23 • Construction and summary of the geologic time scale

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A geologic time scale (GTS2004) is presented that integrates currently available stratigraphic and geochronologic information. Key features of the new scale are outlined, how it was constructed, and how it can be improved. Major impetus to the new scale was provided through:

(a) advances in stratigraphic standardization and refinement of the International Chronostratigraphic Scale;
(b) enhanced methods of extracting linear time from the rock record, leading to numerous high-resolution ages;
(c) progress with the use of global geochemical variations, Milankovitch climate cycles, and magnetic reversals as important stratigraphic calibration tools;
(d) improved statistical techniques for extrapolating ages and associated uncertainties to the relative stratigraphic scale, using high-resolution biozonations, including composite standards, that scale stages.

23.1 CONSTRUCTION OF GTS2004

23.1.1 The components of GTS2004

The Geologic Time Scale 2004 (GTS2004) project, that commenced in 1998, has compiled integrated scales of selected components of Earth history including:

1. Formal international subdivisions of the "rock-time" chronostratigraphic scale as ratified, or being considered, by the International Commission on Stratigraphy (ICS). The brief historical review of these subdivisions shows the progress toward the goal of a full international standard for chronostratigraphy. Due to space limitations, correlations of selected regional stratigraphic scales to the international standard are only included for some periods. The choice was ours.
2. An informal proposal to subdivide Precambrian time into eons and eras that reflect natural stages in planetary evolution rather than a subdivision in arbitrary numerical ages.
3. Major biostratigraphic zonations and datums for each geologic period in the Phanerozoic. Composite zonations derived from graphical correlation or constrained optimization methods were assembled for most Paleozoic periods, and parts of the Triassic.
4. Magnetic reversal patterns throughout the Phanerozoic.
5. Major geochemical trends of strontium, carbon, and oxygen isotopes in seawater.
6. High-resolution cyclic climatic and oceanographic changes physically and chemically recorded in the sedimentary record.
7. Other significant events (large igneous provinces, impacts, etc.) which are important for global correlation or may have this future potential.
8. Radiometric dates selected for their stratigraphic importance and reliability.

This massive array of information was melded together to produce a framework for Earth geologic history scaled to linear time. The summary of the geologic time scale in Fig. 23.1 (see also Table 23.1) is a calibration of the Phanerozoic part of the International Stratigraphic Chart. Ages of chronostratigraphic boundaries and durations of stages include estimates of the 95% uncertainty (2-sigma). The Neogene portion is calibrated by astronomical cycles to within an orbital-precession oscillation (~20 kyr). Parts of the Paleocene, Cretaceous, Jurassic, and Triassic are also scaled using Milankowitch cycle durations.

We are still a considerable distance from the goal where geologic time scale calibration is achieved by precise direct astronomical tuning or radiometric age dating of all successive stage, zonal, or magnetic polarity chron boundaries. In fact, it is doubtful if the rock record on Earth harbors all the precise age information. This sparse skeleton of age control, especially prior to ~30 Ma (as of 2004), leaves considerable room for interpolation in construction of a geologic time scale. Future time scales will undoubtedly re-examine and reprocess a more expanded array of Earth history data, and will undoubtedly employ even more sophisticated means of interpolation.

