Gauging the Duration of Stages: A New Approach for the Jurassic

by Gerd Westermann

A major concern in stratigraphy is the calculation of numerical time scales. This article reviews some recent approaches for the Jurassic and presents a new "scaled equal-subzone method." Here the lowest consistent chronostratigraphic category, the ammonite standard subzone, is the basis of relative length estimates for ammonite standard zones. Relative stage length is assumed to be proportional to the number of their zonal units. Compounding of independent sets of zones and subzones from the different faunal provinces minimizes taxonomic bias. An improved numerical time scale is constructed by calibration on the recent North American scale.

Chronostratigraphy and Recent Time Scales

The Jurassic stages (Fig. 1 and Table 1) were introduced 100 to 150 years ago in northwestern Europe, mainly by the pre-Darwinian catastrophist Alcide d'Orbigny who believed that

Table 1: Chronostratigraphic and geochronologic terms with examples from the Jurassic.

	Chronostratigraphic	Geochronological
Jurassic	System	Period
Middle Jurassic	Series	Epoch
Bajocian	Stage	Age
<i>Stephanoceras humphriesianum</i>	Chronozone	Chron
<i>Dorsetensia romani</i>	Subzone	Subchron
(<i>Alfeldites bicostatus</i>)	(Horizon)	

they represented cycles of mass creation followed by mass extinction caused by biblical flooding. No attention was paid to the equivalence of stages in terms of sedimentary thickness or duration. Unequal numbers of biozones were soon assigned to the stages, beginning 130 years ago with Albert Oppel, who distinguished consistently superposed assemblages of ammonites.

A century's work has now gone into expanding this single set of stages across the globe, except for the Jurassic two or uppermost where three sets are needed. The stages are now firmly established and invariable, defined by the bases of contiguous ammonite standard zones (chronozones). However, ammonite zones can usually not be extended geographically beyond the limits of faunal provinces, and additional sets of standard zones have had to be devised.

The zonal schemes have thus been revised as new data became available, while the stage scheme has remained essentially unaltered. A good case in point is the Aalenian stage. Introduced by Mayer-Eymar a century ago for the Lower (Early) Bajocian of earlier authors, its relative brevity and, hence, restricted usefulness have caused many debates in Europe and its acceptance in the Americas is still incomplete (Westermann, 1979). Similar problems exist for the brief Purbeckian, while the Kimmeridgian has different meanings in the different realms. The hypothesis of equal zones thus has more validity than that of equal stages.

The smallest, consistent chronostratigraphic formal unit is the standard subzone. This is also the only formal chronostratigraphic unit that can be added or deleted without destabilizing the set of standard zones that best reflects the current state of knowledge. Subzones of a few stages have also been subdivided informally into horizons (bio-horizons). In contrast to standard zones and subzones, which denote intervals, however, horizons are non-contiguous "events."

The three most recently published Jurassic time scales, by Odin (1982), Harland et al. (1982), and Kent and Gradstein (in Palmer,

Figure 1: Recent numerical time scales for the Jurassic, based mainly on radio-chronology, chronostratigraphy, and the stage durations estimated according to the scaled equal-subzone method.

Figure 2: Different methods used for scaling zones and sub-zones for estimates of relative stage duration. See text for explanation.

1983), differ by 9 Ma in the numerical dates for the lower boundary of the period and 14 Ma for the upper boundary (Fig. 1). Even greater differences exist for the durations of the stages or zones (see Fig. 2A). Since pre-Oxfordian dates for the Jurassic are totally inadequate, metering the intra-Jurassic chronostratigraphic scale has been based on approaches involving magnetostratigraphy and assumptions of equal duration of stages or zones (see Fig. 2A). Thus Odin follows Van Hinte (1976) in basing his estimates of the relative durations of series and stages on glauconite radiometric ages, assuming that all standard zones defining the stages are of equal duration.

