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Research paper

The beast burrowed, the fluid followed – Crustacean burrows as methane conduits

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ABSTRACT

An extensive pockmark field with associated methane-seep carbonates has recently been reported from the late Albian (Lower Cretaceous) Ubidepea Mudstone of the Black Flysch Group in the Basque Country, northern Spain, but the exact pathways of the migrating methane-rich fluids remained elusive. Here we provide petrographic, stable carbon and oxygen isotope evidence that abundant crustacean burrows in the surrounding mudstone, preserved as the trace fossil *Thalassinoides*, and the seep carbonates themselves have acted as long-lasting fluid conduits in this system. The *Thalassinoides* infill generations show a diagenetic parasequence often starting with a distinctive lining, followed by one to several phases of cementing of the burrow walls and burrow infills, and finally late diagenetic sparry calcite that filled the remaining open cavities and conduits. The micrite cementing the burrow walls shows negative $\delta^{13}C$ values similar to those reported from the seep carbonates, indicating that methane oxidation was involved in their precipitation, rather than (or in addition to) the oxidation of other organic matter. Even the late diagenetic sparry calcite shows $\delta^{13}C$ values as low as −30.4‰ (versus PDB), providing evidence that these burrows served as fluid conduits for an extended period of time. Our study supports the growing body of evidence that crustacean burrows play an important role in channeling seeping fluids in such systems. We anticipate that this phenomenon is much more widespread than currently appreciated, especially in examples where other types of fluid conduits are absent.

1. Introduction

The intimate association of fossil methane seeps and decapod crustaceans in the geologic history finds its most obvious expression in the often large quantities of crustacean fecal pellets and crustacean remnants in fossil seep carbonates worldwide (e.g. Bishop and Williams, 2000; Campbell et al., 2002; Peckmann et al., 2007; Senowbari-Daryan et al., 2007), and many seep carbonates show evidence of bioturbation by crustaceans. Infaunal callianassid crustaceans can be very abundant at modern seeps (Martin and Haney, 2005), as in a pockmark field located in the Gela Basin near Sicily, where the huge amount of decapod claws led to the distinction of a decamol facies (Taviani et al., 2013). Dense networks of Decapoda-produced burrows, forming sediment-penetrating elements, are well-known features in extant and fossil sediments of the shelf (e.g. Kennedy, 1967; Kedzierski and Uchman, 2001) and the deep-sea (e.g. Uchman, 2001, see Uchman and Wetzel, 2012 for summary).

The most distinctive and sometimes superabundant shelf and deep-sea crustacean burrows are represented by the trace fossils (ichnotaxa) *Spongeliomorpha* Saporta, 1887, *Ophiomorpha* Lundgren, 1891 and *Thalassinoides* Ehrenberg, 1944. *Thalassinoides* is mostly abundant in Mesozoic shelf deposits, where the burrowing crustaceans realized a variety of morphologically variable endobenthic galleries (horizontal networks, 3-D meshworks and boxworks), which linked via (sub)vertical (Fig. 2a), spiraled or oblique shafts either to higher or lower galleries or to the sediment surface. The latter provided the exit of the living animal to the sediment surface and the entrance for oxygenated waters into the burrow systems, enabling burrowing also in oxygen-depleted sediments. Burrowing depth of calliassinid shrimps can reach easily 1–2 m (Tedesco and Wanless, 1991; Dworschak and Ott,

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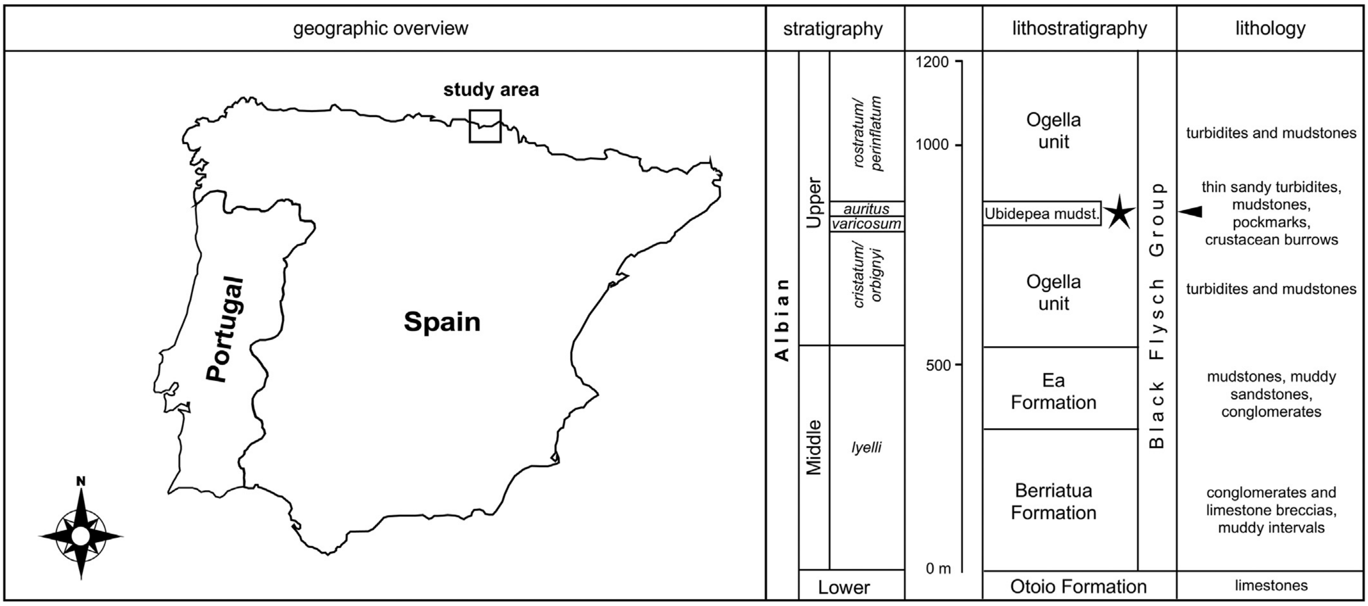