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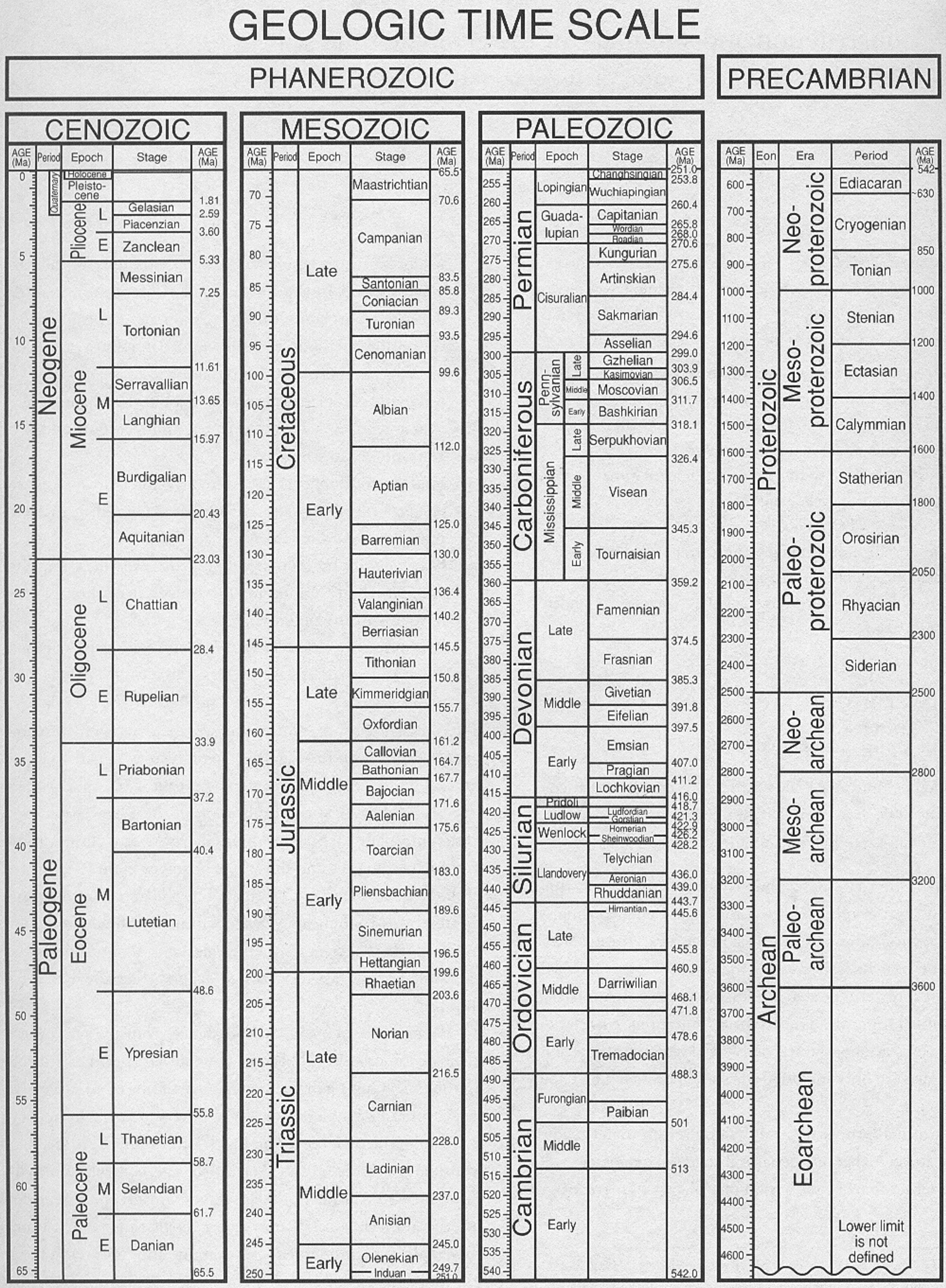

Figure 23.1 Summary of *A Geologic Time Scale 2004*.

Table 23.1 *Summary of ages and durations of stages in GTS2004*[a]

EON, Era, System, Series, Stage	Age of Base (Ma)	Est. ± myr (2-sigma)	Comment	Duration	Est. ± myr (2-sigma)
PHANEROZOIC					
Cenozoic Era					
Neogene System					
Holocene Series					
base Holocene	11.5 ka	0.00			
Pleistocene Series					
base Upper Pleistocene subseries	0.126	0.00		0.115	0.0
base Middle Pleistocene subseries	0.781	0.00		0.655	0.0
base Pleistocene Series	1.806	0.00		1.025	0.0
Pliocene Series					
base Gelasian Stage	2.588	0.00		0.782	0.0
base Piacenzian Stage	3.600	0.00		1.01	0.0
base Zanclean Stage, base Pliocene Series	5.333	0.00		1.73	0.0
Miocene Series					
base Messinian Stage	7.248	0.00		1.92	0.0
base Tortonian Stage	11.608	0.00		4.36	0.0
base Serravallian Stage	13.65	0.00		2.04	0.0
base Langhian Stage	15.97	0.0		2.32	0.0
base Burdigalian Stage	20.43	0.0		4.46	0.0
base Aquitanian Stage, base Miocene Series, base Neogene System	23.03	0.0		2.60	0.0
Paleogene System					
Oligocene Series					
base Chattian Stage	28.4	0.1		5.4	0.0
base Rupelian Stage, base Oligocene Series	33.9	0.1		5.4	0.0
Eocene Series					
base Priabonian Stage	37.2	0.1		3.3	0.0
base Bartonian Stage	40.4	0.2		3.2	0.0
base Lutetian Stage	48.6	0.2		8.2	0.1
base Ypresian Stage, base Eocene Series	55.8	0.2		7.2	0.1
Paleocene Series					
base Thanetian Stage	58.7	0.2		2.9	0.0
base Selandian Stage	61.7	0.2		3.0	0.0
base Danian Stage, base Paleogene System, base Cenozoic	65.5	0.3		3.7	0.0
Mesozoic Era					
Cretaceous System					
Upper					
base Maastrichtian Stage	70.6	0.6	Duration uncertainty increased to reflect correlation problems to GSSP	5.1	0.5
base Campanian Stage	83.5	0.7	Duration uncertainty increased to reflect correlation problems to GSSP	12.9	0.7

