The quest for refined calibration of the Jurassic time-scale

József Pálfy

PÁLFY, J. 2008. The quest for refined calibration of the Jurassic time-scale. *Proceedings of the Geologists’ Association*, 119, 85–95. The Jurassic time-scale assigns numerical ages to boundaries of chronostratigraphic units. A well-established ammonite biochronology forms the basis of stage definitions that are being formalized by Global Stratotype Sections and Points. Two major updates of the Jurassic time-scale (referred to as JTS2000 and GTS2004) were published recently. JTS2000 relies heavily on U–Pb and 40Ar/39Ar dates, whereas GTS2004 emphasizes complementary scaling methods using strontium (Sr) isotope stratigraphy, cyclostratigraphy and magnetostratigraphy. U–Pb and 40Ar/39Ar dates remain the backbone of the time-scale; relevant new developments are reviewed briefly. Fourteen recently published ages are added to the database of calibration points. Floating cyclostratigraphies already cover a significant portion of the Jurassic, allowing measurements of durations that need to be anchored and linked to chronostratigraphy. Where tie-points are sparse, reliance on scaling methods remains necessary. Sr isotope stratigraphy and magnetostratigraphy are increasingly sophisticated and useful for both correlation and scaling. Further refinements of calibration are expected from more accurate and densely spaced radioisotopic age tie-points, especially in the Late Jurassic, and from an extended coverage of Jurassic astrochronology. In the computer era, time-scales increasingly are being delivered digitally, updated continuously and accessed interactively by their users.

Key words: Jurassic, time-scale, chronostratigraphy, geochronology, calibration

Research Group for Paleontology, Hungarian Academy of Sciences-Hungarian Natural History Museum, POB 137, Budapest, H-1431 Hungary (e-mail: palfy@nhmus.hu)

1. INTRODUCTION

Modern Earth sciences demand a precisely and accurately calibrated geological time-scale for effective integration of temporal data from previously disparate disciplines such as stratigraphy, palaeontology, geochemistry and geophysics. Timing and correlation of events and rates of processes are basic concerns common to many disciplines involved with unravelling Earth history. This paper is devoted to a review of current developments in the Jurassic time-scale, i.e. a numerically calibrated chronostratigraphic scale. Jurassic chronostratigraphy has been distilled primarily from ammonoid biostratigraphy and is currently undergoing standardization through establishment of GSSPs (Global Stratotype Sections and Points) for all the stages (see Morton 2008). An array of other stratigraphic methods (e.g. biostratigraphy of other fossil groups, magnetostratigraphy, chemostratigraphy, etc.) are also available and are used to characterize and correlate the chronostratigraphic units. To calibrate the chronostratigraphic units with the chronometric scale that expresses time in million years (Ma), both radioisotopic dating methods and evidence of astronomical cycles in the stratigraphic record can be used. Stratigraphically constrained radioisotopic dates provide calibration tie-points to anchor the chronostratigraphic units and estimate ages for their boundaries, whereas cyclostratigraphy of suitable sedimentary successions may yield floating astrochronological time-scales to determine the duration of the corresponding intervals. The geological time-scale thus calibrates the chronostratigraphic units against the linear chronometric scale, by estimation of the numerical age of unit boundaries.

In the past 15 years, major advances and breakthroughs have occurred in many fields relevant to time-scale research. This paper reviews the most recent updates of the Jurassic time-scale and analyses the underlying developments in chronostratigraphy. An attempt is also made at a qualitative assessment of the current stage boundary age estimates and the article concludes with outlining future directions of time-scale research.

Historically, the Jurassic has been important for the development of concepts of chronostratigraphy. Ammonite biostratigraphy has traditionally played the key role in definition and correlation of units; see, for example, the summaries of Callomon (1984, 2001). For a long time, stratigraphy evolved to distinguish time (i.e. geochronological) and time-rock (i.e. chronostratigraphic) units but the adoption of standardized GSSPs now allows simplification and merger of the dual classification into a single scheme (Zalasiewicz et al. 2004). This approach is followed here, although the reader should be aware of its somewhat controversial
status. Thus, terms used for units of geological time (e.g. Jurassic Period, Early Jurassic Epoch) are herein also applied to the rocks formed during this time, while traditional chronostratigraphic terms (e.g. Jurassic System, Lower Jurassic Series) are abandoned. As an exception, the term Stage – as opposed to Age – is retained, because the latter is too frequently used in its more general sense (Harland et al. 1990). For subdivisions within a Stage, Substage, Chron and Subchron (rather than Zone and Subzone) are used.

