$\delta^{18}O$ values of coexisting brachiopods and fish: Temperature differences and estimates of paleo–water depths

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ABSTRACT

To estimate vertical thermal gradients and paleo–water depths to marine platforms we present a new method based on the difference between $\delta^{18}O$ values of contemporaneous brachiopod carbonate and fish phosphate. Present-day marine fauna of well-known ecology from the surface to the sea floor record isotopic temperatures that agree with measured temperatures. We predict distributions of isotopic data that result from sampling strategy, basin morphology, and fauna ecology and discuss limitations. Application of the method to the Jurassic Paris-London basin gives vertical thermal variations of up to 14 °C associated with depths varying from a few meters to 170 ± 30 m. The estimated depths are minimum values and are greater than those estimated from sedimentological criteria for this ancient epicontinental sea.

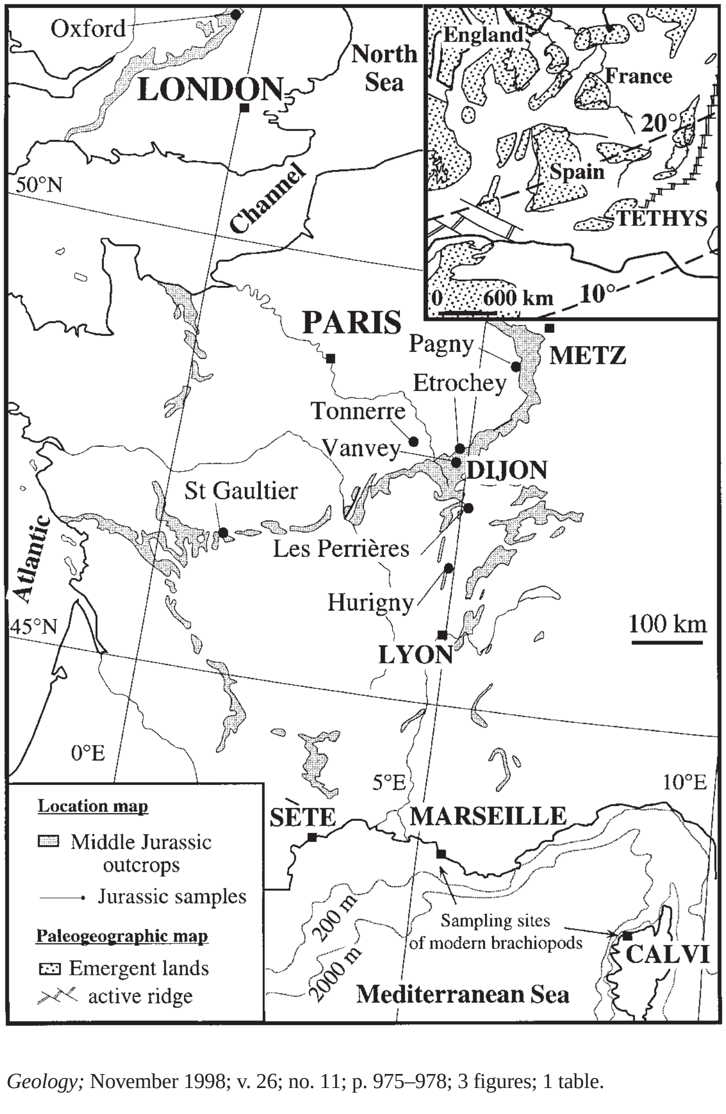


Figure 1. Map of Middle Jurassic sedimentary outcrops marking localities of analyzed brachiopod-fish pairs. Sampling sites in Mediterranean Sea are also indicated for modern brachiopods. Inset sketch map shows that Western Europe was at low latitudes (20° to 30°N) during Middle to Late Jurassic.

INTRODUCTION

The oxygen isotope compositions of brachiopod shells (e.g., Price and Sellwood, 1994) and fish teeth (e.g., Longinelli, 1966; Kolodny and Luz, 1991; Lécuyer et al., 1993) have been used to estimate temperatures and $\delta^{18}O$ values of past seawaters. Low-Mg calcite and apatite that constitute, respectively, articulated brachiopod shells and fish remains (vertebrae, scales, and teeth) are considered to crystallize in apparent isotopic equilibrium with ambient seawater, and the fractionations are very sensitive to temperature (Epstein et al., 1953; Longinelli and Nuti, 1973). Knowledge of marine surface temperatures and thermal gradients is essential to model the structure and dynamics of seawater masses, climates, and water basins. At present, qualitative estimates of paleo–water depths of pre-Cretaceous seas are based on facies substitutions that determine hydrodynamic limits (e.g., Guillocheau, 1991). On the basis of study of modern analogues, hydrodynamic processes are recorded at varying depths that depend on basin morphology, proximity to land, and climate. Below the storm wave base (100 m) the absence of sedimentological criteria precludes any kind of water-depth estimate.