Figure 1. a) Simplified geographic sketch with the position of the working area on the north Spanish coast; stratigraphic and lithologic overview (after Agirrezabala et al., 2013). Asterisk marks the treated interval.

1993; Curran and Martin, 2003). Thus, open *Thalassinoides* systems – which is also true for *Spongeliomorpha* and *Ophiomorpha* or similar crustacean burrow systems in general – represent a sediment penetrating, dense system of interconnected tubes in different levels within the sediment column. In areas where fluids or gases migrate through the sediment, such a tube system can potentially collect fluids, channelize them along stratiform or vertical burrow systems and, finally, may serve either as conduits to the sediment surface or pathways along stratiform burrow systems within the sediments (e.g. Gingras et al., 2012; see Cunningham et al., 2012, p. 885, fig. 9). *Thalassinoides* and similar trace fossils are often early diagenetically cemented by calcium carbonate, and their petrography, geochemistry and stable isotope signature can be used to reconstruct various (bio)geochemical processes that were involved in their formation. Indeed, using the very distinctive isotopic signature of methane (Whiticar et al., 1986), methane seepage through callianassid burrows has been suggested for a few Recent (Andrews, 1988; Wetzel, 2013) and fossil examples (Pirrie and Marshall, 1991; Little et al., 2015).

A Lower Cretaceous (Albian) pockmark field, generated by methane seepage in a deep-sea slope environment, has recently been reported from the Black Flysch Group near the village of Ispaster (Basque Country, northern Spain; Agirrezabala et al., 2013). It consists of more than 50 seep carbonate lenses with a typical Cretaceous, seep-related invertebrate fauna, consisting mainly of the large modiomorphid bivalve *Caspiconcha* sp., the large lucinid bivalve *Tehamatea agirrezabalai*, and the gastropod *Hokkaidoconcha* sp. (Agirrezabala et al., 2013; Kiel, 2013), indicating a well-oxygenated sea floor environment. Some of the carbonate bodies show repeated successions of carbonate formation, self-sealing, and sediment covering, indicating long-lasting fluid flow. Not investigated, however, were the co-occurring, early diagenetically lithified *Thalassinoides* burrows that are scattered throughout the section as locally restricted clusters, resembling seep carbonate lenses or stratiform networks. Here we investigate the diagenetic history of *Thalassinoides* burrows within and between these seep limestones using petrography, stable carbon and oxygen isotope signatures, and discuss their potential as long-lasting conduits for the seeping fluids.

2. Geologic framework

In the Basque Country of northern Spain, seep carbonates with related seep faunas are common in Albian sediments, exposed in coastal sections near Mutriku (Agirrezabala, 2009) and at the coast north of the small village of Ispaster. There, a ca. 40 thick interval with lenticular seep carbonates occurs in the Ubidepea mudstone (Ogella Unit of the Black Flysch Group; *varicosum* to *auritus* ammonite biozones, Upper Albian, Lower Cretaceous; see Fig. 1), which has recently been identified as a spectacular example of a fossil pockmark field and described in great detail (Agirrezabala et al., 2013). The Black Flysch Group represents a more than 1000 m thick succession of limestone breccias, conglomerates and siliciclastic turbidites, but the Ubidepea mudstone marks a muddy interval with only few and/or comparatively thin (some cm to dm) siliciclastic turbidites (Fig. 1; see details and further references in Agirrezabala et al., 2013). The seep carbonates are exposed on the wave-cut platform, and often the turbidite bed that overlies an individual seep carbonate shows a lens-shaped thickening right above the carbonate body, indicating that the carbonate body was situated in the center of a pockmark, forming a depression in the sea floor. Many seep carbonates have been eroded out by the sea and occur either still *in situ* or as beach drift. Agirrezabala et al. (2013) mapped 51 carbonate lenses larger than 50 cm, and the largest size is given by them as 2.5 m thick and ca. 8 m wide. Less distinct are the numerous *Thalassinoides* burrows, which give the mudstone a nodular fabric in some intervals.

3. Crustacean burrows in the Ispaster section

Crustacean burrows in the Ubidepea Mudstone occur in three facies, which are – although narrowly spaced – environmentally different. For taxonomic assessment, we do not follow Fürsich (1973) who lumped *Thalassinoides* and *Ophiomorpha* together