

Stable isotope compositions of a late Jurassic ammonite shell: a record of seasonal surface water temperatures in the southern hemisphere?

C. Lécuyer¹ and H. Bucher²

¹Laboratory “Paléoenvironnements & Paléobiosphère”, UMR CNRS 5125, Bâtiment “Geode”, Université Claude Bernard Lyon I et Institut Universitaire de France, 27–43 Boulevard du 11 Novembre 1918, 69622 Villeurbanne, France

²Paläontologisches Institut und Museum, Universität Zürich, Karl Schmid-Strasse 4, CH-8006 Zürich, Switzerland

Received: 15 March 2006 – Published in eEarth Discuss.: 15 May 2006

Revised: 31 July 2006 – Accepted: 18 August 2006 – Published: 21 August 2006

Abstract. Exceptional preservation of aragonite secreted by ammonites offers an opportunity to determine the seasonal temperature variations of Mesozoic surface waters. Ontogenetic profiles of carbon and oxygen isotope compositions have been obtained from the nacreous layer of a well-preserved Late Jurassic (Oxfordian) ammonite (*Perisphinctes*) from Madagascar. A similar range of oxygen isotope compositions was also obtained from an associated benthic bivalve (*Astarte*) which suggests the absence of sampling bias. Late Jurassic seasonal variations in the southern hemisphere were close to 2.5°C and relatively weak when compared to the 2.5–6.5°C temperature range prevailing in the present-day Indian Ocean at a paleolatitude of 40±1° S. According to the hypothesis of an ice cap-free Late Jurassic Earth, average sea surface temperatures may have been up to 7°C higher than now.

1 Introduction

Quantification of seasonal frequency and associated thermal amplitudes as a function of latitude allow the definition of climate modes for a given geological period. This objective may be accomplished by analyzing the oxygen isotope compositions of growth layers secreted by marine invertebrate shells (Epstein and Lowenstam, 1953). The end of the Jurassic was a period of long-term climate changes characterized by high seafloor spreading rates, volcanic activity, and the beginning of the global radiation of calcareous marine plankton (Frakes et al., 1992). These geological and biological processes certainly helped to deeply modify the surface

carbon cycle and consequently the Earth’s climate (Tajika, 1998). The existence of ice caps has been debated (Frakes and Francis, 1988; Dromart et al., 2003) and remains fundamental to our understanding of the budget of heat transfer and the onset of deep oceanic circulation.

Reconstitution of pre-Cretaceous climates poses a serious challenge because the fate of marine sediments is either subduction in active margins or obduction onto the continents. Therefore they commonly suffered tectonic and burial processes associated with fluid-rock interactions that modified their original stable isotope composition. The exceptional preservation of aragonite secreted by nektonic ammonites provides the possibility to determine seasonal variations of sea surface temperatures (SST) for the Jurassic. These data are required to improve and validate the numerical models of the Earth’s climate dynamics.

An ontogenetic series of carbon and oxygen isotope compositions have been obtained from the nacreous layer of a *Perisphinctes* (*Dichotomoceras*) from the Late Jurassic (Oxfordian) series of the Morondava Basin (Maroroka section, Ilovo valley) of southwestern Madagascar. In this area, the Late Jurassic sedimentary series consists of interfingering shallow marine and continental deposits where bathymetry did not exceed 50 m (Besairie, 1972). A similar ontogenetic sampling of a benthic bivalve (*Astarte*) from the same sediment horizon was also performed to validate the environmental interpretation of the isotopic data obtained from the ammonite. During this period, this shallow marine basin was located approximately 40° S (Besse and Courtillot, 1988). We show here that a periodic oxygen isotope signal may be extracted from the aragonitic shell of a Late Jurassic ammonite, thus providing the quantification of seasonal temperature amplitude for intermediate marine southern latitudes.

Correspondence to: C. Lécuyer
(clecuyer@univ-lyon1.fr)