To estimate vertical thermal gradients and paleo–water depths in the marine-platform environment, we propose to derive temperature differences in a water column that are based on $\delta^{18}O$ measurements of contemporaneous articulated brachiopods and demersal selachians. Modern fish live in either a single or different water masses, depending on the species, whereas brachiopods are benthic. The oxygen isotope compositions of the specimens are thus potentially able to provide a set of temperatures from the surface to the sea floor and from the proximal to the distal parts of a marine basin. The method

TABLE 1. STABLE-ISOTOPE ANALYSES OF MODERN AND JURASSIC BRACHIOPOD CARBONATE AND FISH PHOSPHATE

No.*	Taxon†	Locality (Fig.1)	Age	Depth†	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (SMOW)	T§ (°C)
	MODERN FISH						
I	*Dalatias licha*	Sète	Modern	<500 m	–	24.8	12
II	*Squalus acanthias*	Sète	Modern	0-200 m	–	23.7	17
III	*Galeorhinus galeus*	Sète	Modern	0-200 m	–	24.1	15
IV	*Myliobatis aquila*	Sète	Modern	surface	–	22.9	21
V	*Mustelus mustelus*	N. Atlantic	Modern	5-100 m	–	23.4	11
	BRACHIOPODS						
1	*Burmirhynchia turgida*	St. Gaultier	Bathonian	protected	1.1	28.0	25
1	*Burmirhynchia turgida*	St. Gaultier	Bathonian	protected	0.7	28.1	24
2	*Kutchirhynchia morieri*	Les Perrières	Bathonian	l.BPZ	1.6	30.0	16
2	*Kutchirhynchia obsoleta*	Les Perrières	Bathonian	l.BPZ	3.0	30.0	16
3	*Burmirhynchia* sp.	Vanvey	Bathonian	shoreface	2.0	27.0	30
3	*Tubithyris globata*	Vanvey	Bathonian	shoreface	1.8	27.0	30
4	*Dorsoplicathyris d.*	Etrochey	E. Callovian	u.PZ	2.0	29.2	20
4	*Zeilleria* sp.	Etrochey	E. Callovian	u.PZ	1.9	29.1	20
5	*Dorsoplicathyris d.*	Etrochey	E. Callovian	u.PZ	2.3	28.3	23
5	*Torquirhynchia* sp.	Etrochey	E. Callovian	u.PZ	2.9	29.7	17
6	*Digonella divionensis*	Dijon	E. Callovian	u.PZ	1.9	27.9	25
7	*Septaliphoria* sp.	Tonnerre	Rauracian	u.PZ	2.7	28.3	23
7	*Septaliphoria* sp.	Tonnerre	Rauracian	u.PZ	2.6	28.6	22
8	*Septaliphoria* sp.	Pagny	L. Oxfordian	u.PZ	3.2	30.1	15
8	*Zeilleria* sp.	Pagny	L. Oxfordian	u.PZ	2.4	28.4	23
	FISH						
1	*Asteracanthus*	St. Gaultier	Bathonian	protected	–	20.3	20
2	*Asteracanthus*	Les Perrières	L. Bathonian	l.BPZ	–	19.1	25
2	Pycnodont	Les Perrières	L. Bathonian	l.BPZ	–	18.8	26
2	Pycnodont	Les Perrières	L. Bathonian	l.BPZ	–	18.7	27
3	*Asteracanthus*	Vanvey	Bathonian	shoreface	–	19.7	22
4-5	*Asteracanthus*	Etrochey	E. Callovian	u.PZ	–	18.8	26
4-5	Pycnodont	Etrochey	E. Callovian	u.PZ	–	20.0	21
6	*Asteracanthus*	Dijon	E. Callovian	u.PZ	–	19.6	23
7	*Asteracanthus*	Tonnerre	Rauracian	u.PZ	–	19.7	22
8	Pycnodont	Pagny	L. Oxfordian	protected	–	20.6	19

* Associated samples have same number.

† Abbreviations: s. = *semiglobosa* , d. = *dorsoplicata*, sp. = *species*, PZ = photic zone, BPZ = below the photic zone, E = Early, L = Late, l.= lower offshore, u = upper offshore.