2. HISTORY OF JURASSIC NUMERICAL TIME-SCALES

Time-scales have been subject to continuous refinement ever since Holmes’ (1913) pioneer book entitled The Age of the Earth, which was published soon after the discovery of radioactivity and radioisotopic dating. Early on, the Jurassic Period was deduced by Barrell (1917) to fall somewhere between 120 Ma and 195 Ma and to be of c. 40 Ma in duration. Updates by Holmes (1937, 1959) were published during his long career but it was Harland et al. (1964) who first attempted to estimate stage boundary ages, albeit using a crude interpolation method that assumed equal duration of stages; at that time, there were still no more than a dozen Jurassic radioisotopic ages available for the construction of the scale. The gradual growth of the radioisotopic age database warranted ever more frequent updates, especially from the 1980s. Innovations in stage boundary age calculation included the use of chronograms (Harland et al. 1990) or the maximum likelihood method (Gradstein et al. 1994, 1995). Interpolation between tie-points and boundaries also made use of the chronogram method. The historical development of the Jurassic time-scale up to the mid-1990s has been summarized in detail by Pálfy (1995). Since then two major amendments have been published that deserve discussion: (1) Pálfy et al. (2000c), referred to here as JTS2000; and (2) the work of Ogg (2004), included in the comprehensive volume by Gradstein et al. (2004), abbreviated here as GTS2004 (Fig. 1). Before these works, the scarcity of biostratigraphically well-constrained radioisotopic ages and the dubious accuracy of many old K–Ar ages remained the main obstacles. Therefore, a concerted effort was undertaken in the North American Cordillera to obtain U–Pb zircon ages from volcanic interbeds of ammonite-bearing marine sections of island-arc terranes. This work resulted in 18 new dates (Pálfy et al. 1997, 1999, 2000a, b). The calibration in JTS2000 is more robust than in its predecessors, especially for the Early and early Mid Jurassic. A new level of resolution was attempted by estimating the boundaries of several ammonoid chron or ammonoid subchrons, without resorting to interpolation methods. Another novelty of JTS2000 is the exclusive use of U–Pb and $^{40}Ar/^{39}Ar$ ages, whose reliability could be assessed, rather than K–Ar and Rb–Sr ages that were the mainstay of earlier scales. Interpolation based on magnetostratigraphic correlation to the Pacific ocean floor magnetic anomaly pattern, remained a necessity for the Late Jurassic, because of poor coverage of radioisotopic ages.

The GTS2004 added no new Jurassic date to its radioisotopic dataset but, like JTS2000, it adopted the same approach of accepting only U–Pb and $^{40}Ar/^{39}Ar$ ages with tight stratigraphic constraints. The main difference is that it uses only Early Jurassic ages and one from each of the Mid and Late Jurassic as primary controls on the time-scale, and regards all others as only secondary guides. The calibration methods are different in the Hettangian through Aalenian, Bajocian through Callovian, and the Late Jurassic intervals. Innovative approaches are applied to the Hettangian through Aalenian, where scaling is achieved partly through the maximum linear trend in the Sr isotope curve (discussed in detail in the later section on ‘Interpolation methods’) and partly using duration estimates obtained from cyclostratigraphic studies. The admittedly simplistic method of scaling to equal duration subzones is applied to the Bajocian through Callovian. The Late Jurassic is scaled using a calibration to the M-sequence (where M stands for Mesozoic) magnetic polarity time-scale (Ogg & Smith 2004).

3. JURASSIC CHRONOSTRATIGRAPHY AND CORRELATION

In the chronostratigraphic hierarchy, the Jurassic Period is subdivided into eleven stages (see the earlier comment in the ‘Introduction’). Stage boundaries are the most important targets of time-scale calibration and standardization through GSSPs is also focused at this level of hierarchy.

An up-to-date summary of the status of Jurassic chronostratigraphic units was provided by Morton (2006). A concise history of usage is also found in this work, whereas GTS2004 lists more details on the stages and provides further references.

Four Jurassic stages have ratified GSSPs, and two of the four are located in the UK (see Morton 2008). For the stages that so far lack ratified GSSPs, boundary age estimation for time-scales is not affected if consensus exists regarding the basal ammonite chron of the Stage. This is the case, except for the base of the Jurassic (Hettangian) and the top of the Jurassic (base of the Berriasian). The Triassic–Jurassic (Tr–J) boundary is the only one with candidate sections outside Europe, hence zonations of other bioprovinces may be considered, and primary markers other than ammonite first appearances (notably a radiolarian turnover event (Longridge et al. 2007) or a carbon isotope excursion (McRoberts et al. 2007)) have been proposed. Even more significant are the differences between the options put forward for the Jurassic–Cretaceous (J–K) boundary (see Cope 2008). The difficulties of correlating between Mediterranean and Boreal ammonite faunas have so far hindered reaching a consensus on boundary definition. Both JTS2000 and GTS2004 opted for
the oldest datum, the first occurrence of the ammonite *Berriasella jacobi* Mazenot.

As Jurassic chronostratigraphy is based on the northwest European standard ammonite biochronology, most GSSPs have been or will be defined within this region. As an epicontinental sea at the passive margin of Tethys, a lack of Jurassic volcanism characterizes the region’s geology. Because of this, to obtain radioisotopic ages for time-scale calibration, it remains necessary to turn to other areas and rely on stratigraphic correlation, as discussed in the following section.

