Revisiting the genesis of red Mediterranean soils

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Abstract: This work, aside from being a classical discussion on the processes of rubefaction and illuviation, is an attempt to cross the abundant literature on red Mediterranean soils (RMSs) written by pedologists, and also by paleopedologists and geologists, with the climatic frame established by paleoclimatologists for the Quaternary. Such an approach leads us to consider that the development of the RMSs was discontinuous, occurring during periods of environmental stability, i.e. interglacials, characterized by a humid climate (precipitations exceeding evapotranspiration) with dry and hot summers. The impact of glacial intervals on the RMS covers is presently only partially documented. Aeolian processes during atmospheric instability episodes played a dominant role; however, hydric erosion and resedimentation cannot be ignored. Severe wind storms have reworked the RMS covers locally, but long distance dusts were also incorporated into the soils. Outbursts are proposed to explain the disruption observed in pre-Holocene red B horizons. Calcite from aeolian dusts was dissolved in surface horizons and recrystallized in deeper horizons in the form of discrete features and calcrete. During the more humid phases of these intervals, RMS became waterlogged in presently humid areas of the Mediterranean basin. The impact of frost on the RMS covers has been exaggerated. Precise correlations between the climatic fluctuations identified by paleoclimatologists and features and facies in the soil covers generated during the glacial intervals are almost impossible to establish.

Key Words: Rubefaction, illuviation, behavior of red Mediterranean soils during glacial intervals

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1. Introduction

Pedologists, geologists, and geographers recognized long ago that red colors characterize the soil covers of the Mediterranean basin (Ramann 1911; Blanck 1930; Reifenberg 1947; Kubiëna 1953; Bouline 1984). Many detailed monographs of the red Mediterranean soils (RMSs) have been produced (e.g., Atalay 1997; Bech et al. 1997; Darwish & Zurayk 1997; Yassoglou et al. 1997; Noulas 2009). RMSs located on stepped fluvial and marine terraces have attracted many pedologists and paleopedologists, especially in southern Italy (Sevink et al. 1982; Scarciglia et al. 2006; Sauer et al. 2010), as have those buried in alluvial fans (Günster & Skowronek 2001; Ortiz et al. 2002; Carboni et al. 2006; Magliulo et al. 2006; Zembo 2010; Wagner et al. 2012) or intercalated within eolianites (Elhajraoui 1985; Muhs et al. 2010). Many specific soil-forming processes have never been detected in RMSs; however, they are clearly related to the Mediterranean basin and also to areas of the world affected by a Mediterranean type of climate (Yaalon 1997). Most of the RMSs infill karst of hard limestones and dolomites (e.g., Atalay 1997; Bech et al. 1997), but they can be observed on any type of hard bedrock as well as on any type of unconsolidated sediment. They differ from tropical red soils by their lower iron oxide content and mixed clay minerals, whereas in the tropics, only kaolinite is present.

The basic soil-forming processes responsible for the genesis of RMSs, i.e. rubefaction and clay illuviation, are presently well understood. However, the environmental factors required for rubefaction are not quite clearly perceived. RMSs, when not eroded, appear as texture-contrasted soils characterized by an argillic horizon according to the USDA (1999), or an argic in the IUSS Working Group of the FAO (2006); however, in many of these argillic (argic) horizons, clay coatings could not be identified (Reynders 1972; Bresson 1974). Pedogenic carbonates occur frequently in RMSs, the role of which is also not fully understood. The origin of the RMSs' parental material has also been widely discussed in terms of autochthonous vs. allochthonous (Bronger & Bruhn-Lobin 1997; Muhs et al. 2010). In the first section, we will review the literature on parental materials and on the soil-forming processes occurring in RMSs.

The theory of uniformitarianism, i.e. that the present is the key to the past, applied to pedology by Marbut (1935),
supports most of the investigations of the genesis of RMSs. According to this theory, soils are supposed to develop linearly under the influence of environmental factors until they reach an equilibrium with prevailing environmental conditions, the steady state. Anomalies observed in applying to soils the theory of linear development had led to the introduction of subsidiary concepts, such as the threshold concept, which explains abrupt changes in the soil development in the absence of environmental change (Yaalon 1971) as well as the feedback system (Yaalon 1983), which is supposed to be the result of soil internal evolution. Most papers on the genesis of RMSs are based on such an approach, even some that are recent, e.g., Recio Espejo et al. (2008). Lobeck (1939) pointed out that geomorphic processes are periodic and soil development is related to them. Ehhart (1956) proposed the theory of biorhexistasy, which supposes an alternation of periods of soil formation followed by episodes of soil erosion. Butler (1959) and Hack and Goodlett (1960) also provided evidence that soil development and erosion have been periodic and are driven by episodic geomorphic processes. Bockheim et al. (2005) considered that soil development and erosion have been periodic rather than continuous. Sequences in which red paleosols are intercalated in loess (Günster et al. 2001) or eolianites (Muhs et al. 2010) have been investigated (Figure 1). In the second section, based on the now well-accepted theory that soil development is the long-term result of an alternation of the pedogenic phases and of episodic soil cover disruption and erosion, we will try to set the rubefaction–illuviation phase within pedosedimentary cycles (Fedoroff et al. 2010) (Figures 2 and 3). The concept of pedosedimentary cycles supposes a close integration of the impact on soil covers of environmental fluctuations, i.e. long-term climatic fluctuations, glacial vs. interglacial, and abrupt environmental crisis (Dansgaard et al. 1993; Sanchez Goñi et al. 2002; Hemming 2004; Martrat et al. 2004).

2. Origin of RMS parental materials
This origin has been debated for decades and is still controversial. Many pedologists (e.g., Reifenberg 1947; Dudal et al. 1966) considered that terra rossa on limestone was developed on the residuum of the dissolution of the parental bedrock. Glazovskaya and Parfenova (1974) admitted that slope colluviums can also contribute to RMSs. However, Kubiëna (1953) envisaged an enrichment of terra rossa by aeolian materials. This approach was developed by Yaalon and Ganor (1973), and then by Rapp (1984) and Yaalon (1997). This assumption was not easy to demonstrate, due to loessic additions to soils in the loess belt. Specific features and facies due to dust-like loess cannot be detected in the field as well as in thin sections; however, more sophisticated techniques have enabled the identification of the input of aeolian dust in RMSs. MacLeod (1980) compared the low siliceous residue in

**Figure 1.** Red sands intercalated between 2 cemented, cross-bedded eolianites. Morocco, Atlantic coast, north of Rabat.