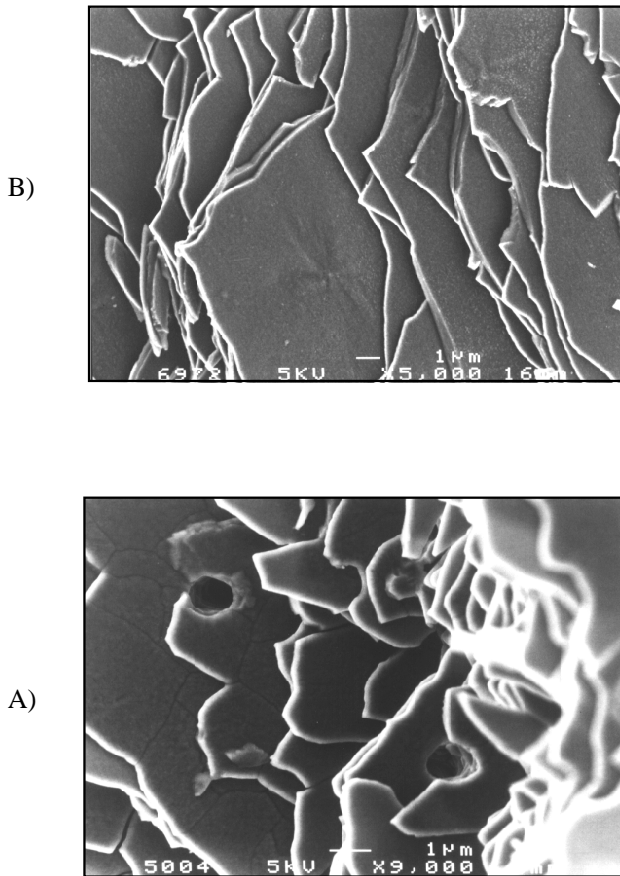


Fig. 1. Scanning electron microscope (SEM) image of the nacreous layer of a *Nautilus pompilius* (5000 x).

At a higher magnification (9000 x), the external shell structure of the studied Oxfordian *Perisphinctes* sp. displays a similar pristine stacking of nacreous lamellae without dissolution features or recrystallization into calcite. The two holes may have been formed by symbiotic micro-algae.

2 Sampling strategy and methods

A specimen of *Perisphinctes* was selected for its exceptional mineralogical preservation. X-ray diffraction analysis suggests that at least 99% of its nacreous layer is made of aragonite. However, Dauphin and Denis (1990, 1999) have reported that the diagenetic alteration of the microstructure of ammonite shells may sometimes be observed despite the preservation of their original aragonite mineralogy. In this case study, scanning electron microscope image of the shell at high magnification reveals a pristine aragonite ultrastructure of stacked nacreous lamellae (Buchardt and Weiner, 1981) comparable to that of the living *Nautilus pompilius* (Fig. 1). The examination of the ultrastructure also reveals the absence of diagenetic cement that could have precipitated between the nacreous lamellae. Radial sampling with a micro-driller of the inner nacreous layer between the primary

Table 1. Oxygen and carbon isotope compositions of external shell increments of an Oxfordian ammonoid *Perisphinctes* sp. from Madagascar. The start of the measured ontogenetic sequence is arbitrarily set at zero ventral length.

Sample	$\delta^{13}\text{C}$ (‰) (PDB)	$\delta^{18}\text{O}$ (‰) (PDB)	ventral length (mm)
G1	0.67	-1.25	325.0
G2	0.59	-1.29	321.2
G3	0.23	-1.37	314.0
G4	0.28	-1.26	307.0
G5	0.47	-1.11	302.5
G6	0.04	-1.32	298.0
G7	0.44	-1.12	294.0
G8	0.60	-1.31	289.4
G9	0.29	-1.21	285.5
G10	0.37	-1.35	280.8
G11	0.35	-1.28	277.6
G12	0.29	-1.55	273.1
G13	0.38	-1.25	268.0
G14	0.51	-1.33	263.0
G15	0.45	-1.32	258.5
G16	0.56	-1.34	253.4
G17	0.36	-1.58	248.8
G19	0.18	-1.85	240.0
G21	0.14	-1.81	230.8
G23	0.23	-1.69	222.5
G25	0.18	-1.71	213.5
G27	0.25	-1.80	204.5
G29	0.20	-1.70	196.3
G31	-0.13	-1.74	188.4
G33	0.35	-1.77	180.2
G35	0.30	-1.61	172.5
G37	0.43	-1.47	163.0
G39	0.38	-1.62	156.0
G41	0.02	-1.68	148.0
G43	-2.85	-1.67	140.6
G45	-1.50	-1.69	133.0
G47	0.05	-1.24	125.7
G49	0.02	-1.14	118.3
G51	0.00	-1.07	108.7
G53	0.02	-1.24	101.0
G55	-0.44	-1.28	94.6
G57	-7.02	-1.65	87.3
G59	-6.39	-1.83	81.0
G61	-6.83	-1.59	74.6
G63	-5.82	-1.94	68.5
G65	-2.76	-1.36	61.6
G67	-3.49	-1.18	55.6
G69	-2.89	-1.28	50.2
G71	-2.66	-1.38	44.4
G73	-1.96	-1.27	38.6
G75	-4.91	-1.42	33.0
G77	-2.33	-1.24	27.6
G79	-1.95	-1.40	22.2
G81	-5.88	-1.39	17.6
G83	-7.13	-1.14	13.0
G85	-9.67	-1.32	8.4
G87	-6.52	-1.11	3.8
G89	-9.62	-1.41	0.0

