an actively debated and noteworthy issue, which still warrants strong research efforts to deepen in the understanding of the mechanisms responsible of their peculiar features. Among the major hypotheses proposed in the literature, nicely summarized by Bockheim & Hartemink (2013), are the following: hydro-consolidation of wet soil material overloaded

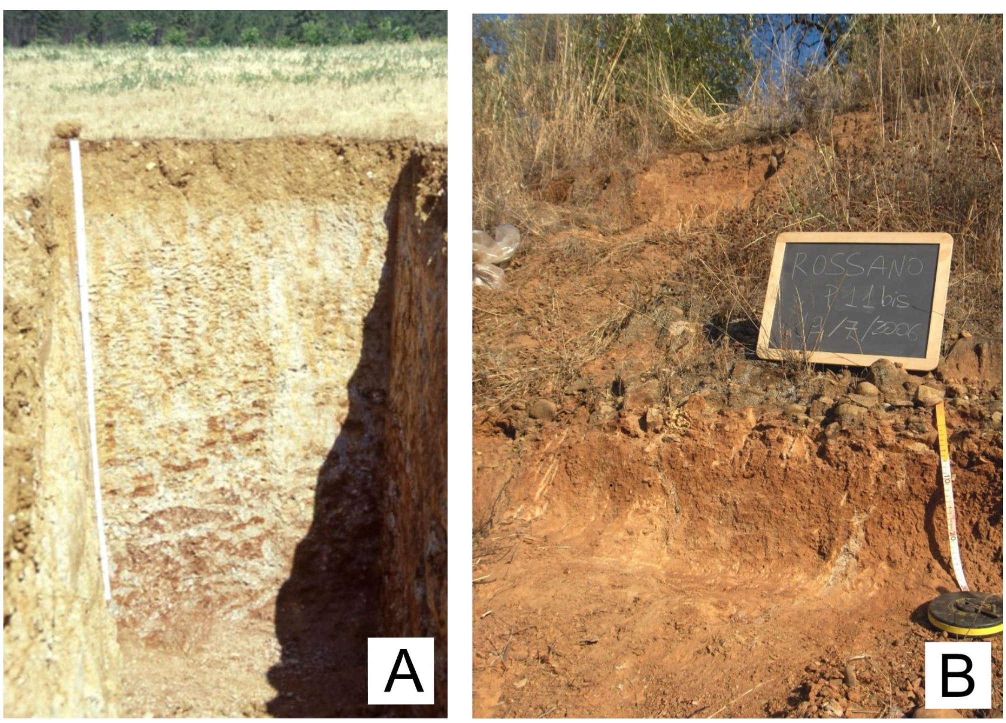


Fig. 14 - Paleosols exhibiting densely-packed horizons with hard consistence and fragic properties, which contributed to the development of glossic features, in places marking lenticular (A) or angular blocky to prismatic (B) structures. (A) Montagnola Senese, Tuscany; (B) Trionto River basin, Calabria).

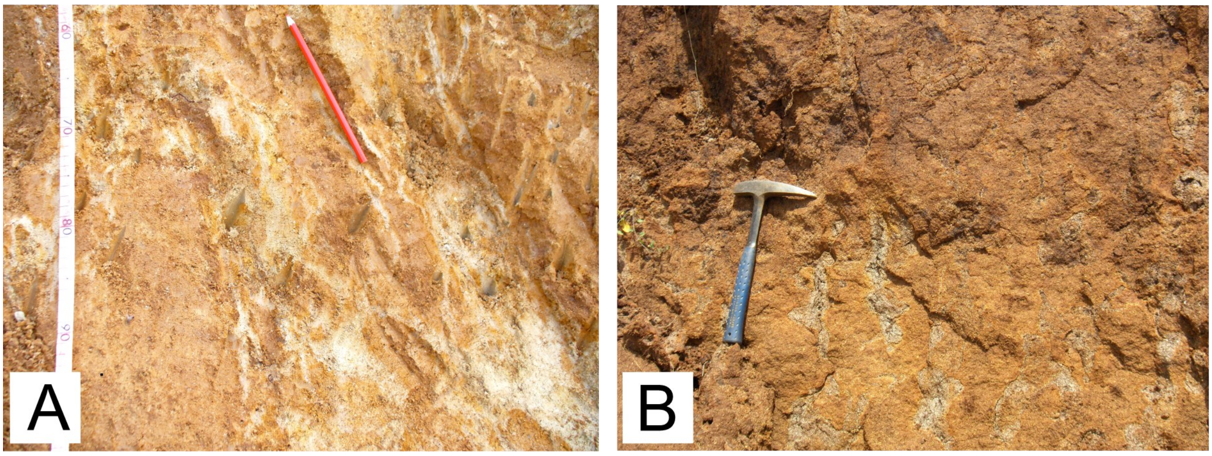


Fig. 15 - Irregular to reticulate (A) and tongued (B) redox depletion zones surrounded by iron-oxide stained pedogenic matrix in two plaeosols developed on middle Pleistocene fluvial and marine terraces from the Tyrrhenian and Ionian coasts of Calabria, respectively.

by younger heavy sediments upon wetting and drying; mechanical compaction and close-packing of soil particles, in cases promoted by shrink-swell cycles or ice growth and freeze-thaw cycles under relict periglacial conditions; the presence of lithologic discontinuities or paralithic/lithic contacts across soil profiles; seismic shaking and liquefaction; bonding by precipitated iron, aluminum, silica and/or clays. Costantini & Napoli (1996) studied in detail some fragipans and other close-packed horizons from different paleosols, developed during the Pleistocene on alluvial and colluvial deposits derived from metamorphic rocks in the Montagnola Senese area, in Tuscany. They showed silt-dominated textures, with alternatively high contents of sand or clay, overall hard consistence, high bulk and package density, poor hydraulic conductivity with prevalent micropores, varying extent of illuvial clay coatings/infillings often partially disrupted, high amounts of iron-oxides and free iron, redox depletion zones, no carbonate and poor contents of extractable silica.