**Figure 2.** Cumulic RMS. Morocco, Casablanca. Thomas Quarry, south Sidi Abderrahmane section. From top to bottom: 1) plow layer, 2) B horizon, 3) IIB horizon, 4) gravelly layer, 5) IIIB horizon, 6) in situ argillic B horizon characterized by red clay coatings and infillings, 7) partially dissolved eolianites.
carbonate bedrock with the grain size distribution in terra rossa to infer an aeolian origin for these soils in Greece. Durn et al. (1999), using clay minerals and geochemical indicators, concluded that terra rossa in Croatia derives from loessic sediments. Genova et al. (2001), studying red soils in Sardinia using neutron activation analysis, concluded aeolian additions to these soils. Jackson et al. (1982) utilized oxygen isotopes in quartz to support a dominant aeolian origin in the terra rossa soils of Italy, as did Nihlén and Olsson (1995) in Crete. Delgado et al. (2003), who investigated RMSs in southern Spain, reported mineralogical evidence in favor of a double origin, residue from the bedrock and aeolian. Recently, Erel and Torrent (2010) measured the concentrations and isotopic composition of Pb and Sr in the Al silicates and Fe oxides of 2 red soils in the Granada Depression, from which they concluded that Saharan dust makes up a significant fraction of the Al silicates and Fe oxides of the studied soils. Muhs et al. (2010), by analyzing immobile trace elements in Majorca in red paleosols lying on eolianites, found that the noncarbonate fractions of the eolianites have more distinctive Zr/Hf, La/Yb, Cr/Sc, and Th/Ta values than the overlying red soils, which led these authors to conclude that African dust may explain the origin of much terra rossa on carbonate bedrock around the Mediterranean region.

We can consider that the input of African dust in RMSs is presently accepted by pedologists. However, the following remarks have to be made about the published results on this subject:

- Authors refer to present day conditions of aeolian erosion and dust transportation considering that in the past the parental materials of RMSs accreted during interglacials (Muhs et al. 2010). What happened to RMS covers during glacial periods during which many severe wind storms occurred? Andreucci et al. (2011) determined that the Saharan dust input in northwestern Sardinian (Italy) buried red paleosols/sediments, together with local materials, via trace element analyses and the presence of palygorskite and rounded-indented quartz grains.

- The forms in which desert dusts, e.g., clay coatings, are incorporated to RMSs were never investigated.

- RMSs are often associated with secondary calcitic discrete or continuous (calcrete) features, which are considered by many authors to also be aeolian in origin (Kapur et al. 1990; Goodfriend et al. 1996; Kubilay et al. 1997; Kapur et al. 1998; von Suchodoletz et al. 2009). The relationships between the accretion of calcite-free and calcite-rich dusts in RMSs have never been investigated.

Recently, Diaz-Hernandez and Parraga (2008) mentioned microspherulites (60–90 µm in diameter) sampled in the Granada Depression, consisting of complex mineral assemblages and also containing biological remains (plants, silica shells, plankton), which may also contribute to the genesis of RMSs. Courty et al. (2008) described on 2 ends of the Mediterranean basin, in the Vera basin (southeastern Spain) and in the eastern Khabur basin (northeastern Syria), a dust event at 4 ka BP due to the fallback of impact ejecta.

3. Pedogenic processes involved in the genesis of RMSs
To reach a reliable understanding of the RMSs’ genesis, a prerequisite is a good comprehension of the basic soil-forming processes that lead to RMS development, rubefaction, and clay illuviation. Weathering of parental minerals must also be taken in account.

3.1. Rubefaction
Rubefaction is considered to be the leading soil-forming process in RMSs, essentially because pedologists, but also geographers, were and are attracted by the red color of the soils, which has led them to underestimate or even ignore other processes that took place and are taking place in these soils. Various explanations for rubefaction have been proposed in the past (e.g., Agafonoff & Graziansky 1933; Marcelin 1947; Reifenberg 1947; Kubiena 1953). Presently, the process of rubefaction is quite well understood, but its environmental interpretation is still questionable.

Rubefaction results from the microcrystals (Bresson 1974; Mirabella & Carnicelli 1992) in hematite being...
randomly distributed in the ground mass in association with goethite, and maghemite can be also present. The content in the iron oxides in RMSs is rather low, less than 5% according to Torrent (1994), and lower than in tropical red soils. Torrent et al. (1983) interpreted this difference as a weaker aggregation in RMSs. Hematite possesses a high pigmenting power, which masks the goethite.

We follow Bresson (1976), Schwertmann et al. (1974), Torrent and Cabedo (1986), and Noulas et al. (2009), who stated that rubefaction occurs and occurred in surface horizons, and then the rubified material is and was translocated with clays to depth. In monophase, nonreworked RMSs, the distribution of the red color throughout the profile is governed by clay illuviation, and more generally by translocation of the particles. Boero and Schwertmann (1989) supposed that iron is released from primary sources followed by the preferential formation of hematite over goethite, whereas Bresson (1974) and Jouaffre et al. (1991) considered that hematite forms essentially from the in situ modification of goethite. Torrent and Cabedo (1986), on RMSs lying on hematite-free calcarenites, supposed that hematite originated mainly from the alteration of the Fe-bearing smectites. They interpreted the partial loss of the initial goethite as an alteration to the hematite. Schwertmann and Murad (1983) also showed the role of pH in the formation of hematite vs. goethite, whereas Michalet et al. (1993) pointed out the role of amorphous Al-hydroxy polycations.

The distribution of RMSs around the Mediterranean basin implies that rubefaction is related to Mediterranean types of climate characterized by a hot and dry summer and a rainy cool winter. As most RMSs are relics of the past (see Section 6), it is consequently hazardous to use present-day climatic conditions for interpreting their rubefaction. Bresson (1976), Schwertmann et al. (1982), and Jouaffre et al. (1991) reported rubefaction during the Holocene on the northern fringes of Mediterranean basin. Precipitation reaches 1700 mm and the mean annual temperature is 6 °C at the site studied by Jouaffre et al. (1991). It should be mentioned that soils investigated by these authors are very permeable, desiccating in the summer, sufficient to induce the formation of hematite. A pedoclimate characterized by an excess of drainage, as in karst (Boero & Schwertmann 1989; Boero et al. 1992) or in coarse glaciofluvial sediments with periods of desiccation during summer, seems favorable to rubefaction.

