A Geologic Time Scale 2004

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CAMBRIDGE

18 • The Jurassic Period

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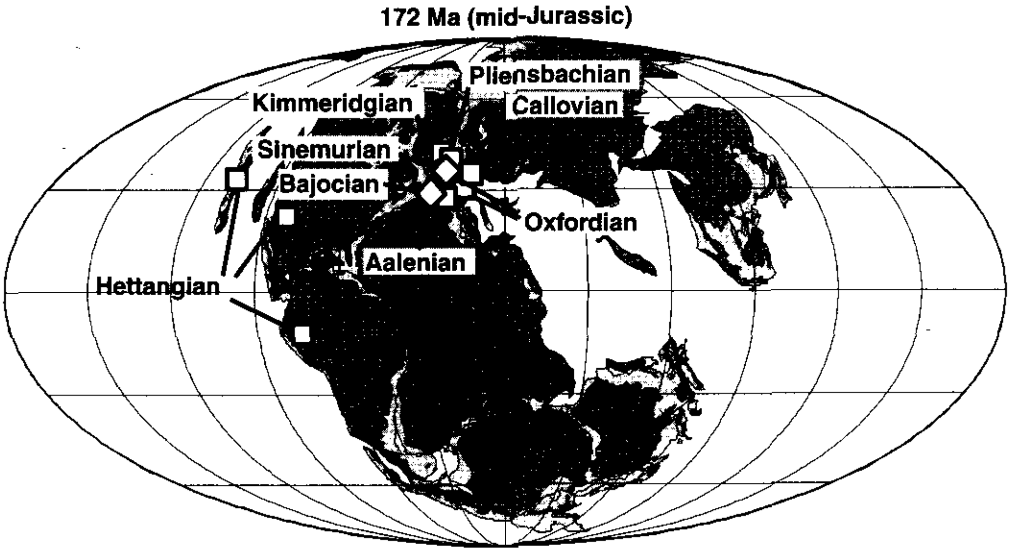

eographic distribution of Jurassic GSSPs that have been ratified (diamonds) or are candidates (squares) on a mid-Jurassic map (status in January 2004; see Table 2.3). Overlaps in Europe have obscured some GSSPs, and not all candidate sections are indicated (see Table 18.1 for more extensive listing). GSSPs for the base-Jurassic, Late Jurassic stages, and some Middle Jurassic stages are undefined. The projection center is at 30° E to place the center of the continents in the center of the map.

inosaurs dominated the land surface. Ammonites are the main fossils r correlating marine deposits. Pangea supercontinent began to break p, and at the end of the Middle Jurassic the Central Atlantic was rn. Organic-rich sediments in several locations eventually became e source rocks helping to fuel modern civilization.

18.1 HISTORY AND SUBDIVISIONS

18.1.1 Overview of the Jurassic

he term "Jura Kalkstein" was applied by Alexander von umboldt (1799) to a series of carbonate shelf deposits exposed the mountainous Jura region of northernmost Switzerland, nd he first recognized that these strata were distinct from e German Muschelkalk (middle Triassic), although he erroneously considered his unit to be older. Alexander Brongniart (1829) coined the term "Terrains Jurassiques" when correlating the "Jura Kalkstein" to the Lower Oolite Series (now assigned to Middle Jurassic) of the British succession. Leopold von Buch (1839) established a three-fold subdivision for the Jurassic. The basic framework of von Buch has been retained as the three Jurassic series, although the nomenclature has varied (Black–Brown–White, Lias–Dogger–Malm, and currently Lower–Middle–Upper).

