Climatic ups and downs in a disturbed Jurassic world

Guillaume Dera[1,2]*, Benjamin Brigaud[3,2], Fabrice Monna[4], Rémi Laffont[2], Emmanuelle Pucéat[2], Jean-François Deconinck[2], Pierre Pellenard[2], Michael M. Joachimski[5], and Christophe Durlet[2]

[1]LSCE-IPSL (Laboratoire des Sciences du Climat et de l'Environnement–Institut Pierre Simon Laplace), CNRS-UMR 8212, CEA, F-91191 Gif-sur-Yvette, France
[2]Biogéosciences, CNRS-UMR 5561, Université de Bourgogne, F-21000 Dijon, France
[3]IDES (Interactions et Dynamique des Environnements de Surface), CNRS-UMR 8148, Université Paris Sud, F-91405 Orsay, France
[4]ARTeHIS (Archéologie, Terre, Histoire, Sociétés), CNRS-UMR 5594, Université de Bourgogne, F-21000 Dijon, France
[5]GeoZentrum Nordbayern, Universität Erlangen-Nürnberg, D-91054 Erlangen, Germany

ABSTRACT

The tropical, warm, and equable climate of the Jurassic world is regularly challenged by geoscientists, especially since oxygen isotopes ($\delta^{18}O$) of fossil hardparts have been used to reconstruct the paleotemperature history of seawater. By applying the innovative "SiZer" (significant zero crossings of the derivatives) statistical approach to a newly compiled $\delta^{18}O$ database for the Jurassic, we demonstrate the occurrence of major and multiscale $\delta^{18}O$ changes mainly related to climate disturbances. For the first time, two long-term anomalies in $\delta^{18}O$ are identified during the Toarcian and the Late Jurassic, in conjunction with intensive volcanism in large igneous provinces. These results support a strong influence of repeated volcanic pulses on the modulation of pCO_2, temperatures, and polar ice cap volumes over protracted periods. At shorter time scales, 13 relatively rapid (0.5–1 m.y.) and significant warming and cooling events are identified, the causes of which include transient fluctuations in greenhouse gas concentrations related to still-debated mechanisms.

INTRODUCTION

In the context of current global warming, reconstruction of climate history based on sedimentary archives, isotope geochemistry, and numerical modeling is of major interest because it allows comparison with current climate change in terms of rapidity, magnitude, origin, and potential consequences. During the past two decades, oxygen and carbon isotope analyses ($\delta^{18}O$ and $\delta^{13}C$) performed on well-preserved marine fossils have highlighted major changes in seawater temperature, carbon cycle, and polar ice volume during the Phanerozoic (e.g., Zachos et al., 2001). For example, $\delta^{18}O$ data measured on biostratigraphically well-dated bivalves (Brigaud et al., 2008), belemnites (van de Schootbrugge et al., 2005), brachiopods (Suan et al., 2010), ammonites (Wierzbowski and Joachimski, 2007), and fish teeth (Dera et al., 2009b; Lécuyer et al., 2003) from European domains have challenged former views of an equable and warm Jurassic climate with a low latitudinal gradient (Frakes et al., 1992). However, paleoclimatic changes inferred from isotopic records data may be questioned because, in spite of noisy $\delta^{18}O$ time series, the trends were never statistically tested. In addition, oxygen isotope signals measured on various biological hardparts may be discordant owing to nonequilibrium oxygen isotope fractionation of extinct organisms and/or differences in paleoecological behaviors of taxa (McArthur et al., 2007). Studies embracing the entire Jurassic interval (200–145 Ma) are scarce (Jenkyns et al., 2002), although they are required to identify the processes responsible for long-term $\delta^{18}O$ variations during this time period characterized by continental break-up and major volcanic events.

