Jurassic Sea-Level Variations: A Reappraisal

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Cover Photo: Early Jurassic Blue Lias Formation at Lyme Regis, Dorset, UK. Abundant ammonite fossils (one seen in the foreground) form the basis for a well-resolved biostratigraphy that allows correlation of depositional sequences on regional and, in some cases, global scales. [Photo courtesy: Steven Andrews, Camborne School of Mines, University of Exeter, UK, 2017]

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ABSTRACT

An accurate chronostratigraphy of the timing and magnitude of global sea-level trends and their short-term variations is an indispensable tool in high-resolution correlations, exploration, and paleoenvironmental and geodynamic models. This paper is a reappraisal of the Jurassic sea-level history in view of recent updates in time scales and a large body of new chronostratigraphic data accrued since 1998, when the last such synthesis was presented. A review of the Jurassic sea-level history has also been keenly awaited by explorationists given that the Jurassic continues to be a major exploration target for the industry. As in previous eustatic models of this period, the updated Jurassic sea-level curve remains largely Eurocentric due to the limitations imposed by biostratigraphic correlation criteria (provinciality of ammonite and microfossil zones), though it can now be extended to some parts of the Tethys toward the east. The updated long-term curve indicates that there was a general rise of sea level through the Jurassic that began close to a level similar to or below the present-day mean sea level (pdmsl) in the early Jurassic, culminating in the peak high in the late Kimmeridgian–early Tithonian interval, before stabilizing in the earliest Cretaceous at ~110 m above pdmsl. Within this long-term trend are relative second-order highs in the Toarcian and Aalenian, and at Bathonian-Callovian and Kimmeridgian-Oxfordian boundaries. Superimposed are 64 third- and fourth-order fluctuations of which 15 are considered major with base-level falls of more than 75 m, although precise amplitudes of drawdowns are often difficult to establish. Higher resolution fourth-order cyclicity (~410 k.y.) is also observable in many Jurassic sections whenever sedimentation rates were high. Causes for the third-order cyclicity, in the absence of major ice sheets in the Jurassic, remains enigmatic.

INTRODUCTION

A record of sea-level variations of the past inferred from the stratigraphy of continental margins and interior basins (where the movements of the shoreline can be best documented) is a key predictive tool in hydrocarbon exploration. These data can provide insights into several pre-drill assessment criteria, including the migration of reservoir facies in response to rises and falls of sea level, the frequency and duration of subaerial exposure during lowstands, and the generation and preservation of source rocks during transgressions and highstands. The broad trends in Jurassic sea-level variations have been known for some time (Vail et al., 1977; Hallam, 1978, 2001; Haq et al., 1987, 1988; Hardenbol et al., 1998; Haq and Al-Qahtani, 2005), but recent updates of time scales and the accrual of new stratigraphic data from the period dictate a reappraisal of Jurassic eustatic history, especially at the third-order (shorter-term) time scales. A reappraisal of the long- and short-term trends of the base level would also be useful for academic research because such information can be the basis of stratigraphic, paleoenvironmental, and geodynamic models. In this communication, a brief summary of the updated version of the Jurassic sea-level history is presented so that it can be expediently made available to the research community.

The Jurassic period is currently estimated to have lasted some 55.6 m.y. (201.3–145.7 Ma) (Ogg et al., 2016). The period saw relatively low sea levels in the Early Jurassic, with the exception of the early Toarcian, which witnessed a relative high, a variable overall lowstand in the Middle Jurassic, and a gradual rise thereafter that lasted through much of the Late Jurassic. Climates also paralleled these trends. Faunal and isotopic data imply relatively warm climates for most of the Jurassic, with some exceptions, lacking credible evidence for widespread glaciations in much of this period. However, the relative warmth of the Hettangian through Toarcian interval seems to have been interrupted by a cooler late Pliensbachian through early Toarcian (Hinnov and Park, 1999; Dera et al., 2009; Suan et al., 2010; Korte and Hesselbo, 2011; Korte et al., 2015). Korte and Hesselbo (2011) believe that the Early Jurassic may have fluctuated between greenhouse and icehouse conditions. There may also have been some cooler intervals in the Aalenian, Bajocian, Bathonian, and early Callovian (Rogov and Zakharov, 2010), as well as a cold spell near the Middle–Late Jurassic transition (in the late Callovian) (Dromart et al., 2003). Most of the Late Jurassic is interpreted to have been relatively warmer and equable, experiencing peak warmth in the Kimmeridgian (Frakes et al., 1992; Zakharov et al., 2006; Brigaud et al., 2008). Although actual global temperatures and atmospheric or oceanic latitudinal thermal gradients of the Jurassic are only conjectured, modeling indicates that pCO_2 levels may have been a minimum of four times the present-day levels (see, e.g., Sellwood and Valdes, 2008). The long-term sea level and climatic trends also show an apparent correspondence.

JURASSIC TIME SCALE

Jurassic time scales have been in a significant state of flux since the last third-order sea-level curve for this period was published by Haq et al. (1988) or the later update by Hardenbol et al. (1998). Considerable advancements have been made to better delimit the stage boundaries of the Jurassic, and the most recent effort to update this time scale was presented by

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Ogg and Hinnov (2012) and Ogg et al. (2016). The last version of the Jurassic time scale is partially based on constraints from best fits of numerical radiometric ages, partially on cyclostratigraphy in strata of various stages and oxygen and other isotopic data. Magnetostratigraphy was helpful only in the Bajocian through Tithonian interval (with a hiatus at Callovian-Oxfordian transition) where the low-amplitude seafloor magnetic anomalies (from Ocean Drilling Program site 801 on the older part of eastern Pacific Plate) could be tied to magnetostratigraphy. The attempts to astronomically fine-tune discrete intervals of the Jurassic (see, e.g., Strasser, 2007, and a summary by Huang *in* Ogg and Hinnov, 2012) may help with duration of some zonal intervals, but such piecemeal efforts do not alleviate the precision issues of all of the stage boundaries that are exacerbated by the lack of reproducible radiometric control for much of the Middle and Late Jurassic. This implies that, in general, the time scale of the Jurassic and precision of the ages of many biostratigraphic zonal boundaries still remain less than well constrained. As Ogg and Hinnov (2012) state, the Jurassic scale "should be considered a work in progress" and although new constraints have refined the overall numerical chronology, "several intervals lack adequate constraints." Any future modifications of the time scale will obviously necessitate the recalibration of the sea-level chronology.