The impact of vegetal cover burning on rubefaction has been also been studied. Yellowish goethites are readily dehydrated by heating, and in the presence of organic matter, they first form a dark reddish brown maghemite; with further heating, they change into a bright red hematite (Terefe et al. 2005; Terefe et al. 2008).

3.2. Clay illuviation
Tavernier (1957) and many other pedologists (e.g., Torrent 1976; Cremaschi 1987) considered clay illuviation as a leading process in RMSs, responsible for the clay-enriched subsurface horizon. However, a thin-section analysis of most RMSs’ argillic horizons reveals an absence of clay coatings (e.g., Reynders 1972; Bresson 1974) in these horizons (Figure 4). However, in RMSs in which the argillic horizon appears free of clay coatings, such features can be present in deeper horizons (Figure 5), where they can be identified only at high magnifications. In the weathering zones of igneous and metamorphic rocks (Penven et al. 1981; Lahmar & Bresson 1987), an accurate analysis under PolM reveals frequent fragments of clay coatings in the apparently homogeneous red ground mass (Scarcaglia et al. 2006; Priori et al. 2008). Servat (1966) and Duchaufour (1977) proposed the concept of “appauvrissement” (surficial depletions), which is supposed to result from subsurface runoff, in order to explain the abrupt contrast in the clay content existing frequently in RMSs between A and B horizons. Nevertheless, clay coatings have been observed in the B horizons of RMSs that are Holocene in age on the northern fringe of the Mediterranean basin: for instance, in Jura (Bresson 1974), in low terraces of the middle Rhône valley, and in northwestern Spain (Fedoroff 1997).

The absence of clay coatings in B horizons of RMSs has led to the following hypothesis: 1) self-mixing postulates that illuvial clays are incorporated into the B ground mass as soon as they have been deposited as a result of shrink–swell (Fedoroff 1972; Reynders 1972); 2) the B ground mass can be churned by the soil fauna (Fitzpatrick 1993), and 3) the high stability of red fersiallitic ground mass prevents clay dispersion (Lamouroux et al. 1978). Here we explain this absence by the severe reworking that has affected all

![Figure 4. Typical microstructure of a Mediterranean red argillic horizon (high magnification). Algeria, vicinity of Tlemcen. Dense, irregular packing of rounded to subrounded microaggregates. Dark red, quasi-opaque ferruginous fragments randomly distributed in the red ground mass.](image-url)
RMSs during erosion and aeolian episodes though the whole Pleistocene period, except for those that were buried immediately after a rubefaction–illuviation phase. Figure 4 illustrates this view point, where rounded to subrounded microaggregates have to be considered as wind-winnowed pseudosands and not as fecal pellets, of which they do not have the morphology and composition. In Figure 5, the microaggregates are coalescent, but their initial forms can be recognized, whereas some remaining packing voids are infilled almost totally by translucent illuvial clays. Our interpretation of this typical RMS of northwestern Algeria is the following: 1) a RMS cover was deeply disturbed and wind eroded, 2) the red material was locally wind-winnowed and redeposited, and 3) later, a very weak clay eluviation affected the reworked red material, whereas translocated clays were trapped in residual packing voids at the base of the B horizon. These illuvial clays cannot be identified in the field or even during a routine thin-section analysis. Achyuthan and Fedoroff (2008) described a similar case in southern India.

3.3. Weathering of primary minerals in RMSs
Rubefaction is independent of primary and clay mineral weathering. In recent rubified soils, i.e. the Holocene, any weathering is detected, except for some vermiculitization of illites (Bresson 1974; Jouaffre et al. 1991; Colombo & Terribile 1994). As the age of the RMS increases, e.g., on stepped terraces, kaolinite tends to dominate (Terhorst & Ottner 2003; Wagner et al. 2007). The weathering of primary minerals, present in gravel beds upon which the RMSs are frequently developed, increases with the age of the terrace on which they have been deposited (Billard 1995). The rubified material penetrates into the weathered gravel in the form of red clay coatings independently of their degree of weathering (Penven et al. 1981).

4. Other features and facies present in RMSs
The features of dissolution of primary and secondary carbonates as well as various facies of carbonate accretion exist in RMSs, and redoximorphic features and facies can also be present in RMS covers. The secondary carbonates are located in drier regions of the Mediterranean basin, whereas redoximorphic features and facies characterize wetter ones, with some overlapping. The development of both of these features and facies increases with age, weakly developed in the Late Pleistocene and well-developed in the Early Pleistocene. Frost-related features and facies have been described even in the core of the Mediterranean basin at sea level.

4.1. Carbonate dissolution and accretion in RMSs
Pedologists presently agree that carbonate dissolution, primary as well secondary, occurred synchronously with rubefaction and illuviation (Alonso et al. 2004; Carboni et al. 2006).

Close and frequently complex relationships exist between RMSs and secondary carbonate accumulations (Alonso et al. 2004) (Figure 6). Such RMSs are located in regions (Spain, northern Africa, Near and Middle East) presently under subarid climates, whereas RMSs under present humid and subhumid climates, such as the northern fringe of the Mediterranean basin (France; northern and central Italy), are free of secondary calcium carbonate. The development and complexity of these secondary calcium carbonate accumulations increase with time (Alonso et al. 2004; Badia et al. 2009). Young soils (Holocene and late Pleistocene) contain only discrete, monophased (sensu Fedoroff et al. 2010), calcitic features, whereas older ones (Middle and Early Pleistocene) are characterized by continuous (calcrete) and polyphased

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**Figure 5.** Massive microstructure with residual packing voids infilled by yellow illuviated clays near the base of a Mediterranean red argillic horizon (high magnification), half a meter below previous micrograph. Algeria, vicinity of Tlemcen.

**Figure 6.** Transition red argillic horizon to calcrete. Morocco, Casablanca. Thomas Quarry, north Sidi Abderrahmane section. 1) Thick, clay feature – first phase of clay illuviation; 2) calcitic aggradation; 3) partial calcite dissolution; 4) thin, dusty clay coatings on secondary calcite surface and in dissolution voids – second phase of clay illuviation.
calcitic facies (Alonso et al. 2004; Badia et al. 2009). Kapur et al. (1987) described evolutionary sequences proceeding from the Middle to the Early Pleistocene covering a phase of sedimentation (from a mud flow) to the final outcome, the massive calcrete crust, with the weathered overlying red soil.