The immense wealth of fossils, particularly ammonites, in the Jurassic strata of Britain, France, Germany, and Switzerland was a magnet for innovative geologists, and modern concepts of biostratigraphy, chronostratigraphy, correlation, and paleogeography grew out of their studies. Alcide d'Orbigny (1842–51, 1852), a French paleontologist, grouped the Jurassic ammonite and other fossil assemblages of France and England into ten main divisions, which he termed "étages" (stages). Seven of d'Orbigny's stages are used today, but none of them has retained its original stratigraphic range. Simultaneously,

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Quenstedt (1848) subdivided each of the three Jurassic series of von Buch of the Swabian Alb of southwestern Germany into six lithostratigraphic subdivisions, which he characterized by ammonites and other fossils and denoted by Greek letters (*alpha–zeta*; Geyer and Gwinner, 1979). Alfred Oppel (1856–8), Quenstedt's pupil, subdivided the Jurassic stages into biostratigraphic zones, was the first to correlate Jurassic units successfully among England, France, and southwestern Germany, and modified d'Orbigny's stage framework.

Ammonites have provided a high-resolution correlation and subdivision of Jurassic strata throughout the globe (e.g. Arkell, 1956). The bases of nearly all Jurassic stages and substages are traditionally assigned to the base of ammonite zones in marginal-marine sections in western Europe (e.g. Oppel, 1856–8), and this philosophy was formalized at the Colloque du Jurassique à Luxembourg 1962 (Maubeuge, 1964; see also Morton, 1974), where the majority of the current suite of eleven Jurassic stages were defined in terms of component ammonite zones. Therefore, the process of assigning bases of Jurassic stages at GSSPs continues this historical practice, in which the GSSP placement is commonly locked into recognizing or defining the basal ammonite horizon of the lowest component zone. However, much of the historical subdivision of the Jurassic was limited to shallow-marine deposits of the northwest European region (England to southwest Germany), therefore, establishing reliable high-resolution correlation to tropical (Tethyan), Pacific, deep-sea, continental, and other settings has commonly remained tenuous. In particular, this difficulty in global correlation has frustrated efforts to define with GSSPs both the base and the top of the Jurassic and the bases of the Kimmeridgian and Tithonian stages.

Detailed reviews of the history, subdivisions, biostratigraphic zonations, and correlation of individual Jurassic stages are compiled in several sources, including Arkell (1933, 1956), Cope *et al.* (1980a,b), Harland *et al.* (1982, 1990), Krymholts *et al.* (1982, 1988), Burger (1995), and Groupe Français d'Etude du Jurassique (1997), and our brief summaries have been distilled from their narratives.

18.1.2 Lower Jurassic

A marine transgression in northwest Europe during the latest Triassic and earliest Jurassic resulted in widespread clay-rich calcareous deposits. These distinctive strata in southwest Germany were called the Black Jurassic (schwarzen Jura) by von Buch (1839), and were called Lias in southern England by Conybeare and Phillips (1822). The base of the historical Hettangian Stage is the initial influx of ammonites into southern England during the early stages of the transgression. This series was subdivided into three stages (Sinemurian, Liasian, and Toarcian) by d'Orbigny (1842–51, 1852), then Oppel (1856–8) replaced the Liasian with the Pliensbachian Stage and Renevier (1864) separated the lower Sinemurian as a distinct Hettangian Stage. Widespread hiatuses or condensation horizons mark the bases of the classical Sinemurian, Pliensbachian, and Toarcian stages.

TRIASSIC–JURASSIC BOUNDARY AND THE HETTANGIAN STAGE

The original Sinemurian Stage of d'Orbigny (1842–51, 1852) extended to the base of the Jurassic. Indeed, the Lower Jurassic tentatively included the Rhaetian (Bonebed of southwest Germany, portions of Penarth Beds in England, Rhätische Gruppe of German and Austrian Alps, etc.), which is now assigned to the uppermost Triassic. Overlying this basal unit, Oppel (1856–8) assigned the base of his Jurassic to the lowest ammonite assemblage which is characterized by the *planorbis* species, and referred to characteristic coastal sections in southern England including Lyme Regis in Dorset and Watchet in Somerset.

Renevier (1864) proposed the Hettangian Stage to encompass the *Psiloceras planorbis* and *Schlotheimia angulatus* ammonite zones as interpreted by Oppel. The stage was named after a quarry near the village of Hettange-Grande in Lorraine (northeastern France), 22 km south of Luxembourg, although the strata in this locality are primarily sandstone with no fossils in the lowermost part.

