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Groundwater table fluctuations recorded in zonation of microbial siderites from end-Triassic strata

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ABSTRACT

In a terrestrial Triassic–Jurassic boundary succession of southern Sweden, perfectly zoned sphaerosiderites are restricted to a specific sandy interval deposited during the end-Triassic event. Underlying and overlying this sand interval there are several other types of siderite micromorphologies, i.e. poorly zoned sphaerosiderite, spheroidal (ellipsoid) siderite, spherical siderite and rhombohedral siderite. Siderite overgrowths occur mainly as rhombohedral crystals on perfectly zoned sphaerosiderite and as radiating fibrous crystals on spheroidal siderite. Concretionary sparry, microspar and/or micritic siderite cement postdate all of these micromorphologies. The carbon isotope composition of the siderite measured by conventional mass spectrometry shows the characteristic broad span of data, probably as a result of multiple stages of microbial activity. SIMS (secondary ion mass spectrometry) revealed generally higher $\delta^{13}C$ values for the concretionary cement than the perfectly zoned sphaerosiderite, spheroidal siderite and their overgrowths, which marks a change in the carbon source during burial. All the various siderite morphologies have almost identical oxygen isotope values reflecting the palaeo-groundwater composition. A pedogenic/freshwater origin is supported by the trace element compositions of varying Fe:Mn ratios and low Mg contents. Fluctuating groundwater is the most likely explanation for uniform repeated siderite zones of varying Fe:Mn ratios reflecting alternating physiochemical conditions and hostility to microbial life/activity. Bacterially mediated siderite precipitation likely incorporated Mn and other metal ions during conditions that are not favourable for the bacteria and continued with Fe-rich siderite precipitation as the physico-chemical conditions changed into optimal conditions again, reflecting the response to groundwater fluctuations.

1. Introduction

Siderite is a common early diagenetic mineral occurring with a variety of morphologies in different depositional environments. Rhombohedral and spheroidal (ellipsoid-shaped) siderite are known from marine mudstones and sandstones (e.g. Mozley and Carothers, 1992; Mortimer et al., 1997; Wilkinson et al., 2000; Weibel et al., 2010), whereas sphaerosiderite (with internal radial and/or concentric zonation) and spherulitic siderite morphologies (with internal radial structures) and nodules/spheres of siderite (without clear internal structures) are commonly of pedogenic origin (e.g. Browne and Kingston, 1993; Retallack, 1997; Driese et al., 2010; Robinson et al., 2010; Suarez et al., 2010; Rosenau et al., 2013) and are occasionally found in tidal flats (Choi et al., 2003). A morphological change from spherulitic to rhombohedral siderite during diagenesis has recently been suggested by Köhler et al. (2013) and renders the probability of other explanations for the varying siderite morphologies. In a similar way to the changes during burial of marine sediments, the initial microbial mediated fast precipitation may change into rhombohedral growth, as the supply of Fe becomes slower during increased burial of continental deposits. Zonation is common in rhombohedral and spheroidal siderite, and sphaerosiderites are characterized by internal radial-concentric microstructures. Siderite zonation has previously been ascribed to mixing of meteoric and marine waters (Mozley, 1989; Choi et al., 2003), diagenetic evolution of freshwater or brackish–marine pore water during burial (Matsumoto and Iijima, 1981; Lim et al., 2004), or modification of the original marine pore waters during successive stages of microbial decomposition of organic matter (Mozley and Carothers, 1992; Wilkinson et al., 2000; Lim et al., 2004). Despite

