by *F M Gradstein and J Ogg*

A Phanerozoic time scale

(The full-colour chart may be found as a detachable insert after page 26)

A geological time scale chart is presented for the Phanerozoic, that integrates currently available geochronological information.

Since the publication of time scales in the eighties/early nineties (Haq et al., 1988; Cowie and Bassett, 1989; Odin and Odin, 1990; Harland et al., 1990) a considerable number of new dates and more detailed magneto- and biostratigraphical data have become available, leading to a more precise and more accurate Phanerozoic geochronology.

The Cenozoic time scale is primarily calibrated from biostratigraphical correlations with magnetic polarity chrons, which in turn are scaled according to marine magnetic anomaly profiles from the South Atlantic seafloor, pinned to a selected set of nine Ar/Ar radiometric ages (Berggren et al., 1995). Interpolation, using constancy of seafloor spreading between radiometrically constrained profile segments, assigns ages to magnetic polarity chrons which, in turn calibrates zonal events and stage boundaries. The combination of magnetostratigraphy and astrostratigraphy presently refines the Neogene time scale in a continuous and linear manner for the last 6 million years (Hilgen et al., 1991).

In contrast, the Mesozoic time scale lacks a unifying interpolation concept, because marine magnetic anomaly profiles extend back only to the Callovian stage, and much of the middle Cretaceous Period lacks a magnetic anomaly signature. In addition, the radiometric data set has inadequate precision to constrain the age assignments of most stage boundaries. Therefore, whereas portions of the Mesozoic time scale can now be exactly determined by a combination of precise radiometric ages, many being published in the last five years on biostratigraphically constrained sections, the majority of the stage boundaries have been dated through geological and mathematical interpolation methods. Although hand-fitted, graphical methods of interpolation are popular in earth sciences, mathematical interpolation makes it possible to estimate confidence limits on the ages of stage boundaries (Agterberg, 1994). Hence, the Mesozoic time scale (Gradstein et al., 1995) was one of the first geochronologies to incorporate error bars on all (31) stage boundaries.

Since the appearance of the chronostratigraphical and geochronological compilation for the Paleozoic in Harland et al. (1990), several studies have been published that use relatively precise isotope datings to improve Paleozoic chronology below the Carboniferous (Tucker and McKerrow, 1995; Roberts et al., 1995). Nevertheless, there remains a general paucity of relatively precise and stratigraphically meaningful age dates in the Paleozoic. This, together with problems in inter-regional stage assignments, and the absence of standard zonations for extended parts of the Paleozoic (R Cocks, personal communication, 1996) makes the Paleozoic time scale more uncertain.

We have incorporated the new Cenozoic, Mesozoic and Paleozoic age assignments in the geological time scale chart presented here, with reference to its sources. The Cenozoic scale is after Berggren et al. (1995), and Hilgen (1991), and the Mesozoic one after Gradstein et al. (1995). The Paleozoic time scale is constructed from Harland et al. (1990), with the pre-Carboniferous updated by more precise isotopic ages for stage boundaries by Roberts et al. (1995) and Tucker and McKerrow (1995). A recent magnetostratigraphy for the Phanerozoic has been published by Ogg (1995).

The consistent Cenozoic–Mesozoic time scale forms the basis for an extensive suite of chronostratigraphical and sequence-stratigraphy compilations for Europe (Hardenbol et al., in preparation). The latter author is to be credited with stimulating time-scale research in the last decade in order to correlate interregional sequence stratigraphical models.