§ Temperatures of seawater calculated from fish phosphate (Longinelli and Nuti, 1973) or brachiopod calcite (Epstein et al., 1953) with $\delta^{18}O$ water of 1.7‰ for samples I to IV and 0‰ for V, and -1‰ for 1 to 8.

is calibrated by studying present-day fauna of well-known ecology that live in the Mediterranean Sea and Atlantic Ocean.

First, we evaluated the potential and limits of this method by predicting distributions of isotopic data that result from sampling strategy, basin morphology, and ecology of studied fauna. Second, we tested the method by performing oxygen isotope measurements on brachiopod-fish pairs from the Jurassic marine basin of France and England with known stratigraphy, paleogeographic context, and depositional environments (Gaumet et al., 1996). The results are discussed in terms of temperatures, estimated thermal gradients, and water depths.

SAMPLING STRATEGY AND METHODS

Modern specimens of brachiopods, *Gryphus vitreus* and *Terebratulina retusa*, and fish (Table 1) were collected alive at various depths from the western Mediterranean Sea (Fig. 1) and the North Atlantic Ocean. Additional data are compiled in Figure 2 and Table 1.

Contemporaneous pairs of Bajocian to Oxfordian brachiopod shells and fish teeth were selected (Fig. 1). These nondiagenetically altered samples are representative of various shallow to moderately deep water depositional environments: (1) the shoreface above the permanent wave-action limit, (2) the upper offshore between the permanent and the storm wave bases, and (3) the lower offshore below the storm wave base (Table 1). The distinction between being above or below the photic zone uses the occurrence of photosynthetic organisms like green algae or symbiotic corals. Protected environments, almost of lagoon type, are characterized by strongly reduced wave hydrodynamics.

Fish teeth come from the selachian *Asteracanthus* and from bony fish. All brachiopod and fish pairs come from the same sedimentary bed, except for the Pagny samples where the pycnodont tooth was sampled in fine laminated marlstone, representing a protected environment, <1 m below the brachiopod-bearing storm deposits (upper offshore). Two extra pairs combined $\delta^{18}O$ values obtained on marine crocodilians, *Asteracanthus* (Anderson et al., 1994), and bivalves (Hudson, 1978) from the same bed of the Callovian Oxford Clay, near Oxford, England.

Using a microcircular saw, we sampled the adult part of the pedoncular valve of the modern and ancient articulated brachiopods, which is the most suitable portion for the reconstruction of paleoenvironments (Carpenter and Lohmann, 1995). Modern fish teeth were treated for 3 days with H_2O_2 to eliminate organic matter and rinsed with deionized water. Isotopic compositions on quantitatively extracted CO_2 (McCrea, 1950; Lécuyer et al., 1993; O'Neil et al., 1994) are quoted in the δ notation in per mil relative to PDB (Peedee belemnite) for carbon isotopes and SMOW (standard mean ocean water) for oxygen isotopes. For carbonates, uncertainties obtained for duplicate samples are ±0.05‰ for $\delta^{13}C$ and ±0.1‰ for $\delta^{18}O$ values, whereas for phosphates, they are ±0.2‰.

RESULTS

Mediterranean articulated brachiopods sampled between 118 and 162 m show a narrow range of $\delta^{18}O$ values from 33.0‰ to 33.4‰ with one value at 32.5‰. The $\delta^{18}O$ values of Atlantic brachiopods increase from 32.4‰ at 280 m (11.2 °C) to 33.9‰ at 2175 m (3.2 °C) in agreement with decreasing measured temperatures of seawater. The $\delta^{18}O$ values of fish also increase with depth from 22.9‰ for a ray that lives in coastal surface waters (Table 1, no. IV) up to 24.8‰ for a shark that swims in deep waters (Table 1, no. I). In agreement with their ecology, shark species that swim from surface waters down to 200 m in depth record intermediate $\delta^{18}O$ values of 23.7‰ and 24.1‰.

Oxygen and carbon isotope compositions of Middle to Upper Jurassic brachiopods (Table 1) range from 27‰ to 30.1‰. Fossil brachiopods have $\delta^{18}O$ values increasing from the shallowest paleoenvironments that are shoreface (Vanvey) and protected environments (St. Gaultier) to the deepest ones represented by the upper-offshore photic zone (Dijon) or lower-offshore below-photic zone (Les Perrières, Table 1). Note that we observe $\delta^{18}O$ differences between some genera and species of brachiopods. They are small for *Septaliphoria* from Tonnerre (0.3‰) but up to 1.7‰ between *Septaliphoria* and *Zeilleria* from Pagny, whereas in most cases they remain within the analytical errors. Compared to the brachiopods, Jurassic fish (Table 1) show a more restricted range of $\delta^{18}O$ values, from 18.7‰ to 20.6‰.