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the wide occurrence of sphaerosiderite, little is known of the pedogenetic conditions (physical, chemical and biological) under which they form and when different siderite morphologies are likely to precipitate (Driese et al., 2010). Precipitation of siderite, even within historical time (<100 years) shows that microbial degradation of organic contaminants can enhance siderite precipitation rate (Driese et al., 2010). Hence, microbial activity in the pedogenic regime may have promoted precipitation of sphaerosiderite. Siderite formation has been interpreted to be microbially mediated in various environments; marine (Mozley and Carothers, 1992; Wilkinson et al., 2000), tidal (Choi et al., 2003), and lacustrine (Fisher et al., 1998). A wide range in carbon isotope composition ($\delta^{13}C$) of spharerosiderites is interpreted to originate from variations in the type of microbial activity in soils (e.g. Robinson et al., 2010), whereas a more narrow range of oxygen isotope compositions ($\delta^{18}O$) is thought to reflect meteoric water compositions (e.g. Ufnar et al., 2004b; Driese et al., 2010; Robinson et al., 2010; Suarez et al., 2010). The latter has therefore been used as a palaeoproxy for the isotope composition of rainfall, primarily during the Cretaceous (Ludvigson et al., 1998; Ufnar et al., 2001, 2002, 2004a, 2004b, Suarez et al., 2010; Robinson et al., 2010).

The end-Triassic event is one of the five largest biotic crises during the Phanerozoic (Bond and Wignall, 2014). It is temporally linked to the emplacement of intrusive and extrusive volcanic rocks during the formation of the Central Atlantic Magmatic Province (Schoene et al., 2010; Blackburn et al., 2013), and degassing from this volcanism is generally believed to have played a major part in the extinction scenario (e.g. Hesselbo et al., 2002; Ruhl et al., 2011; Lindström et al., 2012). Organic $\delta^{13}C$ records across the Triassic–Jurassic boundary show large negative perturbations in the carbon cycle interpreted as reflecting input of light carbon from the volcanism or from methane release (e.g. Hesselbo et al., 2002). In the terrestrial realm, physiological responses in fossil plants indicate intense global warming across the Triassic–Jurassic boundary (McElwain et al., 1999). Increased storminess and lightning activity are further indicated by charcoal records showing increased wildfire activity from Greenland, Denmark, Sweden and Poland (Marynowski and Simoneit, 2009; Belcher et al., 2010; Petersen and Lindström, 2012). Sedimentary records from the Danish Basin indicate increased reworking of palynological material (Lindström et al., 2012), and marked changes in fluvial terrestrial successions in Sweden and Greenland seem to indicate an increased water content in the hydrological cycle across the boundary (Lindström and Erlström, 2006; Steinthorsdottir et al., 2012).

Sphaerosiderites and other siderite morphologies have previously been reported from Triassic–Jurassic boundary sediments (Höganäs Formation) in Scania, southern Sweden (Fig. 1; Troedsson, 1951; Ahlberg, 1994). Troedsson (1951) reported sphaerosiderites from early–middle Rhaetian clayey sediments (Vallåkra Member of the Höganäs Formation) in several old cored wells and outcrops in northwest and central Scania, and concluded that sphaerosiderites were restricted to this particular interval. Here, we show that sphaerosiderites also occur within the latest Rhaetian sand and sandstones (Helsingborg Member of the Höganäs Formation), although they are apparently absent from the intermediate part (Bjuv member of the Höganäs Formation) (Fig. 1). The purpose of this study is to find explanations for the different siderite morphologies and contribute to the understanding of sphaerosiderite formation, and its implications regarding Triassic–Jurassic boundary events. In northwest Scania, southern Sweden, the end-Triassic terrestrial succession is characterized by a pronounced shift in depositional style and in occurrence of various types of authigenic siderite. Mid to late Rhaetian forest mires and confined fluvial channel deposits are completely free of authigenic siderite, whereas the overlying latest Rhaetian unconfined and probably episodic braided river deposits are dominated by siderite concretions and authigenic siderite. In this sense, the Albert-1 core, Norra Albert quarry and the Fleninge No. 266 core (Fig. 2), which together encompass Norian–Hettangian strata, provide excellent opportunities for such investigations as perfectly zoned sphaerosiderite occur juxtaposed with other siderite morphologies.