MATERIAL AND METHODS

We present an extensive $\delta^{18}O$ database covering the entire Jurassic and we use statistical methods, rarely applied to geochemical time series, both to test the robustness of warming and cooling events suggested in previous studies and to identify possible longer term climate trends. Our data set is based on an exhaustive compilation of 2809 published oxygen and carbon isotope values measured on various pristine fossil shells (see the GSA Data Repository[1]). All shells derive from the European realm representing shallow epicontinental seas (<200 m in depth) of the subtropical northwest Tethyan area. The data set was supplemented by 127 new analyses performed on Pliensbachian–Toarcian belemnites and Tithonian oysters from northern and eastern France (see the Data Repository). The geochemical data are constrained to the ammonite biozone resolution (~0.5 to 1 m.y. on average) to generate reliable temporal series calibrated to numerical ages of the time scale of Ogg et al. (2008). For paleoclimate reconstructions, only $\delta^{18}O$ data measured on well-preserved b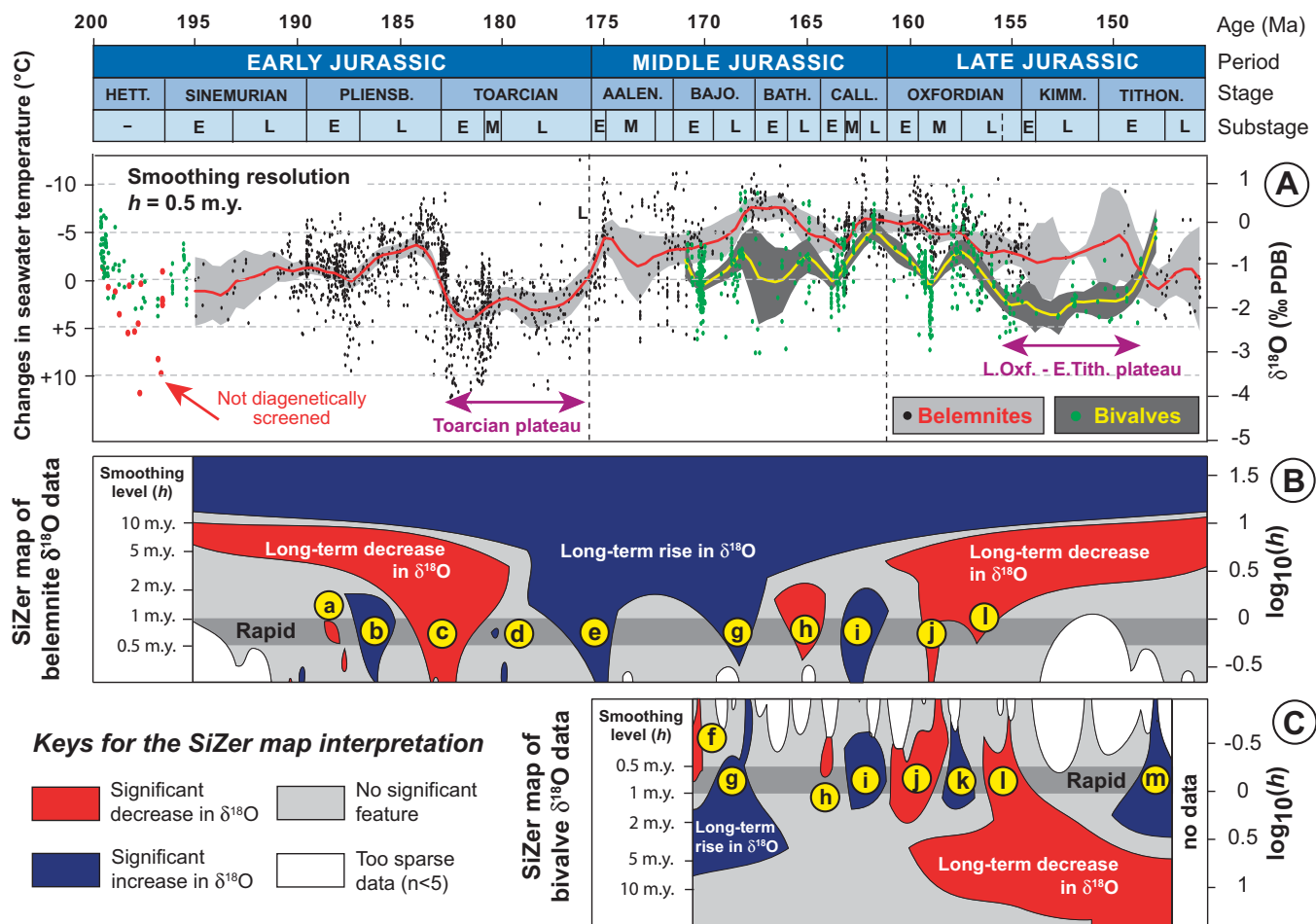elemnite rostra ($n = 1926$) and calcitic bivalve shells ($n = 759$) were considered, as these data sets constitute the most continuous geochemical records. The "SiZer" statistical approach (significant zero crossings of the derivatives; Marron and Chaudhuri, 1998) is used to compare $\delta^{18}O$ patterns of the two organisms and to detect significant climatic trends (see the Data Repository). This method is based on the construction of curves fitting time series using different levels of smoothing (h). The first derivatives of each curve (i.e., the slopes) are simultaneously computed with their 95% confidence intervals, allowing the signs of derivative estimates to be statistically tested. The results of multiple tests are then reported under the form of SiZer maps with different colors that enable simultaneously significant features to be identified at different time scales (Fig. 1). This includes rapid $\delta^{18}O$ variations ($0.5 < h < 1$ m.y.), as well as middle- to long-term trends spanning several million years. Features detected below the temporal resolution boundary (<0.5 m.y.) are not considered.