Two questions have puzzled geologists and pedologists about the secondary carbonates in RMSs, which still remain controversial. The first concerns their origin and the processes responsible for their accretion, whereas the second deals with the effect of carbonates on the host red material during their accretion.

Different origins of secondary carbonate in RMSs have to be considered (Candy & Black 2009): 1) carbonates are leached from upper horizons and accreted in lower horizons, the per descendum origin; 2) carbonates are provided by ground water and they can accrete in the capillary fringe, a per ascendent origin (Recio Espejo et al. 2008); 3) in the saturated zone, carbonates originate from leaching of calcareous bedrocks, transported laterally in solution and precipitated when ground water comes close to the soil surface and is consequently evaporated; or 4) the deposition of calcium carbonate-rich aeolian dust is followed by a redistribution in the soil profile by capillary or saturated water. The per descendum origin has to be refuted as almost all RMSs, when carbonates accreted, were already free of parental carbonates (Ortiz et al. 2002; Alonso et al. 2004). The presence of calcified soils and calcretes on parental bedrocks as granites (Ducloix et al. 1990) or basalts (Hamidi et al. 2001) strengthen the aeolian hypothesis.

Two facies exist between the host red silicate material and the secondary carbonates, clearly expressed under polarizing microscope: 1) the host material appears as progressively replaced by carbonates, and 2) residual grains, e.g., quartz and feldspars, float within the secondary calcitic ground mass. The replacement of host material affects the whole ground mass, including the coarse fraction in fully calcified horizons dating back to the Early and Middle Pleistocene (Alonso et al. 2004). Grains appear fragmented (brecciated according to Paquet & Ruellan 1997), embedded in a sparitic ground mass, whereas the replacement of fine mass by carbonates produced yellowish brown calcite of thick fibrous crystals (Alonso et al. 2004). In younger calcified horizons, the calcification can be followed in all of its phases from the initial phase of clay coating disruption to the complete dispersion of the clayey mass in the calcitic ground mass, in which yellowish and reddish colors keep the memory of the host material (Alonso et al. 2004). Biotites in such calcified horizons are characterized at the initial stage by the presence of calcitic crystals between exfoliated plates; in the next stage, biotite plates appear separated, embedded in a continuous calcitic ground mass; and finally they appear dispersed in this mass. The properties in the plain and polarized lights of biotites through all of these stages are preserved. Commonly (Nahon & Ruellan 1975; Millot 1979; Watts 1980; Paquet & Ruellan 1997), floating quartz is interpreted as a silica dissolution under high pH due to the supersaturation of the soil solution in pCO₂, which leads one to consider the replacement of the red clayey mass, sometimes called epigenesis (Reheis 1988; Hamidi et al. 2001), as a geochemical process consisting of the lixiviation (dissolution) of all silicate minerals and their replacement by calcite. The theory of replacement (epigenesis) implies that silicate lixiviation, including quartz, was forced supposing a linear soil development. In fact, RMSs and the related calcitic accretions are a result of a cyclic evolution. Each cycle consists schematically of the 2 pedogenic phases (Fedoroff et al. 2010): 1) a phase of rubefaction, illuviation, and carbonate dissolution in relation to a climatic period characterized by acid rains and precipitations exceeding evapotranspiration; and 2) a phase dominated by carbonate accretion. Carbonate dissolution affects parental carbonates as well as secondary carbonates accreted in an earlier phase. The facies of floating quartz is formed during this phase of dissolution. Low pCO₂ water penetrates the pores of secondary calcite that is partially dissolved, especially around quartz grains, which leads to the floating grain morphology. When the parental material consists of sand grains coated by red clays, the coatings remain unaltered when the sand grains become floating. Such a behavior of clay-coated sand grains firmly supports the assertion that in floating quartz, the embedding calcite is partially dissolved and not the silica. On the contrary, the process of host material replacement (epigenesis) occurs during a phase of soil saturation by high pCO₂ water favoring calcite precipitation, which leads to a progressive dilution of the host material. A lixiviation of calcite is not invoked. Such an assertion is supported by the fragmentation followed by the dispersion of biotite without any alteration of its properties.

4.2. Redoximorphic features and facies in RMSs
Redoximorphic features and facies are common in RMS covers. Their development increases with age. The most developed features and facies are observed in soils of higher terraces and in buried soils of the Middle and Early Pleistocene (Bornand 1978; Elhajraoui 1985; Carboni et al. 2006). These redoximorphic features and facies occur preferentially in the presently wettest area of the Mediterranean basin, which implies a mutual exclusion of these features and calcitic ones; however, both can be present in some profiles. At the first stage of development, a few small, yellowish mottles dispersed in a red ground mass appear, and eventually Fe-Mn concretions appear (Fedoroff 1997). At the maximum of development, the B
horizon appears totally mottled, yellowish, and red, with grayish iron- and clay-depleted tongues in which in the tongue bottom can be recognized in thin-section silty clay intercalations, whereas Fe-Mn concretions can be present on the B horizon (Elhajraoui 1985; Scarciglia et al. 2003a, 2003b; Terhorst & Ottner 2003; Kühn et al. 2006).

These redoximorphic features and facies correspond to a seasonal soil water logging, which in the case of their maximum development should have reached the top soil and lasted several months. Such water logging supposes precipitations largely exceeding the soil water filtration.

4.3. Evidence of past frost action in RMSs

Fossil cryogenic features and facies have been identified in soils of the Mediterranean basin, even at rather low elevations. Dimase (2006) in the Sila massif (southern Italy) at an elevation of 1350 m described sand infilled ice wedges, whereas Günster et al. (2001) in the Granada basin, between 500–900 m elevation, mentioned cryoclasts and gelification as well as ice wedge infillings. These features and facies indicate that frost has penetrated deep into the soils, and even that a permafrost existed, to which the infilled ice wedges testify. At sea level, in the middle and southern shores of the Mediterranean basin, the absence of infilled ice wedges means that permafrost has never developed; however, all ante-Holocene RMSs are reworked (see Section 5). At low elevation, in buried paleosols formed during glacial intervals, Scarciglia et al. (2003a, 2003b) reported layered silt and clay coatings and vesicular pores along the coast of Campania, which resulted from the rapid thaw of a thick snow cover in spring according to Fedoroff et al. (1981) and consequently characterize a more boreal climate than a periglacial. However, in surface RMSs, no cryogenic features and facies have ever been described.