2. Geological setting

During the Late Triassic–Early Jurassic, the Norwegian–Danish Basin was situated on the margin of an epicontinental basin covering NW Europe (e.g. Fischer and Mudge, 1998; Nielsen, 2003). Southern Sweden was part of the Fennoscandian Border Zone, which is structurally defined by the Sorgenfrei–Tornquist Zone, and marks the transition from the Fennoscandian Shield to the north-east and the gradually deepening (epicontinental) basin towards the south-west (Fig. 1; Liboriussen et al., 1987; Mogensen and Kortsgård, 2003; Nielsen, 2003). Therefore, minor sea-level changes played a significant role in controlling the lateral facies distribution (Ahlberg et al., 2003). In Scania, the southernmost part of Sweden, typical continental red beds of the Norian Kågeröd Formation, deposited under a semi-arid regime, are succeeded by claystones, sandstones and coals belonging to the Rhaetian–Hettangian Höganäs Formation (Fig. 1). The oldest member of the Höganäs Formation, the Vallåkra Member, consists of variegated smectitic clays and sands which constitute a transition from the underlying red beds of the Kågeröd Formation to the kaolinite-rich underclays, mature sands and coals of the Bjuv Member (Ahlberg et al., 2003). The Norwegian–Danish Basin was transgressed in two steps (indicated on Fig. 1) during the Rhaetian, culminating with a maximum transgression (MFS7) that can be traced all over the Danish part of the Norwegian–Danish Basin (Figs. 1, 3; Nielsen, 2003; Lindström and Erlström, 2006). The marine transgression reached as far in Scania as the localities Helsingborg and Lunnom, and at Norra Albert an incursion of marine dinoflagellates probably represents marine waters entering the rivers during storm episodes (Fig. 1; Lindström and Erlström, 2006). The precursor mires, resulting in the Bjuv Member coals/coaly beds, were formed on a low-relief coast affected by a transgressive event in the mid–late Rhaetian (Petersen et al., 2013). The change from a semi-arid climate during the Norian to more humid conditions during the Rhaetian has been attributed to effects of the marine inundation of the Central European Basin from the Tethys (Ahlberg et al., 2002). Climatic changes at the Triassic–Jurassic boundary that forced supraregional deforestation in NW Europe (van de Schootbrugge et al., 2009), which severely affected the forest mires (Petersen and Lindström, 2012), may have triggered the changes in continental deposits from mire forests and wetlands with confined fluvial channels (Bjuv Member) to braided streams of the Boserup beds (Helsingborg Member) (Lindström et al., 2015). The Boserup beds constitute the basal part of the Helsingborg Member (Sivhed, 1984; Troedsson, 1951). Some authors have placed the boundary between the Bjuv Member and the Helsingborg Member at the top of coal bed A, i.e. at c. 3 m in Fig. 3A (Sivhed, 1984). In the Norra Albert quarry, the boundary of the Boserup beds has not been formally defined. In the present paper, it is placed at 6 m in Fig. 3A based on sedimentological considerations. The Bjuv Member is characterized by mudstones and coal beds with subordinate sandstones interpreted as fluvial deposits. The overall depositional environment is interpreted as a floodplain. The coal bed A is overlain by carbonaceous mudstone and with strongly deformed sand beds 5.0–6.2 m (Fig. 3A). This succession comprises thin beds of fine-grained sand with graded bedding separated by mud-drapes. The sand shows ripple cross-lamination, indistinct lamination and locally parallel bedding. The sedimentary structures suggest episodic, non-channelized deposition of sand in a flood-plain environment. Two phases of soft-sediment deformations are interpreted caused by seismic shocks (Lindström et al., 2015). They are erosionally overlain by the Boserup beds, which are a distinct association of facies dominated by structure-less, parallel bedded and trough cross-bedded sand, with several large concretions. The Boserup beds are interpreted as braided stream deposits.

At the Norra Albert quarry and in the Fleninge No. 266 well, the terrestrial ecosystem change is marked by a gradual loss of Taxodiacean/Cupressacean gymnosperm pollen (*Perinopollenites elatoides*) from trees that thrived in mires in favour of the enigmatic gymnosperm