### 4. MEASURING JURASSIC TIME

Two main chronometric methods are available for use in the Jurassic time-scale: radioisotopic dating can identify directly the age of certain minerals, whereas cyclostratigraphy can identify the duration of the time taken for the deposition of sediments under the influence of astronomically controlled environmental variations. Chronostratigraphically constrained radioisotopic dates form the backbone of the Jurassic time-scale, whereas floating cyclostratigraphic time-scales

---

**Fig. 1.** Comparison of Jurassic time-scales JTS2000 (Pálfy *et al.* 2000c) and GTS2004 (Ogg 2004), showing recently obtained biochronologically constrained radioisotopic ages and floating cyclochronologies. Open diamonds represent $^{40}$Ar/$^{39}$Ar ages; shaded diamonds, U–Pb ages; shaded ellipse, U–Pb age with undetermined error; rectangles, intervals with minimum duration derived from cyclostratigraphy. Abbreviations: e, early; m, middle; l, late; RHA, Rhaetian; HET, Hettangian; SIN, Sinemurian; PLB, Pliensbachian; TOA, Toarcian; AAL, Aalenian; BAJ, Bajocian; BTH, Bathonian; OXF, Oxfordian; KIM, Kimmeridgian; TTH, Tithonian; BER, Berriasian. Tie-points referenced to items listed in Table 1. Sources of cyclostratigraphies: A, Weedon *et al.* (1999); B, C, Hinnov & Park (1999); D, Hinnov in Ogg (2004); E, Weedon *et al.* (2004); F, Colombié & Strasser (2005). For details, see text.
offer exciting new possibilities for refinements, possibly at a high resolution measured in tens of thousands of years.

**Radioisotopic ages in the Jurassic**

**Recent advances in radioisotopic dating**

Significant recent advances in geochronology, which have implications for the published time-scales and will affect new calibrations, are reviewed here. As both JTS2000 and GTS2004 restrict their radioisotopic database to U–Pb and \(^{40}\)Ar\(^{39}\)Ar ages, our treatment is limited largely to these methods.

The majority of the newly obtained U–Pb dates for use in JTS2000 are based on analyses of multi-grain fractions of zircon. Effects of Pb loss and inherited older components are commonly evident from these analyses, rendering age interpretation difficult (Pálfy et al. 1999, 2000a, b). Using the similarly complex systematics of zircons from the Permian–Triassic boundary ash layers in South China as an example, Mundil et al. (2001) demonstrated that subtle heterogeneities in zircon crystals are commonly masked in multi-grain analyses. The net effect is that ages from multi-grain fractions tend to err on the young side if Pb loss has occurred (and some remains undetected) in the sample. With improved laboratory blanks and increased instrumental sensitivity, it is now possible to analyse routinely single zircon crystals, which is therefore preferable to multi-grain analyses. The multi-grain results should be viewed as minimum ages, prone to slight (c. +1–2 Ma) adjustment. A case in point is the age of an ash bed immediately below the Tr–J boundary from Kunga Island, British Columbia (Pálfy et al. 2000a). Complexities and Pb loss are indicated by discordance of several fractions; hence the age of 199.6 ± 0.4 Ma, originally interpreted from the apparently concordant fractions, may also be too young. This date is featured prominently as the defining control of the Tr–J boundary in both JTS2000 and GTS2004, hence a re-analysis using single crystals is much awaited.

Earlier attempts to mitigate the problem of Pb loss used air abrasion to remove physically the outer domains of crystals that suffered most of the Pb loss. A new method, the chemical abrasion pioneered by Mattinson (2005), subjects zircons to high temperature and subsequent annealing of radiation damage, then to pre-treatment by hydrofluoric acid prior to dissolution and mass spectrometry. The effectiveness of the chemical abrasion technique has been demonstrated increasingly, e.g. by a new study of the Permian–Triassic boundary (Mundil et al. 2004). Concordant suites of single crystals make possible the calculation of \(^{206}\)Pb/\(^{238}\)U ages with precision better than 0.1%.

Microprobe techniques offer spatial resolution within single crystals to detect heterogeneities, but this comes at the expense of precision which limits their use in Jurassic time-scale studies. Neither the SHRIMP (sensitive high-resolution ion microprobe) nor the LA–ICP–MS (laser ablation–inductively coupled plasma–mass spectrometry) methods can approach the precision of the ID–TIMS (isotope dilution–thermal ionization mass spectrometry) used in most time-scale studies but improvements are leading to smaller (1% and 3%, respectively) uncertainty levels (Black et al. 2004).

The less than 0.1% internal analytical precision of ID–TIMS U–Pb geochronology makes it imperative to assess the relative role of decay constant uncertainty and interlaboratory bias for realistic comparison and use of these dates. Schoene et al. (2006) concluded that a quantifiable bias exists in the accepted decay constant of \(^{235}\)U. Experiments are now underway to determine if interlaboratory bias also exists (Kamo et al. 2006) and to mitigate against it by use of common tracer solutions (Parrish et al. 2006).