REVISION OF THE JURASSIC SEA-LEVEL CURVE

The main correlative tool in the Jurassic marine strata is ammonite biostratigraphy, occasionally assisted by other fossil groups, such as dinoflagellates, radiolaria, calcareous nannofossils, and calpionellids (the last only in the Late Jurassic). In the earlier Meso-Cenozoic sequence chronostratigraphy of third-order sea-level changes (Haq et al., 1988, and later by Hardenbol et al., 1998), the Jurassic sequence chronostratigraphy was based on sections in northern and central Europe (northern and southern coasts of England, west-central France, southern Germany, and Switzerland) and their ammonite and microfossil content (mostly dinoflagellates, foraminifera, nannoplankton, and calpionellids). In that Meso-Cenozoic synthesis (Haq et al., 1988; Hardenbol et al., 1998), a special attempt was made to study all available stage stratotype (or neo-stratotype) sections (including those from the Jurassic) that form the basis (or a global standard) for biochronostratigraphy. For the Mesozoic, most of these sections happen to have been chosen in NW Europe. Another reason for the Eurocentricity of the Jurassic sea-level curve was the limitations posed by the provinciality of the ammonite zones that do not permit precise correlations for a truly globally based chronology of eustatic events. These correlations become somewhat easier in the latest Jurassic (Tithonian) where one can draw on multiple correlative tools, but for much of the Jurassic the correlation limitations persist. In the current synthesis, all available additional studies in Jurassic stratigraphic sections (from 1988 through 2017) with good biostratigraphic data were reevaluated. As a result, the correlation net has now been widened somewhat to include other areas to the east in the Tethyan realm and to the Southern Hemisphere; i.e., Argentina's Neuquén Basin, where a nearly complete Jurassic record is preserved (e.g., Legarreta and Uliana, 1996). The heavy dependence on ammonite zones for correlation means that there is a built-in uncertainty in the ages of the sequence boundaries. While the sequence boundaries are placed according to their relative stratigraphic position within an ammonite zone (e.g., at the base, middle, top, or at the zonal boundary), theoretically the error bar could extend to the entire duration of the zone or subzone in question.

The long-term sea-level trends are similar to those shown in Haq et al. (1987, 1988) and Hardenbol et al. (1998). The original long-term curve for the Jurassic was based on continental flooding data, but unlike the Cretaceous (see Haq, 2014), knowledge of the oceanic crustal production rates for the Jurassic (i.e., variations in the mean age of the oceanic lithosphere, variations in the production rates at mid-ocean ridges, duration of the emplacement of seamounts, and large igneous provinces on the seafloor) is fragmentary because most of the seafloor of Jurassic age has since been subducted.

The documentation of the shorter-term sea-level changes (third-order events) are, of course, based on sequence-stratigraphic information from some relatively longer duration sections, but in most locations this information is pieced together from several sections within the Jurassic. Data from these studies were evaluated (and sequence-stratigraphically reinterpreted, as needed) before inclusion in the current synthesis. The Jurassic paleontological cross-correlations (i.e., zonal schemes based on different fossil groups and in different regions; Hardenbol et al., 1998) proved to be invaluable in aiding correlations in some cases. The sequence-stratigraphic interpretation criteria are well established and do not need repetition; however, in addition to these, other lithological and paleontological criteria (originally listed in Haq and Schutter, 2008; Haq, 2014) can also aid in the identification of system tracts, depositional surfaces, and sequence boundaries in outcrop and well-log sections. These include forced regressive facies, condensed section deposits, transgressive coals, evaporites, carbonate megabreccias, exposure-related deposits (i.e., incised valley fills, autochthonous coals, eolian sandstones, and karst in carbonates), as well as laterite/bauxite deposits. General trends in oxygen-isotopic data, in as much as they reflect broad climatic trends, can also lend greater confidence to the longer-term eustatic trends, and when the shorter-term isotopic excursions are distinctive, they can aid in the positioning of the timing of the sequence boundaries within a long-duration biostratigraphic zone (see Haq, 2014, for further discussion). In this synthesis, $\delta^{18}O$ isotopic data from Jurassic belemnites collected from the European sections (from the Sinemurian through Tithonian interval; see Martinez and Dera, 2015) were plotted against the sea-level curve (and smoothed by Robust Lowess Regression) for comparison (see GSA Data Repository Fig. S1[1]). The general trends in these data (which represent broad climatic variations) show an apparent similarity to the long-term sea-level curve, even though the ice-volume

[1]GSA Data Repository Item 2017387, documentation of depositional sequences comprising the new Jurassic sea-level curve, is online at www.geosociety.org/pubs/ft2017.htm.

component in the oxygen-isotopic signal is considered negligible in the Jurassic.