The latest Triassic and Triassic–Jurassic boundary interval span one of the five most significant mass extinctions of the Phanerozoic, including termination of conodonts and major declines of ammonites and bivalves (e.g. Hallam, 1996; [illegible] 1999). This progressive decline, coupled with the low-diversity survivor fauna and transgressive facies migration during the early Hettangian, has greatly limited the choice of markers for defining the base of the Jurassic. The base of the Hettangian is traditionally assigned to the first occurrence of the [illegible] *planorbis* group within the ammonite genus *Psiloceras*, which are ubiquitous from the eastern Pacific and Tethys to the European Boreal province. Ammonite diversity was very low in Rhaetian time (*Choristoceras marshi* Zone), and the Hettangian genus *Psiloceras* must be derived from the Triassic genus [illegible] the family Discophyllitidae, which lives mainly in the open [illegible] (von Hillebrandt, 1997). The Triassic–Jurassic boundary, as recognized in the marine realm, is within the earliest [illegible] a transgression following a major sequence boundary (H

g. 18.1) and eustatic lowstand (Hesselbo and Jenkyns, 1998; llam and Wignall, 1999).

The age of the Triassic–Jurassic boundary is constrained a U–Pb zircon age of 199.6 ± 0.3 Ma on a tuff layer in the permost Rhaetian (top of Triassic) on Kunga Island (Pálfy *al.*, 2000a). A floral turnover and peak in tetrapod extinc- n in eastern North America, that had been considered to ncide with the Triassic–Jurassic boundary (e.g. Fowell and en, 1993), has an age no younger than 200.6 Ma; therefore, is continental level appears to represent part of the progres- e loss of diversity within the latest Triassic (Pálfy *et al.*, 00a,b). Olsen *et al.* (2003) favor an age of 202 Ma for this ontinental Triassic–Jurassic boundary," based on the aver- e of ages from the overlying basalts in the Newark Basin ccessions.

There are four main candidates for the placement of the se-Jurassic GSSP (Warrington, 1999, 2003; Table 18.1):) Chilingote, Peru, on the west side of the Utcubamba Valley;) southeast shore of Kunga Island, Queen Charlotte Islands, itish Columbia, Canada; (3) Muller or New York Canyon ea, Gabbs Valley Range, Nevada; and (4) St. Audrie's Bay, merset, England. Only the Peru and Nevada sections con- n ammonite assemblages of both the uppermost Rhaetian d lowermost Hettangian; but St. Audrie's Bay has magne- tratigraphy and Kunga Island has dated tuff layers.

There is no accepted grouping into substages of the three ettangian ammonite zones (*Psiloceras planorbis*, *Alsatites lia- us*, and *Schlotheimia angulata*).

