GSA data repository item 2017387

Online Supporting Material for:

Jurassic Sea Level Variations: A reappraisal

Bilal U. Haq, *Smithsonian Institution, Washington DC, and Institut des Sciences de la Terre, Sorbonne Universités, UPMC, Paris, France.*

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 $\delta^{18}O$ 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 4th-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.

Main References for Documentation of widespread sea-level events (for additional references, see text in the main paper).

(1) Haq et al., 1987 and 1988: (NW Europe: Dorset, France, Switzerland)
(2) Hardenbol et al., 1998: (NW Europe: Dorset, France, Switzerland)
(3) Pienkowski et al., 2004 (Poland)
(4) Li, and Grant-Mackie, 1993 (Tibet)
(5) Surlyk, 1990 (East Greenland)
(6) Mitchum and Uliana, 1985; Lagretta and Uliana, 1996 (Argentina: Neuquen Basin)
(7) Hesselbo, 2008 (Onshore UK basins)
(8) Haq and Al-Qahtani, 2005 (Arabian Platform)
(9) Sahagian et al., 1996 (Russian Platform and Siberia)
(10) Krishna, 2005 (SW India, Kutch Basin)
(11) Pinous et al., 1999. (West Siberia)
(12) Leinfelder, 1993 (Lusitanian Basin, Portugal)
(13) Wignall, 1991 (Dorset, UK and France)
(14) Williams et al., 2001 (Wessex Basin, UK)
(15) Johannessen et al., 1996; Johannessen, 2003 (Northern Danish Central Trough)

References

Haq, B.U. , Hardenbol, J. and Vail, P.R. 1987, The chronology of fluctuating sea level since the Triassic. Science, v. 235, p. 1156-1167.

Haq, B.U., Hardenbol, J. and Vail, P.R., 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. Society of Economic Paleontologists and Mineralogists, Special Publication, v. 42, p. 71-108.

Haq, B.U. and al-Qahtani, A.M., 2005, Phanerozoic cycles of sea-level change on the Arabian Platform. GeoArabia, v. 10(2), p. 127-160.

Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., De Graciansky, P.C. and Vail, P.R., 1998, Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. Society of Economic Paleontologists and Mineralogists, Special Publication, 60, p. 3–13 (Chart 6 Jurassic Chronostratigraphy).

Hesselbo, S.P., 2008, Sequence stratigraphy and inferred relative sea-level change from the onshore British Jurassic. Proceedings Geological Association., v. 119(1), p.19-34.

Johannessen, P.N., 2003, Sedimentology and sequence stratigraphy of paralic and shallow marine Upper Jurassic sandstones in the northern Danish Central Graben. The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin, v. 1, p. 367-402.

Johannessen, P.N., Dybkjaer, K. and Rasmussen, E.S., 1996, Sequence stratigraphy of Upper Jurassic reservoir sandstones in the northern part of the Danish Central Trough, North Sea. Marine and Petroleum Geology, v. 13(7), p. 755-770.

Krishna, J., 2005, Update of Kuchchh Jurassic Ammonoid zonation: Summarised intra-basinal to global perspectives. Dera Dun, India, Association of Petroleum Geologists, Special Publication, v. 1, p. 76-79.

Legaretta, L, and Uliana, M.A., 1996, The Jurassic succession in west-central Argentina: Stratal patterns, sequences and paleogeographic evolution. Palaeogeography Palaeoclimatology, Palaeoecology, v., 120, p. 303-330.

Leinfelder, R.R., 1993, A sequence stratigraphic approach to the Upper Jurassic mixed carbonate-siliciclastic succession of the central Lusitanian Basin, Portugal. Profil, v. 5, p. 119-140.

Li, X. and Grant-Mackie, J.A., 1993, Jurassic sedimentary cycles and eustatic sea-level changes in southern Tibet. Palaeogeography Palaeoclimatology, Palaeoecology, v. 101(1), p. 27-48.

Martinez, M., & Dera, G., 2015, Orbital pacing of carbon fluxes by a~ 9-My eccentricity cycle during the Mesozoic. Proceedings National Academy of Science, v. 112(41), p. 12604-12609.

Mitchum, R.M. and Uliana, M.A., 1985, Seismic stratigraphy of carbonate depositional sequences, Upper Jurassic-Lower Cretaceous, Neuquen Basin, Argentina. American Association of Petroleum Geologists Memoir, v. 39, p. 255-275.

Ogg, J.G., Ogg, G. and Gradstein, F.M., 2016, A Concise Geologic Time Scale: 2016. Elsevier.

Pienkowski, G., 2004, The epicontinental Lower Jurassic of Poland. Polish Geological Institute, Special Publication, v. 12, p. 1-152.

Pinous, O.V., Sahagian, D.L., Shurygin, B.N. and Nikitenko, B.L., 1999, High-resolution sequence stratigraphic analysis and sea-level interpretation of the middle and upper Jurassic strata of the Nyurolskaya depression and vicinity (southeastern West Siberia, Russia). Marine and Petroleum Geology, v. 16(3), p. 245-257.