ribs yielded an ontogenetic sequence of 53 samples spanning 1.7 whorls of this immature specimen (Table 1). In terms of the shell diameter, the sequence begins at 20 mm (sample G89) and ends at 74 mm (sample G1). In terms of the ventral perimeter, the sampled ontogenetic sequence amounts to 324 mm. Exclusion of submature and mature stages from the sampled sequence prevents time averaging and distortion of the isotopic signal (Bucher et al., 1996). Careful examination of the outer shell did not reveal any breakage or growth stop that would alter the isotopic record of the environmental signal. Moreover, septal spacing observed on the polished median plane did not display any crowding as commonly generated by a prolonged pause or a temporary decrease of the apertural growth rate. For the low-Mg calcite *Astarte* shell, samples of the inner shell layer have been drilled at regular intervals over a linear distance of 8 cm from the umbo to the ventral edge (time series A to O; Table 2), which corresponds to the maximum growth axis of the valve. Approximately 1 mg of each powdered sample was reacted off-line with anhydrous phosphoric acid at 30°C over a period of 24 h. Carbon dioxide was analyzed with a Finnigan Delta-E at the Laboratory UMR 5125 “PEPS”, University Claude Bernard Lyon 1. Isotopic compositions are quoted in the standard δ notation relative to Vienna Pee Dee Belemnite (V-PDB). Carbon and oxygen isotope measurements were calibrated to the international standards NBS-18 and NBS-19. External reproducibilities for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are $\pm 0.1\text{‰}$ and $\pm 0.05\text{‰}$ (1σ).

Strontium and calcium concentrations were measured by ICP-AES and ICP-MS. In the latter case, indium was used as an internal standard and the masses ^{44}Ca and ^{88}Sr were measured in order to avoid isobaric interferences with Ar compounds. Distilled HNO_3 (4.5 mol.L^{-1}) was used for the digestion of shell aragonite. Three international standards assessed the accuracy of measurements. These are the “Florida Phosphorite” SRM120c, the “Bone Ash” SRM1400, both from the National Institute of Standards and Technology, and the “Moroccan Phosphorite” BCR32 from the Institute for Reference Material and Measurements.

3 Results

Oxygen and carbon isotope compositions of samples G1 to G89 of *Perisphinctes* are given in Table 1 along with their respective position along the perimeter of the venter (arbitrary origin of the perimeter set at G89). Carbon isotope compositions vary from -9.7 to $+0.7\text{‰}$ throughout the sampled ontogenetic series (Fig. 2). Marked fluctuations occur between 0 mm and 160 mm, whereas nearly constant $\delta^{13}\text{C}$ values around 0.5‰ occur between 160 mm and 325 mm. Oxygen isotope compositions vary less than carbon, from -1.9 to -1.1‰ , and display successive stages of low ($\approx -1.8\text{‰}$) and high ($\approx -1.2\text{‰}$) $\delta^{18}\text{O}$ values along the sampled interval (Fig. 2). A detailed examination of these isotopic records

Table 2. Ontogenetic record of carbon and oxygen isotope compositions of *Astarte* sp. indet. This bivalve comes from the same horizon than *Perisphinctes*. Samples have been drilled from the intermediate shell layer at regular intervals over a linear distance of 8 cm, which corresponds to the maximum growth axis of the valve. Aging from samples A to O.

Sample	$\delta^{13}\text{C}$ ‰ (PDB)	$\delta^{18}\text{O}$ ‰ (PDB)
Ast-A	1.18	-1.91
Ast-B	0.44	-1.79
Ast-C	0.93	-2.57
Ast-D	1.01	-1.95
Ast-E	1.49	-2.11
Ast-F	1.26	-2.11
Ast-G	1.06	-2.39
Ast-H	1.33	-2.04
Ast-I	1.07	-2.04
Ast-J	0.96	-1.83
Ast-K	0.97	-2.11
Ast-L	1.46	-1.89
Ast-M	1.28	-2.11
Ast-N	1.34	-2.12
Ast-O	1.62	-2.19
Mean	1.16	-2.08
Std dev (1σ)	0.29	0.21

reveals two intervals, called “isotopic events”, from 70 mm to 90 mm and from 130 mm to 145 mm. These intervals are characterized by decreases of both carbon and oxygen isotope compositions (Fig. 2). Oxygen and carbon isotope compositions of samples A to O from the *Astarte* are given in Table 2. Carbon isotope compositions range from $+0.44$ to $+1.62$ whereas $\delta^{18}\text{O}$ values vary from -2.6 to -1.8‰ .