COMPARISONS BETWEEN ORGANISMS

Independently of the smoothing resolution, the SiZer maps based on belemnite and bivalve $\delta^{18}O$ values depict significant trends that, despite differences in absolute $\delta^{18}O$ values and the amplitude of major variations (Fig. 1A), are fairly concordant during overlap intervals such as the Middle and Late Jurassic (Figs. 1B and 1C). Some divergence can be observed during the late Kimmeridgian and Tithonian, possibly because the data are too sparse. At high frequency ($0.5 < h < 1$ m.y.), only three short events (periods f, k, m; Fig. 1) are not recorded by belemnite rostra. Except during the Tithonian, belemnites generally display higher $\delta^{18}O$ values than bivalves (with an offset varying between 0.5‰ and 1.5‰) and lower amplitudes in $\delta^{18}O$ fluctuations. This difference may be related to the ecological behavior of Jurassic belemnites, which are generally considered as nektobenthic cephalopods that were able to swim in deeper and cooler waters less affected by temperature fluctuations (e.g., Wierzbowski and Joachimski, 2007). Bivalves were sessile molluscs living in warmer and shallow (0–50 m) platform or ramp

*E-mail: guillaume.dera@lsce.ipsl.fr.

[1]GSA Data Repository item 2011085, new data, statistical method, additional references, and Table DR1 (Jurassic geochemical database), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure 1. Evolution of belemnite and bivalve $\delta^{18}O$ values and respective SiZer (significant zero crossings of the derivatives) maps (in opposite view to better compare short-term trends). A: Smoothed curves and 95% confidence intervals calculated for belemnite and bivalve $\delta^{18}O$ time series are generated using Kernel regressions with a bandwidth (h) of 0.5 m.y. representing maximal time resolution; $\delta^{18}O$ variations are converted into relative changes in seawater temperature using calcite fractionation equation of Anderson and Arthur (1983). Abbreviations: PDB—Peedee belemnite; HETT.—Hettangian; PLIENSBA.—Pliensbachian; AALEN—Aalenian; BAJO—Bajocian; BATHO—Bathonian; CALL—Callovian; KIMM.—Kimmeridgian; TITHON.—Tithonian (E—early, M—middle, L—late). B, C: Gray bands depict significant and relatively rapid $\delta^{18}O$ variations (0.5 < h < 1 m.y.) identified using letters a–m.

environments, in waters prone to evaporation or dilution by riverine runoff. Similarly to belemnite and fish tooth $\delta^{18}O$ signals observed during the Pliensbachian–Toarcian interval (Dera et al., 2009b), the discrepancy between the two $\delta^{18}O$ time series could reflect a temperature gradient and/or difference in seawater $\delta^{18}O$ due to a change in salinity in the water column. The similarity in SiZer maps for organisms with distinct modes of life points to a primary control of paleoenvironmental factors (not biotic) on Jurassic geochemical trends.