5. Evidence of erosion and severe reworking of RMS covers during Pleistocene

Pedologists considered that RMS covers, including Pleistocene-inherited ones, remained stable, only affected by the soil forming processes. However, this point of view is far from corresponding to facts recently published.

Red pedosediments have been frequently considered as in situ RMSs. In Mamora (Morocco), Aberkan (1989) showed that red layers intercalated in eolianites, earlier considered as RMSs, are in fact red sediments (see also Fedoroff 1997) (Figures 1 and 2). Van Andel (1998) in Greece showed the high degree of erosion and redeposition of red soil covers.

Buried RMSs always appear truncated, except some Holocene ones (Ortiz et al. 2002). Günster and Skowronek (2001) in the Granada basin observed that an erosion of upper horizons, even frequently only the calcium carbonate-cemented horizon, is the sign of a RMS.

Aside from truncations, RMS sections, when investigated with scrutiny, appear to consist of superimposed profiles separated by truncations (Fedoroff 1997; Priori et al. 2008) (Figure 2). In Casablanca quarries (Texier et al. 1992; Raynal et al. 2010) in which RMSs are exposed in wide and numerous sections, truncations are evidenced by gravel beds (e.g., the gravelly layer of Figure 2 in which Paleolithic tools may be present). In these quarries, thin, truncated (only the base of the argillic horizon is preserved), developed in situ RMSs are present in and just above the karstified eolianites, as in horizon 6 of Figure 2 (Fedoroff 1997). Laterally, the eolianites are covered by a calcrite with a lamellar crust on top, in which Paleolithic tools were found. Red profiles lying on the lamellar crust show reworked characters.

Truncations of buried RMSs can be explained by hydric erosion as a result of an episode of heavy rains, a rheistic phase sensu Ehhart (1956). However, water-reworked red pedosediments characterized by layering and variable sorting have been rarely mentioned (Hourani & Courty 1997). Instead, reworked RMSs are usually characterized by a homogeneous, and in general rather dense, packing of rounded, well-sorted red microaggregates of coarse silt and fine sand in size (Figure 4), which probably results from a winnowing, although a geochemical explanation has been proposed for this microaggregation (Michalet et al. 1993). The close relationship existing between in situ RMS roots and aeolian reworked red soils has to be interpreted as short-distance transportation. The emptying of karstic holes and their infilling by reworked red material should be the result of very powerful winds (Aberkan 1989). However, such an aeolian reworking of RMSs is almost not mentioned in the literature. Such reworked RMSs along the Atlantic coast of Morocco should be considered in a first approximation as a lateral facies of eolianites.

Anomalies in the distribution of illuvial clays in red B horizons show that RMS covers have been deeply reworked many times during the Pleistocene (Figures 1 and 2). In situ and almost undisturbed clay coatings exist only in recent (Holocene) argillic B (Bresson 1976), and eventually in deep B3t and in C. These anomalies have been ignored or misinterpreted.

Various degrees of deformation, fragmentation, and dispersion in the ground mass of illuvial clays have been observed in RMSs. Scarciglia et al. (2003a), following, e.g., Catt (1989) and Kemp (1998), described “degenerated” clay coatings, characterized by a disjointed birefringence fabric. However, most commonly, the illuvial clay features are fragmented and dispersed in the ground mass. The abundance and size vary considerably. The ground mass can consist entirely of clay fragments, which can be a few millimeters in size (Mücher et al. 1972), such a facies being usually observed just above a calcrite. In the Thomas quarry
(Casablanca, Morocco), Fedoroff (1997) observed, above the in situ RMS root, 2 soils characterized at a microscopic level by (Figure 2) a fine spongy microstructure, small fragments of red clay coatings in variable abundance regularly distributed in the ground mass, and weakly expressed calcitic features. Most frequently, as in the Thomas quarry, small (from some to 100 µm), birefringent domains in variable abundance are randomly distributed in the ground mass (Scarcaglia et al. 2006; Priori et al. 2008). The identification of these domains as illuvial clay fragments supposes thin sections of good quality and an accurate analysis at high magnifications, which explains why most micromorphologists have missed them. Unsorted or poorly sorted silty clay to silty infillings, in which fragments of illuvial clay can be present, can be observed below the truncation line (Kühn et al. 2006; Fedoroff et al. 2010).

The fragmentation and dispersion of illuvial clay features in the RMS ground mass have been interpreted as disturbances due to frost, e.g., Ortiz et al. (2002). However, this fragmentation has never been observed in RMSs in association with cryogenic features. Moreover, comparable fragmented and dispersed illuvial clay features have been described in the tropics, e.g., in Cuba (Boulet et al. 1985), in the Yucatan (Cabadas et al. 2010), and in Lanzarote (Canary Islands; von Suchodoletz et al. 2009). Consequently, another hypothesis other than frost action is needed to explain this global fragmentation (Fedoroff et al. 2010). Airbursts, such as those envisaged by Courty et al. (2008), are a good candidate. Sudden and considerable pressure shook the soils, significantly fragmenting those that were not displaced. Later, the fragile fragmented materials were winnowed locally by severe winds following the airburst and were deposited. In the Thomas quarry, the spongy microstructure is a result of a packing of winnowed red fragments rich in illuvial clay, whereas calcitic features are postdepositional. The fragments of illuvial clays present in silty clay infillings can be interpreted as resulting from a percolation of water loaded with disrupted soil material from above immediately after the soil disruption.

6. Development of RMSs during the Quaternary
Almost all authors of recent publications on RMSs agree on the following points:

1. The development of RMSs was discontinuous through the Quaternary, occurring in the form of pedogenic phases (sensu Fedoroff et al. 2010) characterized by carbonate dissolution, rubefaction, clay illuviation, and episodes of erosion and sedimentation, frequently aeolian origin (Figures 2 and 3).

2. RMSs show an increase, from the Late to Early Quaternary, in the reddening of the clay content and in the weathering of primary and clay minerals (Remmelzwaal 1979; Arduino et al. 1986; Simon et al. 2000; Wagner et al. 2007; Sauer et al. 2010).

3. Phases of rubefaction–illuviation correspond to wet climate, whereas the carbonate accretion is bound to a drier one (e.g., Bahia et al. 2009; Wagner et al. 2012).