DISCUSSION

Calculated temperatures of selachian $\delta^{18}O$ values (Table 1) are close to measured seawater temperatures (Pierre et al., 1986; Emig, 1997; Fig. 2). Isotopic temperatures of 13–15 °C for extant brachiopods are in good agreement with Mediterranean bottom water temperatures of 13.2 ± 0.1 °C. Atlantic brachiopods record temperatures of 5 °C at 2175 m and 11 °C at 280 m, similar to the measured temperatures of 3.2 °C and 11.2 °C (Angrieshem, 1985). For modern selachians, the isotopic temperatures reflect the average temperature of the seawater layer where they spent most of their lives (Fig. 2). These results confirm that the $\delta^{18}O$ values of brachiopods and fish record their environmental temperatures. Thus, the coexisting remains of brachiopods and fish should record at least two temperature points in the water column.

Figure 3 reports the difference between $\delta^{18}O$ values of coexisting brachiopod and fish ($\delta^{18}O_b - \delta^{18}O_f = \Delta^{18}O$) plotted against the brachiopod value. This diagram illustrates the principles of the relationship between temperature differences in the water column and the sea-floor temperature. The $\delta^{18}O$ value of a brachiopod ($\delta^{18}O_b$) on the *x*-axis increases with decreasing temperature for seawater with constant isotopic composition. The highest $\delta^{18}O_b$ value should thus record the coldest and, therefore, deepest waters. Brachiopod-fish pairs with a $\Delta^{18}O$ of +8‰ are expected to live in waters of similar temperature, according to our knowledge of the isotopic fractionations between carbonate and phosphate (Epstein et al., 1953; Longinelli and Nuti, 1973). Depending on the patterns of fauna distributions in a given marine basin, three linear distributions of $\Delta^{18}O$ values for brachiopod-fish pairs may be expected. In Figure 3, brachiopod-fish pairs living in warm waters at similar temperatures plot in the lower left corner, whereas pairs that plot in the upper right corner are compatible with the presence of a well-developed vertical thermal gradient from warm (surface) to cold (bottom) waters.

According to our sampling strategy of Jurassic fossils from the proximal to the distal parts of the Paris-London marine basin, the distribution of $\delta^{18}O$ values for brachiopod-fish pairs should lie on or close to a line with a positive slope of 1 (see trend 3 of Fig. 3). Most of our data on these pairs are compatible with a linear distribution close to the theoretical trend 3. However, the slope of the regression line is 1.4 ± 0.16, which is statistically different from a slope of 1. Moreover, most pairs fall within the error envelope except Pagny. This case emphasizes the importance of studying strictly coexisting pairs; the fish and brachiopod do not come from exactly the same bed.

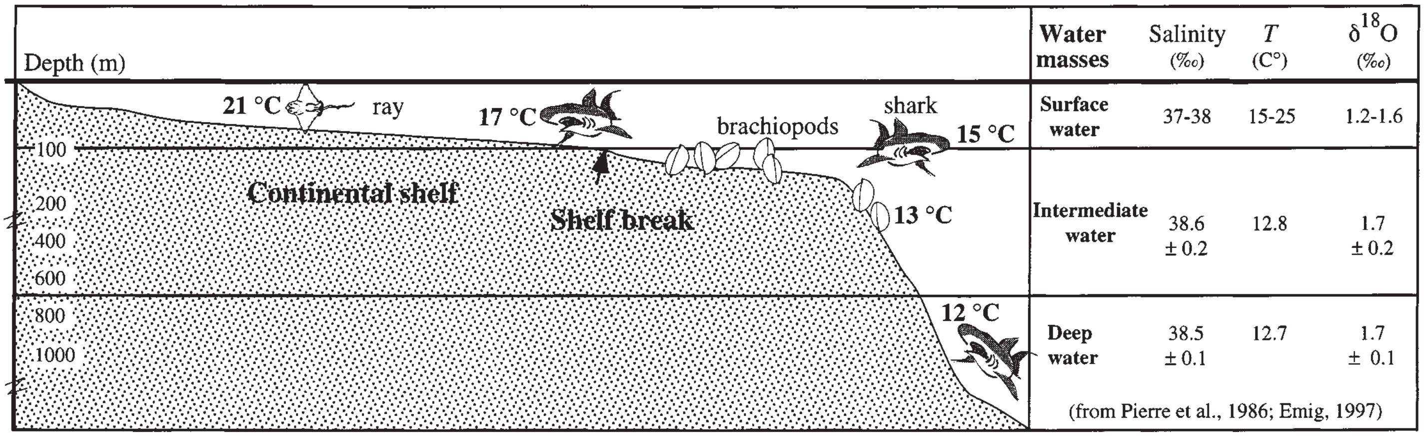
The general distribution of the isotopic data on Figure 3 is in good agreement with the inferred depositional environments. Both the $\delta^{18}O_b$ values and $\Delta^{18}O$ values increase with deepening of the basin. Fauna from shoreface and protected environments have the smallest $\Delta^{18}O$ values around 7‰ to 8‰. The largest $\Delta^{18}O$ value, 11.2‰ for Les Perrières, is recorded by the pair that comes from a lower-offshore environment (Fig. 3). Samples from upper offshore environments plot in an intermediate position. These results indicate that, at least qualitatively, the method works for coexisting fossils from the Jurassic.