The time scale that underpins the Exxonian tectono-eustatic sequence stratigraphy model was published (without much documentation) in 1988 by Haq et al. Despite its synthetic quality, the time scale for this model suffers because it combines age dates from both tuffs or intrusives and from glauconites. As demonstrated by Gradstein et al. (1988; 1995) and Harland et al. (1990), K/Ar isotope age dates on glauconites may be significantly younger than dates on tuff and intrusives of comparable chronostratigraphical assignment. Haq et al. (1988) relied heavily on the low temperature glauconite dates, which explains why the Jurassic–Cretaceous boundary in that scale is 131 Ma, versus 145 Ma in Harland et al. (1990) based on high-temperature tuff and intrusives dates (as in Gradstein et al., 1995). Similarly, the estimated age range of the Barremian stage does not overlap, and the duration differs by a factor of three between the Haq et al. (1988) and Harland et al. (1990) time scales (approximately 114–116 Ma as opposed to 125–132 Ma). As an interpolation tool Haq et al. (1988) employed a composite of several marine magnetic spreading profiles in different oceans to linearly scale Late Jurassic through Early Cretaceous chronostratigraphy. It is not clear if the composite spreading profiles in fact increase reliability of the interpolation.

A special problem in calculating time scales is the advent of methods for dating with less than 1% analytical error. Although unresolved discrepancies between Ar/Ar and zircon dates exist (discussed for example by Tucker and McKerrow, 1995), absolute age dates are becoming increasingly more precise and more accurate. Such dates furnish a major challenge to biostratigraphy. It used to be that biostratigraphical resolution in the Mesozoic and Paleozoic Eras largely surpassed that based on radiometric dates, but the gap is closing. Even the most detailed biostratigraphical scheme probably has no biozonal units of less than 0.5–1.0 my duration, not to speak of the actual precision in dating a particular 'piercing point' for which an Ar/Ar or zircon age estimate would be available with an analytical uncertainty of 0.1–0.5 my. The combination of such dates with high-resolution biostratigraphy, magnetostratigraphy, or Milankowitch cyclicity is a major challenge for time-scale studies. Mathematical interpolation methods must combine stratigraphical and analytical age estimates in a balanced manner.

The age assignments for the geological time scale as presented in the chart now published, are relatively well understood for at least the younger part of the Phanerozoic, approximately above the Barremian–Albian interval. Changes, some of them significant, may be expected for the age of stage boundaries in part of the Jurassic and Neocomian, early part of Triassic, Permian–Carboniferous and part of the Cambrian.

Although standard geological time scales heavily rely on (often more detailed) lower latitude biostratigraphy for Mesozoic and Cenozoic chronostratigraphy, for higher latitudes boreal zonations may pose an advantage in local age calibrations. A case in point is the definition of the Jurassic–Cretaceous boundary. The standard time scale defines this epoch boundary between the Tithonian and Berriasian stages, but offshore Norway a definition between the Volgian and Ryazanian stages is advantageous. The latter benefits from

a proposal by Hoedemaeker (1991) and Hoedemaeker et al. (1993). In this proposal, the J/Cr boundary is taken at the top of the *grandis/jacobi* ammonite Zone, correlative to the base of the *S. subalpina* calpionellid Zone, at the base of the original Berriasian of Coquand (defined in 1871). The basal *S. subalpina* Zone correlates to the basal *C. sibericus* ammonite Zone, generally accepted as the boundary between Volgian and Ryazanian in Siberia. The basal *S. subalpina* Zone equates with the calpionellid B/C' zones boundary, which is observed at widespread localities, and may coincide with the top of the British Portlandian (Ogg et al., 1991). The age of the boreal J/Cr boundary is interpolated at 142 Ma $\pm$ 2.6 my at the 95% confidence level.

A minor issue concerns the use of colours to denote successive stratigraphical units. As pointed out by A Voges and J Remane (personal communication, 1996; see also Harland et al., 1990, Appendix 6) there is no standard colour scheme in chronostratigraphy. Certain colour ranges have been adopted by national surveys and by the Commission for the Geological Map of the World (CGMW, Unesco, Paris), an offshoot of the second International Geological Congress in Bologna in 1881. We note that these colours differ significantly from a colouring standard advocated by the United States Geological Survey. In our chart, the colours used for the geological time scale follow those adopted in the wall chart of Harland et al. (1990).