On the other hand, Harland and his colleagues revert more or less to the old equal-stage assumption, which as shown earlier is clearly an inferior approach. Ironically the Aalenian is among the three stages given a 7 versus a 6 Ma duration. Kent and Gradstein combined magnetostratigraphic and whole-rock radiometric tie-points for the Triassic/Jurassic (208 Ma) and Oxfordian/Kimmeridgian (156 Ma) boundaries with the equal-zone method of Van Hinte (see Fig. 1), using Hallam's (1975) table of northwest European standard zones.

The Scaled Equal-Subzone Method

The relative durations of regional to cosmopolitan ammonite standard zones can be estimated by the number of formal or standard subzones they comprise, just as relative lengths of stages have been judged from the number of standard zones that they contain. A combination of both should therefore provide improved estimates.

Although zones and subzones have different hierarchical ranks in stratigraphy, some workers assume that subzones are equal in time to undivided ("simple") zones (Fig. 2B) and use them as the basis for scaling zonal duration (e.g. Callomon and Birkelund, 1983; Tozer, pers. commun.). In this "simple equal-subzone" method, a zone with two subzones is given equal duration to two independent, undivided zones. An alternative method (Fig. 2C) involves the arbitrary choice for the duration of a subzone as equal to 75% of that of an undivided zone or zonal unit (ZU). Since standard zones vary from undivided to those including four subzones, ZU ranges from 1 to 3. It appears more reasonable to assume, for example, that zone 1 (2 subzones) = 1.5 x zone 2 (undivided) than that zone 1 = 2 x zone 2. The value of 1.5 is

conveniently intermediate between zone 1 in its as yet undivided state and its split state with two full zones, a possible future fate.

The estimates of the relative durations of stages are based on the number of zonal units included. These, in turn, are derived by averaging sets of zonal units, which were compounded from the different ammonite provinces and realms in order to avoid taxonomic bias differences in longevity, and rates of evolution. This multi-provincial approach is obviously limited by the availability of well-established zonations and reliable time-correlations between stage boundaries. Furthermore, strict numerical treatment of zonal units from different areas, based on zonations established by different authors over different periods of time, is not possible because the units probably vary in reliability and consistency. Some subjective weighting has, therefore, been applied.

The taxonomic bias is further reduced by the curious fact that zonal sequences are rarely based on successions of species. Approximately 90% of the ammonite standard zones of the Jurassic are named after different genera, despite their average range through two to three zones. Related species and probably single clades, however, frequently give the names to subzones, particularly in the Boreal provinces. Thus, post-Bajocian subzonal index species of a Boreal province typically belong to only 26 genera, while those of a Tethyan province with a similar number of subzones belong to 49 genera. This probably reflects greater average duration of Boreal versus Tethyan clades. While Boreal faunas were much less diverse, the longevity of their species appears to have been similar to that in Tethys.

Zonal units		% Jurassic		Ma	
Boreal	Tethyan	Jurassic=64Ma			
Volgian 16 ~7.5 ~5.5	Submed. Medit. Tithonian 10 9	6.3	13.5	4	8.5
Portlandian s.l. 8.5 UKimm.s.angl. 10		7.2	T&V	4.5	T&V
Boreal 7.5 Kimmeridg.s.s. 7.75	Subboreal 7.5	6.5	29	4	19
Oxfordian 12 10.5 11.25	U 4.5 M 3 L 3.75	4 2.7 3.3	10	2.6 1.7 2.1	6.5
Callovian 10 10	U 3.5 M 3 L 3.5	3.2 2.6 3.2	9	2 1.7 2	5.5
Bathonian >6 8.5 8.5	U 6 M 6 L 2.5	5.5 2.1	7.6	3.5 1.5	5
Bajocian 13.5	U 6.5 L 7	5.8 6.2	12	3.7 4	7.5
Aalenian 7		6		4	
Toarcian 13.5	U 6 L 7.5	5.5 6.5	12	3.5 4	7.5
Pliensbachian 12	U 4 L 8	3.5 7	10.5	2.2 4.5	6.5
Sinemurian 13	U 7 L 6	6.5 5.5	12	4.2 3.5	7.5
Hettangian 5		4.5		3	

Figure 3: Weighted average durations (Ma) of stages and sub-stages as percentage of the Jurassic, assuming a 65 Ma Jurassic. In the left column, zonal units of substages are in small numbers. Also shown here are the zonal units for the entire stages in the different faunal provinces, the large numbers indicating the weighted mean values for each stage. In the center and right columns, the small numbers belong to the substages, while the large numbers are the rounded (nearest 0.5 Ma) values for the stages and epochs.