An examination of the available sequence-stratigraphic reports of the Jurassic (up to 2017) revealed that many sections around the world cannot be correlated with precision with the European stage stratotypes due to the provincial nature of ammonites, though other fossil groups can be helpful for cross-correlations. The earlier syntheses presented by Haq et al. (1988) and Hardenbol et al. (1998) still form the basis of the current synthesis. Additional information on third-order sequences that form a part of this reappraisal comes from Britain and France (Wignall, 1991, from Kimmeridgian of Dorset and France; Partington et al., 1993, Kimmeridgian to Ryazanian of North Sea; Herbin et al., 1995, Kimmeridgian and Tithonian of Dorset and Yorkshire in the UK and Boulonnais Basin in France; Taylor et al., 2001, Late Jurassic of Wessex-Weald Basin; Williams et al., 2001, Kimmeridgian and Tithonian of Wessex Basin; Hesselbo, 2008, from the Jurassic onshore sections of Britain); Poland (Pienkowski, 2004, Early Jurassic of Polish Basins); Greenland (Surlyk, 1990, Jurassic of East Greenland); Russia (Sahagian et al., 1996, mid- to Late Jurassic of Russian Platform; Pinous et al., 1999, Callovian to Oxfordian of western Siberia); Portugal (Leinfelder, 1993, Kimmeridgian of Lusitanian Basin); Denmark (Johannessen et al., 1996, and Johannessen, 2003, Late Jurassic of North Sea and Danish Central Graben); and northern Switzerland (Gygi et al., 1998, Oxfordian-Kimmeridgian; Colombié and Ramell, 2007, Kimmeridgian). Other areas of the Tethys include the Arabian Platform (Sharland et al., 2001, 2004; Haq and Al-Qahtani, 2005, mid- to Late Jurassic; Al-Husseini and Matthews, 2006, Oxfordian–early Kimmeridgian), and India (Krishna, 2005, mid- to Late Jurassic of Kutch Basin). For the depositional cycles identified in Tibet, where a nearly complete Jurassic record exists (Li and Grant-Mackie, 1993), direct correlation with the sub-boreal third-order cycles of Europe and those from the western Tethys could not be established due to differences in ammonite assemblages, but the authors show similarity in trends, and even tie some of the major sequence boundaries with those in Europe. From the Southern Hemisphere the only data that could be considered for this synthesis come from Argentina (Mitchum and Uliana, 1985; Legarreta and Uliana, 1996, Jurassic of the Neuquén Basin). A number of other studies of the Jurassic that were undertaken at the broader (second-order) scales were not considered relevant for a third-order scale synthesis, but they do sometimes provide additional constraints for the long-term trends. As our ability to more precisely correlate sequences improves in the future (through ancillary fossil biozones and other multiple, overlapping, correlative criteria, such as chemostratigraphic methods), these depositional cycles may be extended to other parts of the globe where the marine Jurassic record is well preserved, such as New Zealand.

RESULTS

The cycle chart resulting from the reappraisal of global stratigraphic data of the Jurassic is presented as two figures (Fig. 1 for the Early Jurassic and Fig. 2 for the Middle and Late Jurassic). The figures represent the established biochronostratigraphy of the Jurassic, plotted against the results of the current synthesis of the sequence cycles, their revised ages (and an updated numbering system partly adapted from Hardenbol et al., 1998). A sea-level curve based on the onlap record is the final product of the synthesis. The biochronostratigraphic parts of the figures show the latest (GTS 2016 of Ogg et al., 2016) age model from the Rhaetian (latest Triassic stage) through Berriasian (the early Cretaceous stage). This is tied to a composite paleomagnetic reversal scale that remains tentative below the Bajocian. The seafloor magnetic anomaly record is fragmentary below this level because the older Jurassic oceanic lithosphere has been largely subducted. Even for the Bajocian through Tithonian interval, it is dependent on a single site from the eastern Pacific (ODP site 801). The polarity scale from the Oxfordian to Tithonian is, nevertheless, fairly well verified in multiple sections and basins. The stages, Hettangian to Tithonian, currently considered standard subdivisions for the Jurassic, are tied to ammonite zones that, much like in the Cretaceous, are the most common fossil group for correlation in the Jurassic. The cross-correlation between zones from the relatively warm-water Tethyan regions and cooler-water boreal/sub-boreal regions (though still a part of the western Tethys) follow those suggested by Hardenbol et al. (1998) and later by Ogg and Hinnov (2012). Calcareous nannofossil zones of the Jurassic, also included, are mostly of long duration and of limited correlative utility in this period. However, sometimes they do provide additional criteria for correlations.

The two columns on the right in Figures 1 and 2 show sea-level events (mostly third-order and some consistent fourth-order sequence boundaries) and sea-level curves (long-term and short-term) for the Jurassic. When sequence boundaries are correlatable in several basins they are considered widespread (though global validity cannot be verified due to the Eurocentric nature of most of the data). The criteria for the long-term curves (shown in the last column on the right) have been discussed earlier in this paper, and the shorter-term sea-level curve that is derived from the sequence-stratigraphic data to its left. The amplitudes of third-order sea-level changes (rise and falls in meters) shown here are averaged from stratigraphic estimates in several basins and should be considered approximate (see discussion in Haq, 2014). They are subdivided into three magnitude categories of sea-level falls: major (>75 m), medium (25–75 m), and minor (<25 m). Most sea-level events fall within the medium category.

The long-term sea-level envelope (indicating the maximum flooding of continental margins and interior basins) shows that sea level remained close to or below present-day mean sea level (pdmsl) from the latest Triassic through the Hettangian and early Sinemurian, rising only a few tens of meters above pdmsl in the late Sinemurian-Pliensbachian, and by the late Pliensbachian it reverted back to levels comparable to pdmsl. In the Toarcian, there is an apparent long-term rise that may have peaked at ~75 m above pdmsl. In the latest Toarcian, the sea levels fell again to a few tens of meters above pdmsl, a trend that continued into the early Aalenian. From the late Aalenian onward, there is a gradual sea-level rise trend, with a few tens of meters of dip in the Bajocian and another in the latest Callovian–earliest Oxfordian that culminated in the peak high of the Jurassic in the late Kimmeridgian–early Tithonian. Near the Kimmeridgian-Tithonian boundary, the sea level may have been as high as ~140 m above pdmsl.