LONG-TERM CHANGES IN $\delta^{18}O$

The SiZer analysis of both data sets attests to the occurrence of middle- to long-term variations in $\delta^{18}O$ (~2–10 m.y.), including a significant $\delta^{18}O$ decrease during the Early Jurassic, a progressive increase during the Middle Jurassic, and a second decrease during the Late Jurassic (Figs. 1B and 1C). These changes are related to two phases with relatively homogeneous $\delta^{18}O$

values of −2‰ during the Toarcian (belemnites) and the late Oxfordian–early Tithonian interval (bivalves), separated by steady high $\delta^{18}O$ values of ~0‰ during the Middle Jurassic (Fig. 1A). It is interesting that time intervals characterized by negative $\delta^{18}O$ values roughly correspond to periods of protracted and intensive magmatism in the Karoo-Ferrar (Jourdan et al., 2007) and northeast Asian igneous provinces (Wang et al., 2006) (Fig. 2E). By promoting high pCO_2 levels, repetitive volcanic pulses could have both maintained warmer climatic conditions over relatively long time periods and favored high freshwater runoffs, leading to regional water freshening and low seawater $\delta^{18}O$ values reflected in biogenic calcite $\delta^{18}O$. These increases in riverine inputs are supported by contemporary rises in $^{87}Sr/^{86}Sr$ ratios, indicating relatively high continental weathering rates during the Toarcian and the Late Jurassic (Fig. 2C). Conversely, high-latitude glacial deposits such as tillites, dropstones, and glendonites are reported during