In the same region, Certini et al. (2007) characterized some discontinuously distributed fragipans using field, physical, chemical, mineralogical, micromorphological analyses and radiocarbon dating, and argued that dewatering of past earthflow deposits could have led to consolidation of the soil material rather than other causes such as frost action. Scalenghe et al. (2004) addressed similar hypotheses, pointing to the role of liquefaction of soil material caused by earthquakes, after performing experimental freeze-thaw cycles and vibrations of dry and water-saturated soil materials at different amplitude and time spans. Ajmone Marsan & Torrent (1989) hypothesized the role of amorphous silica compounds associated with Fe oxides (mostly goethite) as bonding agents in a paleosol with fragic properties developed on a river terrace of Pleistocene age in NW Italy, using citrate-bicarbonate-dithionite and acid oxalate extractions. Other works on fragipans of Italy are those of Ajmone Marsan et al. (1994) and Falsone & Bonifacio (2009) on such types of dense/indurated horizons in the Piedmont region. They highlighted the role of soil porosity in terms of pore size distribution and spatial arrangement of coarse and fine particles, controlled by the nature of the parent materials and by pedogenic processes, applying physical analyses, Hg intrusion porosimetry and/or image analysis of thin sections along with morphological observations. Assallay et al. (1998) suggested the possibility of fragipan formation in loess soils after hydroconsolidation, and Zerboni et al. (2015) detected fragic properties were in Bt(x) soil horizons from the Monte Netto loess sequence. Based on our experience, some transitional horizons that display reticulate, lenticular or tongued eluvial and Fe-depleted patterns within Fe- and clay-enriched matrix, such as EBt, BEt, E/Bt and B/Et horizons (Fig. 15) (Scarciglia et al 2003a, b, 2015; Robustelli et al., 2009) warrants attention, as occasionally observed in some paleosols of Italy of middle Pleistocene age. Among these are some described by Robustelli et al. (2009) in Calabria, which were extremely hard to sample even using a geological hammer but slaked quickly after immersion in water, and might represent fragipans (EBtx, BEtx, E/Btx and Bx/Et) to be investigated deeply, trying to assess their complex genesis. Preliminary data suggest that they could have been derived from seasonal freezing and thawing during glacial stages, overprinted on mostly interglacial features.

Rellini et al. (2015) provide another case study on an indurated, petroplinthic horizon from a polygenetic paleosol, in the frame of a reconstruction of Quaternary paleoenvironmental changes in a coastal pedosedimentary sequence from northwestern Italy. By combining physico-chemical analyses, X-ray diffraction, micromorphological observations in thin section and scanning electron microscopy, the authors suggested that the hardening of petroplinthite derived from secondary Fe-oxide enrichment due to intensely weathered, lateritic nodules reworked from an upslope, dismantled plinthite paleosol, which had previously undergone lateritization processes under different, tropical-like conditions.