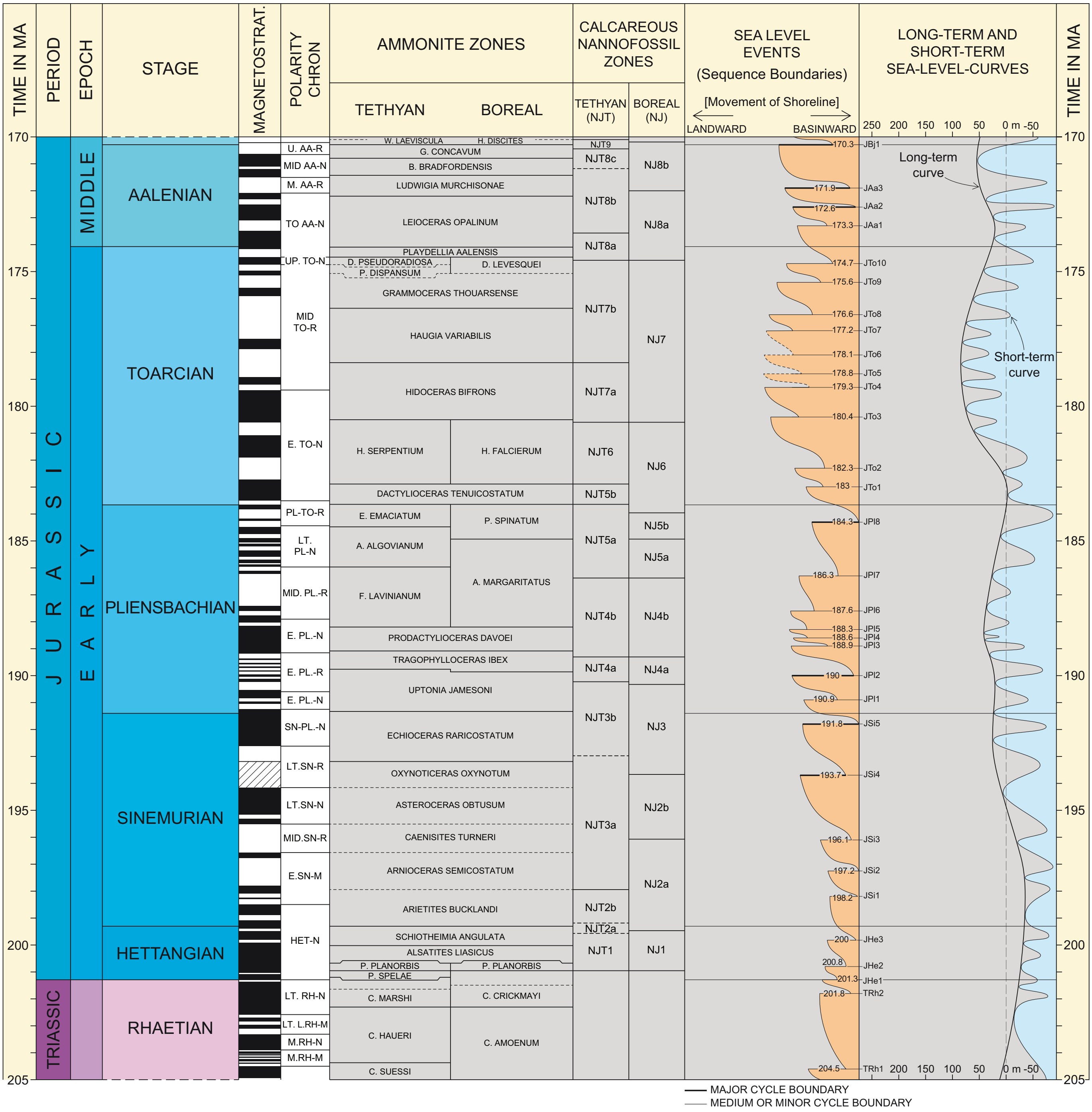

Figure 1. Early Jurassic sequences and variations of sea level. Time scale after Ogg et al. (2016). Biozone cross-correlations are after Hardenbol et al. (1998). Sequence boundaries (sea-level fall events) are redesignated following a numbering scheme suggested by Hardenbol et al. (1998) and Snedden and Liu (2010); however, the letters Tr, J, and K are prefixed to each designation for convenience to make the numbers unique and not to confuse them with similar numbers in other periods. (Three events in the Toarcian [JTo5–JTo7] are included provisionally, pending documentation of more widespread occurrence.)

In the late Tithonian, the sea level is seen to fall somewhat (from the peak high to ~100 m above pdmsl at the Tithonian-Berriasian boundary) before stabilizing in the earliest Cretaceous at ~110 m above pdmsl. It needs to be underscored that these amplitudes are at best guesstimates based on available data, which are not always definitive.

As mentioned, the short-term sea-level curve is largely a record of the third-order events (modeled as temporary removal or storage of water causing sea-level falls) that have been documented consistently in several basins and are thus considered widespread. These third-order events show variation in both the duration and magnitude of sea-level falls. The timing of the sea-level falls is accurate within a biozone (or subzone), but their numerical placement is approximated from their position