episodes of relative volcanic quiescence (Price, 1999), in conjunction with high $\delta^{18}O$ values (Fig. 2D). This congruence points to the possible waxing of polar ice caps over long periods, enriching seawater in ^{18}O. In relation with global temperature modulation, changes in ice volume could in part explain the major shifts in $\delta^{18}O$ before and after the Toarcian and late Oxfordian–early Tithonian anomalies. Nevertheless, mechanisms related to the incipient opening of the central Atlantic and Ligurian Oceans at the end of the Toarcian cannot be excluded as an explanation for Middle Jurassic high $\delta^{18}O$ values. Enhanced production of oceanic crust may have induced high-temperature alteration processes and hydrothermal venting, and contributed to high seawater $\delta^{18}O$ values (Jaffrés et al., 2007). Both scenarios imply that the calculation of absolute paleotemperatures using a constant seawater $\delta^{18}O$ for the Jurassic is problematic, owing to the complexity of processes modulating seawater $\delta^{18}O$ variations.
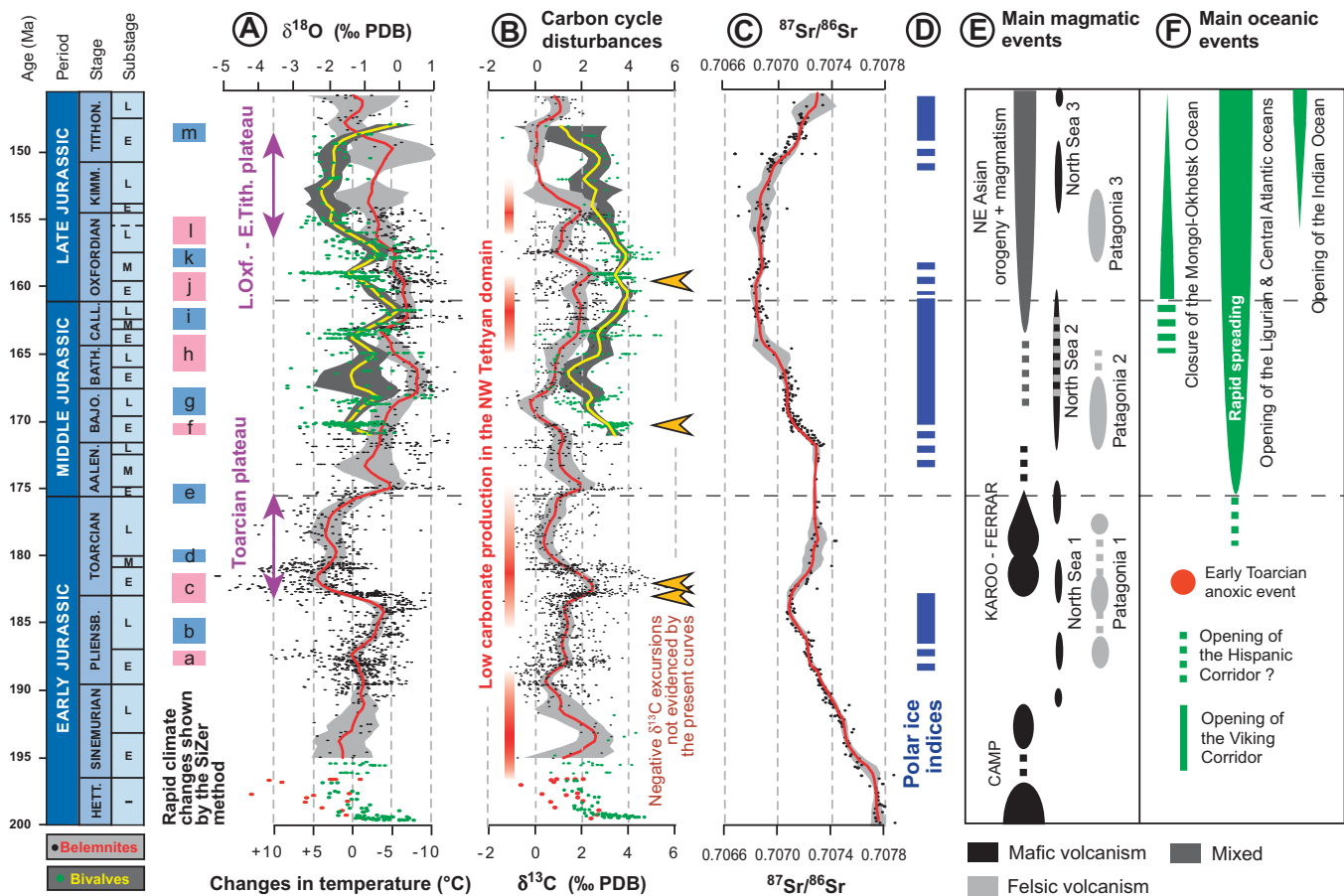
Figure 2. Comparison between oxygen, carbon, and strontium isotope records and Jurassic paleoenvironmental events. $^{87}Sr/^{86}Sr$ data and polar ice records are from Jones et al. (1994) and Price (1999). (For references concerning paleoenvironmental, oceanic, and magmatic events, see the Data Repository [see footnote 1]). Width of features representing volcanic events is roughly proportional to volume of erupted volcanic rocks. Abbreviations as in Figure 1.

SHORT-TERM CHANGES IN $\delta^{18}O$

In parallel, the SiZer maps computed for $\delta^{18}O$ time series of both fossil organisms allow a statistical evaluation of 13 rapid $\delta^{18}O$ changes (0.5 < h < 1 m.y.) previously reported by different studies (e.g., Jenkyns, 2003) (Figs. 1B and 1C). These include transient decreases in $\delta^{18}O$ during the early Pliensbachian (a), early Toarcian (c), early Bajocian (f), Bathonian-Callovian transition (h), early–middle Oxfordian (j), and late Oxfordian (l), as well as rapid $\delta^{18}O$ rises during the late Pliensbachian (b), middle-late Toarcian transition (d), Toarcian-Aalenian transition (e), late Bajocian–early Bathonian (g), middle–late Callovian (i), middle Oxfordian (k), and middle-late Toarcian transition. Other changes in oxygen isotopes, such as the decrease in $\delta^{18}O$ in the late Toarcian (Gómez et al., 2008), are not statistically validated and require further investigation. Small but significant variations of 0.5‰– 1‰ (i.e., a, b, d, g, h, k) correspond, if solely explained in terms of temperature, to changes in seawater temperature of 1–4 °C (Fig. 1A). In contrast, changes in $\delta^{18}O$ recorded during the early Toarcian, Toarcian-Aalenian transition, middle–late Callovian, late Oxfordian, and