The other method of choice for Jurassic time-scale studies, \(^{40}\)Ar\(^{39}\)Ar dating, has also advanced to a level of internal precision of the order of 0.1%. However, it has become increasingly evident that a systematic bias exists so that apparent \(^{40}\)Ar\(^{39}\)Ar ages are \(\pm 1\%\) younger than the U–Pb ages of the same samples (Min et al. 2000). This has important consequences for the Jurassic time-scale that have not been addressed yet. The source of this bias is the inaccurately known decay constant of \(^{40}\)K, an issue that is being resolved through new experiments for determination of this geologically important constant (Villa & Renne 2005). Before precise recalculation of \(^{40}\)Ar\(^{39}\)Ar ages becomes possible, it may be advisable to adjust all \(^{40}\)Ar\(^{39}\)Ar used in the time-scale by +1%.

A different, emerging method is the rhenium–osmium (Re–Os) dating of black shales. Direct dating of sedimentary rocks or authigenic sedimentary minerals is clearly tempting for time-scale work as these rocks commonly occur in fossiliferous successions. After the earlier attempts of K–Ar dating of glaucony were proved to be plagued with problems, Re–Os dating may offer fresh hope for finding time-scale calibration points in sedimentary sections otherwise not amenable to numerical dating. Cohen et al. (1999) obtained a suite of Re–Os ages from organic-rich mudrocks in British Jurassic successions, which permit ammonite biochronological constraints at the standard subchron level. Useful, although relatively imprecise whole-rock ages of 207 ± 12 Ma were reported from the Angulata Subchron (Late Hettangian) of Lyme Regis, Dorset, 181 ± 13 Ma from the Exaratum Subchron (Early Toarcian) of Port Mulgrave, Yorkshire and 155 ± 4.3 Ma from the Wheatleyensis Subchron (Early Tithonian, or Bolonian (formerly Late Kimmeridgian) in British usage) from Kimmeridge, Dorset. With their uncertainties, these dates are broadly consistent with both JTS2000 and GTS2004 (except for the Late Jurassic age that is marginally younger). Further advances in methodology may push the error limits beneath the threshold where they can truly contribute to time-scale refinements.
Recently published dates useful for the Jurassic time-scale

After the publication of JTS2000 and GTS2004, several new radioisotopic ages have been published that are useful for time-scale calibration. They are listed in Table 1, plotted in Figure 1 and comments are offered below in chronological order.

A large number of recently obtained ages are available from volcanics of the Central Atlantic Magmatic Province (CAMP); a critical compilation is found in Nomade et al. (2007). Fifty-eight $^{40}\text{Ar}/^{39}\text{Ar}$ ages of acceptable quality define a main peak at 199.1 Ma. If one considers a hotly debated scenario, which links CAMP volcanism to environmental and biotic change, extinction (e.g. Pálfy 2003; Lucas & Tanner 2007), then the age of paroxysmal volcanism can be regarded to manifest as carbon cycle perturbations and mass extinction (Pálfy 2003; Lucas & Tanner 2007), then the age of paroxysmal volcanism can be regarded to approximate the Tr–J boundary. Here are listed only the age of paroxysmal volcanism can be regarded to approximate the Tr–J boundary. Here are listed only those ages related directly to palynostratigraphy of the sediments immediately underlying the basalts, namely four $^{40}\text{Ar}/^{39}\text{Ar}$ ages from Morocco (Marzoli et al. 2004) and a U–Pb age from eastern Canada (Schoene et al. 2006). The latter is significant in improving the precision and accuracy of an earlier age determination on the same lava flow (Hodych & Dunning 1992).

For the Early Jurassic, two new calibration points have been obtained from the Early Sinemurian (Pálfy & Mundil 2006) and the Pliensbachian (Hall et al. 2004), although full analytical documentation of these ammonite-constrained U–Pb dates is still lacking. Four new Mid Jurassic U–Pb dates were published on ash beds in ammonite-bearing strata in western Canada (Hall et al. 2004) but also without full details.

The Late Jurassic remains the poorest epoch regarding the availability of calibration points. Potentially useful $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the Stonyford Volcanic Complex (California) are constrained loosely by radiolarian biostratigraphy (Shervais et al. 2005). However, the less than stage-level chronostratigraphic resolution and tectonic complexity of the area hinder their use in calibration. Important new constraints on the J–K boundary are provided by Mahoney et al. (2005) from the northwest Pacific Ocean at Shatsky Rise. Two $^{40}\text{Ar}/^{39}\text{Ar}$ ages with a mean of 144.6 ± 0.8 Ma were obtained from basaltic sills that intrude earliest Berriasian sediments dated by calcareous nanofossils and radiolarians.