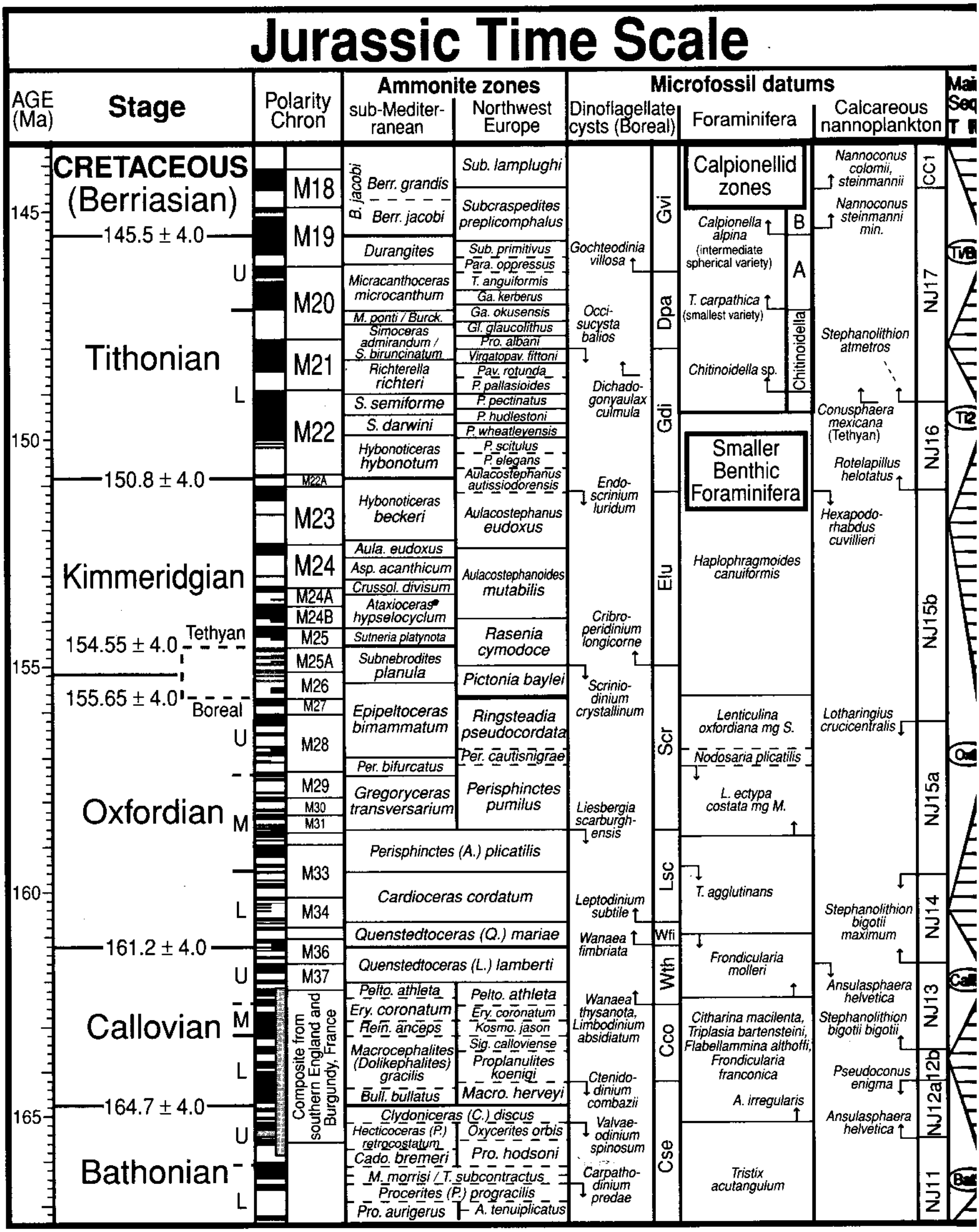
NEMURIAN

story, definition, and boundary stratotype The Sinemurian age was named by d'Orbigny (1842–51, 1852) after the town of Semur-en-Auxois (Sinemurum Briennense castrum in Latin) in the Cote d'Or department of eastern central France. After the establishment of the Hettangian Stage removed the lower ammonite zones (Renevier, 1864), the base of the Sinemurian was traditionally assigned to the proliferation of the Arietitidae ammonite group, particularly the lowest occurrence of the early genera *Vermiceras* and *Metophioceras* (base of *Metophioceras conybeari* subzone of the *Arietites bucklandi* Zone. However, the stage boundary was never defined by a generally accepted species or assemblage (Sinemurian Boundary Working Group, 2000). In addition, a gap exists between the Hettangian and Sinemurian throughout most of northwest Europe.

Only in rapidly subsiding troughs in western Britain was sedimentation continuous across the boundary interval. Therefore, the boundary GSSP was placed in inter-bedded limestone and claystone at coastal exposures near East Quantoxhead, Somerset, England (Page *et al.*, 2000; Sinemurian Boundary Working Group, 2000; Bloos and Page, 2002; Table 18.1). The GSSP is at the lowest occurrence of arietitid ammonite genera *Vermiceras* and *Metophioceras*. This level is just below the highest occurrence of the ammonite genera *Schlotheimia* that is characteristic of the uppermost Hettangian. This turnover of ammonite genera is a global event that marks the boundary interval (Sinemurian Boundary Working Group, 2000; Bloos and Page, 2002).