(*cont.*)

Table 23.1 (*cont.*)

EON, Era, System, Series, Stage	Age of Base (Ma)	Est. ± myr (2-sigma)	Comment	Duration	Est. ± myr (2-sigma)
base Santonian Stage	85.8	0.7		2.3	0.1
base Coniacian Stage	89.3	1.0	0.2 myr added to uncertainty to account for offset to actual proposed GSSP marker	3.5	0.3
base Turonian Stage	93.5	0.8		4.2	0.3
base Cenomanian Stage	99.6	0.9		6.1	0.3
Lower					
base Albian Stage	112.0	1.0		12.4	0.3
base Aptian Stage	125.0	1.0		13.0	0.5
base Barremian Stage	130.0	1.5		5.0	0.5
base Hauterivian Stage	136.4	2.0		6.4	1.0
base Valanginian Stage	140.2	3.0		3.8	1.0
base Berriasian Stage, base Cretaceous System	145.5	4.0		5.3	1.7
Jurassic System					
Upper					
base Tithonian Stage	150.8	4.0		5.3	1.8
base Kimmeridgian Stage	155.7	4.0	Boreal placement	4.2	1.5
base Oxfordian Stage	161.2	4.0		6.2	1.5
Middle					
base Callovian Stage	164.7	4.0		3.5	1.0
base Bathonian Stage	167.7	3.5		3.0	1.0
base Bajocian Stage	171.6	3.0		3.9	1.0
base Aalenian Stage	175.6	2.0		4.0	1.0
Lower					
base Toarcian Stage	183.0	1.5		7.4	1.0
base Pliensbachian Stage	189.6	1.5		6.6	0.8
base Sinemurian Stage	196.5	1.0		6.9	0.8
base Hettangian Stage, base Jurassic System	199.6	0.6		3.1	0.5
Triassic System					
Upper					
base Rhaetian Stage	203.6	1.5		4.0	1.0
base Norian Stage	216.5	2.0		12.9	0.5
base Carnian Stage	228.0	2.0		11.5	0.5
Middle					
base Ladinian Stage	237.0	2.0		9.0	0.5
base Anisian Stage	245.0	1.5		8.0	1.5
Lower					
base Olenekian Stage	249.7	0.7		4.7	1.0
base Induan Stage, base Triassic System, base Mesozoic	251.0	0.4		1.3	0.3
Paleozoic Era					
Permian System					
Lopingian Series					
base Changhsingian Stage	253.8	0.7		2.8	0.1
base Wuchiapingian Stage	260.4	0.7		6.6	0.1

Table 23.1 (*cont.*)

