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Early Albian marine environments in Madagascar: An integrated approach based on oxygen, carbon and strontium isotopic data

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ABSTRACT

New palaeotemperature reconstructions have been obtained on the basis of oxygen isotopic analysis of 178 aragonitic shell samples taken from specimens of three ammonoid orders (and some corresponding families): Phylloceratida (Phylloceratidae), Lytoceratida (Tetragonitidae) and Ammonitida (Oppeliidae, Desmoceratidae, Silesitidae, Cleoniceratidae and Douvilleiceratidae). Those obtained from aragonite shells, secreted in the lower epipelagic and in the middle mesopelagic zones during coolest season (winter), range from 15.4 to 16.8 °C, and from 11.8 to 12.0 °C, respectively. Presumed spring/autumn palaeotemperatures obtained from aragonite shells, secreted apparently in the upper and lower epipelagic, upper and middle mesopelagic zones, are somewhat higher. Presumed summer palaeotemperatures, calculated apparently for the upper and lower epipelagic, and upper mesopelagic zones range from 19.4 to 21.7 °C, from 17.7 to 19.4 °C, and from 14.4 to 16.1 °C, respectively. The predominant part of investigated ammonoids from Madagascar inhabited the epipelagic zone, but some phylloceratid, tetragonitid and silesitid ammonoids preferred deeper, cooler conditions (upper-middle mesopelagic zone). The study supports the hypothesis that Madagascar was located in middle latitudes within the tropical-subtropical climatic zone during the early Albian. Available carbon and strontium isotope data allow us to assume a more or less expressed carbon and strontium isotope stratification of the water column in this region in the early Albian. On the basis of the stable isotope data, following partly Lukeneder (2015), two large ethological groups can be recognised mainly in mid-aged and adult ammonoids. Some ammonoids (group 1) preferred apparently mesopelagic conditions, and to a lesser degree the epipelagic zone, being mainly cool-requiring animals. However, a significant part of the isotopically investigated ammonoids (group 2) preferred, on the contrary, only epipelagic conditions, being mainly thermophilic dwellers.

1. Introduction

There is a comprehensive literature on Triassic, Jurassic and Cretaceous ammonoids (Cephalopoda) from Madagascar (e.g., Collignon, 1932, 1933–1934, 1949, 1950a, 1950b). However, since only the aragonite preserved in Jurassic and Cretaceous cephalopods can be used for isotopic investigations, there are still few works on this respect about Madagascar faunas. Among Late Jurassic (Oxfordian) molluscs from the region only the ammonoid *Perisphinctites* and the bivalve *Astarte* from southwestern Madagascar (Morondava Basin) have been investigated isotopically by Lécuyer and Bucher (2006), who documented that $\delta^{18}O$ values in most well preserved aragonitic ammonoid shells and calcitic bivalve shells fluctuate from −0.85 to −1.11‰ and from −2.57 to −1.79‰, respectively. However, the first data on oxygen isotope values, obtained from some cephalopod shells from the lower Albian Ambarrimaninga Formation of northwestern Madagascar (Mahajanga Province), show that they are noticeably higher (Zakharov, Shigeta, Nagendra, et al., 2011), which illustrates that early Albian climate in Madagascar was cooler compared to the Oxfordian in the same region.

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In this work, we focus on seasonal palaeotemperature fluctuations in Madagascar during the early Albian (*Cleoniceras besairiei* and possibly *Douvilleiceras inaequinodum* zones), using the most representative original data on stable isotope composition of aragonitic cephalopod shells from the Mahajanga Province.

2. Geographical and geological setting

The ammonoid locality in the Mahajanga Province, northwestern Madagascar is situated in a long quarry near the top of an escarpment, 3 km to the west of the village of Ambatolafia (coordinates: Lat. 16°33′23.6″ S, Long. 46°12′10.2′ E) (Fig. 1). All investigated cephalopod fossils occur most likely in the 15–20-cm-thick hard, basal glauconitic sandstone layer, (Ambarrimaninga Formation, Ambatolafia locality), where local villagers have collected ammonoid shells for sale during many years; above the ammonoid-bearing bed follows a nearly 15 cm thick layer of dark grey, glauconitic siltstone ("microfossil bed") (Kiel, 2006).

Based on assemblages recovered mainly from Ambarimaninga, Ambatolafia, Bafamonto and Diégo Suarez areas, the Albian of Madagascar is represented by the following 10 ammonoid zones in descending orders (Collignon, 1963; corresponding zones and subzones in the European faunal province are given in parentheses according to Hart, Amédro, & Owen, 1996; and Owen, 1999): (1) *Pseudosonneraila sakalava* Zone (the *Leymeriella acuticostata* Subzone of the lower Albian *Leymeriella tardefurcata* Zone), (2) *Cleoniceras besairiei* Zone (possibly the lower *Cleoniceras flaridum* Subzone of the *Sonneratia chalenis* Zone), (3) *Douvilleiceras inaequinodum* Zone (possibly the upper *Cleoniceras flaridum* Subzone of the lower Albian *Sonneratia chalenis* Zone), (4) *Lemuroceras spathi—Brancoceras besairiei* Zone (possibly the lower Albian *Otohoplites auritiformis* Zone), (5) *Lyelliceras lyelli* Zone (the same name subzone of the middle Albian *Hiplites dentatus* Zone), (6) *Oxytropidoceras acutocarinatum—"Manuaniceras"* [= *Oxytropidoceras*; Wright, Callomon, & Howarth, 1996] *jacobi* Zone (possibly middle Albian *Euhoplites loricatus* Zone), (7) *Dipoloceras cristatum* Zone (the same name subzone of the upper Albian *Mortoniceras* (*Mortoniceras*) *inflatum* Zone), (8) *Hysteroceras binum* Zone (possibly the upper part of the upper Albian *Mortoniceras* (*Mortoniceras*) *inflatum* Zone), (9) *"Pervinquieria"*[= *Mortoniceras*; Wright et al. 1996] *inflata* Zone (possibly the *Mortoniceras rostratum* and *Mortoniceras* (*Durnovarites*) *parinflatum* subzones of the upper Albian *Stoiczkaia dispar* Zone), and (10) *Neophlycticeras madagascariense* Zone (possibly the *Pleurohoplites* (*Arrhaphoceras*) *briacensis* Subzone of the upper Albian *Stoiczkaia dispar* Zone).

