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Original article

Strontium isotope record of the *Hygophum hygomii* otoliths from the European middle Miocene☆

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ABSTRACT

$^{87}Sr/^{86}Sr$ values from otoliths of the worldwide-distributed fish *Hygophum hygomii* are used for the purpose of isotope chemostratigraphy. In order to evaluate the potential of *H. hygomii* otoliths for strontium (Sr) isotopic studies, we first compare the $^{87}Sr/^{86}Sr$ ratio of current representatives of the species with that of modern sea water. Then, three fossil otoliths of *H. hygomii* collected in middle Miocene sediments of the Aquitaine Basin (Lafaurie locality, SW France) and the Carpathian Foredeep of the Central Paratethys (Brno-Kralovo Pole locality, SE Czech Republic) are analysed. The age inferred from the $^{87}Sr/^{86}Sr$ ratio at Lafaurie places the two analysed otoliths within the time interval of 15.5–15.1 Ma. This time interval matches the published early Langhian age obtained from the $^{87}Sr/^{86}Sr$ ratio of bivalves measured at the same locality. At the Brno-Kralovo Pole, the $^{87}Sr/^{86}Sr$ ratio of the analysed otolith returns a wider timespan of 14.78–13.10 Ma, falling into an interval of poor time resolution of the $^{87}Sr/^{86}Sr$ chemostratigraphy. Comparisons with published biostratigraphic and paleoclimatic data suggest that the analysed fossil otoliths of *H. hygomii* were mineralized during the late part of the Langhian, at ~14.2 Ma. This work represents a first attempt to use otoliths for $^{87}Sr/^{86}Sr$ chemostratigraphy, and indicates that such a use may represent a powerful tool for testing stratigraphic correlations in the future.

1. Introduction

Otoliths are earstones (Fig. 1) of teleost fishes. They are composed mostly of calcium carbonate; the organic matrix accounts for only 3–5% and inorganic impurities for less than 1% of the total mass (Campana, 1999). Calcium carbonate is represented principally by orthorhombic aragonite and by a much smaller amount of hexagonal vaterite; it often includes minor and trace amounts of other elements. The minor elements are represented by Na, Sr, K, S, N, Cl and P, while the bulk of the trace elements is present in concentrations less than 10 ppm (Degens et al., 1969; Gauldie, 1996; Campana, 1999; Falini et al., 2005; Melancon et al., 2005). For chemostratigraphical purposes, Strontium (Sr) has been one of the most reliable minor elements to quantify. It is assumed that strontium is bound within the aragonitic calcium carbonate lattice of otoliths via the random chemical replacement of calcium (Campana, 1999; Doubleday et al., 2013). The studies of Sr isotopes in the otoliths have shown that the $^{87}Sr/^{86}Sr$ ratio corresponds to the ratio in enclosing water (Kennedy et al., 2000). In contemporary sea water of normal salinity, the Sr-isotope ratio has a constant value of 0.70918 (Hodell et al., 1989), while in fresh and brackish waters the ratio oscillates and depends on the character of the rocks – there, it can be lower but also higher than in marine water of normal salinity. Consequently, Sr isotopic analyses of otoliths have focused so far on the study of migration of extant marine fish populations (Campana, 2005; Walther and Thorrold, 2008; Thorrold and Swearer, 2009; Walther and Limburg, 2012).