However, a few important points concerning the development of RMSs through the Quaternary remain controversial or poorly understood. One of the main controversies concerns the simultaneity of rubefaction–illuviation during the Holocene over the whole Mediterranean basin as well as during earlier periods. Rubefaction–illuviation in Holocene soils was reported mainly on the northern fringe of the Mediterranean basin (Bresson 1974, 1976; Schwertmann et al. 1982; Jouaffre et al. 1991) and probably also in Italy (Bini & Garlato 1999), whereas Zielhofer et al. (2009) in northern Tunisia concluded that Holocene soils were not affected by rubefaction. However, Aberkan (1989) mentioned that in northern Mamora (Morocco), reddish soils characterized by impure clay coatings developed on eolianites dated from the very Late Pleistocene, whereas Texier et al. (1992) described more in the interior of the Mamora in yellow aeolian, carbonate-free sands, and reddish brown impure clay coatings, organized in the form of bands that were supposed to have been formed during the Holocene. Cremaschi & Trombino (1998) in southern Fezzan (Saharan Libya) reported on rubified soils dating to the Early and Middle Holocene. Gvirtzman & Wieder (2001) in the Sharon plain (Israel) described a weak rubefaction between 10 and 7.5 ka. We will conclude that rubefaction–illuviation occurred all around the Mediterranean basin during the Early Holocene, but was more expressed on its northern fringes.

Most authors consider that rubefaction–illuviation phases occurred during interglacials (Carboni et al. 2006; Zembo 2010). However, the available data mainly concern the last interglacial oxygen isotope stage (OIS 5). Günster et al. (2001) identified in the Granada basin a rubefaction–illuviation phase during OIS 5e, whereas interstadial soils, according to these authors, are gray to brown in color (7.5–10 YR) and free of clay illuviation. Muhs et al. (2010) in Mallorca considered that the red paleosols probably represent interglacials or interstadials, whereas the eolianites correspond to glacial periods. Fedoroff (1997) in the Mamora (Morocco) described a karstic dissolution of eolianites, on which lies a red argillic horizon, characterized by red microlaminated clay coatings that are supposed to date from the last interglacial, and eventually from earlier ones (Figure 2).

According to Ortiz et al. (2002), in the Granada basin, the Middle Pleistocene OIS 7 (186,000–242,000 BP) was the most favorable for rubefaction–illuviation, whereas during OIS 9 (301,000–334,000 BP) and OIS 11 (364,000–
427,000 BP), climatic conditions were less favorable. Alonso et al. (2010) in the Tormes river basin (central Spain) distinguished 2 periods, around 200 and 500 ka, favorable for carbonate dissolution and rubefaction–illuviation.

In southern Italy, outcropping red soils, some buried, on stepped fluvial and marine terraces offer a good opportunity for understanding the genesis of RMSs through the Quaternary (Colorti and Pieruccini 2000; Carboni et al. 2006; Magliulo et al. 2006; Sauer et al. 2010; Zembo 2010). According to these authors, these soils were formed during interglacials and then truncated. In northern Cilento (South Italy) at sea level, Scarciglia et al. (2003a) described a buried RMS that the authors attributed to OIS 7. Cremaschi and Trombino (1998) in southern Fezzan also suggested that well-expressed red soils have developed during interglacials. However, in northern Cilento, Scarciglia et al. (2003a) described an OIS 5 paleosol characterized by strong hydromorphic characters.

On the contrary, ZIELHOFER et al. (2009) in northern Tunisia observed a strong rubefaction (5–7.5 Y/R 4/6) in decalcified Bt horizons between 40 and 10 ka, whereas von SUCHODOLETZ et al. (2009) proposed that in Lanzarote (Canary Islands), rubefaction–illuviation occurred during OISs 2, 3, 4 and 6, which excludes the last interglacial. RMSs intercalated between eolianites have been intensively studied, dated by many radiometric dates, in the coastal plain of Israel. According to FRECHEN et al. (2004), rubefaction took place in the Carmel coastal plain between 140 and 130 ka, at the beginning of OIS 5e, and then around 80, 65, and 60 ka and between 20 and 12 ka, whereas in the Sharon coastal plain, red soils have developed, according to FRECHEN et al. (2002), between 35 and 25 ka and 15 and 12 ka. However, Gvritzman and Wieder (2001) in the same Sharon plain considered that the most expressed red soils developed between 40 and 12.5 ka and later were buried by loess deposited during the Younger Dryas.

These controversies about the occurrences of the rubefaction–illuviation phases during the Late Pleistocene do not result from the climate zoning in the Mediterranean basin as some authors have supposed, but are probably from a misinterpretation of investigated red soils. Thus, the red soils (hamra) studied in Israel could be reworked red soils as those in Mamora (Morocco) formed during an earlier interglacial. Radiometric dates (Gvritzman & Wieder 2001; Frechen et al. 2004, 2006) provided for these hamra soils correspond to their reworking and not to their genesis. Von SUCHODOLETZ et al. (2009) for Lanzarote admitted that the investigated red layers are colluvial. These authors suggested that the genesis of corresponding in situ red soils could have occurred during glacial intervals just because of the climate zoning. In Tunisia (ZIELHOFER et al. 2009), the mentioned RMSs could also have been reworked. We would conclude that rubefaction–illuviation occurred during interglacials simultaneously all around the Mediterranean basin, probably during the whole Pleistocene.

The literature does not provide much information about the duration of the rubefaction–illuviation phase. Courty (1994) described in northeastern Syria such a phase during the Holocene first climatic optimum, whereas Courty et al. (1998) detected a short phase of rubefaction–illuviation that lasted 100 years following the 4000-year cosmic event. Günster et al. (2001) showed in the loess–paleosol sequence of the last interglacial–glacial cycle of the Granada basin that rubefaction associated with clay illuviation occurred only during OIS stage 5e. As a hypothesis, we propose that rubefaction–illuviation phases lasted a few thousand years based on the high number of microlaminations and the thickness of the clay coatings and their abundance. Macklin et al. (2002), analyzing fluvial sequences in the Mediterranean basin, demonstrated that only during the earlier part of OIS 5e were the Mediterranean landscapes stable, whereas pronounced landscape changes had already occurred during OIS 5d (109–111 ka) and most notably at the OIS boundary of 5b/5a (88 ka).

Relationships between environmental parameters and the rubefaction–illuviation phases are usually not discussed in detail. Authors just mention that these phases correspond to a wet climate, whereas carbonate accretion corresponds to a drier one (e.g., Wagner et al. 2012). Calcite dissolution at any depth in RMS profiles means that the sum of the precipitations exceeded evapotranspiration during this phase, whereas the rains were probably acidic. The regular microlamination of clay coatings indicates a regular rain distribution of rains without any water excess and also an interannual stability of precipitations. However, rubefaction supposes a severe desiccation of surface horizons during at least some days/weeks of rather high temperatures during summer.