#### 4.6. Volcanic paleosols

Given the long-lasting eruptive history of peninsular and insular Italian volcanoes over the Pleistocene (and the Pliocene) (Peccerillo, 2005), several strictly volcanic and peri-volcanic to distal environments appear potentially good natural archives where lava flows and/or fall deposits were spread and potentially led to associated soil formation. When the eruptive products can be dated by radiometric techniques or their provenance can be identified directly in the field or using geochemical tracers or minero-petrographic imprints, tephra reveal as very useful tools to fix time constraint to pedogenesis, achieve tephrostratigraphic correlations (see section 2) and allow paleoclimatic/environmental reconstructions at varying spatial and temporal scales. Volcanic parent materials weathered to different extents, and in places mixed with different local substrates of non-volcanic origin, were widely identified in Pleistocene pedostratigraphic successions across the Italian territory. However, in many cases, the corresponding soil profiles and horizons did not exhibit typical features directly linked to the volcanic input (Fig. 2B) (Aucelli et al., 2011; Colombo et al., 2016) or were not sufficiently characterized in terms of specific analytical techniques from such a diagnostic perspective (Magaldi et al., 2009; Peresani & Nicosia, 2015; Marinari et al., 2017; Zuffetti et al., 2018; Pereira et al., 2020). In some other cases, paleosols developed on tephra displayed distinct andic properties, typical of Andisols/Andosols (Soil Survey Staff, 2014; IUSS Working Group, 2015) and related to neoformed SROM, i.e. short-range order (poorly crystalline) clay minerals (allophane, imogolite) and Fe-hydroxide (ferrihydrite), or at least andic-like features despite belonging to other soil groups. Frezzotti & Narcisi (1996) identified a buried paleosol (Pedomarker A) with andic properties, occasionally truncated, widespread in the central Apennine chain. It developed on volcanic ashes sourced from the well-known Campanian Ignimbrite explosive eruption from the Phlegrean Fields (Campania region), overlies carbonate outwash fan, alluvial and stratified slope deposits, and is sealed by similar types of clastic sediments and loess. The authors' results indicate that this paleosol formed under temperate humid climatic conditions, likely occurred during the last interstadial oscillations of the Pleniglacial, approximately between 39 and 30 ka. Its development was interrupted by the early onset of colder and drier conditions of the Last Glacial Maximum, which led to the emplacement of periglacial deposits, along with soil degradation, erosion and colluviation. De Rosa et al. (2016) reported partly similar findings studying in detail the major pedogenic and syn-eruptive hydromagmatic emplacement features and processes of some brown tuffs, located on Lipari Island and widespread in the Aeolian archipelago within a similar time span (ca. 40 to 27 ka). The poor development of andic properties is consistent with a prevalent dry climate during the last glacial period. Nonetheless, some seasonal contrast between subhumid to dry conditions favored the neogenesis of phyllosilicate (crystalline) clay minerals, in particular the transformation of smectite (derived from the hydrothermal alteration of primary volcanic glass) to halloysite, rather than poorly crystalline clays (preferentially promoted under prolonged moisture availability). Similarly, such conditions, likely occurred during milder glacial interstadials, were prone to the illuviation of clay coatings. The paper of Mirabella et al. (2005) is in line with the absence of andic properties in other paleosols and soils of late Pleistocene ages on the same island, which conversely displayed vitric and vertic features. In turn, Egli et al. (2008) explored the relationships between time spans of pedogenesis and some soil properties in other Pleistocene pedons on Mt. Etna volcano in NE Sicily, where andic properties and short-range order minerals were identified, along with phyllosilicate clays, but also recorded a clear addition of younger volcanic ashes contributing to soil formation. Still formed during the last glacial period are some buried paleosols located in the piedmont of Mt. Vesuvius volcano and the surrounding plain, overlain by Holocene volcanic soils (Scarciglia et al., 2014; Vogel et al., 2016). Based on the well-dated eruptions from the Vesuvius and the Phlegrean Fields in the range of ca. 22 to 12 ka, along with detailed geochemical, mineralogical, micromorphological analyses and pedogenic Fe indices, Scarciglia et al. (2014) emphasized the role of time and climate in respect of the development of andic properties. Predominant SROM components were found in the pedogenic horizons corresponding to the early post-glacial amelioration and a milder interstadial of the LGM just predating the last Pleniglacial culmination, during which climatic conditions were moister than the intermediate stadial and the subsequent Lateglacial. Conversely, in the paleosol horizons developed during proper glacial stages, phyllosilicate clay minerals prevailed thanks to drier and more seasonally contrasted environments. Vacca et al. (2003) highlighted that in the Roccamonfina volcano area (ca. 60 km NW of the Vesuvius), allophanic and non-allophanic Pleistocene soils coexist in similar landscapes under similar climatic conditions, probably as a response to different hydraulic properties of the parent material and different time ranges of pedogenesis. Allophanic soils developed in younger, porous and permeable ash deposits, which favored a rapid weathering of glass fragments and consequent release and availability of Al and Si to enter the lattice of poorly crystalline clays. Diversely, non-allophanic soils developed in older, less porous and less permeable scoria and consolidated tuffs, promoting the neoformation of crystalline clays (including halloysite) as a weathering product of volcanic glass. Colombo et al. (2007) highlighted the prominent role of the duration of pedogenesis, along with climate, land use and human disturbance, for the varying degree of development of andic properties in volcanic paleosols of Latium and Campania which they considered more important than the role of parent materials with different mineralogical compositions.

## 5. SOME APPLICATIONS OF PALEOSOL STUDIES

### 5.1. Paleosol fertility and cultural value

A relevant field of application of the paleosol knowledge in the Italian peninsula regards fertility, especially in relation to the uniqueness and irreproducibility of paleosol features. Costantini et al. (2012) investigated the main relationships between soil/paleosol properties, fertility, functional traits (soil texture, stoniness, root depth, bulk density, organic carbon, pH, cation exchange capacity, available water capacity, total carbonate, electrical conductivity, topography, pedoclimatic regime) and viticultural and oenological behavior, grape productivity and organoleptic characteristics of a worldwide famous vintage wine in some vineyards of Tuscany. Pedological properties of Pleistocene (and Holocene) paleosols and corresponding vine varieties and quality changed remarkably even when developed on the same types of sediments, in response to unique natural geomorphological events and human impact on landscape shaping, in turn affecting the equilibrium between soil formation and erosion. Therefore, such terroirs represent soil-climate-vineyard ecosystems that partly inherited their properties from past climatic/environmental conditions, but at the same time, they are intrinsically fragile and potentially prone to degradation. Costantini et al. (2012) emphasized the need for considering them as part of the cultural heritage and legacy, worth of sustainable management and protection, especially to prevent possible ecological and economic losses, and increase the awareness of stakeholders through a deeper comprehension of the paleosols in the frame of the Quaternary landscape evolution. Adequate strategies of land planning should thus include information about paleosols and associated paleolandscapes, largely threatened by urbanization and other human activities, along with their cultural value rated through a set of intrinsic and extrinsic information. Among these are their location and extension, geological setting and age, rarity of the diagnostic horizons, type of scientific interest and level of knowledge, state of preservation, type and intensity of risk, active and potential measures of protection, accessibility, exposure and visibility, tested through a large database of paleosols in Italy (Costantini et al., 2007a; Costantini & L'Abate, 2009; Costantini, 2018). Based on a study in the Lombardy region, Costantini et al. (2007a) proposed an enlargement of parks and natural protected areas as a suitable policy for the preservation of the paleosol heritage, especially those of outstanding cultural value. Moreover, Costantini (2018) stressed the need for compiling a red list of the European (and possibly worldwide) "pedosites" where paleosols pedodiversity (sensu Ibanez & Bockheim, 2013) have high risk of degradation and extinction. Costantini & L'Abate (2009) and Bollati & Zerboni (2021) remarked how paleopedological heritage and pedodiversity recorded by paleosols in natural and archaeological contexts (in places also including paleontological remnants) can contribute to the geodiversity and geomorphodiversity expressed by traditional "geosites". They can thus add value to the geoheritage, not only from a scientific perspective related to a site-intrinsic geodiversity, but also from their potential for use. In this respect, paleosols are expressions of richness and diversity of the natural and human-related history of the local territory and valuable resources for the citizens living therein, in terms of cultural and educational values, along with functional, aesthetic, recreational and geotouristic potential, worth of being promoted and valorized, for instance planning 'soil trails' (Masseroli et al., 2022) as geocultural itineraries. Therefore, the pedodiversity of Pleistocene paleosols needs to be protected from its vulnerability to natural and anthropogenic threats.