EON, Era, System, Series, Stage	Age of Base (Ma)	Est. ± myr (2-sigma)	Comment	Duration	Est. ± myr (2-sigma)
Guadalupian Series					
base Capitanian Stage	265.8	0.7		5.4	0.1
base Wordian Stage	268.0	0.7		2.2	0.0
base Roadian Stage	270.6	0.7		2.6	0.1
base Kungurian Stage	275.6	0.7		5.0	0.1
base Artinskian Stage	284.4	0.7		8.8	0.2
base Sakmarian Stage	294.6	0.8		10.2	0.2
base Asselian Stage, base Permian System	299.0	0.8		4.4	0.1
Carboniferous System					
Pennsylvanian Subsystem					
base Gzhelian Stage	303.9	0.9		4.9	0.1
base Kasimovian Stage	306.5	1.0		2.6	0.0
base Moscovian Stage	311.7	1.1		5.2	0.1
base Bashkirian Stage, base Pennsylvanian Subsystem	318.1	1.3		6.4	0.2
Mississippian Subsystem					
base Serpukhovian	326.4	1.6		8.4	0.2
base Visean	345.3	2.1		18.9	0.7
base Tournaisian, base Mississippian Subsystem, base Carboniferous System	359.2	2.5		13.9	0.6
Devonian System					
Upper					
base Famennian Stage	374.5	2.6		15.3	0.6
base Frasnian Stage	385.3	2.6		10.8	0.4
Middle					
base Givetian Stage	391.8	2.7		6.5	0.3
base Eifelian Stage	397.5	2.7		5.7	0.2
Lower					
base Emsian Stage	407.0	2.8		9.5	0.4
base Pragian Stage	411.2	2.8		4.2	0.2
base Lochkovian Stage, base Devonian System	416.0	2.8		4.8	0.2
Silurian System					
Pridoli Series					
base Pridoli Series (*not subdivided in stages*)	418.7	2.7	Uncertainties "ramped" from computed base-Devonian to "low" value at base-Silurian	2.7	0.1
Ludlow Series					
base Ludfordian Stage	421.3	2.6		2.5	0.1
base Gorstian Stage	422.9	2.5		1.7	0.1
Wenlock Series					
base Homerian Stage	426.2	2.4		3.3	0.1
base Sheinwoodian Stage	428.2	2.3		2.0	0.1

(*cont.*)

Table 23.1 (*cont.*)

EON, Era, System, Series, Stage	Age of Base (Ma)	Est. ± myr (2-sigma)	Comment	Duration	Est. ± myr (2-sigma)
Llandovery Series					
base Telychian Stage	436.0	1.9		7.8	0.2
base Aeronian Stage	439.0	1.8		3.0	0.1
base Rhuddanian Stage, base Silurian System	443.7	1.5		4.7	0.1
Ordovician System					
Upper					
base Hirnantian stage	445.6	1.5		1.9	0.1
base of sixth stage *(not yet named)*	455.8	1.6		10.2	0.3
base of fifth stage *(not yet named)*	460.9	1.6		5.1	0.2
Middle					
base Darriwilian Stage	468.1	1.6		7.3	0.2
base of third stage *(not yet named)*	471.8	1.6		3.7	0.1
Lower					
base of second stage *(not yet named)*	478.6	1.7		6.8	0.1
base of Tremadocian Stage, base Ordovician System	488.3	1.7		9.7	0.2
Cambrian System					
Upper ("Furongian") Series					
upper stage(s) in Furongian	*not defined*				
base Paibian Stage, base Furongian Series	501.0	2.0	Age of boundary is "approximate estimate" (see text)		
Middle	513.0	2.0	Age of boundary is "approximate estimate" (see text)		
Lower					
base Cambrian System, base Paleozoic, base PHANEROZOIC	542.0	1.0			

[a] Uncertainties are 2-sigma (95% confidence).

23.1.2 Calibration methods to linear time used in GTS2004

The main steps involved in GTS2004 time scale construction were:

Step 1. Construct an updated global chronostratigraphic scale for the Earth's rock record.

Step 2. Identify key linear-age calibration levels for the chronostratigraphic scale using radiometric age dates, and/or apply astronomical tuning to cyclic sediment or stable isotope sequences which had biostratigraphic or magnetostratigraphic correlations.

Step 3. Interpolate the combined chronostratigraphic and chronometric scale where direct information is insufficient.

Step 4. Calculate or estimate error bars on the combined chronostratigraphic and chronometric information to obtain a geologic time scale with estimates of uncertainty on boundaries and on unit durations.