What happened to RMS covers in the Mediterranean basin during glacial intervals is only partially understood. The memory of RMSs related to these intervals has been more or less largely erased. Moreover, little research has been attempted to analyze the remaining memory of these intervals in RMSs. Soil development during these intervals is documented only locally, with a high resolution, by studying buried soils (Günster & Skowronek 2001; Günster et al. 2001; Scarciglia et al. 2003a, 2003b; Kühn et al. 2006). The available results principally concern the last glacial interval (from OIS 5d to 2). Based on this literature, soil and landscape evolution appear to be characterized by: 1) a great instability of soil covers and even of landscapes,
2) being affected by various soil forming processes, and 3) short periods of soil development (Günster et al. 2001). The thick, yellow, microlaminated clay feature of Figure 7 is an example of clay illuviation during glacial intervals. This feature indicates that during these intervals, rubefaction was replaced by brunification; more humid and cooler temperatures favored goethite formation and probably the replacement of hematite by goethite. The great thickness of this feature is also typical for these intervals (e.g., Scarciglia et al. 2003a, 2003b; Kühn et al. 2006).

The instability of soil covers is evidenced by soil truncations, which are mentioned by all authors in sequences of buried soils. Aeolian erosion and sedimentation in the form of loess and locally winnowed red soils have extensively affected Mediterranean soil covers. Loess in which fragments of RMSs can be present have been described in northern Italy (Cremaschi 1987; Billard 1995), in northeastern Spain (Mücher et al. 1990), in southern Spain (Günster et al. 2001), in southern Tunisia (Coudé-Gaussen & Rognon 1988), and in Israel (Dan 1990). Coudé-Gaussen and Rognon (1988) and Mücher et al. (1990) insist on the local origin of aeolian sediments. Along shorelines, red layers consisting of wind-reworked RMSs are frequently intercalated (Figure 1) with eolianites, but most geoscientists (e.g., Muhs et al. 2010) considered them as being RMSs formed in situ. Figures 1, 2, and 3 represent the most typical cases of the relationship existing between eolianites and RMSs on the Atlantic coast of Morocco. In Figure 1, a red layer intercalated between 2 eolianites, which could be considered as a RMS, is in fact a severely wind-eroded RMS and was transported as red-coated sands in which almost no in situ pedofeatures are present. In Figure 2, only the very base of the section is an in situ RMS, whereas the ground mass of the upper 3 B horizons consists of a dense packing of rounded microaggregates, which must be interpreted as wind-winnowed RMS. Calcitic nodules (not seen in the photograph) present in these B horizons, especially in the IIIB, also indicate calcite-rich dust falls. A thick, polyphased, weakly disturbed, dark red argillic horizon (just its top is seen in the photograph), which developed on the eolianites and is deeply karstified, is truncated and covered by sands (Figure 3). These aeolian, calcite-free sands were deposited during 2 episodes, separated by a gravely layer. The upper sands are coated by thin, rare, yellowish red clays. This clay illuviation phase could be Holocene. These 3 photographs give an idea of the complex history during the Quaternary of the Atlantic coast of Morocco, during which have alternated phases of the RMS genesis, some very marked as in Chaperon rouge (Figure 3) and aeolian episodes, as well as an episode of hydric erosion characterized by gravelly layers.

The fragmented illuvial clays within the ground mass and even the absence of any illuvial features in most ante-Holocene RMSs have to be related to this landscape instability due to hydric erosion, but essentially to very severe wind storms. We have suggested above that an initial shock in the form of an outburst is responsible for the soil disruption, followed by very severe wind storms that displaced the disrupted soils and also by some heavy rains responsible for the truncations. The hypothesis that periglacial thixotropy was responsible for this soil disruption (e.g., Scarciglia et al. 2003a, 2003b) must consequently be abandoned. The worldwide distribution, including the tropics, is a strong argument in favor of this abandonment.

6.1. Soil-forming processes affecting RMS covers during glacial intervals

The translocation of the silt fraction is characterized by bleached tongues and at a microscopic level by silty features, but most frequently by more or less regular silty and clayey layers (Scarciglia et al. 2003a, 2003b). According to Fedoroff et al. (1981), this translocation of silt and silt and clay results from the rapid thaw of a thick snow cover in the spring and consequently characterizes a boreal climate without a deep soil frost rather than a periglacial one with a permafrost. Such silty features in the Mediterranean basin at sea level have never been observed as associated with fossil ice wedges or even fossil ice lenses.

The accumulation of organic matter has been observed in the form of gray to grayish brown Ah horizons (Günster et al. 2001) and at a microscopic level as dark brown to brownish black, thick, dusty, unlabeled infillings (Scarciglia et al. 2003a, 2003b). The chemical and mineralogical compositions of these infillings have never been microanalyzed. Under PolM, the dark color is interpreted as being due to black carbon (Fedoroff et al. 2010). Guo (1990) identified such blackish infillings in

Figure 7. Thick, yellow, microlaminated clay feature in yellowish brown argillic horizon on eolianites. Morocco, Atlantic coast, vicinity of Rabat.
loess in the Loess Plateau in China at the transition OISs 5 to 4. Other existing data on black carbon present in sediments and soils were all obtained from bulk samples. These data show an increase of black carbon during glacial periods (e.g., Luo et al. 2001; Wang et al. 2005). In the Mediterranean basin, Kühn et al. (2006) and Fedoroff et al. (2005) did not relate these infillings to a precise phase or episode; however, Günster et al. (2001) described paleosols and sediments rich in organic matter due to steppic vegetation, dated at OISs 5a and 5c, and Ferraro et al. (2004) described 3 organic matter enriched paleosols that could have formed during the interstadials of OISs 3 and 4. As a hypothesis, we consider that these infillings testify to wildfires of high intensity based on the fact that the feature is unlayered.