Figure 4: The different correlations of uppermost Jurassic boundaries according to Casey (1973), Wimbledon (1980), Jeletzky (in press) and Zeiss (1983). Vertical scale in zonal units.

Relative Durations of Jurassic Stages

The relative durations of stages and substages (Fig. 3) are transformed to numerical intervals by application of the 64 Ma estimate for the entire Jurassic most recently calculated by Kent and Gradstein (in Palmer, 1983).

Three problems exist in estimating the uppermost (latest) Jurassic stages (Fig. 4). First, coeval (correlative) stages of the different faunal realms and major provinces differ in their zonal unit values, particularly the Tethyan Tithonian from the two Boreal sequences. Second, the zonations can not often be correlated and, third, the upper boundaries do not coincide, with specialists disagreeing by more than a substage (e.g. Casey, 1973; Wimbledon, 1980; Zeiss, 1983; Jeletzky, in press, with comments by Zeiss). Since most authors support one of the higher correlations, the overall average for the post-Kimmeridgian (s.s.) Jurassic (Tithonian, Volgian) is about 15 zonal units (8.6 Ma, see Fig. 3). The apportioning by interpolation of these modified zonal units and durations of the northwest European Boreal stages would accordingly be: Upper Kimmeridgian (sensu anglico) 8 zonal units (4.6 Ma), Portlandian s.l. 7 zonal units (4 Ma).

Calibration on Absolute Time Scale

Figure 1 shows that the relative series durations proposed here are similar to those proposed by Kent and Gradstein (in Palmer, 1983), and somewhat distinct from the time scales of Van Hinte (1976), Odin (1982), and Harland and others (1982). The time scales in the older papers differ consistently from the present estimates in their relatively longer Middle Jurassic and, in most cases, their shorter Lower and Upper Jurassic. The relative stage durations calculated here also resemble those proposed by Kent and Gradstein (17% mean stage deviation) much more closely than those of the others, with the equal-stage estimates of Harland deviating 25% and those of Odin 27%. In particular, the new estimates presented here are longer (relatively) for the Sinemurian to Toarcian and for the Tithonian/Volgian, and shorter for the Hettangian, Aalenian and Bathonian.

If one excludes the latest radiometric estimate of 64 Ma for the duration of the Jurassic, then the absolute durations of stages range from approximately 3 Ma (Hettangian) to 8.5 Ma

(Tithonian and Volgian) as indicated in Figures 1 and 3. The mean stage duration is 6 Ma, and the rounded estimates for the substages range from 1.5 Ma for the Lower Bathonian to 4.5 Ma for the Lower Pliensbachian (Fig. 2). Accordingly, the Early Jurassic lasted approximately 24 Ma, the Middle Jurassic 22 Ma and the Late Jurassic 19 Ma. Standard zones (1 to 3 zonal units) ranged from 0.6 to 1.8 Ma (mean ca. 1.0 Ma), with post-Kimmeridgian s.s. zonal units of the Boreal Realm markedly shorter than Tethyan zonal units. An average subzone lasted approximately 0.45 Ma. The stage duration estimates have all been rounded to the nearest 500 000 years (0.5 Ma), which is about the assumed resolution of this method.