Step 5. Peer review the geologic time scale

The first step, integrating multiple types of stratigraphic information in order to construct the chronostratigraphic scale, is the most time-consuming; it summarizes and synthesizes centuries of detailed geological research. The second step, identifying which radiometric and cycle-stratigraphic studies would be used as the primary constraints for assigning linear ages, is the one that is evolving most rapidly since the last decade. Historically, time scale building went from an exercise with very few and relatively inaccurate radiometric dates, as used by Holmes (1947, 1960), to one with many dates with greatly varying analytical precision (like GTS89 or, to some extent, SEPM95). Next came studies that selected a few radiometric dates with high internal analytical precision (e.g. Cande and Kent, 1992a, 1995; Obradovich, 1993; Cooper, 1999b) or measure time relative to present using astronomical cycles (e.g. Hilgen *et al.*, 1995, 2000c; Shackleton *et al.*, 1999). This new philosophy is also adhered to in this book.

In addition to selecting radiometric ages based upon their stratigraphic control and analytical precision, we also applied the following criteria or corrections:

1. Stratigraphically constrained radiometric ages with the U–Pb method on zircons were accepted from the isotope dilution mass spectrometry (TIMS) method, but generally not from the high-resolution ion microprobe (HR-SIMS, also known as "SHRIMP") that uses the Sri Lanka (SL)13 standard. An exception is the Carboniferous Period, where there is a dearth of TIMS dates and more uncertainty.
2. $^{40}Ar/^{39}Ar$ radiometric ages were re-computed to be in accord with the revised ages for laboratory monitor standards: 523.1 $\pm$ 4.6 Ma for MMhb-1 (McClure Mountain hornblende), 28.34 $\pm$ 0.28 Ma for TCR (Taylor Creek Rhyolite sanidine) and 28.02 $\pm$ 0.28 Ma for FCT (Fish Canyon Tuff sanidine). Systematic ("external") errors and uncertainties in decay constants were partially incorporated (see Chapters 6 and 8). No glauconite dates were used.

The bases of the Paleozoic, Mesozoic, and Cenozoic are bracketed by analytically precise ages at their GSSP or primary correlation markers – 542 $\pm$ 1.0, 251.0 $\pm$ 0.4 and 65.5 $\pm$ 0.3 Ma, respectively – and there are direct age dates on base-Carboniferous, base-Permian, base-Jurassic, and base-Oligocene; but most other period or stage boundaries prior to the Neogene lack direct age control. Therefore, the third step, linear interpolation, plays a key role for most of GTS2004. This detailed and high-resolution process incorporated several techniques, depending upon the available information (Fig. 23.2):

1. A composite standard of graptolite zones spanning the latest Cambrian, Ordovician, and Silurian interval was derived from 200+ sections in oceanic and slope environment basins using the constrained optimization method (see Chapters 12 and 13). With zone thickness taken as directly proportional to zone duration, the detailed composite sequence was scaled using selected, high-precision zircon and sanidine age dates. For the Carboniferous through Permian, a composite standard of conodont, fusulinid, and ammonoid events from many classical sections was calibrated to a combination of U–Pb and $^{40}Ar/^{39}Ar$ dates with assigned external error estimates. A composite standard of conodont zones was used for Early Triassic. This procedure directly scaled all stage boundaries and biostratigraphic horizons.
2. Detailed direct ammonite-zone ages for the Late Cretaceous of the Western Interior of the USA were obtained by a cubic-spline fit of the zonal events and 25 $^{40}Ar/^{39}Ar$ dates. The base-Turonian age is directly bracketed by this $^{40}Ar/^{39}Ar$ set, and ages of other stage boundaries and stratigraphic events are estimated using calibrations to this primary scale.
3. Seafloor-spreading interpolations were done on a composite marine magnetic lineation pattern for the Late Jurassic through Early Cretaceous in the Western Pacific and for the Late Cretaceous through early Neogene in the South Atlantic Ocean. Ages of biostratigraphic events were assigned according to their calibration to these magnetic polarity time scales.
4. Astronomical tuning of cyclic sediments was used for the Neogene and Late Triassic, and portions of the Early and Middle Jurassic, the middle part of the Cretaceous, and the Paleocene. The Neogene astronomical scale is directly tied to the Present; the astronomical scale provides linear-duration constraints on polarity chrons, biostratigraphic zones, and entire stages.
5. Proportional scaling relative to component biozones or subzones. In intervals where none of the above information under Items 1–4 was available it was necessary to return to the methodology employed by past time scales. This procedure was necessary in portions of the Middle Triassic and Middle Jurassic. Devonian stages were scaled from approximate equal duration of a set of high-resolution subzones of ammonoids and conodonts, fitted to an array of high-precision dates.

