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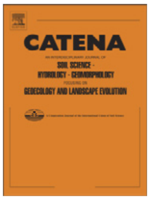

Buried palaeosols of NW Sardinia (Italy) as archives of the Late Quaternary climatic fluctuations

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ABSTRACT

A multi-disciplinary approach was performed to investigate two compound geosols included between wind-blown deposits at the top, and interglacial (MIS 5) beach sediments at the bottom, located along the Alghero coast (North-western Sardinia, Italy). A sedimentological and morphological study was carried out on the profile in the field, and samples collected on the main pedomembers were subjected to several laboratory analyses, consisting of physical and chemical determinations on bulk samples, mineralogy (XRD), micromorphology on undisturbed samples (thin Section, SEM), and EDAX-micro probe analyses. Dating was performed by means of Optically Stimulated Luminescence (OSL). The studied geosols show the evidence of a complex pedosedimentary evolution. Around 80 to 70 ka the lower geosol underwent weathering and clay illuviation (wet and warm conditions), followed by calcification-recalcification processes (dry-contrasted), and finally by strong bioturbation. Around 70 ka the onset of the glacial period (MIS 4) is marked by the deposition of a sand dune, capping the lower geosol. These results indicate that the coastal area of the central Mediterranean kept the relatively warm conditions typical of the interglacial climate for most of the Early Würm and reached cold conditions only at about 70 ka, possibly in relation to the rapid cooling of the Heinrich event H7. The upper geosol developed on colluvial material including abundant pedorelicts and reddish earth material, deposited around 50 ka. Before being buried by aeolian sand around 43 ka, this deposit underwent pedogenesis phases possibly associated to Middle Würm interstadial events, indicating that in the study area these events were intense enough to influence pedogenesis.

1. Introduction

Red or reddish-brown palaeosols were observed in Quaternary sedimentary successions worldwide (Feng et al., 1994; Marković et al., 2008; Muhs and Budahn, 2009; Stevens and Lu, 2009; Zhang et al., 2009). The study of their pedogenic features can complement the knowledge on the palaeoenvironmental conditions related to the climatic fluctuations. Palaeosols offer long-term and fairly continuous palaeoclimatic records, in particular when placed (buried) within an appropriate sedimentological and stratigraphical context (Kraus and Bown, 1986; Mack, 1992). The term geosol has been proposed to designate the buried palaeosols that have a consistent stratigraphic position and can constitute a reference unit in pedostratigraphy (Catt, 1998).

Geosols, and more generally speaking buried palaeosols, are increasingly studied by interdisciplinary analytical methods as archives of palaeoclimatic information (Sheldon and Tabor, 2009). Under certain conditions, it can be assumed that different types of palaeosols represent distinct palaeoenvironments (Retallack, 2001). However, palaeosols preserve an intricate record in which features generated by multiple pedogenic phases are superimposed, as the result of successive cycles of soil development (Duchaufour, 1983; Schaetzl and Anderson, 2005). Buried palaeosols have the advantage of having been subjected to time-bound pedogenic periods. On the other hand, these soil-forming intervals may have been too short (centuries to few thousand years) to allow the achievement of soil–climate equilibrium conditions, and the formation of the corresponding diagnostic pedogenic features (Birkeland, 1984; Meyer, 1987; Yaalon, 1971). Furthermore, soils may

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have been partially eroded before burial, and a range of processes can still have taken place after burial, deeply influencing the palaeosol properties (Retallack, 2001).

Variable sets of diagnostic features have been traditionally adopted to study the palaeoenvironmental features of palaeosols. Among these, some are linked to field-based properties such as soil profile development (Birkeland, 1984, 1985; Harden, 1982), B-horizon color (Hurst, 1977; Sauer, 2010; Torrent et al., 1983), and carbonate status (Machette, 1985). Other diagnostic characters are based on chemical properties such as extractable iron oxides, often integrated by mineralogical studies (Alexander, 1974; Arduino et al., 1986; Boero and Schwertmann, 1989; Torrent et al., 1980). In-depth studies have been especially focused on micromorphology. Among these, Fedoroff and Goldberg (1982), Fedoroff et al. (1990), Bronger and Bruhn-Lobin (1993), and McCarthy et al. (1998) particularly explored the potential of micromorphology in palaeonvironmental research. Micromorphology is thought to provide genetic, temporal and spatial information that is critical to better understand soil-forming processes and past environmental conditions (McCarthy et al., 1998).

Interdisciplinary studies of geosols could be particularly important to shed light on periods poorly documented by palaeoclimatic evidence, such as the Late Quaternary in the central Mediterranean area. Few pedosedimentary studies actually cover this period (e.g.: Carboni et al., 2006; Coltorti and Pieruccini, 2006; Scarciglia et al., 2006; Sauer et al., 2010; Scarciglia et al., 2011), whose climatic conditions remain relatively poorly known.

It is recognized worldwide that during the Marine Isotopic sub-Stage MIS 5e (ca 115–130 ka) the sea level was several meters higher than the present (e.g.: Waelbroeck et al., 2002). Less agreement exists on the sea level elevation during the following substages MIS 5c (105–95 ka) and MIS 5a (81–78 ka; Dorale et al., 2010). Some authors pointed to a sea level position of several meters below the present (e.g.: Waelbroeck et al., 2002), whereas a few others suggested a similar or slightly higher elevation (e.g.: Andreucci et al., 2010a; Coyne et al., 2007; Dorale et al., 2010; Muhs et al., 2012; Pascucci et al., 2014). However, all authors agree with a fast sea level drop after ca 78 ka (beginning of the MIS 4), and reaching the final depth of −120 m b.s.l. during the last glacial stage (MIS 2 ca 20 ka; e.g.: Waelbroeck et al., 2002).