Molar Sr/Ca ratios of the *Perisphinctes* aragonite range from 5.22×10^{-3} to 5.39×10^{-3} for two shell parts, both of which are characterized by the relatively low and high $\delta^{18}\text{O}$ values (Fig. 2).

4 Discussion

When analyzing a single ammonite specimen it must be asked whether its isotopic record can be representative of the local environmental conditions. The validity of the geochemical signal of the ammonite was tested with additional measurements from an associated calcitic, benthic bivalve (*Astarte*). Carbon isotope compositions of the bivalve are higher than those measured in the cephalopod (Tables 1–2). A similar observation was made by Malchus and Steuber (2002) who suggested that ammonites built their shell out of equilibrium with the ambient seawater carbon.

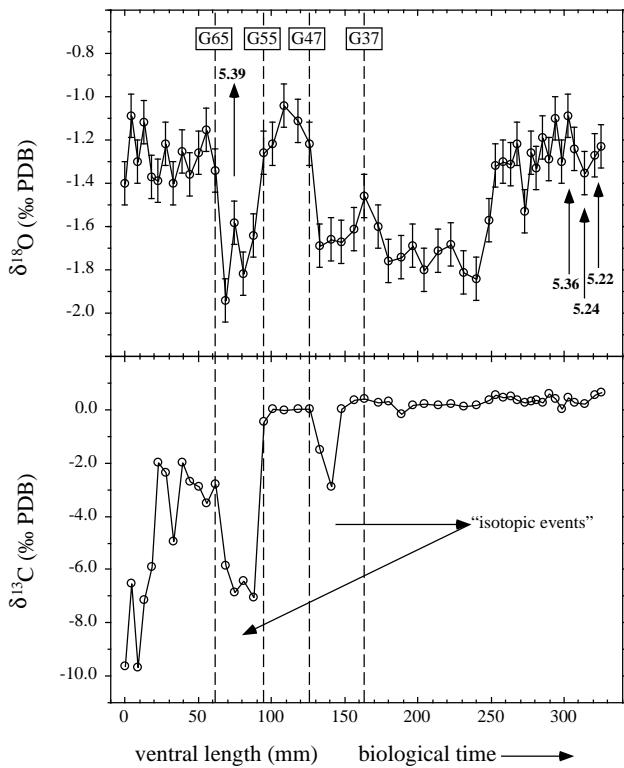


Fig. 2. Variations in the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of aragonite as a function of the ventral length of an Oxfordian *Perisphinctes* from Madagascar.

Two zones of the shell are characterized by associated decreases in both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values down to -1.7‰ and -2.9‰ from G37 to G47, and down to -1.9‰ and -7‰ from G55 to G65, respectively. Numbers in bold refer to molar Sr/Ca ratios.

Despite the absence of cyclicity in the ontogenetic $\delta^{18}\text{O}$ record of *Astarte* (Table 2), the difference between the mean $\delta^{18}\text{O}$ values of *Astarte* and *Perisphinctes* remains small ($\approx 0.6\text{‰}$) and variations in the internal shell compositions are similar ($\approx 0.8\text{‰}$). This difference of 0.6‰ could correspond to a slight difference in the oxygen isotope fractionation between calcite-water and aragonite-water. However, the direction and amplitude of this fractionation is still poorly known. On one hand, calcite is considered to be depleted in ^{18}O relative to aragonite according to some precipitation experiments (e.g. Tarutani et al., 1969; Kim and O'Neil, 1997) and natural observations (e.g. Grossman and Ku, 1986; Barrera et al., 1994; Thorrold et al., 1997). On the other hand, theoretical calculations (Zheng, 1999) and some field observations (e.g. Horibe and Oba, 1972) suggest that calcite is ^{18}O -enriched in comparison to aragonite. More recently, Lécuyer et al. (2004) did not observe significant oxygen isotope difference between aragonitic inner and calcitic outer layers secreted by the present-day gastropod *Nerita tessellata* from Martinique Island. Similarly, the authors observed that calcite precipitated by the oyster *Crassostrea virginica*

has a mean $\delta^{18}\text{O}$ indistinguishable from several co-existing species of aragonitic bivalves.

In any case, the measured mean $\delta^{18}\text{O}$ difference between *Astarte* and *Perisphinctes* corresponds to a small temperature difference (about 2°C) that can be considered as the record of natural fluctuating environmental conditions. Consequently, the oxygen isotope record obtained from the *Perisphinctes* is thought to provide a reliable estimate of marine paleotemperatures. Moreover, such convergence in the respective ranges of oxygen isotope compositions suggests that both organisms dwelled in the same water mass, which is consistent with the shallow water context.

