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Micromorphology and formation of pedogenic ooids in calcic soils and petrocalcic horizons

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ABSTRACT

Ooids, pisoids, nodules, concretions, and a host of other terms are used to describe concentrically-zoned pedogenic carbonate, phyllosilicates, silica, and other minerals in calcic and petrocalcic horizons worldwide. The pedogenic and paleoenvironmental significance of such features is not always easy to interpret because variations in size, structure, composition, and soil-geomorphic context have been used to infer distinct modes of genesis for features that appear similar. Using both optical and scanning electron microscopy, petrocalcic soil samples from the Jornada La Mesa geomorphic surface in New Mexico and the Mormon Mesa geomorphic surface in Nevada were studied to reconsider the formation of pedogenic ooids. In this paper, "ooids" are <2 mm in diameter and are comprised of concentrically alternating carbonate and fibrous clay laminae. "Pisoids" are >2 mm in diameter and have a range of internal morphologies. Ooids were especially common within features including clast pendant laminae, pisoids, and laminar horizons or laminar horizon caps. We propose a possible new mode of ooid genesis, suggesting that crystal growth can move ooids tiny, incremental distances over time, and that phyllosilicates are an important genetic component. Ooids are interpreted to form via: (1) mineralization during the evaporation of solutions held by surface tension around mineral grains, clasts, or petrocalcic fragments, with or without the presence of organic matter, (2) hydration and plastic behavior of pervasive, pedogenic, fibrous phyllosilicates that co-precipitate with pedogenic calcite, and (3) tiny, successive movements caused by the crystallization pressure of pedogenic carbonate and other minerals during soil solution evaporation. Spheroidal morphology is initially promoted by chemical precipitation from evaporating solutions around grains. Next, crystallization pressures from the surrounding matrix displace grains non-uniformly, promoting stochastic contacts or 'knocking' of ooids against one another and against the soil matrix. Over long time spans, this micrometer-scale, episodic translocation and rotation, in tandem with the plastic behavior of fibrous phyllosilicates, enhances the spherical shape of ooids. The model described here does not preclude possible biological contributions to ooid genesis, nor refute the role of other processes in producing similar features in the same soil. Finally, ooid size is limited by physical and hydrological thresholds. Pisoids, as larger features, are more complex and are more likely to involve erosion; they do not form in the same manner as ooids. This study has implications for paleoenvironmental interpretations of calcic and petrocalcic horizons, and for the selection of pedogenic features for isotopic analysis.

1. Introduction

Spheroidal, concentrically laminated or zoned structures ranging from micrometers to centimeters in diameter are intriguing structural components that form in a remarkably broad range of soils (from Oxisols to Aridisols) and sediments (from terrestrial to marine) (Stoops et al., 2010; Kendall et al., 2014; Soil Survey Staff, 2014). Fundamentally, these concretionary features reflect the dynamic interactions of chemical, biological, and/or physical processes. Their analysis can potentially yield important interpretations of solution chemistry, sedimentology, and microbiology in modern as well as ancient environments. In soils, some of these concretionary structures form concurrently with mineralogical and morphological development of the surrounding matrix (Soil Survey Staff, 2014). Common compositions include silica, carbonate, bauxite, and iron and/or titanium oxides (Soil Survey Staff, 2014). In other cases, the structures are interpreted to be inherited (i.e., lithogenic) rather than pedogenic in origin, or of mixed sedimentary and diagenic origin (Esteban, 1976; Alonso-Zarza and Silva, 2002). Careful study of their (micro)morphology, mineralogy, geochemistry, and field context is needed to interpret their genesis. Importantly, study of these features is pertinent for isotopic analysis or dating of soils or paleosols (e.g., Khadkikar

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et al., 2000; Colin et al., 2005), because discrete morphological components of soils can yield different isotopic signatures or ages, or exhibit distinct closed- vs. open-system behavior. A thorough understanding of ooid genesis in modern environments is especially needed for analysis of ancient paleosols or sediments, where signals from sedimentary processes, soil genesis, and/or phreatic or deep-crustal diagenesis may be superimposed (e.g., Mazzullo and Birdwell, 1989; Monger and Adams, 1996; Meyer, 1997; Warren, 2006; Alçiçek and Alçiçek, 2014).

