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Petrography, micromorphology and genesis of Holocene pedogenic calcrete in Al-Jabal Al-Akhdar, Sultanate of Oman

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ABSTRACT

Holocene pedogenic calcrete nodules occur within Quaternary terra rossa soil that fills shallow phytokarst cavities in the Permian-Triassic carbonate sequence of Al-Jabal Al-Akhdar in the Sultanate of Oman. They are preferentially clustered around plant roots and are almost wholly formed of calcite. Holocene pedogenic calcrete nodules developed within a Mediterranean-like climate that is characterized by intermittent wet and dry seasons. Petrographic examination revealed that the host terra rossa soil is partially calcitized and that the calcrete nodules consist of smaller coalesced diffused and/or discrete granular nodules. The latter consist of several types of rhizoliths floating in a groundmass formed of micrite and microspar, as well as spar to a lesser extent. Several textures of calcrete groundmass are recognized; the most common is partially neomorphosed micrite. Three types of rhizoliths are recognized, root moulds, root casts and petrified (calcified) root tissues. The latter were developed by mimic replacement of the tissue cells by cytomorphic calcite. SEM investigation of the calcite forming the calcrete nodules revealed that it consists of closely stacked sheets formed of calcareous nanoglobules agglutinated by EPS and entombed calcareous microbial fossils, which indicate a biogenic origin.

The calcareous nature of the bedrock, climatic conditions and prevalence of biological activities of microorganisms associated with the plant root system in the host soil have significantly controlled the development and texture of these nodules. The relative abundance of scalenohedral calcite within the calcrete groundmass is attributed to the impact of Mg ions and organic compounds. It has been concluded that the studied pedogenic calcrete is a type of freshwater terrestrial thrombolitic microbialite. This study may help improve the understanding of the palaeoenvironmental conditions of analogue fossil calcretes.

1. Introduction

Calcrete, a synonym for indurated caliche, is mostly formed within arid and semi-arid climates with annual rainfall less than 600 mm and evaporation exceeding precipitation (Goudie, 1983; Wright and Tucker, 1991). It is widely used to reconstruct palaeoclimatic conditions (Reeves, 1976; Alonso-Zarza, 2003). Calcretes have been studied for over a century; however, the role of organisms in their formation has received attention only in the last three decades (Klappa, 1979a, 1979b, 1980; Wright, 1986; Phillips and Self, 1987; Phillips et al., 1987; Jones and Ng, 1988; Wright, 1990; Jaillard, 1992; Verrecchia et al., 1995; Wright et al., 1995; Alonso-Zarza et al., 1998; Kosir, 2004; Zhou and Chafetz, 2009). The nature of the host material, climate, and vegetation may also control the formation of pedogenic calcrete (Wieder and Yaalon, 1982; Wright, 1987). Watts (1980) described the various processes responsible for the development of pedogenic calcrete in the Kalahari Desert. Monger (2002) used four models to describe pedogenic carbonate formation, namely, per decensum, per ascensum, in situ, and biogenic models.

Dal'Bo et al. (2009) and Pereira et al. (2015) described, in detail, the macro- and microscopic pedogenic calcretes within the paleosol (Aridisols) profiles of the Marília Formation (Maastrichtian) in southeastern Brazil and calculated the paleoprecipitation during the pedogenic calcretization. Horn et al. (2013) studied calcrete associated with laminated, fossiliferous red silty mudstones of the Triassic Santa Maria Supersequence in the central portion of Rio Grande do Sul State, Brazil. In spite of the plentiful rhizoliths in this calcrete, they suggested an inorganic origin that was developed under mixed phreatic and vadose conditions by per descensum processes during rainy seasons.