Also the Cecita Lake geosol mentioned above (section 2) warrants attention in respect of its use, fertility and protection. Its complex genesis, partly linked to the mixed origin of its parent materials, highlights the beneficial effects of the late Pleistocene and Holocene volcanic ashes as natural fertilizers. The rapid weathering of volcanic glass and associated pedogenic processes led to the neogenesis of poorly crystalline clay minerals (Scarciglia et al., 2008), which contribute, together with a dominant loamy texture, to the high water-holding capacity under well-drained conditions. These geopedological properties likely promote the good quality of the local potato, along with the large temperature ranges between day and night and the cold winter climatic conditions, controlled by the elevation above 1000 m a.s.l.. The thickest and high waterproof peel of the Sila tuber than other potatoes cultivated in Europe, acts as a very efficient protective barrier against large temperature shifts. These in turn minimize the parasitizing potential, making treatments with pesticides less intensive or unnecessary. Indeed, this agrifood product of excellence, largely cultivated in the Sila plateau, displays specific organoleptic properties (higher starch content than average values, with consequent greater nutritious value and taste), based on which it holds the protected geographical indication (PGI) trademark attributed by the European Union (data from Ifex - Italian Food Excellence Group, 2014). Nonetheless, the severe surface erosion that affects the Sila upland (Raab et al., 2018; Scarciglia et al., 2020), represents a real threat not only for the geosol itself, but even for the potato as a typical agricultural resource and other crops (mainly cereals, such as wheat and oats). Actually, these are among the main drivers of the local economy together with pasture and farming, which in turn benefit from a good quality of grassland growing in the natural soil, sourcing hay and plant fruits for cattle, sheep and pigs, and direct food derivatives (milk, cheese and sausages).

### 5.2. Pedogenic processes and potential pollution of paleosols

Another key issue regarding soil quality refers to the source, amount and spatial distribution of the so called "heavy metals", i.e. potentially toxic elements (PTEs), the role of the soil system as an environmental filter and the evaluation of its potential pollution. The work of Costantini et al. (2002) pointed out the relevance of natural, pedogenic processes in addressing element behavior in some soil profiles of the Montagnola Senese (Tuscany), and especially an enrichment in paleosols and deep horizons, often neglected in favor of investigations involving topsoils only. Among the main results are a control of metal amounts by neogenesis and illuviation of clays, with local element depletion and leaching within eluvial zones and under reducing conditions, along with an increase of some PTEs (Cr, Pb, Zn, Mn) with soil age, thus showing higher amounts in early and middle Pleistocene paleosols than in Holocene soils. These results support the need of a detailed methodological approach combining field data with physical and geochemical laboratory analyses in order to evaluate the effective filter and sink capacity of soils and paleosols in respect to pollutants, and the need for an adequate regulation. Similar findings and highlights were reported with more detailed, multi-analytical and multiscale methodologies in a series of linked papers, where for the first time inductively coupled plasma mass spectrometry equipped with laser ablation (LA-ICP-MS) was applied on thin sections of soils and paleosols of Sardinia in the Muravera area (see section 4.1), and integrated with soil micromorphology and geochemistry (Scarciglia et al., 2009, 2011; Scarciglia & Barca, 2017). These works successfully traced the behavior and fate of trace elements including rare earths and potential pollutants at the microsite level, allowing discriminating the contribution of PTEs in relation to the intrinsic spatial variability of soil profiles and pedogenic features. In particular, trace metals were assessed in discrete soil subcomponents, such as skeletal rock fragments, clay-enriched and humified pedogenic matrix, and specific pedofeatures of illuvial origin (unstained or iron-stained clay coatings) in A and Bt horizons. The role of mineral weathering and soil formation processes was clearly demonstrated, tracing the release and fractionation of PTEs and other trace metals from primary components of the parent rocks, their adsorption onto negatively charged surfaces of clay minerals, iron oxyhydroxides and/or organic matter through their cation exchange capacity, and their enrichment/migration through illuviation processes. This approach permitted to assess PTEs even at very low contents, i.e. at early stages of concentration due to pedogenic processes, which could be an efficient tool for prevention of soil pollution and adequate risk mitigation strategies. Scarciglia and co-authors revealed an anthropogenic contribution of heavy metal-bearing mineral grains sourced from abandoned mine plants, in addition to the natural host rocks, and a prominent interplay of soil-forming processes with geomorphic dynamics to explain the spatial distribution of trace elements. Part of the geochemical behavior in different horizons of the paleosols can be considered as inherited from past, now inactive genetic processes, superimposed by younger and current processes.