The actual geomathematics employed for the above data sets (Items 1, 2, 3, and 5) constructed for the Ordovician–Silurian,

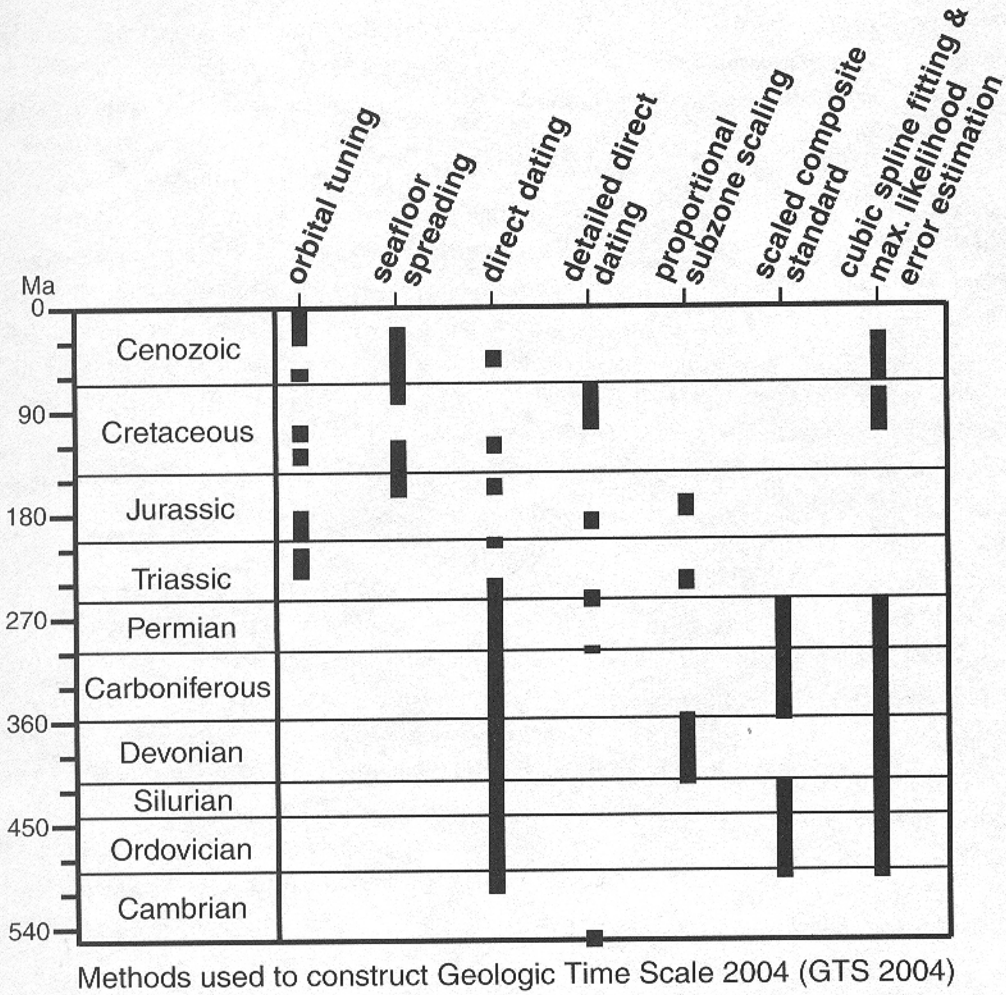

Figure 23.2 Methods used to construct *A Geologic Time Scale 2004* (GTS2004) integrate different techniques depending on the quality of data available within different intervals.

Devonian, Carboniferous–Permian, Late Cretaceous, and Paleogene involved cubic-spline curve fitting to relate the observed ages to their stratigraphic position. During this process the ages were weighted according to their variances based on the lengths of their error bars. A chi-square test was used for identifying and reducing the weights of relatively few outliers with error bars that were much narrower than could be expected on the basis of most ages in the data set.