Outlook

The usefulness of proper scaling particularly for the Jurassic, which lacks isotopic data, is obvious, when one considers the importance of this period for evolutionary and plate-tectonic theories. Rates of origination, longevity and extinction at the species and genus levels should be based on scaled stage and substage scales, in contrast with the approaches used in the current literature, and biostratigraphic range charts and subsequent biozonations will also be greatly improved in this way. In magnetostratigraphy, J.G. Ogg and his associates (personal communication) are currently testing different Jurassic time scales against Atlantic and Pacific ocean-floor spreading rates based on magnetic reversals. The stage scaling presented here fits their results based on the hypothesis on equal spreading rates more closely than previous scales.

Although other periods appear to have better isotopic age data than the Jurassic, a similar scaling of stages based on their subzones would permit testing of geophysical data against biostratigraphic data and would probably result in refined and improved time scales.

Prof. Gerd Westermann is based at the Geology Department of McMaster University (Hamilton, Ontario, Canada L8S 4M1). His research activities involve Jurassic ammonite biostratigraphy, chronostratigraphy and biogeography on many continents. He is the leader of IGCP Project 171 on the Circum-Pacific Jurassic.

References

- Callomon, J.H., and Birkehead, T., 1983. The ammonite zones of the Boreal Volgian (Upper Jurassic) in East Greenland. *Canadian Society of Petroleum Geologists Memoir* 8, p. 349-369.
- Casey, R., 1973. The ammonite succession at the Jurassic-Cretaceous boundary in eastern England. In: Casey, R. and Rawson, P.F., (eds.), *The Boreal Lower Cretaceous*. Geological Society, Special Issue 5, p. 193-266.
- Hallam, A., 1975. *Jurassic environments*. Cambridge Earth Science Series, Cambridge University Press, 269p.
- Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G. and Walters, R., 1982. *A geologic time scale*. Cambridge University Press, 131p.
- Jeletzky, J.A., in press. Jurassic-Cretaceous boundary beds of western and Arctic Canada and the problem of the Tithonian-Berriasian Stages in the Boreal realm. In: Westermann, G.E.G., (ed.), *Jurassic-Cretaceous Biochronology and Biogeography of North America*. Geological Association of Canada Special Paper.
- Odin, G.S., 1982. The Phanerozoic time scale revisited. *Episodes*, 1982, no. 3, p. 3-9.
- Palmer, A.R. (compiler), 1983. *The decade of North American geology 1983 geologic time scale*. *Geology*, v. 11, no. 9, p. 503-504.
- Van Hinte, J.E., 1976. A Jurassic time scale. *American Association of Petroleum Geologists Bulletin*, v. 60, no. 4, p. 489-497.
- Westermann, G.E.G., 1979. Troublesome definition of the Lower/Middle Jurassic boundary. *Canadian Journal of Earth Sciences*, v. 16, no. 10, p. 2060-62.
- Wimbledon, W.A., 1980. Portlandian correlation chart. In: Cope, J.C.W., Getty, T.A., Howard, M.K., Morton, N. and Torrens, H.S., *A Correlation of the Jurassic Rocks in the British Isles, Part 2: Middle and Upper Jurassic*. Geological Society of London, Special Report No. 14, p. 85-92.
- Zeiss, A., 1983. Zur Frage der Äquivalenz der Stufen Tithon/Berrias/Volga/Portland in Eurasien und Amerika: ein Beitrag zur Klärung der Weltweiten Korrelation der Jura/Kreide-Grenz-Schichten im Marinen Bereich. *Zitteliana*, v. 10, p. 427-438.

The many strata of Springer earth sciences

A. D. Miall

Principles of Sedimentary Basin Analysis

1984. 387 figures. Approx. 550 pages
Cloth DM 120,-; approx. US \$ 47.10. ISBN 3-540-90941-9

Contents: Introduction. – Collecting the data. – Stratigraphic correlation. – Facies analysis. – Basin mapping methods. – Depositional systems. – Burial history. – Regional and global stratigraphic cycles. – Sedimentation and plate tectonics. – Conclusions.