The seasonal temperature variations potentially recorded in the *Perisphinctes* shell may be modified either by environmental perturbations or changes in the metabolic activity of the animal. The decreases in both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, characterizing the two “isotopic events”, could be interpreted as either an accidental decrease of the salinity of ambient seawater or from local diagenetic alterations of the shell. The latter case may be ruled out because X-ray diffraction analyses did not reveal re-crystallization of aragonite into calcite. Moreover, the molar Sr/Ca ratio of the shell sample G61 is similar to those measured in the G1–G5 portion of the shell. Sr/Ca ratios that range from 5.22×10^{-3} to 5.39×10^{-3} for the studied *Perisphinctes* are in good agreement with the average value of 5.53×10^{-3} for modern aragonitic mollusks and the value of 5.78×10^{-3} for *Nautilus* (Milliman, 1974). Buchardt and Weiner (1981) have also analyzed numerous Upper Cretaceous specimens of *Scaphites* and *Baculites* from West Greenland. They found that Sr/Ca ratios of aragonite shells range from 5.11×10^{-3} to 7.23×10^{-3} while the Sr/Ca ratios decrease to 2×10^{-3} for samples totally re-crystallized into calcite. These observations suggest that the *Perisphinctes* shell sections with low $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values have resulted from environmental changes that occurred during the life of the specimen. As shown by Lécuyer et al. (2004), even a limited input (about 10%) of fresh organic-rich waters into seawater can constitute a significant source of dissolved ^{12}C during the oxidation of organic matter without significantly modifying the oxygen isotope composition of seawater. Indeed, the carbon and oxygen isotope compositions of modern shells living in mangroves are about 4‰ and 1‰ lower, respectively, than those living in the neighbouring open marine waters of Martinique Island. In the case study of *Perisphinctes*, it is noteworthy that the two “isotopic events” (Fig. 2) are characterized by a decrease of $\delta^{13}\text{C}$ values that is at least five times larger than the corresponding decrease of $\delta^{18}\text{O}$ values.

Excluding these two “isotopic events”, the $\delta^{13}\text{C}$ values increase regularly from -9.6‰ towards values close to 0‰ during the first part of the studied interval (from 0 to 160 mm; Fig. 2). Increasing $\delta^{13}\text{C}$ values with age may possibly be interpreted as the result of a kinetic fractionation linked to a higher linear growth rate during the early ontogenetic stage. Such large carbon isotope fractionations have been already

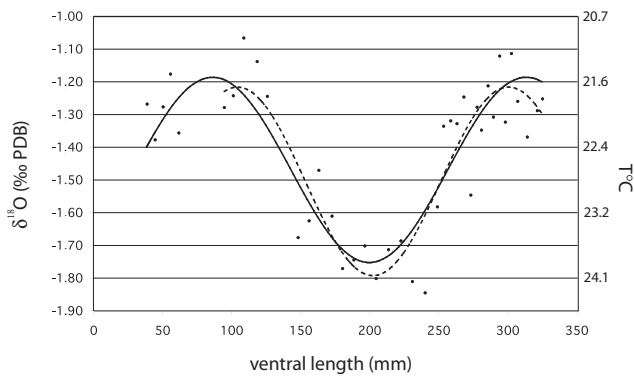


Fig. 3. Seasonal oxygen isotope variations recorded in the external shell growth layers of the Oxfordian ammonite *Perisphinctes* sp. The data have been fitted by least square approximations with a cosine wave function ($\delta^{18}\text{O}=\{A\times\cos([2\times\pi\times\text{Length}/T]+P)\}+S$, where A is the amplitude, T the period, P the phase, and S a shifting constant) after removal of data corresponding to the two “isotopic events” (G43, G45 and G57 to G63) and the youngest studied part of the shell (G75 to G89) (solid curve: $A=-0.283$, $T=227.1$, $P=0.749$, $S=-1.471$; $R^2=0.75$) as well as after removal of all data with negative $\delta^{13}\text{C}$ values (G43, G45 and G55 to G89) (dashed curve: $A=-0.288$, $T=196.4$, $P=-0.202$, $S=-1.506$; $R^2=0.79$). Marine temperatures, that have been reported on the right vertical axis of the diagram, have been calculated using the fractionation equation of Grossman and Ku (1986) for biogenic aragonite and assuming that the ambient seawater had a constant $\delta^{18}\text{O}$ value of -1‰ (hypothesis of an ice cap-free world).