Stratigraphic uncertainty was incorporated in the weights assigned to the observed ages during the spline-curve fitting. In the final stage of analysis, Ripley's MLFR algorithm, for maximum likelihood fitting of a functional relationship, was used for error estimation, resulting in 2-sigma (95% confidence) error bars for the estimated chronostratigraphic boundary ages and stage durations. The uncertainties on older stage boundaries generally increase owing to potential systematic errors in the different radiometric methods, rather than to the analytical precision of the laboratory measurements (Table 23.1 and Fig. 23.3). In this connection, we mention that biostratigraphic error is fossil event and fossil zone dependent, rather than age dependent.

In Mesozoic intervals that were scaled using the seafloor-spreading model or proportionally scaled using paleontological subzones, the assigned uncertainties are conservative estimates based on variability observed when applying different assumptions (see discussions in Chapters 5, 17–19). Ages and durations of Neogene stages derived from orbital tuning are considered to be accurate to within a precession cycle (~20 kyr) assuming that all cycles are correctly identified and that the theoretical astronomical tuning for progressively older deposits is precise.

23.2 FUTURE TRENDS IN GEOLOGIC TIME SCALES

The changing philosophy in time scale building has made it more important to undertake high-resolution radiometric study of critical stratigraphic boundaries and extend the

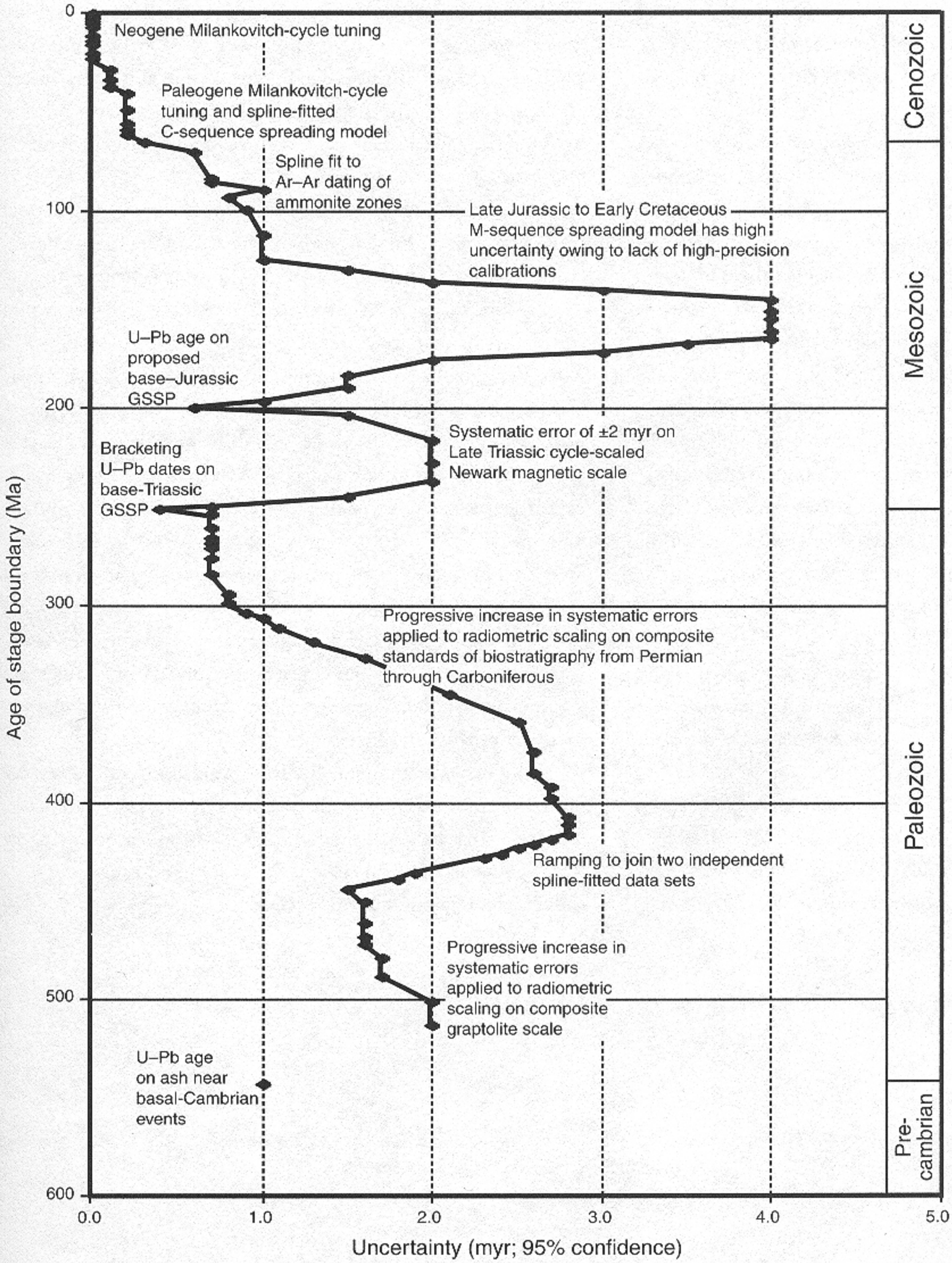

Figure 23.3 Estimated uncertainties (95% confidence) on linear ages of stage boundaries. These estimates partially incorporate potential systematic errors in radiometric methods. Orbital tuning relative to the present yields negligible uncertainties in the Neogene. The Triassic through middle Cretaceous generally has higher uncertainties owing to the dearth of precise radiometric ages and inadequate calibration of seafloor-spreading models.

astronomical tuning into progressively older sediments. Good examples are Bowring *et al.* (1998) for basal-Triassic, Amthor *et al.* (2003) for basal-Cambrian, and Hilgen *et al.* (2000c) for base-Tortonian. The philosophy is that obtaining high-precision age dating at a precisely defined stratigraphic boundary avoids stratigraphic bias and its associated uncertainty in rock and in time. In this respect, it is of vital importance that the ICS not only completes the definition of all stage boundaries, but also actively considers definition of subdivisions within the many long stages (see Chapter 2). Regional and philosophical arguments between stratigraphers should be actively resolved to reach consensus conclusions with focus on global correlation implications. Stratigraphic standardization precedes linear time calibration.