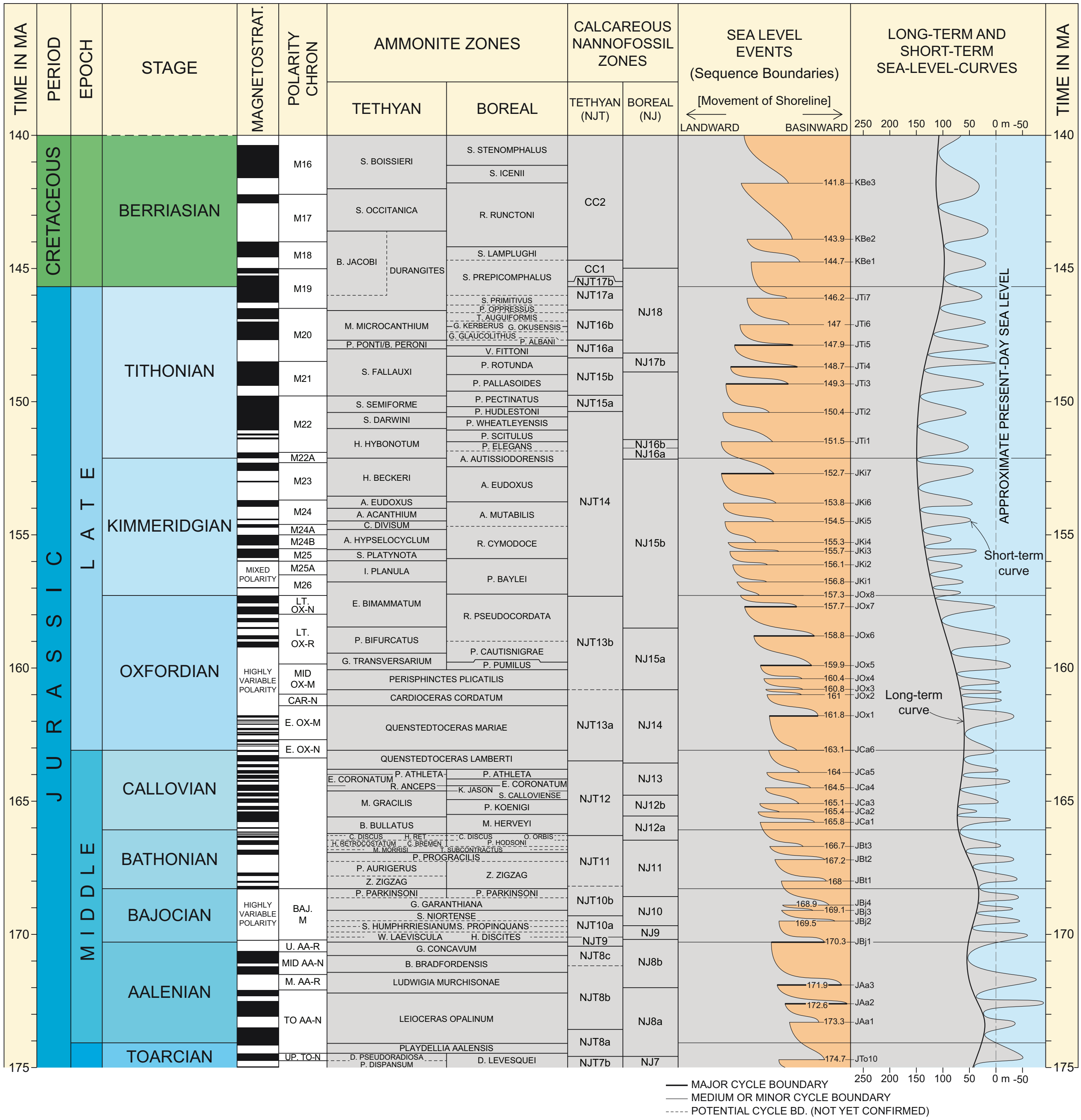

Figure 2. Middle–Late Jurassic sequences and variations of the sea level. (See Fig. 1 caption for details.)

in the outcrop sections (when sedimentation rates can be calculated), and sometimes when oxygen-isotopic data are available that show distinct excursions from the overall trends (see the GSA Data Repository [see footnote 1]). The magnitude (amplitude) of sea-level falls as shown on the curves is, however, more difficult to estimate and has to be averaged from several sections (see discussion in Haq, 2014). Fifty-six third- and eight fourth-order consistently occurring events have been identified in the Jurassic of the sub-boreal and Tethyan regions, of which 25 are additional to the older synthesis (Haq et al., 1988). Three events in the Toarcian (JTo5–JTo7) are included here tentatively, pending wider confirmation. Fourteen sea-level falls are considered as major, with drawdown of more than 75 m (JSi4 in Sinemurian; JPl2 and JPl8 in Pliensbachian; JAa2, JAa3 in Aalenian; JBj1 at the base of Bajocian; JOx1, JOx5, JOx6, JOx7 in Oxfordian; JKi7 in Kimmeridgian; and JTi3, JTi4, JTi5 in Tithonian). All other events are within the medium or minor range. The amplitude of sea-level falls is estimated to range from as little as <25 m for minor falls, to as much as ~150 m for major falls. The average duration of the third-order events is just over a million years, while fourth-order events average at ~410 k.y. Much like the Cretaceous (see Haq, 2014), the fourth-order cyclicity also seems to be a common feature in the Jurassic and is observable locally in sections with relatively high sedimentation rates. This higher-order cyclicity is considered to represent the long-period orbital eccentricity control on depositional cycles.

