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Cementation and blackening of Holocene sands by peat-derived humates: A case study from the Great Dune of Pilat, Landes des Gascogne, Southwestern France

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ABSTRACT

The base sand layers of the aeolian Great Dune of Pilat, which stretches along the coast of Arcachon Bay, have been locally impregnated with a dark brown to black amorphous organic substance of humate composition. The humate-cemented sand forms a well-indurated horizon 40–50 cm in thickness that developed immediately beneath the Holocene peaty layer (P1"paleosoil"). The humate, identified by means of FT-IR and Raman micro-spectroscopy, acted both as a cementing agent and as a coloring agent; it formed thin coats and meniscus cements between individual sandstone grains which, in turn, caused the dark, asphaltic-like appearance of the sandstone. Field observations, combined with geochemical analyses, and the presence of identical geochemical compounds recognized in the peat and sandstone humate cement, suggest that the peat-containing low-coalified ($R_r = 0.2\%$) fragments of higher, submerged and floating plants and marine algae deposited in a saline and reducing environment served as an obvious source rock for the humate. The humate derived from decaying organic remains that descended from the peat into the permeable sand, where it indurated irreversibly over a period shorter than 3500 years.

The present-day actions of waves and tides contribute to the erosion of the frontal parts of the humate-impregnated sandstone horizon, resulting in the formation of the dark rounded sandstone slabs and pebbles that are deposited on nearby beaches. This process provides a fine example of recent black pebble formation that derived from pre-existing organic matter-impregnated source rocks. In contrast to their tropical carbonate counterparts, however, the humate-induced blackening of the sandstone pebbles appears to be relatively unstable, as the impregnated fragments bleach when exposed to air and seawater for a few seasons.

1. Introduction

Partially to completely cemented sand layers commonly occur within the otherwise unconsolidated Quaternary coastal sands deposited in tropical to temperate regions. These indurated, brown-to-black colored horizons are spectacular features of podzolic fossil soil profiles in coastal lowlands, in coastal dune deposits and on ocean beaches (Brookfield and Ahlbrandt, 1983; Pye and Tsar, 2009). The cementation of individual sand grains is usually due to various inorganic substances, e.g. secondary silica, imogolite–allophane complex, or Al-complexes that are mobilized by weathering and deposited within the B horizon of leached soils (Farmer et al., 1983; Tucker, 1991). However, in some densely vegetated coastal areas, where organic humic substances are readily available through the decomposition of plant remains, humate gels may form that can easily migrate into the pore space of the sand. On drying, the humic material may harden irreversibly to form intergranular sandstone cements. Humate-cemented sand layers of this kind, which have been termed "humicretes" by analogy with calcretes and silcretes (e.g. Pye, 1982), have been reported from the Quaternary sand dunes stretching along hundreds of kilometers of the Atlantic coast of the United States and the southeastern Gulf of Mexico (Swanson and Palacas, 1965). Other occurrences of humate-cemented coastal dune sands have previously been described under a number of local names, including "sandrock", "waterloo rock", and "coffee rock" from the eastern coast of Australia (Brooke et al., 2008; Cox et al., 2002).

In this paper, we report on the occurrence and examine the fabrics, the geochemical composition and the origin of the humate cementing substance in the coastal sands forming the basement of the huge Late Quaternary aeolian sand Dune of Pilat on the Atlantic coast of France. We describe a peculiar sequence of *per descendum* organic mineralization

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with humates, which is genetically closely related to the nearby Holocene peat deposits. Our study is of importance in two different aspects. First, it offers an insight into the composition and the formation processes of organic cements, and provides information on the rates at which cementation occurs in Quaternary coastal deposits. Second, the black-colored sandstone pebbles that result from ongoing coastal erosion of humate-cemented sand layers by waves and tides offer a rare actualistic example of the present-day formation of so-called black pebbles. These reworked lithoclasts with a distinctive black penetrative coloration have previously been described from many ancient shallow-water sequences and interpreted as key indicators of subaerial exposure, coastlines, or islands (Vera and de Cisneros, 1993). Although present-day formation black pebbles have been widely encountered in tropical and subtropical carbonate settings (Strasser, 1984; see also Flügel, 2004 and the references therein), very few, if any, examples of these organic-impregnated lithoclasts have until now been described from modern siliciclastic depositional environments (e.g. Bernier and Strasser, 1988).

2. Geological setting and samples

The Acquitane coast of France, from the mouth of the Gironde in the north to Biarritz in the south is characterized by the development of relatively narrow, sand- and gravel-dominated siliciclastic beaches that are fringed by a massive system of aeolian subaerial sand dunes about 230 km in length. These dunes are locally known as Les Landes de Gascogne (c.f. Bressolier et al., 1990; Tastet and Pontee, 1998). In particular, the area near the entrance to the Bay of Arcachon, where this study was undertaken, is dominated by the Great Dune of Pilat, which is a huge aeolian sand body about 100 m in height, 500 m in width and 2500 m in length (Fig. 1). The asymmetrical cross-section of the dune is shaped by westerly winds, resulting in more abrupt slopes leeward to the east and relatively gentle slopes windward to the west. The dune has been progressively formed over the last 5000 years, primarily due to the accumulation of sands windblown from the sandbank bodies once stretched in front of the present coast line.