Despite the abundance of pedogenic calcrete, soil scientists tend not to use the term calcrete. They commonly refer to it as calcic and petrocalcic soil horizons in Aridisols, Vertisols, Mollisols and Alfisols (Soil Survey Staff, 1975; Birkeland, 1999). The term calcic horizon is used for a soil K-horizon that has a prominent accumulation of carbonates (Gile et al., 1966). The term petrocalcic horizon is commonly used if the horizon is continuously cemented with carbonates (Soil Survey Staff, 1975). Owliaie (2012) described the texture and composition of pedogenic calcrete nodules as calcitic pedofeatures. Therefore,

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pedogenic calcretes may form a considerable portion of soil profiles (Wright and Tucker, 1991).

Pedogenic calcrete usually occurs as nodules of various sizes and commonly consists of a calcareous groundmass enclosing rhizoliths (Klappa, 1980). The latter are organo-sedimentary structures that are produced by living and decayed plant roots (Jones and Ng, 1988; Jones and Squair, 1989; Klappa, 1980; Mount and Cohen, 1984; Zhou and Chafetz, 2009). Several terminologies have been used to describe these structures, such as 'rhizomorph' (Northrop, 1890), 'rhizoconcretion' (Kindle, 1925), 'rhizocretions' (Calvet et al., 1975), 'root rock' (Perkins, 1977), 'rhizolith' (Klappa, 1980), 'rhizomorpheous structures' (Jaillard, 1992) and 'rootcrete' (Alonso-Zarza and Jones, 2007). Klappa (1980) identified five basic structures of a rhizolith as root moulds, root casts, root tubules, rhizocretions (which are pedodiagenetic mineral accumulations that occur around the plant roots), and root petrifications. He attributed root petrification to the replacement of organic matter within root cells by minerals that have partly or completely preserved the anatomical features of the roots. Roots in the vadose zone occur in association with microorganisms, such as bacteria, cyanobacteria, and fungi (Jones, 1994). These are thought to play an important role in the development of pedogenic calcrete (Alonso-Zarza et al., 1998; Jones, 1994; Singh et al., 2007).

The present study is the first documentation of a Holocene pedogenic calcrete developed within a phytokarst terra rossa soil in the Al-Jabal Al-Akhdar region of the Sultanate of Oman. It describes, in detail, the petrographic characteristics, micromorphological features and mineralogy of the calcrete. It also discusses the role of microorganisms in calcrete genesis. It sheds light on the climatic conditions under which this calcrete was developed.

2. Methodology

The field occurrence and sedimentary and biogenic structures of pedogenic calcrete were described. Seventeen samples were collected from calcrete nodules, four samples from the host terra rossa soil and three samples from bedrock. Terra rossa samples were granulometrically analysed using standard sieving techniques (Folk, 1974), and the sand and silt fractions were microscopically examined. Collected nodules were described and photographed. They were cut into two halves to expose their internal structures. Fifty thin sections of calcrete nodules, terra rossa soil and bedrock samples were prepared and microscopically investigated. The $CaCO_3$% in the studied samples was determined by the simple method of the dissolution of sample powder in dilute HCl. The main mineral constituents of all collected samples were identified using a BrukerD5000 X-ray diffractometer (XRD). The XRD patterns were collected in a 2θ angular range between 10° and 80°, with a 2θ scan step of 0.015° and a step time of 2 s, using CuKα1 radiation ($\lambda = 1.5406$ Å) and a Ni filter at a voltage of 40 kV and current of 40 mA. The computer program DIFFRACplus with the International Center for Diffraction Data (ICDD) library was used for mineral identification and semi-quantification. Semi-quantitative analysis of the major oxides within the studied samples was carried out using X-ray fluorescence (XRF). Powdered samples mixed with a binder were pressed into pellets. Empirical calibration was performed using standards of known elemental composition. Calcrete fragments, mounted on SEM stubs, were examined on a Supra 50 LEO-141 variable pressure scanning electron microscopy (VPSEM) system equipped with an energy dispersive X-ray spectroscopy (EDS) detector and Quantax software v. 1.5. EDS provided semi-quantitative data of the elemental composition of the investigated spots within the studied samples.