Floating cyclostratigraphies and astrochronology in the Jurassic

A promising approach to measuring interval durations is the identification of orbitally forced and climatically mediated cycles in the sedimentary record. Orbital forcing has been recognized in several Jurassic sedimentary basins. Following the identification of the primary forcing parameter (i.e. distinction between precession, obliquity and eccentricity cycles), cycle patterns can be translated into duration of sedimentation. Its significance for the Jurassic time-scale was exploited systematically first in GTS2004. The astrochronical time-scale is already vital for the Neogene (Lourens et al. 2004) and is being developed for the Palaeogene. Concerns that chaotic behaviour of the planets would preclude precise determination of the Earth’s orbital parameters for the more distant geological past have fades. Laskar et al. (2004) suggested that at least the c. 405 ka duration of long eccentricity cycles remained stable enough (with >0.2% uncertainty) to allow their use in the astronomical time-scale back to 250 Ma.

Coe & Weedon (2006) estimated that currently about 70% of the Jurassic is covered by floating Milankovitch time-scales. The best constrained intervals are shown in Figure 1. Cyclic lacustrine strata of the Newark and adjacent basins (eastern North America) span the Tr–J boundary, although the vast majority are Late Triassic in age. They preserve nearly 30 Ma of orbitally forced sedimentary record and, on the basis of the long eccentricity cycles, were used to develop an astrochronology for the Late Triassic (Olsen & Kent 1999). The most recent estimate for the duration of the earliest Jurassic part, which includes CAMP basalt flows, is 610 ka (Whiteside et al. 2007).

Orbitally forced cyclicity has also been demonstrated in Jurassic epicontinental siliciclastic sequences from the UK (Weedon & Jenkyns 1999; Weedon et al. 1999, 2004) as well as Tethyan carbonates from the Alps (Weedon 1989; Hinnov & Park 1999; Hinnov et al. 2000). The duration of the Hettangian Stage and the earliest Sinemurian Bucklandi Chron was estimated from the obliquity cycles that dominate the Blue Lias Formation in southwest England. Due to known gaps in the succession, only a minimum estimate of 1.29 Ma for the duration of the Hettangian could be calculated.

The Early Pliensbachian Belemnite Marl preserves precession-dominated cyclicity within seven subchrons of two ammonite chronos, deposition of which required a minimum of 1.78 Ma (Weedon & Jenkyns 1999). Significantly, estimated chron durations were used to derive the slope of the Sr isotope curve, thereby leading to a combination method to scale the Early Jurassic chronostratigraphic units (see below). A longer section of the Domaro Limestone in the Italian Southern Alps yielded a similarly precession-forced cyclochronology of 4.98 Ma duration (Hinnov & Park 1999). It is thought to encompass the entire Late Pliensbachian but its Early Pliensbachian beginning remains loosely constrained. The Toarcian and Aalenian stages also have cyclochronologies from the Sogne Formation of the Southern Alps, suggesting a combined duration of 11.37 Ma (Hinnov & Park 1999). Of this, GTS2004 apportions 4 Ma to the Aalenian, based on unpublished cyclochronological results from central Italy.

At present, no cyclostratigraphy is known from the Bajocian and Bathonian, but Callovian–Oxfordian studies on sections in the UK (Oxford Clay) are in progress. A detailed cyclochronology is established for...
Table 1. Recently obtained radioisotopic ages not previously used in Jurassic time-scale calibration.