The measured isotopic differences can be interpreted as temperature differences if the isotopic composition of the water was constant. Assuming the seawater heterogeneities were similar to actual variations in the top 400 m of the water column (±0.5‰), then uncertainties in the temperatures and their differences are ±2 °C. Brachiopod-fish pairs from shoreface and protected environments give no significant difference, whereas lower-offshore pairs indicate temperature differences of ~14 °C. If the fish was a surface-water dweller, then the temperature difference is the maximum for this water column. Interpretation of $\delta^{18}O_b$ as a temperature requires knowledge of the isotopic composition of seawater. Assuming $\delta^{18}O$ seawater is –1‰ ± 0.5‰ for a polar ice-free world gives Jurassic sea-floor temperatures of 25–30 °C for protected and shoreface environments and 15–16 °C for lower-offshore environments. Sea-surface temperatures of 19–27 °C (Table 1) for the fish are consistent with present-day surface temperatures at low latitudes.

Model temperature gradients and/or paleo-depths can be derived from these temperature differences if the temperature structure of the ocean is known. We assume that the modern thermal structure of 1/14 °C/m (Adlis et al., 1988) at low latitudes is a satisfactory analogue and that both the isotopic composition of waters and the thermal gradients were constant throughout the basin. Neglecting a correction for the unknown thickness of the thermally homogeneous surface-water layer (~25 m at 10°S; Adlis et al., 1988), we estimate that paleo–water depths of the upper offshore environment were 130 m, or 170 m including the high value of Etrochey. A paleo–water depth of 170 ± 30 m is estimated for the lower-offshore. For modern shelves, the limit between median and distal upper offshore is 80 m (Guillocheau, 1991), and the storm wave base is observed between 100 and 150 m water depth. Thus, our model paleo–water depths are roughly in accordance with modern values, but higher than those based on sedimentological criteria for the upper- to lower-offshore limit in ancient environments.

Model water depths require a record of maximum temperature differences within the water column. The fish sample, therefore, should be a species that was restricted to the near-surface-water layer. The precision on the difference in depth between two localities for a given time is probably higher than that for the individual depth values. The method is particularly applicable to marine areas with well-developed thermoclines that principally occur from 0° to 60° latitude.

We conclude that the oxygen isotope measurements of brachiopod-fish pairs is a promising approach to decipher the thermal structure and topography of marine basins at least as old as Jurassic. The existence of independent methods for estimating marine paleo–water depths should stimulate the debate about the dimensions and



Water masses	Salinity (‰)	*T* (C°)	$\delta^{18}O$ (‰)
Surface water	37-38	15-25	1.2-1.6
Intermediate water	38.6 ± 0.2	12.8	1.7 ± 0.2
Deep water	38.5 ± 0.1	12.7	1.7 ± 0.1

(from Pierre et al., 1986; Emig, 1997)

Figure 2. Measured salinities, temperatures, and $\delta^{18}O$ values of surface, intermediate, and deep waters of northwestern Mediterranean Sea (right side) are compared to calculated temperatures from $\delta^{18}O$ values of brachiopod carbonate and fish phosphate (left side). Brachiopods record temperature of sea-floor water whereas various genera of selachians record average temperatures from shallow to deep water masses depending on their habitat. Vertical thermal difference of 9 °C is inferred from difference of $\delta^{18}O$ values between ray that lived in shallow waters and brachiopods or bathyal shark species (*Dalatias licha*). Empirically calculated thermal gradient of ~1/17 °C/m is similar to measured one, with present-day average surface-seawater temperatures ~20–22 °C.