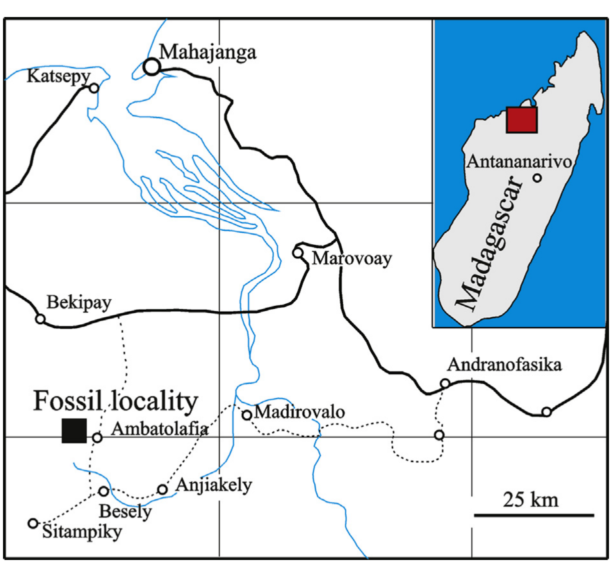

Fig. 1. The lower Albian fossil locality in the Mahajanga Basin, northeastern Madagascar (based on Kiel, 2006).

Stratigraphically the ammonoid fauna from the Ambatolafia locality belongs to the *Cleoniceras besairiei* (Kiel, 2006) and possibly *Douvilleiceras inaequinodum* zones of the middle part of the lower Albian. In a sequence stratigraphic content, the glauconitic sandstones, which occur commonly in the Albian of Madagascar (Luger et al., 1994), are frequently associated with condensed sections and transgressive-systems-tracts (e.g., Harding et al., 2014; Webby & Van Den Houvel, 1965). Judging from a plate tectonic reconstruction (e.g., Stampfli & Borel, 2002), the area was located at palaeolatitudes of 40–45°S in late Early Cretaceous times.

3. Material and methods

Isotopically investigated early Albian ammonoids from the Mahajanga Province consist of nine species of the following genera: *Phylloceras*, *Eotetragonites*, *Aconeceras*, *Puzosia*, *Beudanticeras*, *Neosilesites*, *Desmoceras*, *Cleoniceras* and *Douvilleiceras*. Specimens were selected from the collections in the National Museum of Nature and Science, Tsukuba and the University Museum, the University of Tokyo.

In addition, well-preserved ammonoid shells of *Leymeriella schrammeni* (Jacob) from the lower Albian of the Lower Saxony Basin, Germany (K. Tanabe's coll.) were analized for comparison.

The following criteria were used to determine diagenetic alteration: (1) hand-sample visual indications (Fig. 2 and Fig. S1), (2) percentage of aragonite in cephalopod shells, which were originally represented by 100% aragonite, (3) presence or lack of diagenetic admixture, determined by X-ray diffraction analysis, (4) the degree of integrity of shell microstructure, determined under a scanning electron microscope (SEM) (Figs. 3–4).

We have usually recognized four stages in diagenetic alteration of aragonitic cephalopod shells: 1st stage, where secondary calcite is absent (100% aragonite) or presented by a small portion, not more than 1–5%; 2nd stage characterised by appearance of a larger portion (5–30%) of secondary calcite; 3rd stage, where shell material consists of approximately 30–50% secondary calcite; 4th stage characterised by presence of more than 50% secondary calcite with very pronounced change in isotopic composition (Zakharov, Naidin, & Teiss, 1975, 2006c, 2013a).

Polished sections (Fig. S1) of selected cephalopod shell samples were investigated with a SEM (EVO50 XVP), after etching with 1.0% HCl with frequent interruptions for visual control – total treatment duration was about 3–6 min, as recommended by Sælen (1989), Podlaha, Mutterlose, and Veizer (1998) and Voigt, Wilmsen, Mortimore, and Voigt (2003), in order to obtain textural information and ascertain the degree of diagenetic alteration.

X-ray powder analyses were carried out at the Analytical Centre (FEGI) in Vladivostok using a desktop X-ray diffractometer MiniFlex II (Rigaku Firm).

SEM and X-ray studies of lower Albian cephalopods from the Madagascar area suggest that all of them, apparently, retain their original shell microstructure, and C, O stable isotope and Sr isotope compositions. The X-ray diffraction analysis particularly shows the lack of secondary admixtures, including α-SiO_2, in the investigated samples from this area and the almost 100% aragonitic composition of most analysed cephalopod shells.

Samples for our stable isotope analyses were carefully removed from the investigated shells using a special method (Zakharov et al., 2005): material was taken by a scalpel mainly from narrow, small areas along growth striations on the external surface of ammonoid shells, which enabled shell material secreted apparently during