<table>
<thead>
<tr>
<th>Item</th>
<th>Name and description</th>
<th>Chronostratigraphic constraints</th>
<th>Method*</th>
<th>Age (Ma)b</th>
<th>Reference</th>
<th>Comment c</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fundy Basin (Nova Scotia), North Mountain basalt</td>
<td>earliest Hettangian</td>
<td>U–Pb (zr, sg, aa)</td>
<td>201.27±0.27</td>
<td>Schoene et al. (2006)</td>
<td>weighted mean $^{206}$Pb/$^{238}$U age from same locality as Hodych &amp; Dunning (1992) (item 8 in JTS2000)</td>
</tr>
<tr>
<td>2</td>
<td>Central High Atlas (Aït Ouir, Morocco), lower basalt</td>
<td>latest Rhaetian</td>
<td>$^{40}$Ar/$^{39}$Ar (pa, pl)</td>
<td>200.3±2.6</td>
<td>Marzoli et al. (2004)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Central High Atlas (Jebel Imizar, Morocco), lower basalt</td>
<td>latest Rhaetian</td>
<td>$^{40}$Ar/$^{39}$Ar (pa, pl)</td>
<td>199.3±0.6</td>
<td>Marzoli et al. (2004)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Central High Atlas (Tiourjdal, Morocco), lower basalt</td>
<td>latest Rhaetian</td>
<td>$^{40}$Ar/$^{39}$Ar (pa, pl)</td>
<td>198.7±1.0</td>
<td>Marzoli et al. (2004)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Argana Basin (Oujda, Morocco) lower basalt</td>
<td>latest Rhaetian</td>
<td>$^{40}$Ar/$^{39}$Ar (pa, pl)</td>
<td>198.0±0.8</td>
<td>Marzoli et al. (2004)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Pécs-Vasas (Hungary), tuff in Meceek Coal Fm.</td>
<td>Early Sinemurian</td>
<td>U–Pb (zr, sg, ca)</td>
<td>198.0±0.8</td>
<td>Pálfy &amp; Mundil (2006)</td>
<td>ND</td>
</tr>
<tr>
<td>7</td>
<td>Bighorn Creek east (Alberta), ash bed in Red Deer Mb. (Fernie Fm.)</td>
<td>(Early?) Pliensbachian</td>
<td>U–Pb (zr, mg, aa)</td>
<td>188.3±1.5/−1</td>
<td>Hall et al. (2004), Hall (2006)</td>
<td>ND, five marginally concordant fractions with spread in age</td>
</tr>
<tr>
<td>8</td>
<td>Bighorn Creek east (Alberta), bentonitic clay in Highwood Mb. (Fernie Fm.)</td>
<td>Early Bajocian</td>
<td>U–Pb (zr, mg, aa)</td>
<td>c. 173</td>
<td>Hall et al. (2004), Hall (2006)</td>
<td>ND, single concordant fraction of 172.7±0.4</td>
</tr>
<tr>
<td>9</td>
<td>ODP Site 801 (Pigafetta basin, W Pacific Ocean), basalt</td>
<td>Late Bajocian to mid-Bathonian</td>
<td>$^{40}$Ar/$^{39}$Ar (pa, pl)</td>
<td>167.4±1.4</td>
<td>Bartolini &amp; Larson (2001), Koppers et al. (2003)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Fording River (British Columbia), bentonitic clay in ‘Grey Beds’ (Fernie Fm.)</td>
<td>early Late Bathonian</td>
<td>U–Pb (zr, mg, aa)</td>
<td>167.0±0.2</td>
<td>Hall et al. (2004), Hall (2006)</td>
<td>ND, 6 m below fossiliferous level; weighted average $^{206}$Pb/$^{238}$U age of five fractions</td>
</tr>
<tr>
<td>11</td>
<td>Fording River (British Columbia), bentonitic clay in ‘Grey Beds’ (Fernie Fm.)</td>
<td>early Late Bathonian</td>
<td>U–Pb (zr, mg, aa)</td>
<td>165.6±0.3</td>
<td>Hall et al. (2004), Hall (2006)</td>
<td>min., ND, 2 m above fossiliferous level</td>
</tr>
<tr>
<td>12</td>
<td>Bighorn Creek east (Alberta), bentonitic clay in ‘Grey Beds’ (Fernie Fm.)</td>
<td>early Late Bathonian</td>
<td>U–Pb (zr, mg, aa)</td>
<td>165.4±0.3</td>
<td>Hall et al. (2004), Hall (2006)</td>
<td>ND, directly above fossiliferous level, weighted average $^{206}$Pb/$^{238}$U age of four fractions</td>
</tr>
<tr>
<td>13</td>
<td>ODP 198, Hole 1213B, Shatsky Rise, lower basalt sill</td>
<td>earliest Berriasian</td>
<td>$^{40}$Ar/$^{39}$Ar (pa, pl)</td>
<td>143.7±3.0</td>
<td>Mahoney et al. (2005)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>ODP 198, Hole 1213B, Shatsky Rise, middle basalt sill</td>
<td>earliest Berriasian</td>
<td>$^{40}$Ar/$^{39}$Ar (pa, wr)</td>
<td>144.8±1.2</td>
<td>Mahoney et al. (2005)</td>
<td>min.</td>
</tr>
</tbody>
</table>

*Abbreviations: zr, zircon; sg, single grain; mg, multi-grain; aa, air abrasion; ca, chemical abrasion; pa, plateau age; pl, plagioclase; wr, whole rock.

bErrors are quoted at 2σ level.

cmin., minimum age; max., maximum age; ND, no analytical details published.
the Kimmeridge Clay that spans the Kimmeridgian and Bolonian of British stratigraphic usage (Weedon et al. 2004). In total, a minimum of 7.52 Ma is represented by obliquity-dominated cycles. Of this, the Kimmeridgian Stage, as defined by the Submediterranean ammonite biochronology, represents 3.3 Ma. Comparable results were obtained from the Swiss Jura Mts by Colombié & Strasser (2005) who determined 3.2 (or 3.6) Ma for the length of the Kimmeridgian.