DISCUSSION AND CONCLUSIONS

The causes for third-order cyclicity in the Jurassic, in a period where there is little direct evidence of major ice sheets, remain unresolved (see a discussion in Haq and Huber, 2016). A variety of solid-Earth tectonic influences can affect sea-level changes (see, e.g., Conrad, 2013; Haq, 2014). But these influences can only provide some explanations for the local, very short time-scale changes of hundreds of years to 100 k.y. (such as those due to isostatic elastic and viscous responses of the lithosphere due to ice and water loading and unloading), or for the widespread but much longer time-scale changes on multiple millions of years (see a discussion in Haq, 2014, and Cloetingh and Haq, 2015). They fail to account for changes on third-order time scales of ~1 m.y./cycle. As an example, dynamic topography (see, e.g., Gurnis, 1993; Flament et al., 2013) can explain the reasons for the amplitude disparities of sea-level falls as measured physically along different margins, but the time scales involved in dynamic topographic changes are several million years and do not shed light on third-order cyclicity. The conclusions reached in the earlier synthesis of Cretaceous cyclicity (Haq, 2014; Cloetingh and Haq, 2015) that all measures of sea-level change are eurybatic (i.e., local or regional), and that an estimate of eustatic amplitude of sea-level falls cannot be inferred from any single basin or continental margin and must be averaged from global data, are valid for the Jurassic as well. The current synthesis reinforces these inferences. Jurassic sections also display the fourth-order cyclicity of ~410 k.y. whenever the sedimentation rates are high enough to resolve higher-resolution cycles. This periodicity is presumed to be driven by long-term orbital eccentricity, and its occurrence in the Jurassic as well as other periods supports the conclusion that the 410-k.y. periodicity may be considered as a basic element of most sequences, controlled largely by the long-term climatic trends.

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Jurassic Sea Level Variations: A reappraisal

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Documentation of widespread Jurassic sea-level events

In this section the Jurassic sea-level events (sequence boundaries) that are considered to be of wide extent are listed (mostly third-order sea-level falls, but also some fourth-order events). As mentioned in the main text, like earlier Jurassic eustatic models (Haq et al., 1987, 1988; Hardenbol et al, 1998), the documentation of these events largely comes from northwestern Europe, especially the sub-boreal areas (France, Southern Germany, Switzerland and the UK) although in this synthesis attempt has been made to widen the coverage to the east to the Tethys and west to South America. The two earlier syntheses (Haq et al., 1988, and Hardenbol et al., 1998) still comprise the principal basis of the current synthesis.

In this appendix a figure with a complete Jurassic cycle chart, along with the δ^{18}O data from belemnites of European sections (courtesy of Drs. Martinez and Dera), is presented. For ease of comparison the oxygen-isotopic data has been smoothed (with Robust Lowess Regression method) to show prominent excursions that might aid in pinning down the timing of sequence boundaries within long-duration biozones (see discussion in Haq, 2014). Events considered relatively widespread are listed for each standard stage, with the list of sections and the relevant references where the principal documentation is derived from. For brevity, references are numbered and listed at the end of this section. The timing of the sequence boundaries is approximated from their relative position within a section and the relevant biozone, sometimes aided by isotopic excursions. All sequence boundaries (as originally interpreted or as reinterpreted here) are recalibrated to the GTS2016 (Ogg et al., 2016).

Early Jurassic

The documentation for the Early Jurassic depositional cycles comes from NW European basins, Poland, East Greenland, Tibet (although correlations in this basin are considered tentative) and the Neuquen Basin in Argentina.

Hettangian

Three sea-level falls have been documented in the Hettangian. The first, **JHe1** (201.3 Ma), occurs at the Triassic-Jurassic transition and can be seen in NW European basins (here includes sections in France, southern Germany and Switzerland, excluding the UK, see Refs. 1, 2 below), Poland (3) and potentially also in Tibet (4). Event **JHe2** (200.8 Ma) has been recorded in NW European basins (1, 2), and **JHe3** (200 Ma), in addition to NW European basins, also occurs in Poland (3), and potentially also occurs in East Greenland, where it is recorded as occurring at the end of Hettangian (5), and in the same interval in Tibet (4). This depositional cycle is also recorded in Argentina's Neuquen Basin (6). All three Hettangian sea-level falls average minor to medium in magnitude and the duration averages ~1 Myr/cycle.

Sinemurian

Sinemurian is characterized by five prominent sea-level events. The first two sea-level falls, **JSi1** (198.2 Ma) and **JSi2** (19.2 Ma) have been recorded in NW European basins (1, 2) and the UK (7). The third event, **JSi3** (196.1 Ma), in addition to NW Europe and the UK, has also been documented in Poland (3) and Argentina (6). **JSi4** (193.7 Ma) has been recorded in NW European basins (2) the UK (7) and possibly also in Tibet (4). **JSi5** (191.8 Ma), in addition to NW European basins, the UK and Tibet, has also been recorded in Poland (3) and Argentina (6). The youngest two Sinemurian sea-level falls are considered major (>75 m) in amplitude. The duration of depositional sequences in the Sinemurian averages ~1.6 Myrs/cycle.

Pliensbachian

The Pliensbachian is relatively event rich, with eight depositional sequences occurring consistently in many basins. **JPl1** (190.9 Ma) is a medium sea-level fall that has been recorded in NW European basins (2), while **JPl2** (190 Ma) is a major fall that has also been recorded in the UK (7) and potentially in East Greenland as well, where is it characterized as occurring at the end of early Pliensbachian (5). **JPl3** (188.9 Ma) event has been reported from the NW European basins (1, 2) and the UK (7), as well as Argentina (6). Depositional cycle **JPl4** (188.6 Ma) has been recorded in NW Europe (1, 2), Poland (3) and Argentina (6). **JPl5** (188.3 Ma) event has so far been only recorded only in NW European basins, and **JPl6** (187.6 Ma) occurs in addition in the UK (7) and Poland (3). Both JPl4 and JPl5 are of minor amplitude falls and together with JPl3 may represent 4^{th}-order cyclicity. **JPl7** (186.3 Ma) event was a relatively medium amplitude fall and has been recorded in NW Europe (2), the UK (7), Poland (3) and possibly Tibet as well (4). In comparison, **JPl8** (184.3 Ma) was a major sea-level fall in NW Europe (1, 2), but has also been documented in the UK (7), Poland (3), Argentina (6) and in East Greenland (5) where is characterized as end late Pliensbachian event. The duration of the depositional cycles in Pliensbachian averages around ~1 Myr/cycle.