B. P. Tissot, D. H. Welte

Petroleum Formation and Occurrence

2nd revised and enlarged edition 1984.
327 figures. Approx. 560 pages
Cloth DM 128,-; approx. US \$ 50.20. ISBN 3-540-13281-3
"Few technical books have had the initial impact on their respective disciplines that this hallmark work has had... Current and authoritative with many advanced concepts... that will keep it in the forefront of reference material for years to come... an excellent reference... recommended without reservation."
AAPG Bulletin

W. E. Galloway, D. K. Hobday

Terrigenous Clastic Depositional Systems

Applications to Petroleum, Coal, and Uranium Exploration

1983. 237 figures. XV, 423 pages
Cloth DM 98,-; approx. US \$ 38.50. ISBN 3-540-90827-7

R. V. Fisher, H.-U. Schmincke

Pyroclastic Rocks

1984. 339 figures. XIV, 472 pages
Cloth DM 138,-; approx. US \$ 54.10. ISBN 3-540-12756-9

This is the first modern comprehensive treatment of what pyroclastic rocks are and how they were formed. The subject is discussed against a background of plate tectonics theory and modern advances in volcanology, sedimentology and igneous petrology.

Living Fossils

Editors: N. Eldredge, S. M. Stanley

1984. 72 figures. Approx. 304 pages
(Casebooks in Earth Sciences)
Cloth DM 138,-; approx. US \$ 54.10.
ISBN 3-540-90957-5

Development and Applications of Geomorphology

Editors: E. Costa, P. J. Fleischer

1984. 120 figures. Approx. 375 pages
Cloth DM 118,-; approx. US \$ 46.30.
ISBN 3-540-13457-3

G. Buntebarth

Geothermics

An Introduction

Translated from the German by
I. M. Chapman, D. S. Chapman
Universitext

1984. 66 figures. X, 143 pages
DM 60,-; approx. US \$ 23.60. ISBN 3-540-12751-8

Contents: Introduction. – Physical Basis of Heat Transfer. – Thermal Properties of Common Rocks. – Analytical Treatment of Conductive Cooling in the Crust. – Thermal State of the Earth's Interior. – Methods for Determining Temperature. – Geothermal Heat as an Energy Source. – Appendix. – References. – Subject Index.

This successful German textbook is now available in an updated translation to English-speaking readers.

M. A. Zharkov

Paleozoic Salt Bearing Formations of the World

Translated from the Russian by
R. E. Sorkina, R. V. Fursenko, T. I. Vasilieva
1984. 166 figures. Approx. 440 pages
Cloth DM 160,-; approx. US \$ 59.70. ISBN 3-540-13133-7

O. P. Mchedlov-Petrosyan, V. I. Babushkin,
G. M. Matveyev

Thermodynamics of Silicates

1984. 93 figures, 135 tables. Approx. 475 pages
Cloth DM 250,-; approx. US \$ 98.00. ISBN 3-540-12750-X

Contents: The Basic Concepts and Laws of Thermodynamics. – Pyrosilicate Reactions. – Hydration Reactions. – Corrosion Reactions. – References. – Appendix 1: Standard Enthalpies, Gibbs Free Energies and Heat Capacity Equations of Some Elements, Simple Substances and Compounds. – Appendix 2: Thermodynamic Properties of Ions and Molecules in Aqueous Solutions. – Appendix 3: Heats of Polymorphic Transitions and Melting. – Subject Index.

E. A. Romankevich

Geochemistry of Organic Matter in the Ocean

1984. 68 figures, 71 tables. Approx. 340 pages
Cloth DM 148,-; approx. US \$ 58.10. ISBN 3-540-12754-2

Always abreast of the latest developments in the field with

Springer-Journals on Earth Science

For more information on these books and journals, or to order a free sample copy of a journal, please write to:

Springer-Verlag Berlin Heidelberg New York Tokyo

Tiergartenstr. 17, D-6900 Heidelberg 1 or 175 Fifth Ave., New York, NY 10010, USA or 37-3, Hongo 3-chome, Bunkyo-ku, Tokyo 113, Japan