Even more refined and more time extensive scaling of zones and stages with the deterministic and probabilistic quantitative methods outlined in Chapter 3 and in Chapters 11–16 is probably feasible today, and should be pursued actively. Progress with a natural time scale for the Precambrian is also a high and challenging priority (Chapter 10), not in the least because a solar scale for all of science should soon be "over the horizon."

In the process of assembling the pieces of the new time scale, i.e. GTS2004, several decisions had to be made with respect to the global radiometric data set. This data set should be subjected to further scrutiny, both within radiometric laboratories and in the field. For example, significant discrepancies exist between U–Pb dates on the P–T boundary beds and in the middle Triassic, both of which appear to be a zircon problem, and the misalignment of HR–SIMS dating, using the SL13 standard, and TIMS dating in parts of the Paleozoic. Other decisions (Chapter 6), i.e. which $^{40}Ar/^{39}Ar$ monitor age value to use, and which decay constant, also need further study and consensus building among radiometric specialists. For example, intercalibration of independent astronomical and radioisotopic dating methods is not yet solved, but new results (Kuiper, 2003) point to an astronomically derived age of 28.24 ± 0.01 Ma for the Fish Canyon Tuff (FCT) sanidine. This precise age requires careful evaluation in the geochronologic community.

Enhanced utilization of geochemical trends and magnetic reversal patterns to resolve linear scaling of critical intervals such as the long Jurassic–Early Cretaceous and parts of the Triassic are also highly desirable. The virtual absence of reliable radiometric age dates for the long Jurassic–Cretaceous interval needs urgent correction.

In summary, improvement and consolidation of the time scale will depend on definition of the remaining stage boundaries, on astronomical tuning of durations of as many intervals as possible, on more evenly time-distributed high-resolution age dating, and on more detailed relative scaling of stages with biozones. For example, tuning and calibration of the Paleogene time scale at much higher levels of resolution and precision than are presently available will be achieved within this decade. Astronomical calibrations of the geologic time scale in its earlier parts is more challenging than in the Neogene and requires careful evaluation of uncertainties. In the medium term, it can be predicted that complete coverage of astronomically calibrated geological markers will exist for the entire Cenozoic and that traditional geochronological scales, astronomical calibrations, and magneto- and biostratigraphic datums and zonal composites will become more closely intertwined and aligned in the Mesozoic and Paleozoic.

A high-resolution geologic time scale allows more insight into the cause and effect of all physical, chemical, and biological processes that have left their enduring and wondrous mark on Earth. The order of things and the order in nature is our goal, such is the reward of our undertakings.