The $^{87}Sr/^{86}Sr$ ratios of the strontium dissolved in the world ocean have varied over time. Sr isotope stratigraphy has thus already provided useful insights (numerical ages) to correlate marine sedimentary rocks worldwide (Burke et al., 1982; McArthur, 1994; Veizer et al., 1997, 1999; McArthur et al., 2001, 2012). The first research relied on the Sr isotope record extracted

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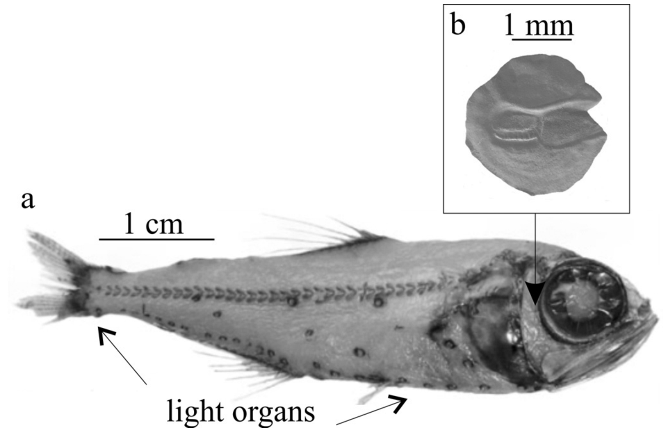

Fig. 1. *Hygophum hygomii* (Lütken, 1892), Recent. **a**. Fish with perspicuous light organs at the ventral part of the body. **b**. Left otolith, inner view (after Froese and Pauly, 2015, modified).

from carbonates (Burke et al., 1982). Further studies have shown that carbonates are prone to a diagenetic imprint and have focused on biogenic carbonates secreted by marine organisms (Hess et al., 1989; Banner, 1995; Reinhardt et al., 2000). Howarth and McArthur (1997) compiled $^{87}Sr/^{86}Sr$ data and fitted to them a nonparametric LOWESS regression function. The resulting curve was then converted into a simple table that gave numerical ages (LOWESS 1). This release has been improved by McArthur and Howarth (1998) (LOWESS 2), and then by McArthur et al. (2001). The LOWESS fitted curve allows quick and easy conversion from any $^{87}Sr/^{86}Sr$ ratio into its corresponding numerical age.

Most of the Neogene LOWESS Sr-calibration curve is based on the analysis of foraminiferal calcite, mostly from DSDP/ODP sites (Miller et al., 1988, 1991; Hodell et al., 1991; Hodell and Woodruff, 1994; Farrell et al., 1995; McArthur et al., 2001, 2012). Sr-isotope analyses were also performed on calcareous nannofossils (El-Shawaihdi et al., 2014) and well-preserved macrofossils, preferably on aragonitic bivalves (Cahuzac et al., 1997; Cahuzac and Turpin, 1999). In the present work, $^{87}Sr/^{86}Sr$ values in recent and fossil otoliths of the worldwide-distributed fish *Hygophum hygomii* are used. Recent representatives were dissected from fish collected in Bermuda and New Caledonia. Fossil representatives were collected in middle Miocene deposits of the Aquitaine Basin (SW France) and of the Carpathian Foredeep of the Central Paratethys (SE Czech Republic) (Fig. 2). The obtained Sr isotopic ages are compared with biostratigraphic data. This paper is a first effort towards verifying the adequacy of otoliths for chronostratigraphic correlation based on Sr-isotope ratio data.

2. Geological setting

The Aquitaine Basin represents the south-east marine projection of the Biscayan Gulf (Fig. 2(b)). It is filled with Cretaceous to Miocene sediments supplied from the uplift of the North Pyrenees. The Burdigalian sedimentation includes predominately deep-water open marine "Marnes des Saubrigues" facies deposited in the Saubrigues Palaeocanyon in the south-west. During the middle Miocene, the Atlantic embayment south of Bordeaux formed in the Pyrenees foreland. The Langhian grey calcareous clays of the uppermost Marnes des Saubrigues contain rich otolith fauna studied in detail by Nolf and Brzobohaty (2002). The analysed otoliths originate from sediment samples collected in the locality of Lafaurie in the Saubrigues area. These samples have been shown to correlate with the early Langhian, based on occurrences of the planktonic foraminifers *Praeorbulina sicana* and *P. curva* (Cahuzac et al., 1997; Cahuzac and Turpin, 1999).