### 5.3. Geotechnical and seismic behavior of paleosols

Few papers showed that the specific properties of some Italian paleosols can have a great relevance also in the light of geotechnical, engineering and construction purposes. It is the case of the hard, cemented *caranto* paleosol extensively found under sediments in the area of the Venice Lagoon (see section 2). Donnici et al. (2011) found relatively high unconfined compressive and shear strengths in response to pedogenic processes and consolidation under aerial exposure conditions, compared to unweathered lagoonal deposits. These properties permitted its use as a valuable substrate for the foundations of only a few larger constructions directly extending into the *caranto*. Conversely, it represented a more resistant layer, able to support the overlying plastic lagoon deposits, loaded by the foundations of most of the Venetian buildings, and thus acting as their lowest constraint. This behavior increased structural stability, drove the location of human settlements since Gothic times ($12^{th}$-$15^{th}$ centuries A.D.), when Venice widely experienced much of its urbanization, and allowed the preservation of buildings even after several historical earthquakes. Another interesting case study is the recent work of Tallini et al. (2020), who explored the potential link of paleosols with seismic site effects in the L'Aquila downtown (Abruzzo region, central Italy). This urban area is characterized by a high seismic risk and was severely damaged by a high magnitude (Mw 6.1) earthquake in 2009. The researchers hypothesized that the shaking effects of the earthquake could have been amplified by the local presence of a reddish colluviated Alfisol developed during the late Pleistocene, overlying a weathered epikarst zone on calcareous slope breccias of middle Pleistocene age, in turn burying a Maso-Cenozoic bedrock. The varying spatial distribution of the red paleosol in terms of surface and depth extension, seems to be responsible for the medium microtremor frequency (3-13 Hz) recorded site-by-site in the area, suggesting a seismic resonance, i.e. a seismic coupling of the shallow geopedological setting with the fundamental frequency of the buildings. The areal distribution of buildings that were affected by damages or collapsed during the 2009 and 1703 earthquakes of L'Aquila strongly supported the hypothesis of a seismic paleosol-building coupling. This work highlighted the great potential of characterizing paleosols, as usually neglected, to assess seismic hazard and associated risk in areas with high current, historical and late Quaternary seismicity, such as almost the entire Italian territory and several other countries worldwide. In many cases paleosols could provide useful data in defining seismic site effects, thus helping in mitigating the seismic risk of urban areas, especially where historical constructions are more vulnerable to earthquake dynamic solicitations and have high cultural heritage value.

### 5.4. Applications to geoarchaeology

The contribution of paleopedology and related analytical methods (especially micropedology) to the archaeological research is well established (Courty et al., 1989; MacPhail & Goldberg, 2017) and relies on the general concept that the formation and preservation of archaeological sites and anthropogenic sequences is ruled out by the same processes that oversee the formation of soil: pedogenesis controls the transformation of each sediment at the Earth's surface including the anthropogenic ones and those entombing artefacts. Several researchers have used archaeological findings (which are widespread and frequently detected in paleosols of Italy because of a long-lasting flourishing of civilizations and pedosedimentary stratification of remains of different epochs) as valuable tools to fix some chronological constraints to paleosol development. To this purpose, both the vestigiae of settlements and human artifacts have revealed their great potential, often allowing a correlation of major paleopedogenic features (and associated processes) with other paleoclimatic/environmental proxies. The investigation of archaeological materials occasionally revealed the exploitation of georesources, including the use of clay-rich B horizons from Pleistocene paleosols to make bricks or pottery, thus allowing to trace the provenance of raw materials. For instance, at the Pulo di Molfetta Neolithic sites, people largely exploited the local clay-rich *Terra Fusca*-type paleosol (Fig. 16A, B), corresponding to the pristine infilling of a sinkhole (Muntoni & Zerboni, 2017).

In general, we must keep in mind that the stratification of archaeological layers and archaeological soils