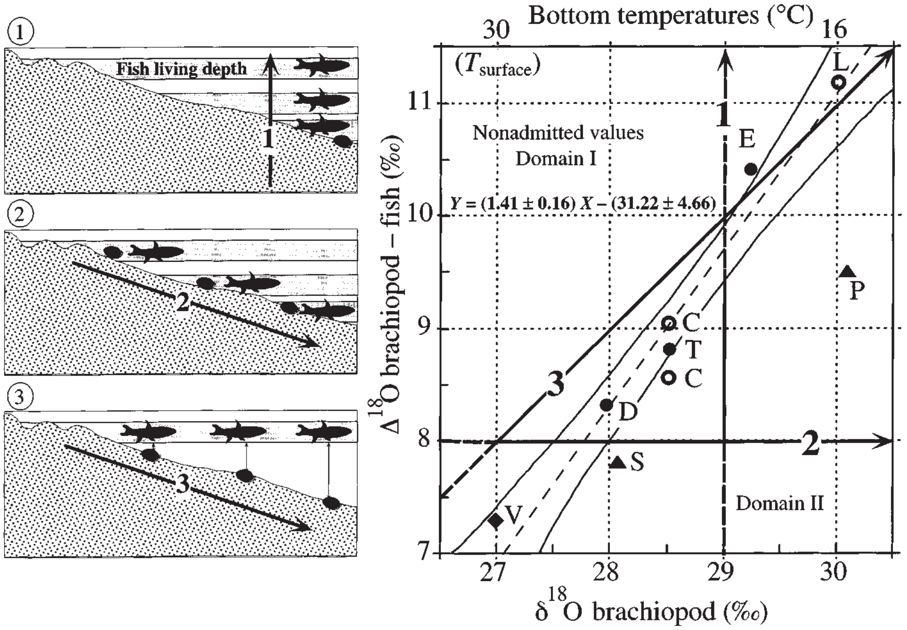


Figure 3. Difference between $\delta^{18}O$ value of associated brachiopod shell carbonate and phosphate of fish tooth plotted against $\delta^{18}O$ value of brachiopod, showing three model trends and Jurassic data. Empirical fractionation equations for biogenic carbonates (Epstein et al., 1953) and phosphates (Longinelli and Nuti, 1973) indicate that a difference of 8‰ is to be expected at a given temperature. Thus horizontal trend 2 represents brachiopod-fish pairs living in same water mass at same temperature (sketch 2). Any positive deviation from this value may be attributed to thermal differences inside the water column, if isotopic composition of water is constant and the fish is from warmer waters (trend 1). A vertical distribution of $\Delta^{18}O$ (trend 1) corresponds to sampling at different levels of water column (sketch 1) above a brachiopod. Trend 3, a line with positive slope of 1, is for fish living in surface-water layer (maximum temperature) but brachiopods coming from near-surface (low $\delta^{18}O$ values) to deeper and colder waters (higher $\delta^{18}O$ values). No data should be observed in domain I because temperatures for fish cannot be higher than surface-water temperatures. Data in domain II, the region below trend 2, indicate that, for example, bathyal fish may swim in colder waters below associated brachiopods that lie on continental slope (see Fig. 2). When several $\delta^{18}O$ values on associated brachiopods were available, the highest one was selected to constitute the isotopic pair, thus limiting possible diagenetic effects, except for Etrochey samples. At this site, brachiopod $\delta^{18}O$ values from layer 4 were preferred to those from layer 5 because of smaller intergeneric isotopic variability. Linear regression line of Jurassic data, excluding Pagny pair, is given, taking into account analytical errors on both *y*- and *x*-axes. A 95% confidence level is assigned to data that fall in envelope defined by the two hyperbola. Locations: C—near Oxford, D—Dijon, E—Etrochey, L—Les Perrières, P—Pagny, S—St. Gaultier, T—Tonnerre, V—Vanvey. Environments: open circle—offshore below photic zone, solid circle—offshore within photic zone, diamond—shoreface, triangle—protected environment.

thermal structure of past water masses that play a key role in the dynamics of sedimentary basins, evolution of climates, and fauna radiations.

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