5. INTERPOLATION METHODS IN CONSTRUCTING THE JURASSIC TIME-SCALE

Because of the lack of sufficiently closely spaced, chronostratigraphically constrained radioisotopic dates, interpolation remains necessary to derive boundary ages of stages and smaller units (substages and chrons). JTS2000 used magnetostratigraphy and oceanic anomaly patterns for the Late Jurassic but otherwise refrained from interpolation. On the other hand, GTS2004, aiming at consistently estimating all chron boundaries, used a combination of magnetostratigraphy for the Late Jurassic, assumed equal subchrons for most of the Mid Jurassic, and assumed a linear Sr isotope trend for most of the Early Jurassic. This section analyses the justification for these approaches.

The assumption of equal duration of chronostratigraphic units has a long history. Refined from stage level (Harland et al. 1964) through chrons (Van Hinte 1976) down to subchrons (Westermann 1984), this simple notion implies that a constant rate of biological evolution is reflected in biochronological scales such that units of equal rank have approximately equal duration. In fact, this method was dictated by necessity and the lack of better alternatives rather than by belief in the underlying principle. As shown above, all detailed cyclostratigraphic studies have demonstrated that this assumption is untenable. In the Kimmeridge Clay, minimum length of ammonite chrons varies by a factor of 50, from 30 ka to 1.49 Ma (Weedon et al. 2004).

The other two methods, magnetostratigraphy and Sr isotope stratigraphy, can more reasonably play a double role as correlation and interpolation tool.

Magnetostratigraphy

The changing polarities of the Earth’s magnetic field preserved in the rock record permit the development of a magnetic polarity time-scale. For the Jurassic, this has been derived from land-based sections where polarity chrons can be correlated with ammonite biochronology. A compilation and detailed discussion is given by Ogg (2004) and Ogg & Smith (2004) in GTS2004. Apart from its use in correlation, the magnetic polarity time-scale may be useful for interpolation from the Bathonian onward, because the oldest preserved marine magnetic anomalies are c. 170 Ma in age (Tivey et al. 2006). Determining the variable but, within limited intervals, near-constant spreading rates, the pattern of magnetic lineations on the ocean floor can be transformed into an age model. The M-sequence of marine magnetic anomalies is preserved in all ocean basins back to M25; this magnetochron is correlated with the base of the Kimmeridgian as defined in the Submediterranean province (Ogg 2004). Older oceanic crust is known from the Pacific, where the M-sequence is extended back to the Bathonian. For GTS2004, Ogg & Smith (2004) developed a synthetic age model using different sources for the western Pacific Hawaiian lineations (Larson & Hilde 1975; Channell et al. 1995; Sager et al. 1998). So far, this is the most robust geomagnetic polarity age model, the details of which are not reproduced here. Nevertheless, some ambiguity remains in accurately anchoring the M-sequence, due to the scarcity of high quality Late Jurassic and earliest Cretaceous radioisotopic dates.

Strontium isotope stratigraphy

Global variations in the Sr isotopic composition of sea water through time are of stratigraphic value. For the Jurassic, the use of this relatively new method received a boost from the establishment of a $^{87}$Sr/$^{86}$Sr reference curve (Jones et al. 1994a, b), largely derived from analyses of belemnites collected in sections with high-resolution ammonite biochronology, many from Britain. An updated version of the curve, based on more data points, was given by Jenkyns et al. (2002). The calibration of the marine Sr isotope curve against the numerical time-scale has now been achieved for almost the entire Phanerozoic (McArthur et al. 2001). In addition to correlation, a novel application for refining the time-scale was developed by Weedon & Jenkyns (1999). They noted that much of the Early Jurassic (Hettangian through Pliensbachian) is characterized by an apparently linear trend on the Sr isotope curve. Determining the slope is possible through integration with cyclostratigraphic data from the Belemnite Marl. Whilst it should be noted that there is no theoretical justification for a strict linearity of the Sr isotope curve, taking the calculated rate of change in the Sr isotope ratio as constant, the following stage durations were suggested: Hettangian – 2.86 Ma, Sinemurian – 7.62 Ma, Pliensbachian – 6.67 Ma.

Shorter linear segments in the Sr curve were also identified in the Early Toarcian and used to calibrate the duration of ammonite chrons and subchrons by McArthur et al. (2000), who documented as much as a thirty-fold variation in subchron durations, which ranged from 0.036 to 1.08 Ma. GTS2004 adopted the Sr isotope scaling for the Hettangian through Early Toarcian, updating the calibrated values after McArthur et al. (2001), which led to only slightly different stage durations. Perusal of the updated curve of Jenkyns et al. (2002) reveals that the plotted Hettangian $^{87}$Sr/$^{86}$Sr ratios form a cluster rather than falling in line with the decreasing trend characteristic
of the Sinemurian and Pliensbachian. Therefore, scaling with linear Sr trend may not be warranted for the Hettangian.

6. ADJUSTMENTS TO JTS2000 AND GTS2004

It is not the aim of this review to present a new, fully recalibrated Jurassic time-scale. It may be appropriate, however, to summarize the expected effect of new developments and better understanding of some calibration components as outlined above (Fig. 1). Of particular importance is the recognition that $^{40}\text{Ar}/^{39}\text{Ar}$ ages will be subject to $c.+1\%$ adjustment once a new decay constant is accepted, and judicious assessment of multi-grain U–Pb zircon ages with hints of Pb loss may also lead to 1–2 Ma upward (i.e. towards older) correction, which can be proven only by re-analyses of single crystals.