documented; kinetic fractionations larger than 10‰ have been measured relative to the expected carbon isotope equilibrium for coral aragonite growing in local seawater (McConnaughey, 1989). Kinetic effects, however, generally also affect oxygen isotopes with a preferential incorporation of the light isotope into the carbonate, a pattern not observed in the case of our specimen (Fig. 2). Alternative explanations could be a metabolic effect or a changing food source (Tourtelot and Rye, 1969) which would only affect carbon isotope fractionation during the growth of the animal (McConnaughey, 1989), or also a different living environment of the juvenile cephalopod in which organic-rich waters represented an important source of bicarbonate ion used for the mineralization of the shell. Carbon isotope compositions of the cephalopod shell could represent a quasi steady-state value of $+0.5\text{‰}$ between G37 and G1, suggesting that stable environmental conditions prevailed during the rest of the studied ontogenetic sequence.

After removal of oxygen isotope compositions corresponding to the two “isotopic events” and parts of the shell characterized by negative $\delta^{13}\text{C}$ values, the remaining data were fitted with a cosine wave function (Fig. 3). The quality of the fit suggest that the oxygen isotope compositions of the ammonite shell could correspond to the record of seasonal surface water temperature variations. Such a seasonal record

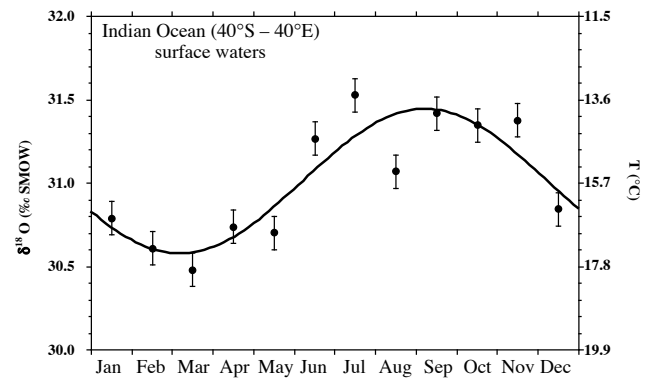


Fig. 4. Seasonal $\delta^{18}\text{O}$ variations of biogenic aragonite calculated with the present-day surface water temperatures of the western Indian Ocean at $40^\circ\text{S}-40^\circ\text{E}$.

Seawater temperature values come from the World Ocean Atlas (Levitus, 1994). This latitude is supposed to be closely that of Madagascar during the Oxfordian. The isotopic values have been calculated using the fractionation for biogenic aragonite (Grossman and Ku, 1986) and fitted by least square approximations ($r=0.88$) with a sine wave function. The $\delta^{18}\text{O}$ value of seawater was set to -1‰ in order to compare with the *Perisphinctes* oxygen isotope record shown in Fig. 3.

is compatible with the ecology of ammonites that were nektonic instead of cephalopods such as the modern *Nautilus pompilius* and *Nautilus macromphalus* for which the isotopic patterns reflect various life stages, vertical migration and the mean temperature of shell secretion below the thermocline (e.g. Cochran et al., 1981; Auclair et al., 2004). It cannot be excluded that seasonally-controlled vertical or horizontal migrations could have produced similar sinusoidal-like oxygen isotope variations recorded in the ammonite shell. However, the comparable range of $\delta^{18}\text{O}$ values obtained from the *Astarte* shell argues in favour of the record of in situ seasonal changes. According to this interpretation, the two resulting $\delta^{18}\text{O}$ maxima of -1.1‰ may represent the cold periods during winter seasons in the southern hemisphere (Fig. 3). If true, the seasonal amplitude is close to $0.6\pm 0.1\text{‰}$ and corresponds to a temperature variation of $2.5\pm 0.4^\circ\text{C}$ between summer and winter seasons.

Seasonal variations of the growth rate may produce asymmetric seasonal $\delta^{18}\text{O}$ curves for marine species that live under latitudes characterized by contrasted and cold seasons (Cornu et al., 1993). In the case of our *Perisphinctes* specimen, high sea surface temperatures were maintained over the complete seasonal cycle and therefore precluded any cessation or decrease in the rate of shell growth. In this seasonal framework, the two identified “isotopic events” one during late winter and the other in spring, did not exceed a month and could correspond to episodic or seasonal runoff from neighbouring hinterlands. A linear growth rate of about $0.7\text{ mm}\cdot\text{day}^{-1}$ is deduced from the seasonal periodic signal. This average rate is lower than that estimated from

the $\delta^{18}\text{O}$ signal of a Campanian *Bacculites* ($0.92 \text{ mm}\cdot\text{day}^{-1}$) from the Western Interior Region of North America (Fatherree et al. 1998). The growth rate obtained for *Perisphinctes* compares with the highest available values (between 0.6 and $0.7 \text{ mm}\cdot\text{day}^{-1}$) measured on *Nautilus* grown in a temperature-controlled aquarium (Ward, 1987).