Tithonian (i.e., c, e, i, l, m) appear more drastic, with calculated temperature variations exceeding 8 °C. Such climatic changes are unlikely for subtropical environments, which are usually less sensitive to temperature fluctuations than polar areas. As proposed here and in previous work (Saelen et al., 1996; Suan et al., 2010), disturbances of the global water cycle, including enhanced freshwater inputs, strong evaporation, and the waxing and waning of ice caps, could have induced regional or global changes in seawater $\delta^{18}O$, resulting in underestimations or overestimations of temperature fluctuations. Independent of recorded oxygen isotope fluctuations, higher abundances of kaolinite, a clay mineral typical of tropical, warm, and humid conditions, have been reported in marine sediments in parallel with transient decreases in $\delta^{18}O$ (Dera et al., 2009a). Most of the inferred climatic changes are also mirrored in latitudinal migrations of marine faunas in the northwest Tethys (Dromart et al., 2003; van de Schootbrugge et al., 2005). This correspondence between geochemical, faunal, and mineralogical proxies supports a climatic interpretation for the $\delta^{18}O$ variations recorded in the northwest Tethyan domain,

therefore excluding major biases related to diagenesis or paleoenvironmental and bathymetric changes. Data from other domains such as the Panthalassa and Arctic seas are, however, crucial to decipher the global versus regional scale of changes (Price and Rogov, 2009), as well as to evaluate paleoclimatic gradients.

ORIGINS OF RAPID WARMING AND COOLING EVENTS

The brief duration of climatic changes (0.5–1 m.y.) in the Jurassic implies relatively short-lived paleoenvironmental disturbances at geological scale. Among the principal causes of warming events, rises both in atmospheric pCO_2 and other greenhouse gases have been suggested, mostly in relation with the destabilization of methane gas hydrates (Jenkyns, 2003). These processes were put forward by the identification of transient negative carbon isotope excursions observed in most carbonate reservoirs (e.g., Hesselbo et al., 2007; Padden et al., 2001) during the early Toarcian, early Bajocian, and middle Oxfordian (Fig. 2B; yellow arrows). However, as these anomalies mostly occur at the end of warming trends (i.e., c, f, j), we suggest

that the destabilization of clathrates may rather represent a consequence of previous warming events. As several transient magmatic events occurred during the Jurassic (Fig. 2E), the frequency of volcanic pulses could explain the rhythm of pCO_2 increases and related warm episodes, at short and long time scales. To test for this causal relationship, it is crucial to obtain further radiometric dating of volcanic events well calibrated with an improved biostratigraphic framework. However, not all warming events seem to be linked to carbon cycle disturbances as, based on the evidence of neodymium isotope data, variations in oceanic currents linked to the break-up of Pangea could explain changes in seawater temperature at the end of the early Pliensbachian (Dera et al., 2009b) (Fig. 2F).

The causes of Jurassic cooling events are still obscure. By analogy with major Phanerozoic glaciations, lowering of atmospheric pCO_2 may be invoked. As supposed for the late Callovian cold interval (Dromart et al., 2003), elevated silicate weathering rates, nutrient influxes, high primary productivity, and organic matter burial during warm intervals are often considered relevant mechanisms to promote subsequent CO_2 drawdown. These feedback models seem convincing, since most Jurassic cold phases were preceded by warm conditions favoring black shale or coal deposition and, as a consequence, positive carbon isotope excursions (Fig. 2B). However, quantification of carbon storage and numerical modeling are required to confirm this scenario, as well as calculations integrating the role of changes in carbonate production rate.

CONCLUSIONS

The SiZer method identifies statistically significant $\delta^{18}O$ variations during the Jurassic at various time scales. We interpret these fluctuations as the result of long- and short-term climate changes, including both temperature and water cycle parameters. We also suggest that protracted magmatic activity in the Karoo-Ferrar and Asian igneous provinces could have promoted prolonged climate disturbances during the Toarcian and the late Oxfordian–early Tithonian interval, reflected by the absence of polar ice caps.

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