Toarcian

The Toarcian strata comprise seven consistently occurring depositional cycles; in addition three events in the mid Toarcian (JTo5, JTo6, JTo7) are also tentatively included on the cycle chart, pending confirmation. **JTo1** (183 Ma) in a relatively minor sequence boundary that has so far only been recorded in NW Europe (2), while **JTo2** (182.3 Ma) is more prominent in European basins and has also been recorded in the UK (7) and can be correlated to an event on the Arabian Platform (8), where five prominent depositional cycles occur in the Toarcian with a cyclicity of ~2 Myrs/cycle. **JTo3** (180.4 Ma) is medium magnitude event that was documented in NW Europe (2) and again can be correlated with one of the five events in the Arabian Platform (8). **JTo4** (179.3 Ma) event, in addition to NW Europe (1, 2) and can also be correlated with events in Poland (3), Tibet (4), East Greenland (5) and Argentina (6). [As stated above, events **JTo5** (178.5 Ma), **JTo6** (178.1 Ma) and **JTo7** (177.2 Ma) are tentative inclusions. These seem to be indicated by oxygen-isotopic excursions (changes in climatic trends). Currently only one of these, JTo5, is correlatable to a sequence boundary on Arabian Platform (8)]. **JTo8** (176.6 Ma) is a prominent medium magnitude event that has been documented widely, in NW European basins (1, 2), the UK (7), Poland (3), East Greenland (5), the Arabian Platform (8) and Argentina (6). **JTo9** (175.6 Ma) is another prominent sea-level fall that has been recorded in NW European basins (1, 2), Poland (3), East Greenland (5) and Argentina (6). The youngest of the Toarcian event, **JTo10** (174.7 Ma), also a prominent medium amplitude sea-level fall, is recorded in NW European basins (2), the UK (7), East Greenland (5) where it is characterized as end Toarcian, the Arabian Platform (8) and Argentina's Neuquen Basin (6). It may also occur in Tibet (4), but the correlation to this area is tentative. The Toarcian cyclicity averages ~0.9 Myr/cycle.

Middle Jurassic

The Middle Jurassic documentation comes from the sections in NW Europe, the UK, East Greenland, but also includes Denmark, the Russian and Arabian Platforms, India, Tibet (where correlations improve somewhat compared to Early Jurassic) and the Neuquen Basin in Argentina.

Aalenian

In the Aalenian three sequence cycles can be distinguished. **JAa1** (173.3 Ma) a prominent medium magnitude event that is currently reported from the NW European basins (2) and can be also be tentatively correlated to an event in Tibet (4). **JAa2** (172.6 Ma) is a major sea-level fall and is recorded in multiple places including the NW European basins (1, 2), the UK (7), in Tibet (3) where it occurs as a major sequence boundary, and in Argentina (6) where it is also prominent. The **JAa3** (171.9 Ma) event is another major sea-level fall that occurs in NW Europe (2), Tibet (4) and in East Greenland where it is characterized as a mid Aalenian event (5). The average duration of Aalenian depositional sequences is ~ 1.3 Myrs/cycle.

Bajocian

A major sequence boundary occurs at the Aalenian-Bajocian transition (and thus could as easily be placed within the Aalenian). Here it is designated at **JBj1** (170.3 Ma). This event is prominent in NW Europe (2), and can also be seen in the UK (7), the Arabian Platform (8) and Argentina (6). **JBj2** (169.5 Ma), also a prominent sequence boundary, has been documented from NW Europe (1, 2), the UK (7) and Argentina (6). In Tibet (4) this event may be represented by one of the multiple minor sequence boundaries in this interval. **JBj3** (169.1 Ma) and **JBj4** (168.9 Ma) are a pair of events that occur very to each other (and while JBj3 is of relatively minor amplitude, JBj4 is very prominent of high medium amplitude), thus it may be difficult to distinguish between these in all sections, unless the sedimentation rates are high. One or both of these has been documented in NW European basins (1, 2), the UK (7), India (10), on the Russian Platform (9), Tibet (4) and Argentina (6). The average duration of cycles in Bajocian is ~0.7 Myr/cycle.

Bathonian

The Bathonian stage comprises three prominent medium amplitude sea-level events in several basins. **JBt1** (168 Ma) has been recorded from NW Europe (2), on the Arabian Platform (8), in India (10) and Tibet (4). **JBt2** (167.2 Ma) is documented from NW Europe (2), India (10), Tibet (4) and Argentina (6) and **JBt3** (166.7 Ma) in addition, is also documented on the Russian (9) and Arabian Platforms (8). The average duration of sequence cycles in Bathonian is ~0.8 Myr/cycle.

Callovian

The Callovian includes six depositional cycles most of them represented as medium amplitude sea-level falls. **JCa1** (165.8 Ma) is a prominent event recorded in NW European basins (2), India (10) and Tibet (4). **JCa2** (165.4 Ma) is a relatively minor event recorded in NW Europe (2), India (10) and East Greenland where it is characterized as an end early Callovian event (5). **JCa3** (165.1 Ma) has documented in NW European basins (1, 2), the UK, where it is a prominent event (7), the Russian Platform (9), Siberia (11), Tibet (4) and Argentina (6). **JCa4** (164.5 Ma), another prominent event, has been documented in NW European basins (2), the UK (7), the Russian Platform (9), Siberia (11), Tibet (4) and India (10). **JCa5** (164 Ma) has been recorded in NW European basins (2), the UK (7), Tibet (4) and India (10). The youngest of the Callovian event, **JCa6** (163.1 Ma), straddles the Callovian-Oxfordian boundary that has been documented from NW European basins (1, 2) and India's Kutch Basin (10). The average duration of depositional sequences in the Callovian is ~1.2 Myrs/cycle.