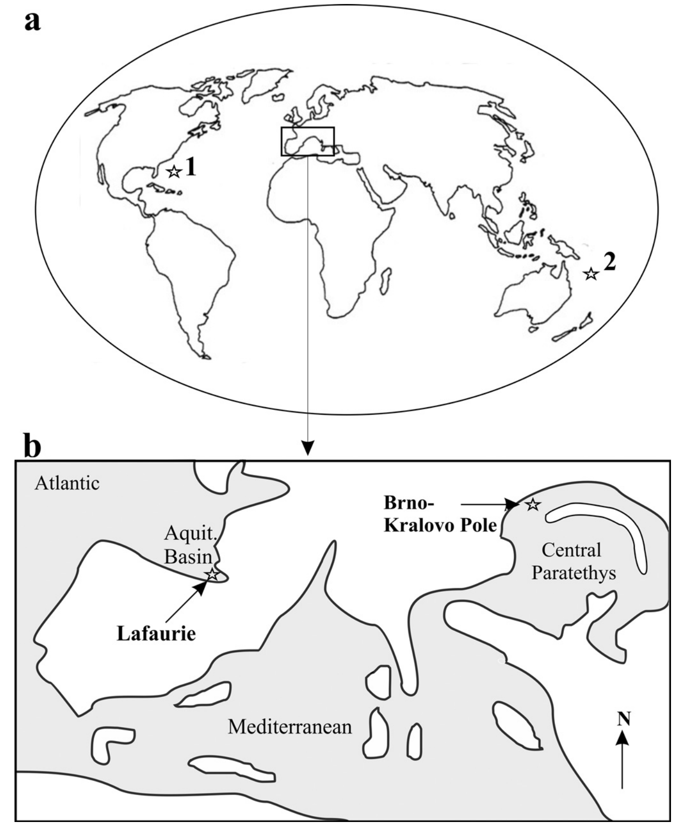

Fig. 2. Position of *Hygophum hygomii* localities. **a**. Recent specimens: Bermuda (1) and New Caledonia (2). **b**. Palaeogeography of the European basins during the early middle Miocene (Gürs et al., 2004) and locations of Lafaurie (Aquitaine Basin, SW France) and Brno-Kralovo Pole (Central Paratethys, Carpathian Foredeep, Moravia, SE Czech Republic).

The Carpathian Foredeep is a peripheral foreland basin of the Western Carpathians filled with Miocene molasse deposits. In the beginning of the middle Miocene (Badenian in the sense of the regional scale of the Central Paratethys), the Carpathian Foredeep represented the northernmost branch of the Paratethys (Fig. 2(b)) that communicated well with the world ocean. Basinal Badenian calcareous clays contain rich microfauna, including otoliths and, locally, also macrofauna. The measured otolith of *H. hygomii* comes from Badenian deep-water calcareous clays in Brno-Kralovo Pole (an old city brickyard Pavlů). They contain the index foraminiferal species *Orbulina suturalis* and calcareous nannofossils of the NN5 Zone (Brzobohatý, 1991). This stratigraphic level is correlated with the time interval around the Lower/Upper Lagenid Zone of the neighbouring Vienna Basin. Consequently, the calcareous clays correlate with the latest part of Chron C5ADn (Browning et al., 2013), and their deposition occurred during the late part of the Middle Badenian. They can therefore be linked to the maximal flooding of the TB 2.4 cycle (Fig. 3) that occurred around 14.2 Ma (Haq et al., 1988; Hohenegger et al., 2014).

3. Material and methods

The species *H. hygomii* has been chosen because of its worldwide distribution and an ecology that is not influenced by migrations in environments of lower salinity, which could influence the Sr isotopic ratios (Kennedy et al., 2000; Campana, 2005). It belongs to the family Myctophidae (lanternfish), which includes predominately small mesopelagic oceanic nekton with light-producing organs (Fig. 1(a)). Modern representatives of this species live in the temperate to subtropic waters of the northern