Concentrically-zoned accumulations of pedogenic carbonate, phyllosilicates, silica, and other minerals are well-documented in calcic and petrocalcic horizons (caliches) of extant, Holocene to Pleistocene or older soils, especially Calcids and Petrocalcids, as well as in paleosols (Reeves, 1976; Bachman and Machette, 1977; Khadkikar et al., 2000; Durand et al., 2010). Fine carbonate masses and nodules, for example, represent the second stage of calcic soil development (Gile et al., 1966; Machette, 1985) and may exhibit a concentric internal structure, though most features called nodules are massive or sparitic (Bachman and Machette, 1977; Durand et al., 2010). Some of these nodules may persist as inclusions, fracture fillings, or brecciated fragments within the petrocalcic horizons of stage V and VI carbonate soils (Bachman and Machette, 1977; Durand et al., 2010).

Unfortunately, pedogenic and paleoenvironmental interpretation of concretionary carbonate pedofeatures is not straightforward, because (1) distinct processes can produce features that appear quite similar in cross-section, and (2) variations in size, structure, composition, and/or soil-geomorphic context may constitute evidence for distinct soil or geomorphic processes that may operate either individually or in combination with one another. The occurrence of concretionary structures in calcic soils and paleosols must be interpreted on a site-specific basis as: (1) pedogenic or non-pedogenic (i.e., inherited marine, lacustrine, fluvial, or groundwater), (2) biotic or abiotic (purely chemical precipitation), (3) formed subaerially or within the subsurface soil matrix, and/or (4) indicative of soil surface erosion or geomorphic stability. Just as climate, biology, and topography cannot truly be separated in catena studies, chemical, biological, and sedimentological processes are more likely to operate in tandem to form ooids and pisoids even if each might theoretically also operate in isolation.

Further complicating matters, micromorphological terminology has proliferated within soil science and sedimentology alike, and a range of features has variably been called coated grains, concretions, glaebules, globules, granules, microaggregates, nodules, oncoids, ooids, pellets, peloids, pisoids, pisolites, pisoliths, spheroidal carbonate, or any of a host of other terms that can have different meanings between or even within disciplines (see Bachman and Machette, 1977; Chafetz and Butler, 1980; Durand et al., 2010; Kendall et al., 2014; and others). Features including calcispheres (Monger and Adams, 1996), *Microcodium* (Klappa, 1978; Monger et al., 1991), ooliths or pisoliths (e.g., Bachman and Machette, 1977), and spherulites (Verrecchia et al., 1995; Durand et al., 2010) are also common in calcic soils, but they are morphologically and genetically distinct from the concretionary carbonate structures. Use of many distinct terms, especially across the 2 mm size threshold, can be viewed as arbitrary outside of sedimentology, and researchers must sometimes define or explicitly simplify their own use of existing terms for clarity (e.g., see Chafetz and Butler, 1980; Alonso-Zarza and Silva, 2002). Generally, such pedofeatures are collectively called nucleic nodules or concentric nodules under conventional terminology (e.g., Stoops, 2003). In this paper, however, concentric structures <2 mm in mean diameter are called ooids, and those >2 mm are called pisoids.