Late Jurassic

The Late Jurassic represents the peak high in long-term sea level of the Jurassic, and for this reason many of the sea-level falls also tend to be high in amplitude. In this interval correlations improve considerably compared to Early and Middle Jurassic. Documentation outside NW Europe and East Greenland includes the Russian Platform, Siberia, the Arabian Platform, India and Argentina.

Oxfordian

The Oxfordian stage comprises eight depositional cycles with four major sequence boundaries. **JOx1** (161.8 Ma) is one such major amplitude sea-level fall that has been recorded in NW European basins (2), India (10) and Argentina (6). **JOx2** (161 Ma), in addition to these areas, has also been recorded from East Greenland (5) where it is characterized as end early Oxfordian. **JOx3** (160.8 Ma) occurs in NW European basins (1, 2), the UK (7), the Russian Platform (9), Siberia (11), the Arabian Platform (8), India (10) and Argentina (6). **JOx4** (160.4 Ma) occurs in NW Europe (2), the UK (7) and India (10). **JOx5** (159.9 Ma) is a prominent major amplitude boundary in NW European basins (1, 2), but less prominent in the UK (7), the Russian Platform (9) and Siberia (11) as well as India (10). **JOx6** (158.8 Ma) is also a major sequence boundary in NW Europe (2), and somewhat less prominent on the Russian Platform (9), India (10) and Argentina (6). The third consecutive sequence boundary, **JOx7** (157.7 Ma), documented in NW European basins (1, 2) as a major sea-level fall, is also expressed in Siberia (11), Portugal (12), the Arabian Platform (8), India (10), and Argentina (6). The youngest Oxfordian cycle boundary, **JOx8** (157.3 Ma), has been recorded near the Oxfordian-Kimmeridgian transition. It is a relatively minor event that has so far only been recorded in the UK (7, 13) but it may also be indicated by an oxygen-isotopic excursion. The average duration of the Oxfordian cycles is ~0.8 Myr/cycle.

Kimmeridgian

The Kimmeridgian interval comprises seven sequence boundaries, last three are prominent medium to major sea-level falls. **JKi1** (156.8 Ma) has been documented in NW Europe (2), the UK (13) and Portugal (12). **JKi2** (156.1 Ma) is documented more widely and in addition to NW Europe (1, 2), the UK (7, 13) and Portugal (12), and it is also expressed in India (10) and Argentina (6). **JKi3** (155.7 Ma) is a prominent sea-level fall that has been recorded in NW Europe (1, 2), the UK (13, 14), Portugal (12), Denmark (15) and India (10). **JKi4** (155.3 Ma) and **JKi5** (154.5 Ma) are two events that are also recorded in NW European basins (1, 2), the UK (13, 14), Portugal (12) and Denmark (15), but JKi5 has also been recorded on the Arabian and Russian Platforms (8, 9). **JKi6** (153.8 Ma) is a prominent sea-level fall in NW European basins (2), the UK (7, 14), the Arabian Platform (8) and Argentina (6). The youngest of the Kimmeridgian sea-level falls, **JKi7** (152.7 M a), is a major event in the NW European basins (2), the UK (7), Portugal (12), India (10) and the Arabian Platform (8). The average duration of depositional cycles in the Kimmeridgian is ~0.8 Myr/cycle.

Tithonian

Tithonian comprises seven sequence cycles, all of them prominent sea-level falls, three of them of major amplitude. **JTi1** (151.5 Ma) has been documented in NW European basins (2), the UK (7, 13, 14), Danish Central Through (15), the Arabian Platform (8) and potentially also in Tibet (4). **JTi2** (150.4 Ma) is also recorded in NW Europe (1), the UK (7, 14) and India (10). **JTi3** (149.3

Ma) a major sequence boundary has been recorded in NW Europe (2), the UK (7, 13, 14), the Arabian Platform (8) and possibly also in Tibet (4). **JTi4** (148.7 Ma) was another major sequence boundary in NW Europe (2), Tibet (4) and Argentina (6). **JTi5** (147.9 Ma) is also a major sea-level fall in NW European basins (1, 2), less prominent in the UK (7) and India (10). The youngest two of the Tithonian sea level falls, **JTi6** (147 Ma) and **JTi7** (146.2 Ma), are prominent in NW European basins (1, 2), the UK (7) and on the Arabian Platform (8). Tibetan record (4) also shows multiple, though less prominent sequence boundaries in this interval two of which may correlate with these events. The average duration of sequence cycles in the Tithonian is also ~0.8 Myr/cycle.

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(2) Hardenbol et al., 1998: (NW Europe: Dorset, France, Switzerland)
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(9) Sahagian et al., 1996 (Russian Platform and Siberia)
(10) Krishna, 2005 (SW India, Kutch Basin)
(11) Pinous et al., 1999. (West Siberia)
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Fig. 1 (below): Revised and updated Jurassic sea-level curve (2017). The sea-level events (depositional sequence boundaries) and long- and short-term curves are based on a reappraisal of global Jurassic stratigraphic data. Time scale is after Ogg and Hinnov (2012) and Ogg et al. (2016). Jurassic biozone cross-correlations are after Hardenbol et al. (1998). Sequence boundaries are redesignated following a numbering scheme suggested by Hardenbol et al. (1998) and Snedden and Liu (2011), however, the letters Tr, J, and K are prefixed to the designations to make the numbers within each Period unique (and not to confuse them with similar numbers in other Periods). This figures also includes the complied $\delta^{18}O$ isotopic data from Jurassic belemnites from European sections by Martinez and Dera (2015), which has been smoothed (with Robust Lowess Regression) for comparison. The general trends in the isotopic data (representing climatic trends) show apparent similarity to the long-term sea-level curve, even though the ice-volume component in the oxygen-isotopic signal is considered negligible in the Jurassic.

JURASSIC SEA-LEVEL CURVE