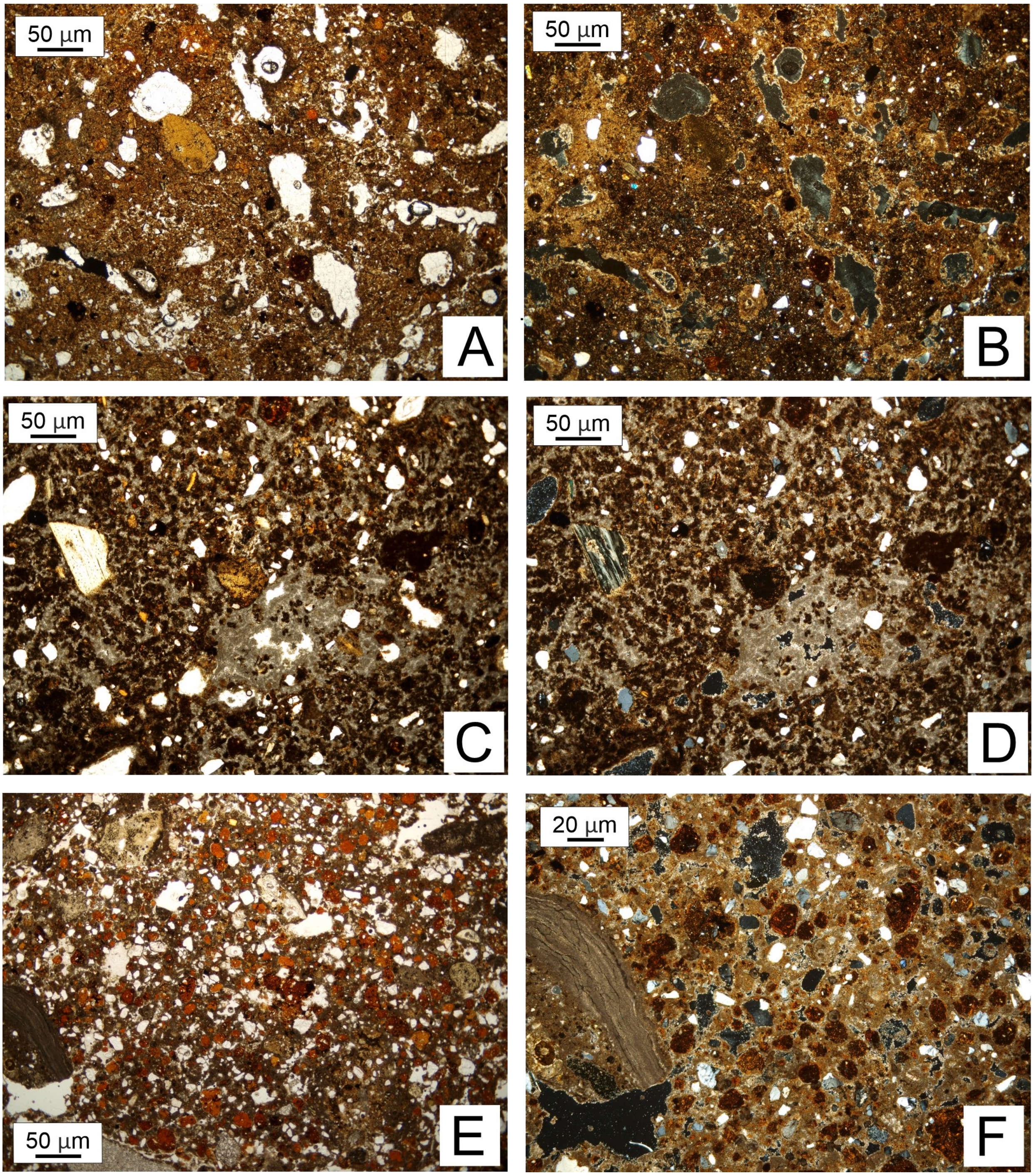


Fig. 16 - Microphotographs of: (A, B) reworked *Terra Fusca*-type soil material from the Pulo di Molfetta archaeological site; (C, D) strong redistribution of $CaCO_3$ from a late Pleistocene occupational layer in the Uluzzo C rock shelter; granular aggregates and occasional bone fragments are visible; (E, F) aeolian quartz grains and red, rounded pedorelicts cemented by calcite from a late Pleistocene layer of the Uluzzo C rock shelter; a fragment of laminated speleothem crust (lithorelict) is visible. F shows at higher magnification the same features as in E. Frames A, C, E are in plane polarized light and frames B, D, F are in crossed polarized light.