3. Field occurrence

The study area is located at approximately 3000 m above sea level within the Jabal Akhdar Mountains of central Oman (Fig. 1). In this region, shallow-marine dolomitized limestones of the Middle Permian Saiq and the Triassic Maheel Formations are well exposed (Koehrer et al., 2010; Baud and Richoz, 2013). Relatively thin phytokarst cavities within this sequence are exposed along a roadcut in the Daen Al Hamra area (Fig. 2A). These cavities were formed during the Holocene wet period. They were developed by biological corrosion of the calcareous bedrock along vertical fractures and were enlarged through further dissolution by meteoric water and the growth of plant roots. These cavities are highly variable in size and morphology and commonly occur at the contact between extensively cracked Mahil dolomitized limestone above and lower hard blackish carbonates of the Saiq Formation below. They reach a thickness of 3 m and extend laterally for more than 5 m. They are filled with residual red soil (terra rossa) mixed with brecciated bedrock fragments. Tree roots grow within the cracks of the dolomitized limestone beds and extend vertically and horizontally in excess of 10 m. Some root cracks reach up to 0.5 m in width. Calcrete nodules are commonly clustered on and around tree roots within the terra rossa soil (Fig. 2B). They also occur as discrete rhizocretions embedded within the terra rossa soil (Fig. 2C).

4. Climate

The Sultanate of Oman lies in an arid to semi-arid global climatic zone. It is characterized by a subtropical dry, hot desert climate with low annual rainfall. Unlike the surrounding desert area, the climate of the Al-Jabal Al-Akhdar region tends to be close to that of the Mediterranean zone. Such climatic variation is attributed to its elevation (3,000 m above sea level) and external climatic influences from the Mediterranean Sea and Indian Ocean. The low pressure systems from the Mediterranean Sea that irregularly cross the region are responsible for heavy rain in the winter (December to April). Rainfall occurs again in the summer (between June and August) when the monsoons from the Arabian Sea affect the area, but the rain is sporadic and varies in quantity from one area to another. The region is affected by infrequent but catastrophic downpours associated with tropical cyclones that originate in the eastern Arabian Sea and northern Indian Ocean and occur, on average, every 50 years. However, cyclone Gunu in 2007 and cyclone Phet in 2010 occurred at a much more frequent interval and caused mass destruction in the region. These storms produced torrential rains and flash floods that uprooted trees (Al-Busaidi, 2012).

In general, the annual rainfall ranges from 115 to 413 mm (Fig. 3), approximately 53.9% of rainfall occurs in the winter, and summer rain accounts for 23.3% of rainfall (Kwarteng et al., 2009). The average winter temperatures range between 1 and 21.5 °C, occasionally dropping below −3 °C in some years. However, temperatures tend to be hot in summer, with an average range of 31 to 34 °C, exceeding 35 °C some years. Average humidity ranges between 22% and 55% in summer and winter, respectively (Al-Busaidi, 2012).

5. Results

5.1. Petrography

5.1.1. Host terra rossa

The terra rossa host soil is reddish-brown, friable, and slightly fissile. In addition to calcrete nodules, it includes bedrock fragments of varying sizes. Grain size analysis of the terra rossa host soil indicates that it is slightly granular sandy mud that has an average composition of 6%, 13%, and 81% of granule, sand, and mud fractions, respectively (Table 1). The granule fraction consists of granular calcareous nodules and fragments of bedrock. The sand fraction is mostly composed of fine sand size and consists of calcite and quartz grains. The mud fraction consists of 21% silt and 60% clay. The insoluble residues constitute, on average, 61% of the total mass and are mostly quartzitic silts and clays.

Microscopic examination revealed that the host terra rossa sediment consists of a reddish clay groundmass with fine sand- and silt-size quartz grains and organic debris (Fig. 4A). It is full of calcite that varies