Assuming a $\delta^{18}\text{O}$ value between -1‰ (i.e. absence of continental ice caps) and 0‰ (i.e. present-day configuration) for Jurassic seawater, the calculated mean annual temperature ranges from 22.5°C to 26.7°C (Fig. 3) according to the aragonite-water fractionation equation determined by Grossman and Ku (1986). These isotopic temperatures are compatible with those obtained from Late Jurassic general circulation models (e.g., Valdes et al., 1995). Late Jurassic seasonal variations in the southern hemisphere were close to 2.5°C and relatively weak when compared to the $2.5\text{--}6.5^\circ\text{C}$ temperature range prevailing in the present-day Indian Ocean at a paleolatitude of $40\pm 1^\circ\text{S}$ (World Ocean Atlas; Levitus 1994). For example, a seasonal oxygen isotope record has been calculated for a hypothetical aragonitic shell that grew in the temperature conditions of present-day surface waters of the Indian Ocean at the precise latitude of $40^\circ\text{S}\text{--}40^\circ\text{E}$ (Fig. 4). The present-day seasonal amplitude of 3.5°C is 50% larger and the mean annual temperature is at least 7°C lower than for Jurassic surface marine waters. Jurassic seasonal variations can be slightly underestimated, however, because the oxygen isotope composition of this nektonic ammonite does not exactly reflect sea surface temperature defined at the seawater-air interface.

5 Conclusions

Oxygen and carbon isotope compositions of aragonite sampled along the perimeter of the venter of an immature *Perisphinctes* specimen record a periodic season signal. Two $\delta^{18}\text{O}$ maxima of -1.1‰ may represent the cold periods during winter seasons in the Morondava Basin of Madagascar in the southern hemisphere (40°S). The seasonal amplitude appears to be close to $0.6\pm 0.05\text{‰}$ and corresponds to a temperature variation of $2.5\pm 0.2^\circ\text{C}$ between summer and winter seasons. This seasonal record allows us to calculate a shell growth rate of about $0.7 \text{ mm}\cdot\text{day}^{-1}$. Assuming a $\delta^{18}\text{O}$ value of ambient seawater comprised between -1‰ and 0‰ , mean annual temperatures higher than 20°C , associated with a low seasonal amplitude, are most likely indicative of tropical climatic conditions at 40°S during the Late Jurassic.

Acknowledgements. The authors thank M. M. Joachimski and G. Price for their constructive reviews that helped us to improve the quality of this work. G. Escarguel performed the statistical treatment of isotopic data.