results from the interplay of two contrasting types of processes (Cremaschi & Rodolfi, 1991; Cremaschi, 2000). On the one hand, human agency controlled all the processes, including the accumulation of sediments and its physical and chemical transformation. Such processes prevailed during the phase of life of an archaeological site. On the other hand, after the abandonment of an archaeological site, the onset of natural processes of pedogenesis modified anthropogenic sediments. In Italy, paleopedology supported the geoarchaeological investigation on several archaeological sequences dating to the Pleistocene, including open-air and sheltered sites. In the case of open-air contexts, archaeological layers interlayered to the pedostratigraphic sequences or archaeological soils containing evidence of human exploitation generally underwent deep pedogenesis affecting also archaeological materials. One of the most important Italian archaeological sites dating to the Lower Paleolithic is the Isernia La Pineta butchering site, dated to the beginning of the early/middle Pleistocene transition. Therein, a complex sequence of fluvial lacustrine, spring, and volcanic sediments includes a layer of cross -bedded gravels, where a thick Alfisols with a well-expressed Bt horizon developed (Coltorti et al., 1982, 2005). Middle Palaeolithic occupation layers are preserved at many localities of the northern margin of the Apennines at the interface between continental fluvial sediments and late Pleistocene loess sediments. At those locations, Mousterian hunters exploited the elevated surface of fluvial terraces to establish temporary campsites. This phase of human occupation was contemporary with the early period of loess sedimentation (Cremaschi et al., 2015). At Ghiardo site (Emilia Romagna), extensive archaeological excavations and paleopedological analyses highlighted the occurrence of deeply weathered loess deposits, including a sequence of Bt horizons laying on top of a Bc horizon marked by the formation of abundant Mn/Fe nodules and concretions (Fig. 12B). Holocene pedogenesis promoted a strong neoformation and illuviation of clay along the loessic soil, whereas in correspondence of the occupation layer water-logged conditions promoted hydromorphic features (Fig. 13). A systematic investigation disclosed the existence of a buried undulated surface, interpreted as a gilgai microrelief and likely caused by long-lasting vertic process (Cremaschi & Christopher, 1984). At those sites, pedogenesis also affected lithic artifacts, whch displayed specific (yellowish-brown to reddish) patination depending on the specific setting of the soil horizons where they were entombed; in this case, soil science is helpful in explaining secondary displacement of archaeological materials. Mousterian artifacts are commonly found along loess sequences at the margin of the Po Plain (Baroni, 1986; Cremaschi, 1987, 1990; Zerboni et al., 2018) and are useful chronological indicators for the age of pedostratigraphic sequences dating to MIS 3. A further example of open-air site is at Monte Netto and displays a multiple human occupation of the top of the hill during the middle and the late Pleistocene (Baroni et al., 1986; Zerboni et al., 2015; Delpiano et al., 2019); therein, the uppermost archaeological soil preserves a Mousterian temporary camp site, whereas the deepest reddish soil contains ephemeral evidence of human occupation in the middle Pleistocene. Those examples suggest that paleosols have a great potential for the interpretation of the environmental conditions at the time of Pleistocene occupation of the Italian peninsula during both glacial (and stadial) and interglacial (and interstadial) phases. The application of paleopedology to cave/rock shelter contexts sometimes is a challenging task, because natural and anthropogenic sediments are juxtaposed and the influence of pedogenesis on the evolution of sediments is hampered by the geomorphological settings. In fact, cave/rock shelter sites are naturally protected from external forcing. If this limits the influence of post-depositional soil-forming processes, on the other hand increases the possibility to preserve archaeological sediments. As acknowledged by Laville et al (1980), the atrial part of caves and rock shelters is a preferential trap for sediments. The same authors reported that each type of sediments found in such contexts at middle latitudes of Europe - thus including Italy - were formed by specific processes triggered by glacial/interglacial climatic conditions. Evidence of the so-called Laville cycle has been identified at several cave-sites in northern Italy (Cremaschi, 2000), where the paleopedological and micromorphological approach supported a precise interpretation of the stratigraphy and the identification of climate-triggered processes. The most iconic investigation was carried out at Fumane Cave (Lessini Mts., Veneto), where pioneering geoarchaeological investigations followed each step of the archaeological excavation since the discovery of the archaeological site. Therein, the paleopedological approach helped in disclosing the meaning of the stratigraphy, identifying at the micro-scale evidence of different processes, likely occurred since the last interglacial up to the apogee of the Last Glacial Maximum (Peresani et al., 2008). The earliest processes recorded in thin sections at Fumane Cave were the weathering of the limestone bedrock of the rock shelter and the formation of a colluvial layer of reddish soil material during warm conditions. A subsequent transition towards cold and arid climate were recorded by loess accumulation interlayered to breccias and anthropogenic layers, alng with frost-related pedofeatures (Ferraro, 2002; Cremaschi et al., 2005). In other cases, paleopedology supported archaeological investigations in reconstructing the processes and rates of cave infilling, as in the Lateglacial Grotta Continenza site in central Italy (Boschian et al., 2017). Therein, thin section micromorphology contributed to interpret the interplay between dust input and colluvial processes in the formation of the stratigraphy. A further example of the investigation on cave-sites concerns caves and rock shelters located along shorelines. Along the Italian peninsula, many caves and rock shelters have been exploited in the middle and late Pleistocene and methods borrowed from soil science revealed the complexity of processes in charge of the formation of archaeological sediments and supported the reconstruction of climatic changes. The Balzi Rossi archaeological area has been investigated since the beginning of the last century, but only few investigations included the study of sediments. For instance, Cremaschi (1993) reported on the ex-Birreria archaeological sequence, which includes at its base a red, clay-rich soil, likely developed at the end of the last interglacial and then buried by colluvia at the onset of the last glacial period; more recently, Zambaldi (2020) came to the same conclusions. In the same area, geoarchaeology supported the identification of a subsequent climatic event at the Riparo Mochi site (Douka et la., 2012), whereas micromorphology in thin sections helped in the identification of bioturbation affecting late Pleistocene archaeological sediments, including cryptotephras at the Riparo Bombrini site (Hirniak et al., 2020). At Grotta Guattari (central Italy), Cremaschi et al. (2022) applied several methods to understand the peculiar pedogenic processes affecting the archaeological stratigraphy and influencing the preservation of biogenic phosphates and heavy minerals. The authors concluded that bones did not survive in some layers and the occurrence of phosphates was related to the formation of Ca-Al and Ca-Fe phosphates derived from the weathering of bat guano. The same conditions affected the heavy mineral assemblage, leading to the disappearance of the most labile ones. Geoarchaeological and paleopedological investigations at several key sites of Apulia (southern Italy) disclosed the interplay between relative sea-level changes, continental surface processes, and human peopling since the middle Pleistocene. At Grotta Paglicci (Gargano promontory) thin section micromorphology and the study of heavy minerals highlighted a first phase of sedimentation controlled by the wind input of weathered volcanic material, followed by cryotic conditions and loess deposition (Cremaschi & Ferraro, 2007). Similar conditions were observed at the Uluzzo C rock shelter (Spinapolice et al., 2022), where micropedology helped in the reconstruction of the formation processes, which include strong bioturbation and, in the Mousterian layers, a huge redistribution of calcite forming an almost continuous breccia (Fig. 16C-F). At the same site, the identification of former *Terra Rossa*-type soil fragments (rolled pedorelicts) and speleothem clasts (Fig. 16E, F) suggested an occasional reactivation of the hydrology of the local karst system under more humid conditions and the erosion of surface soils and older karst infillings. At Grotta Romanelli the application of geoarchaeology and paleopedology helped in the reassessment of the stratigraphic sequence, shedding new light on the formation processes of each stratigraphic unit and the interplay between the deposition and the weathering of sediments (Pieruccini et al., 2022; Russo Ermolli et al., 2022).

## 7. SOME PROBLEMS, OPEN QUESTIONS, CONCLUSIVE REMARKS AND PERSPECTIVES

The nature of paleosols is intrinsically diachronic (time-transgressive) and they are often spatially discontinuous. Nonetheless, the abundant and variegated literature on Italian case studies demonstrates that they can be successfully used as complementary proxies to others that are usually more continuous in time and space or simply intrinsically quantitative. In many cases (Pleistocene) paleosols can be traced with large lateral continuity and allow synchronizing further geological/biological archives interlayered in-between. At regional and extra-regional scales, they may allow a comparison of different local responses to more global paleoclimatic/environmental changes, providing a deeper understanding of the spatio-temporal climate variability during Quaternary times.