Redoximorphic features and facies characterizing soil water logging are weakly developed during the last glacial. According to Günster et al. (2001), impeded drainage occurred during OISs 5a and 5c and a few times during OIS 2 in the Granada basin, which these authors explained by permafrost. The extrapolation of the permafrost hypothesis of Günster et al. (2001) to all soils with redoximorphic characters in the Mediterranean basin does not seem to be sound. Redoximorphic phases are a worldwide phenomenon, including the tropics (e.g., Achyuthan & Fedoroff 2008). In the Mediterranean basin, at least during the Late Pleistocene, these phases occurred during glacial intervals. These phases postdate the reworking episode as redoximorphic features are always superimposed on reworked red soil material. Consequently, we consider that they correspond to a climatic phase of heavy precipitations, during which the soil was water-saturated part of the year, and as goethite is dominant during these phases, we also have to suppose a weak seasonal temperature contrast.

Everyone presently agrees that the accretion of calcite in RMSs was discontinuous and occurred independently of rubefaction–illuviation (Ortiz et al. 2002; Bahia et al. 2009). During the last glacial interval in southern Spain, according to Günster et al. (2001) and Candy and Black (2009), calcite accretion occurred during OIS 5e, apparently immediately after the rubefaction–illuviation phase. Recio Espejo et al. (2008) obtained, for 350 ky, a deep calcic horizon, and for 8.9 ky, nodules present in the Bt horizon. Dating calcite accretion phases is ambiguous. Existing radiometric dates were frequently obtained eventually on secondary and even tertiary crystallization. The aeolian origin of calcite in RMSs is not accepted unanimously and, consequently, we will consider it just as a sound hypothesis. An aeolian origin of calcite means severe wind storms that induce aeolian erosion in areas rich in outcropping carbonate rocks, dust transportation, and deposition, followed by the dissolution of calcitic particles in RMS surface horizons and crystallization in a subsurface horizon. Such calcitic accretion indicates a climate in which evapotranspiration exceeds relative precipitations.

Paleoclimatologists emphasize the temperature fluctuations for which they presently have quite a precise chronology, especially for the last cycle. Martrat et al. (2004) considered that the climate in the Mediterranean basin was predominantly maintained in interglacial-interstadial conditions, whereas the duration of glacial intervals was much shorter. Some of the most prominent events occurred over OISs 5 and 7, after prolonged warm periods of high stability. Sanchez Goñi et al. (2002) showed that in the western Mediterranean basin, rapid (approximately 150 years) and synchronous terrestrial and marine climatic changes occurred, paralleling the Dansgaard–Oeschger cycle (Dansgaard et al. 1993) with an amplification of the climatic signal during Heinrich events, an extreme cooling of 10 °C, and a great dryness occurring during H5 and H4. Sepulchre et al. (2007) confirmed the aridity during H4 over the Iberian Peninsula. Research performed on paleosols developed during glacial intervals of course provide information about temperatures, but also about soil water regimes and consequently about the precipitation regime and environmental events such as outbursts, severe wind storms, and wildfires for which we do not have modern analogs.

A correlation of pedological phases and erosion–soil disruption episodes registered in RMS covers and in buried related paleosols, even for the last glacial with environmental events identified by paleoclimatologists, is presently almost impossible. Paleosols during glacial intervals are supposed to develop during a warmer time span, such as the interstadials (Günster et al. 2001; Ferraro et al. 2004).

The work of Melki et al. (2010) and earlier publications demonstrated that sapropels in the eastern Mediterranean basin correspond to a strong precipitation increase that transformed the whole Mediterranean Sea into a nonconcentration basin. Consequently, the hydromorphic phases could be synchronous with the deposition of sapropels.

7. Conclusions
RMSs are the result of 2 major soil-forming processes, rubefaction and illuviation, occurring in soils in which infiltration exceeds evapotranspiration, also inducing carbonate dissolution and its lixiviation out of the profile. Rubefaction results in an alteration of goethite into hematite in surface horizons, which is distributed through the whole profile by clay illuviation.

Most authors agree that RMSs were formed discontinuously during periods of environmental stability, i.e. interglacials. The behavior of RMS covers during glacial
intervals is just beginning to be deciphered. A large part of the features and facies formed during these intervals are presently erased, but those remaining were not investigated thoroughly and were in most cases misinterpreted. Presently, from the point of view of soil covers, it is possible to conclude that during these intervals: 1) episodes of instability happened in the form of abrupt events during which soils were eroded and disrupted; 2) important dust falls, locally in the form of loess, occurred; and 3) various pedogenic phases took place. The existing data do not enable the establishment of a clear hierarchy between the features and facies, witnesses of each of these episodes and phases. RMS covers were partially and frequently totally eroded, but the most striking phenomenon is the in situ disruption of almost all pre-Holocene RMSs. The RMS disruption is largely underestimated in the literature, which leads one to consider disrupted RMSs as in situ developed soils as well as red pedosols. Consequently, various soil-forming processes, e.g., self-mixing by shrink–swell, were advanced to explain the absence of clay coatings in B horizons of RMSs. During the glacial intervals, RMS covers were also affected by dust falls, which are responsible for the calcitic features and facies present in the RMSs of subarid areas of the Mediterranean basin. The enrichment of organic matter, eventually due to wildfires, has also been mentioned during these intervals.

Redoximorphic features and facies exist in RMS covers. The recent ones, weakly developed, occurred with no doubt during the last glacial period, whereas the environmental conditions of well-developed, earlier ones have to be clarified.

The impact on Mediterranean soil covers of severe cold episodes, which were supposed to be characterized by permafrost, has been exaggerated. Features related to permafrost have never been identified in RMS covers at sea level; however, they appear at a rather low altitude in the Mediterranean basin, e.g., 1000 m. At sea level, textural features corresponding to a thick snow cover exist, but without a deep soil frost.

Heinrich events are presently almost impossible to establish for the correlation of episodes of soil instability as well as pedogenic phases that occurred during glacial intervals with OISs. Earlier pedogenic phases were utilized to define interstadials with warmer periods during a glacial period. As ice cores have shown that 24 interstadials can be referred to as Dansgaard–Oeschger events during the last glacial interval, a new correlation between these events and the pedogenic phases has to be established.

This work shows also that RMS covers (including buried soil–sediment sequences) contain novel data that are not present (or are present in a different form) in ice cores, lakes, and deep sea cores. The data in soil covers concern not only mean temperatures and precipitations, but also the thickness of the snow cover, outbursts, severe wind storms, and wildfires. Unfortunately, investigations performed on the memory preserved in surface RMSs and in buried soil–sediment sequences of the Mediterranean basin are far behind those on ice cores, lakes, and deep sea cores. In the future, such investigations should be undertaken, providing novel and exciting results.

References


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