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Postscript

At the 30th International Geological Congress in August 1996 in Beijing, numerous stratigraphical and some geochronological issues were discussed, relevant to the continuously evolving Phanerozoic time scale. Below, we provide a summary of some important new data.

1 The Working Group on the terminal Proterozoic period chaired by A Knoll is erecting a relatively detailed bio- and isotope stratigraphy framework and geochronology for this 50+ my period below the Cambrian, using new data from Australia and Namibia. A GSSP (Global Boundary Stratotype Section and Point) for the base of the Cambrian is considered in a cap carbonate above Varanger tillites in southern Australia, that from correlations to tuffs with U/Pb dates on zircons in Namibia may be near 570 Ma old. (Grotzinger, J P et al., 1996, Calibrating the terminal Proterozoic scale: 30th IGC, Beijing, Abstract v. 2, p.47).

2 The Subcommittee on Permian Stratigraphy under ICS (see also Jin Yuyan in number 28, June 1996 of the subcommittee's newsletter *Permophiles*) is refining a proposal for Permian stage and series classification, incorporating new insights from China, Kazakhstan, Russia and North America. The 'early' Permian Cisuralian subperiod incorporates the stages Asselian, Sakmarian, Artinskian and Kungurian. The 'middle' Permian Guadalupian subperiod consists of the stages Roadian, Wordian and Capitanian, whereas the youngest Permian subperiod, the Lopingian incorporates the two successive stages Wuchiapingian and Changhsingian. In the same newsletter cited, A Klets et al. quote new U/Pb (SHRIMP) dates from tuffs in the lower Permian of Russia and eastern Australia. Although it is not clear how the dates fit in the above stage classification, Sakmarian through Kungurian stages might shift down 5–10 my, pending stratigraphical and mathematical analysis of calibrations, dates and errorbars.

3 In 1995, M Menning (Potsdam) published a numerical time scale for the Permian in *The Permian of northern Pangea*, v. 1, (Springer Verlag, Berlin, pp.77–97). This includes important information on multiple stratigraphy aspects of this period in Germanic facies.

4 In the ongoing debate on the age of the Paleozoic–Mesozoic boundary and radiometric calibrations, P R Renne and colleagues (see also their review in *Science*, v. 269, pp.1413–1416), radiometrically correlate the (?) oldest flows in the Siberian flood basalts and minor tuffs virtually at the P–T boundary in candidate GSSP section(s) for this boundary in southern China. When adjusting the MMhb-1 standard for Ar/Ar to the Fish Canyon standard for U/Pb, the P–T boundary is at 250 Ma.

5 The Subcommittee on Neogene Stratigraphy has brought to our attention that the Piacenzian, Late Pliocene is now formally subdivided in two (marine) stages, thus rectifying correlations problems in the sandy, Astian, facies in the late Piacenzian. An early Late Pliocene Piacenzian Stage (approximately 3.6–2.6 Ma) is overlain by the late Late Pliocene Gelasian Stage (approximately 2.6–1.8 Ma).

Dr Felix M Gradstein is ex-Chairman of the ICS Committee of Quantitative Stratigraphy. He began quantifying geological information as a student at Utrecht University, when he worked on the taxonomy of planktonic foraminifers using biometrics and Hollerith cards. His time-scale research and development started in 1983, when, with D Kent of Lamont Doherty, he developed the Mesozoic segment of the standard time scale. He is geological advisor to Saga Petroleum and emeritus scientist with the Geological Survey of Canada.

Dr James Ogg is a Professor in the Department of Earth and Atmospheric Sciences at Purdue University, USA, and a corresponding member of the Subcommittee on Jurassic Stratigraphy. Projects in unravelling Jurassic–Cretaceous palaeoceanography from an array of ocean drilling sites and exposed marine sections have enabled him to escape the steamy summers of Indiana. His current time-scale projects include magnetostratigraphical calibrations, scaling of depositional sequences and establishing a digital time-scale database.

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