A relevant issue worth mentioning regards several surface soils widespread from the Alpine chain to the mountainous relieves and coastal areas of southern Italy. They are often poorly differentiated into pedogenic horizons and overall weakly developed, although the ages of their local substrates can be much older (D'Amico et al., 2016; Scarciglia et al., 2015, 2016, 2020; Raab et al., 2018). According to site-specific geo-environmental characteristics, the authors interpreted this behavior as a response to paleo- and/or historical to modern environmental changes that took place over time. Among the possible explanations are extensive Pleistocene glaciations, intrinsic or weathering-induced properties of parent materials, topographic features (namely high local relief and steep slopes) controlled by tectonic uplift or river dissection, climate shifts and/or land-use changes, which made the soil mantles highly susceptible to erosion and efficiently eroded over time. Nonetheless, on some relict planation surfaces characterized by a relative geomorphic stability, and/or buried by younger sediments and associated soils (e.g., in the outermost reaches of the Alps and on the Sila upland plateau), some better developed and mature paleosols are at least partly preserved, often in small patches (D'Amico et al., 2016; Scarciglia et al., 2007, 2008). They display some features that are not consistent with Holocene soil formation processes, but record paleoenvironmental/climatic conditions that can still be adequately reconstructed. However, this task cannot always be achieved, for instance in case of diagnostic features of seasonal freezing and thawing, which form in the active layer, or albic (eluvial) horizons in Podzols. As these processes involve only the topsoil and shallow (subsurface) horizons, their evidence is very frequently lost because of soil profile truncation by erosion. In our opinion, this could be a reason why past periglacial conditions cannot be extensively assessed and might be underestimated in the Italian paleopedological archives. Worth to remark is also the difficult distinction between traces of seasonal freezing and permafrost conditions in paleosols from zones that are nowadays not glaciated or very far from glaciers, even in coastal area, although other paleoclimatic archives, geomorphological, stratigraphic and isotopic signatures may help solving this dilemma. Similarly, several rubified and clay-illuviated paleosols lack of the corresponding surface A horizons and/or clay-depleted E horizons, and in places of part of the Bt horizons themselves. This prevents an estimation of the original soil profile depth and of the extent of clay translocation, and possibly of other diagnostic features. Nonetheless, the occurrence of paleosols with well-developed Bt horizons often at the ground surface (Fig. 5A) appears a clear evidence of severe erosion (Robustelli et al., 2009; Scarciglia et al., 2015). We cannot exclude that a decrease of soil porosity due to stacking of translocated clay particles onto pore surfaces could have hampered water infiltration, enhancing water runoff and erosion. In this respect, an interesting point to investigate would be the possible role of illuvial clay enrichment downprofile as a predisposing factor of shallow landslides affecting paleosols, where the consequently diminished drainage conditions in the subsoil could trigger the detachment and failure of upper horizons. The truncation and exposure of paleosols at the topographic surface, the complementary colluviation downslope triggered by water- or gravity-driven reworking processes and their burial by younger soils are a common cause of a polygenetic imprint of pedogenic processes, some of which may record past environmental/climatic conditions and some others recent or modern ones. A clear discrimination between these different stages of soil formation cannot be always assessed, at least in the field. Such geomorphic dynamics may also cause soil ageing or rejuvenation, e.g., on exposed terraced surfaces of soil chronosequences (cf. section 3), but soil micromorphology and geochemistry revealed to be of great help to provide reliable interpretations. The interpretation of the genesis of buried paleosol can be complicated because of potential modification of their properties after burial, in addition to the above discussed truncation, which is often synchronic with the sedimentation event leading to burial. In case of younger pedogenesis affecting the overlying sediments, further soil formation processes often occurred with two potentially different evolutionary trends. On the one hand, pedogenesis might have kept the same direction under similar climatic/environmental conditions, simply leading to superimposition of different generations of similar features (polycyclic). On the other hand, it might have evolved towards a different direction under varied conditions, with new pedogenic features overprinted on past, relic ones (polygenetic). Major changes might have involved: (i) leaching/eluviation and accumulation/illuviation of soluble substances or suspended particles sourced from the overlying (sometimes allochthonous and genetically different) parent material(s); (ii) compaction and changes in pedogenic structure, soil porosity and permeability, drainage and redox conditions. Therefore, it is sometimes very difficult to interpret the resulting soil properties as occurred prior to or after the burial. This is a hard task to achieve especially when the paleosol is buried by very shallow sediments (and soils), which do not seal the buried paleosol from more recent pedogenesis, possibly masking lithological or erosive discontinuities, or when the overlying deposits, even despite very thick, may be highly porous and permeable and exert a poor sealing effect. This could be still more complicated when the paleosols were buried under submerged (e.g., marine) conditions (Fig. 8) (Scarciglia et al., 2003a, b) and/or were affected by waterlogging (Cremaschi et al., 2015).

The consequences of erosion and pollution (discussed above) and of other natural or human threats, nowadays often enhanced by ongoing climatic changes and increasing anthropogenic pressure on the environment, poses our attention on the potential resilience of Pleistocene paleosols. Their time ranges of development are in the order of $10^4$ to $10^6$ years, possibly under varying climatic/environmental conditions, as potentially subjected to one or more alternations of stadial/interstadial and interglacial/glacial cycles as far as the time spans increased. In such long intervals, the paleosols reached their specific properties, but their possible loss or degradation often took (or might take) place even in much shorter times. This implies their poor or null resilience and recovery at human scale, not only because of this time issue, but also in terms of non-reproducible paleoenvironmental conditions and corresponding pedogenic features. Current and future pedogenesis would have different pathways from the past, and even additional peculiarity if we consider paleosols derived from volcanic products of Pleistocene eruptions, which will not likely occur as in the past. One additional lesson that the Pleistocene paleosols of Italy teach us is the potential ability to discriminate between natural and anthropogenic drivers of landscape dynamics, based on the identification and interpretation of key features of past pedogenesis and corresponding environmental responses. This is a key tool for prediction of the potential responses of the Earth system to forthcoming scenarios and provision of best-suited strategies for adaptation. In addition, Pleistocene paleosols of different ages can be useful proxies for the assessment of geological/geomorphological hazards and associated risks, based on long-term records of periods characterized by relative geomorphic stability prone to pedogenesis alternated to overall unstable and hazardous environments marked by floods, landslides, soil erosion and volcanic eruptions.

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