Sahagian, D., Pinous, O., Olferiev, A. and Zakharov, V., 1996, Eustatic curve for the Middle Jurassic--Cretaceous based on Russian platform and Siberian stratigraphy: Zonal resolution. American Association of Petroleum Geologists Bulletin, v. 80(9), p. 1433-1458.

Snedden J., and Liu, C, 2010, A compilation of Phanerozoic sea-level change, coastal onlaps and recommended sequence designations. Search and Discovery Article, American Association of Petroleum Geologists, no. 40594.

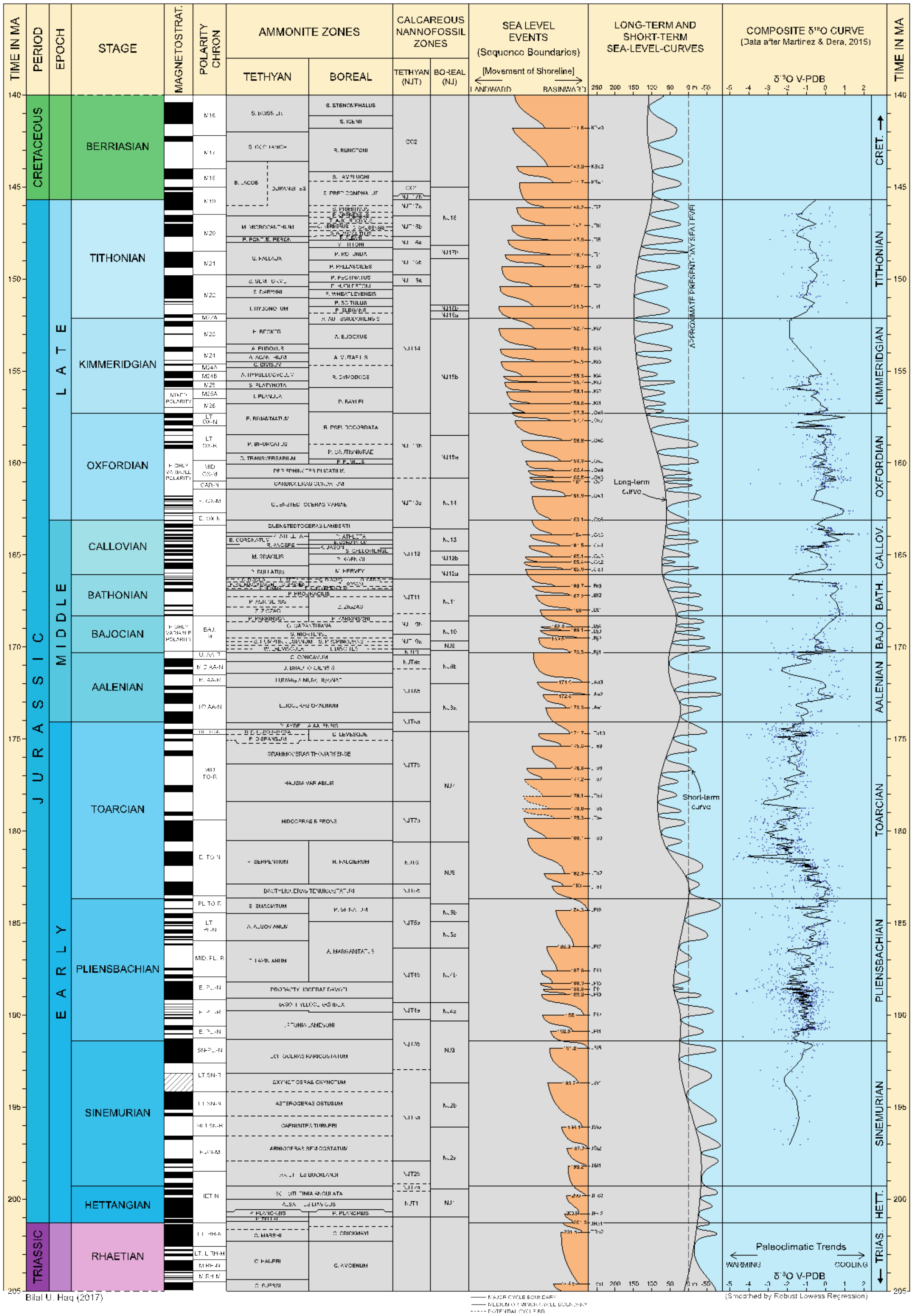
Surlyk, F., 1990, A Jurassic sea-level curve for East Greenland Palaeogeography, Palaeoclimatology, Palaeoecology, v. 78(1-2), p.71-85.

Wignall, P.B., 1991. Test of the concepts of sequence stratigraphy in the Kimmeridgian (Late Jurassic) of England and northern France. Marine and Petroleum Geology, v. 8(4), p.430-441.

Williams, C.J., Hesselbo, S.P., Jenkyns, H.C. and Morgans-Bell, H.S., 2001, Quartz silt in mudrocks as a key to sequence stratigraphy (Kimmeridge Clay Formation, Late Jurassic, Wessex Basin, UK). TerraNova, v. 13(6), p. 449-455.

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



JURASSIC SEA-LEVEL CURVE