This last interglacial/glacial cycle (ca. 130 to 20 ka) was a dynamic period where rapid climate changes occurred due to the Dansgaard–Oeschger (DO) cycles, characterized by abrupt warming and gradual cooling, and the cold Heinrich (H) events (e.g.: Pini et al., 2009; Müller et al., 2011; Moreno et al., 2012). Long and continuous pollen sequences represent a regional reference to study the effects of climate changes on vegetation and can be used as a tool for landward–seaward correlation of the major climatic fluctuations (e.g.: Pini et al., 2009). A well-developed pollen sequence for the Central and Southern Europe is now available and can be used to discriminate the regional climate as well as the main fluctuations (Pini et al., 2009, and reference therein). In particular, all of Europe records a warm climate for the MIS 5e, called Eemian, and a cold mostly woodless “pleniglacial” phase after 70 ka, called Middle Würm (Martrat et al., 2004). On the other hand, the period called Early Würm, or Early Weichselian, referring to the time interval between the end of the Eemian (ca 115 ka) and 70 ka, shows some differences if the “continental Europe” and the Mediterranean area are compared. Pini et al. (2009) and Zucca et al. (in press) revealed that the Alpine area, as well as central Europe, was already cold at about 110 ka and dominated by two main dry phases associated to the MIS 5 interstadials (MIS 5c and 5a, called St. Geneys1 and 2). Hughes et al. (2006) clearly recognized two cold phases, favorable to glacier formation in the mountains (>2500 m high) of Northern Greece: the first peak at around 110 ka (similar to the Alps) and the second one at about 85 ka. The latter would be almost contemporary to the “Iberian last glacial maximum” identified in the central Pyrenees (Moreno et al., 2012). Conversely, Müller et al. (2011) demonstrated that the temperate–warm condition kept going till the beginning of MIS 4 in the coastal area of north-eastern Greece.

This study investigates a sequence cropping out along the north-western Sardinian coast (Alghero, Italy), showing two palaeosols (hereinafter named geosols, as explained in Section 2.1), interbedded within an Upper Pleistocene sedimentary succession.

The objectives of this paper are: (i) to investigate the pedogenic characters of the geosols, and the related formation and evolution processes and (ii) to link the pedogenic features to the palaeo-climatic conditions and fluctuations occurred during the Early and the Middle Würm (MIS 5a to 3 ca. 80 to 44 ka).

1.1. Geological setting and climate

The study site is located 1.5 km southward of the Alghero town (40°32’ N; 8°19’ E; Fig. 1), nearby the present-day sea level. Quaternary sedimentary deposits crop out quasi-continuously along the present rocky coast, and rest on bedrock composed of mainly Permo-Triassic limestones and sandstones, and Oligo-Miocene andesitic pyroclastic deposits (Carmignani et al., 2001). The Quaternary succession cropping out along the NW coast of Sardinia is characterized by an alternation of shallow marine and colluvial/aeolian deposits. In particular sandy to gravelly shallow marine deposits are dated with the Optically Stimulated Luminescence (OSL) methodology to the last interglacial (MIS 5e and 5c) and the colluvial/aeolian deposits to the glacial stages (MIS 8, 6, 4 and 3; Pascucci et al., 2014).

The present-day coast of the study area is composed of small low-cliff-bounded embayments with basal marine terraces, and occasional gravelly and mixed sand–gravelly pocket beaches (Fig. 2A). The present climate of the area is Mediterranean, with mean annual temperature of 16 °C and mean annual rainfall around 570 mm recorded at the Alghero station (1971–2000; CGEIS, 2002). The average temperature ranges from 10 °C in January to about 24 °C in August. The wet season (October to April) accounts for more than 80% of the yearly precipitation. Small, ephemeral streams flow during the wet season. Evergreen thermo-xerophilous Mediterranean maquis constitutes the climax vegetation cover.

1.2. Stratigraphy, ages and paleogeography

Andreucci et al. (2012) provided a stratigraphical and chronological framework of the studied succession highlighting the presence of two unconformity bounded units: U3 and U4 (Fig. 2).

Due to a great lateral variability the studied cove can be subdivided in two different areas: the northern and the southern side (respectively right and left of Fig. 2A). On the northern side of the cove, corresponding to the studied profile of this work (Figs. 2A, C, 3A), U3 is composed of 80 cm-thick (maximum) gravelly with minor sandy beachface deposits resting unconformably over the bedrock. Unit U4 rests on U3 and is characterized by two colluvial deposits separated by a 30 cm-thick yellowish massive sandy wind-blown stratum (aeolian sandsheet). At the top the succession is unconformably overlaid by meter-thick high-angle cross stratified sand dune deposits (Fig. 2A). On the southern side of the studied cove neither the bedrock nor the marine deposits of U3 crop out. U4, instead, is composed of a single 1.5 meter-thick reddish massive matrix-rich colluvial deposit unconformably overlaid by meter-thick high-angle cross stratified sand dune deposits (Fig. 2A).

The shallow marine deposits of U3, because of their grain size (mainly conglomerates), could not be dated using the Optically Stimulated Luminescence (OSL) technique. However, similar coastal deposits cropping out nearby and at the same height above the present sea level, yielded OSL ages of 98 ± 8 ka and 97 ± 6 ka (Andreucci et al., 2010a). Therefore, beachface deposits of unit U3 most probably developed during the last interglacial stage and are tentatively referred to the Marine Isotopic Stage MIS 5c (ca 100 ka). The palaeogeography of the study area during the MIS 5c was (and is now) characterized by a suite of gravelly or mixed sand and gravelly pocket beaches developed