The role of phyllosilicates in the formation and morphology of spheroidal structures, whether at the microscopic or macroscopic scale, is currently underexplored, especially in existing models of ooid genesis in calcic soils. Carbonate clearly dominates the secondary mineralogy of many calcic and most petrocalcic horizons. However, carbonate crystallization cannot be considered as if occurring in a mineralogical vacuum, nor as if from a solution of calcium and bicarbonate ions alone. Phyllosilicates, sulfates, chlorides, and a variety of other mineral groups create important chemical feedbacks with soil solutions in arid soils, particularly with Ca^{2+} and/or HCO_3^- ions (Watts, 1980; Verrecchia and Le Coustumer, 1996; Monger and Daugherty, 1991a; Robins et al., 2012). Calcite precipitation can also progressively change hydraulic conductivity over time, driving geomorphic feedbacks. Thus, the concurrent, linked precipitation of phyllosilicates and other minerals with secondary carbonate may be important for the morphological evolution of the soil horizon, and indeed, the entire profile. Study of phyllosilicates within pedogenic ooids bridges the spatial scale of soil solution chemistry with that of soil profile morphology, and may reveal some of the minute yet profound ways in which mineralogical evolution is directly linked to landscape evolution.

The goals of this paper are to revisit the genesis of concretionary microstructures in calcic and petrocalcic horizons, and to specifically evaluate the hypothesized roles of (1) soil wet–dry cycles, (2) the hydration and plastic behavior of palygorskite and sepiolite, and (3) non-uniform crystallization pressures from calcite and other pedogenic mineral growth in the formation of pedogenic ooids. With the present study, we interpret pedogenic ooids and pisoids in light of existing conceptual mineral development models for calcic soils (e.g., Bachman and Machette, 1977; Watts, 1980; Robins et al., 2012), and in light of the broader scale soil profile development models suggested for calcic soils or petrocalcic horizons by other researchers (e.g., Gile et al., 1966; Machette, 1985; Alonso-Zarza, 2003; Brock and Buck, 2009). We specifically consider the hypothesis that pedogenic mineral growth during early stage (e.g., stage II or higher) calcic soil genesis can cause tiny, stochastic, successive movements of grains or ooids in the soil with each wet–dry-crystallization cycle.

1.1. Occurrence and genesis of pedogenic ooids and pisoids

Durand et al. (2010) summarized the micromorphology, interpretations, and terminology of concretionary pedofeatures in calcic soils; a detailed review therefore exceeds the scope of this paper. Further, ooids and pisoids have long been recognized and described in calcic and/or petrocalcic soils or paleosols in India (Khadkikar et al., 2000), the United States (Reeves, 1976; Bachman and Machette, 1977; Hay and Wiggins, 1980; Reheis, 1988; House et al., 2010; and others), Saudi Arabia (Reeves, 1976), Spain (Esteban, 1976; Reeves, 1976; Calvet and Julià, 1983; Alonso-Zarza and Silva, 2002), South Africa (Francis et al., 2012a), Turkey (Kaplan et al., 2013), and other locations around the world. It is also worth noting that some of the described pisoids in these studies could simply be cross-sectional views of clast pendants. Clast pendants, or pisoids comprised of one or more generations of rotated and successively re-laminated clast pendants, may appear concentric in cross-section even when their three-dimensional shape is non-spherical, and/or even when their true lamination is not concentric (Bachman and Machette, 1977; Brock and Buck, 2009). Such structures are not the focus of this paper.

Ooid and pisoid genesis can begin quite early in the development of a calcic soil horizon — any exhibiting stage II morphology or greater (Gile et al., 1966; Reeves, 1976; Bachman and Machette, 1977; Brock, 2002). Here, we briefly consider the role that biological, sedimentological, and chemical processes play in the genesis of ooids and pisoliths, and on their internal morphology. Unfortunately, most descriptions and interpretations of ooids and pisoliths typically focus on the micromorphology of calcite, with variable, but generally lesser attention paid to any amorphous silica, iron oxides, calcium oxalate, or phyllosilicate constituents also found comprising laminae.

1.1.1. Chemical processes and micromorphology

Ooids may be able to form from purely chemical, abiotic processes. This is supported by experimental data, for instance, Davies et al. (1978) and Tracy et al. (1998a,b) successfully synthesized spherical carbonate microstructures by altering solution concentrations of Mg^{2+}, SO_4^{2-} and other ions. Thus, in a purely chemical model of ooid formation, surface tension and the capillary movement of water produce thin coatings of