The U–Pb age that controls the Tr–J boundary (Pálfy et al. 2000a) in both JTS2000 and GTS2004 is suspected to be too young. Items 1–5 (Table 1) also suggest an upward revision to c. 201–202 Ma. A similar upward shift of the Hettangian–Sinemurian boundary to c. 198–199 Ma is suggested by new dating (item 6 in Table 1). Lesser adjustments are warranted for the Sinemurian–Pliensbachian and Pliensbachian–Toarcian boundaries; the latter is controlled by one single crystal and a suite of multi-grain U–Pb dates. The longer Toarcian and Aalenian in GTS2004 compared to JTS2000 is based on cyclostratigraphy that may need revision to reconcile it with U–Pb dating results (e.g. item 8). Allocation of Mid Jurassic time in GTS2004 is suspect as it is based on equal duration subzone scaling. On the other hand, accuracy of JTS2000 is compromised by a multi-grain U–Pb age controlling the Bathonian–Callovian boundary, with exceedingly small analytical error but probably affected by undetected Pb loss. Upward adjustment of the base of the Bathonian and Callovian in JTS2000 is also suggested by new tie points (items 9–12).

To anchor the M-sequence magnetic polarity time-scale reliably remains a challenge. The Oxfordian is unrealistically short in JTS2000, whereas the Kimmeridgian duration finds support from two independent cyclostratigraphic estimates. New constraints for the J–K boundary (items 13–14) suggest that the value in GTS2004 may need only $c. 1\%$ upward adjustment, in line with the fact that most of the sparse Late Jurassic tie-points are $^{40}\text{Ar}/^{39}\text{Ar}$ ages.

7. FUTURE OF JURASSIC TIME-SCALE RESEARCH

An inherent frustration in time-scale work is that each new edition and update is bound to be superseded and made obsolete by new research sooner rather than later. Obviously every facet of time-scale construction discussed above holds opportunities for refinements. However, it is predicted that the most significant developments in the near future will happen in the areas of radioisotopic and astrochronological dating.

In geochronology, it will be seen how U–Pb dating of chemically abraded single zircon grains from volcanic ash beds continues to contribute high-precision ages, many more of which will put the Mid and Late Jurassic time-scale onto a much firmer footing and also increase accuracy in the Early Jurassic. Interlaboratory calibrations will dissolve any lingering doubt that increasing analytical precision has not been matched by reproducibility. The pending determination of new $^{40}\text{K}$ decay constants will remove the significant uncertainty that now has to be considered when comparing internally highly precise $^{40}\text{Ar}/^{39}\text{Ar}$ and U–Pb ages.

In an optimistic scenario, the coverage of floating cyclostratigraphies will be complete for the entire Jurassic within a few years (Hinnov & Ogg 2007). Accepting the stability of the long eccentricity cycle back to the beginning of Mesozoic time (Laskar et al. 2004), a 0.4 Ma resolution will be possible for the astrochronological scale, provided that the floating segments are firmly anchored with adequate chronostatigraphic correlation.

In addition to its content, the format and modes of use of time-scale also appear to be changing in the computer age. Authoritative paper-bound publications, such as the GTS2004, are still planned to be issued periodically, but probably not indefinitely as time-scales are increasingly published on the internet (Van Couvering & Ogg 2007). Already, several portals, e.g. the International Commission on Stratigraphy (www.stratigraphy.org), Chronos (www.chronos.org) and the Paleobiology Database (www.paleodb.org) offer time-scale modules, tailor-made to suit different user needs. The TimeScale Creator (www.tscreator.com) is a versatile digital reincarnation of GTS2004 where specific user-defined subsets of information can be retrieved and visualized from the large multidisciplinary dataset assembled for the production of the latest comprehensive time-scale project (Ogg & Gradstein 2006). We are likely to see further developments in this vein, such as interactivity in selecting the database elements used for the time-scale calibration (e.g. selective inclusion or exclusion of radioisotopic ages).

Delivering on these promises should lead to unprecedented levels of accuracy, precision and user-friendliness of the time-scale which, in turn, will help resolve a multitude of questions regarding the Jurassic history of the Earth.

ACKNOWLEDGEMENTS

Beris Cox is thanked for inviting this contribution and for patience and encouragement. Helpful comments by her, as well as by P. L. Smith and M. G. Sumbler, improved the manuscript. The research was supported by the Hungarian Scientific Research Fund (T42802 and T72633). This is MTA-MTM Paleo Contribution No. 61 and also a contribution to IGCP Project 506.
REFERENCES


Manuscript received 2 August 2007; revised typescript accepted 25 September 2007