The process of dune accumulation was punctuated by several distinct periods of late-Holocene stability and soil formation, which are preserved as distinctive soil and/or peat horizons at various levels in the dune. These horizons date from approximately 3500 BC until the 19th century (Fig. 2). At the present time, the dune is still continuing to grow; historical and recent measurements show steady inland migration of the dune resulting in the gradual burial of the nearby buildings and pine forest by dune sands (Mugica et al., 2010; Paymal and Friodefond, 2005). Further inland, the sand dune belt gives way to an extensive sandy marsh flat known as the "Sables des Landes", which runs more than 100 km into the mainland of France.

The humate-impregnated black sandstone which is the subject of this study forms a spectacular, slightly seaward-inclined indurated bench, about 50 cm in thickness that is well exposed at the foothill of the Great Dune of Pilat, close to sea level. At low tides, this blackened bench emerges in the lower part of the beach, and its lateral equivalents can also be followed up-dip, close to the high tide level, at the foot of the nearby sand dunes (Fig. 3A). In hand specimens and to the naked eye, the freshly hammered humate-indurated sandstone appears to be homogeneously black, grainy, porous rock strikingly similar in appearance to the asphaltic sand of many oil seeps. Some samples of this unusual sediment are well lithified but more often the blackened sandstone is rather friable, apparently only weakly cemented and with a slight mechanical effort it can easily be disintegrated into sharp-edged chips or even individual blackened sand grains.

Immediately above the blackened sandstone bank, a crispy layer, about 20–25 cm in thickness, of dark brown to black solid organic substance resembling a peat coal is locally developed. This is a P1 "palaeosol" layer, about 3680 years old, which forms the base of the Dune of Pilat (Fénies and Tastet, 2004). Upright pine stumps that are locally present within the peat evidence the autochthony of this organic deposit (Fig. 3B and C).

Large rectangular blocks and boulders of dark, humate cemented sandstone, up to 1 m in diameter, that were eroded from the source

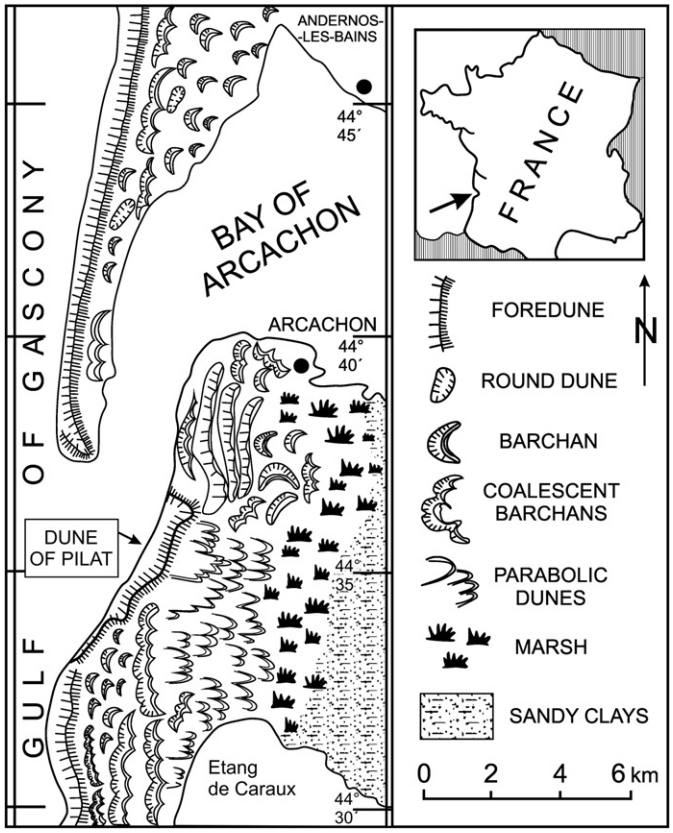

Fig. 1. Schematic map showing the location of the Great Dune of Pilat and the distribution of other sand bodies near Arcachon Bay (modified after Froidefond and Legigan, 1985).

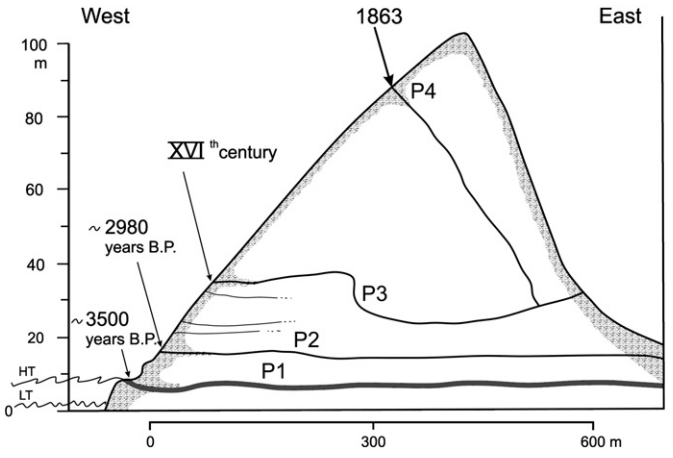

Fig. 2. Sketch profile of the Great Dune of Pilat showing the positions and the respective ages of individual paleosol layers recognized in the dune profile. Paleosol P1, below which the horizon of the blackened indurated sandstone developed, is the oldest paleosol of the dune sequence exposed near sea-level. The ages of individual paleosol layers have been established by radiocarbon dating (Froidefond and Legigan, 1985), by palynologic analyses (Paquereau and Prenant, 1961) and by historical dating (Dautant et al., 1983). Modified after Fénies and Tastet (2004) and Paymal and Friodefond (2005).