Edited by: P. De Groot

References

- Auclair, A.-C., Lécuyer, C., Bucher, H., and Sheppard, S. M. F.: Carbon and oxygen isotope composition of *Nautilus macromphalus*: a record of thermocline waters off New Caledonia, *Chem. Geol.*, 207, 91–100, 2004.
- Barrera, E., Tevesz, M. J. S., Carter, J. G., and McCall, P. L.: Oxygen and carbon isotopic composition and shell microstructure of the bivalve *Latermula elliptica* from Antarctica, *Palaios*, 9, 275–287, 1994.
- Besairie, H.: Géologie de Madagascar. I. Les terrains sédimentaires, *Ann. Géol. Madagascar*, 35 p, 1972.
- Besse, J. and Courtillot, V.: Paleogeographic maps of the continents bordering the Indian Ocean since the Early Jurassic, *J. Geophys. Res.*, 93, 11 719–11 808, 1988.
- Buchardt, B. and Weiner, S.: Diagenesis of aragonite from Upper Cretaceous ammonites: a geochemical case study, *Sedimentology*, 28, 423–438, 1981.
- Bucher, H., Landman, N. H., Klofak, S. M., and Guex, J.: Mode and rate of growth in ammonoids, in: *Ammonoid Paleobiology*, edited by: Landman, N. H., Tanabe, K., and Davis, R. A., Topics in Geobiology, 408–453, Plenum Press, New York, 1996.
- Cochran, J. K., Rye, D. M., and Landman, N. H.: Growth rate and habitat of *Nautilus pompilius* inferred from radioactive and stable isotope studies, *Paleobiol.*, 7, 469–480, 1981.
- Cornu, S., Pätzold, J., Bard, E., Meco, J., and Cuerda-Barcelo, J.: Paleotemperature of the last interglacial period based on $\delta^{18}\text{O}$ of *Strombus bubonius* from the western Mediterranean Sea, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 103, 1–20, 1993.
- Dauphin, Y. and Denis, A.: Analyse microstructurale des tests de mollusques du Callovien de Lukow (Pologne) – Comapraison de l'état de conservation de quelques types structuraux majeurs, *Rev. Paléobiol.*, 9, 27–36, 1990.
- Dauphin, Y. and Denis, A.: Diagenèse comparée des phases minérales et organiques solubles dans les tests aragonitiques de nautilus et d'ammonites, *Bull. Soc. Géol. France*, 170, 355–365, 1999.
- Dromart, G., Garcia, J.-P., Picard, S., Atrops, F., Lécuyer, C., and Sheppard, S. M. F.: Ice age at the Middle-Late Jurassic transition?, *Earth Planet. Sci. Lett.*, 213, 205–220, 2003.
- Epstein, S. and Lowenstam, H. A.: Temperature-shell-growth relations of recent and interglacial Pleistocene shoal-water biota from Bermuda, *J. Geol.*, 61, 424–438, 1953.
- Fatherree, J. W., Harries, P. J., and Quinn, T. M.: Oxygen and carbon isotopic “dissection” of *Baculites compressus* (Mollusca: Cephalopoda) from the Pierre Shale (Upper Campanian) of South Dakota: implications for paleoenvironmental reconstructions, *Palaios*, 13, 376–385, 1998.
- Frakes, L. A. and Francis, J. E.: A guide to Phanerozoic cold polar climates from high-latitude ice-rafting in the Cretaceous, *Nature*, 333, 547–549, 1988.
- Frakes, L. A., Francis, J. E., and Syktus, J. I.: *Climates Modes of the Phanerozoic*, Cambridge University Press, Cambridge, 1992.
- Grossman, E. L. and Ku, T.-L.: Oxygen and carbon isotope fractionation in biogenic aragonite: temperature effects, *Chem. Geol.*, 59, 59–74, 1986.
- Horibe, S. and Oba, T.: Temperature scales of aragonite-water and calcite-water systems, *Fossils*, 23/24, 69–79, 1972.
- Kim, S. T. and O'Neil, J. R.: Equilibrium and nonequilibrium oxygen isotope effects in synthetic carbonates, *Geochim. Cos-*

- mochim. Acta, 61, 3461–3475, 1997.
- Lécuyer, C., Reynard, B., and Martineau, F.: Stable isotope fractionation between mollusc shells and marine waters from Martinique Island, Chem. Geol., 213, 293–305, 2004.
- Levitus 94: World Ocean Atlas, an atlas of objectively analyzed fields of major ocean parameters, <http://ingrid.ldeo.columbia.edu/SOURCES/LEVITUS94/>, 1994.
- Malchus, N. and Steuber, T.: Stable isotope records (O, C) of Jurassic aragonitic shells from England and NW Poland: palaeoecologic and environmental implications, Geobios, 35, 29–39, 2002.
- McConnaughey, T.: ^{13}C and ^{18}O isotopic disequilibrium in biological carbonates: I. Patterns, Geochim. Cosmochim. Acta, 53, 151–162, 1989.
- Milliman, J. D.: Marine Carbonates. Part I. Recent Sedimentary Carbonates, Springer Verlag, Berlin, 375 p, 1974.
- Tajika, E.: Climate change during the last 150 million years: reconstruction from a carbon cycle model, Earth Planet. Sci. Lett., 160, 695–707, 1998.
- Tarutani, T., Clayton, R. N., and Mayeda, T. K.: The effect of polymorphism and magnesium substitution on oxygen isotope fractionation between calcium carbonate and water, Geochim. Cosmochim. Acta, 33, 987–996, 1969.
- Thorrold, S. R., Campana, S. E., Jones, C. M., and Swart, P. K.: Factors determining $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ fractionation in aragonitic otoliths of marine fish, Geochim. Cosmochim. Acta, 61, 2909–2919, 1997.
- Tourtelot, H. A. and Rye, R. O.: Distribution of oxygen and carbon isotopes in fossils of late Cretaceous age, western interior region of north America, Geol. Soc. Am. Bull., 80, 1903–1922, 1969.
- Valdes, P. J., Sellwood, B. W., and Price, G. D.: Modelling Late Jurassic Milankovitch climate variations, in: Orbital Forcing, edited by: House, M. R. and Gale, A. S., Timescales and Cyclostratigraphy, 115–132, Geol. Soc. Spec. Pub., 1995.
- Ward, P. D.: The Natural History of *Nautilus*, Allen & Unwin, Boston, 1987.
- Zheng, Y.-F.: Oxygen isotope fractionation in carbonate and sulfate minerals, Geochem. J., 33, 109–126, 1999.