Sinemurian substages The Sinemurian has two substages. The Colloque du Jurassique à Luxembourg 1962 (Maubeuge, 1964) assigned the base of an upper stage, called Lotharingian (named by Haug, 1910, after the Lorraine region of France), to the base of the *Caenisites turneri* ammonite zone. However, current usage follows Oppel (1856–8) in assigning the base of the Lotharingian substage at the base of the overlying *Asteroceras*

gure 18.1 Jurassic time scale with selected biostratigraphic zonations, magnetic polarity chrons, and major depositional sequences. The imary absolute-age stratigraphic scales are the ammonite zonations of northwest Europe for Hettangian through Bajocian and of the b-Mediterranean province for the Bathonian stage (modified from J. Thierry in Hardenbol *et al.*, 1998, pp. 776–777), and the M-sequence gnetic polarity chrons for Callovian through Tithonian stages. Ages of stage boundaries and other stratigraphic events are from their direct ibration to the primary stratigraphic scale (e.g. magnetostratigraphic correlation of proposed basal-Tithonian ammonite zone boundary) or rapolated from published correlation estimates (e.g. Mesozoic chronostratigraphy charts of Hardenbol *et al.*, 1998) – see text for details. certainty estimates for stage boundaries are given at 95% confidence limits. Dashed lines denote relatively uncertain calibrations of her biostratigraphic events to the primary scale, or intervals in which ammonite zones have been arbitrarily scaled proportional to the ative number of subzones. Most subzonal units are omitted, and only a generalized ammonite stratigraphy is given for some intervals e biostratigraphic chart series in Hardenbol *et al.*, 1998, for full listing and correlation web). Ammonite biozone names and associated igned ages are summarized in Table 18.2. Major flooding or regressive trends of depositional sequences of northwest Europe are labeled at e sequence boundary immediately preceding the maximum lowstand of the respective third-order sequence (extracted from Hardenbol *et al.*, 98). A color version of this figure is in the plate section.


Jurassic Time Scale
AGE (Ma)
Stage
Polarity Chron
Ammonite zones
sub-Mediterranean
Northwest Europe
Microfossil datums
Dinoflagellate cysts (Boreal)
Foraminifera
Calcareous nannoplankton
CRETACEOUS (Berriasian)
145
145.5 ± 4.0
Tithonian
U
L
150
150.8 ± 4.0
Kimmeridgian
154.55 ± 4.0
Tethyan
155
155.65 ± 4.0
Boreal
Oxfordian
U
M
L
160
161.2 ± 4.0
Callovian
U
M
L
164.7 ± 4.0
165
Bathonian
U
L
M18
M19
M20
M21
M22
M22A
M23
M24
M24A
M24B
M25
M25A
M26
M27
M28
M29
M30
M31
M33
M34
M36
M37
Composite from southern England and Burgundy, France
B. jacobi
Berr. grandis
Berr. jacobi
Durangites
Micracanthoceras microcanthum
M. ponti / Burck.
Simoceras admirandum / S. biruncinatum
Richterella richteri
S. semiforme
S. darwini
Hybonoticeras hybonotum
Hybonoticeras beckeri
Aula. eudoxus
Asp. acanthicum
Crussol. divisum
Ataxioceras hypselocyclum
Sutneria platynota
Subnebrodites planula
Epipeltoceras bimammatum
Per. bifurcatus
Gregoryceras transversarium
Perisphinctes (A.) plicatilis
Cardioceras cordatum
Quenstedtoceras (Q.) mariae
Quenstedtoceras (L.) lamberti
Pelto. athleta
Ery. coronatum
Rein. anceps
Macrocephalites (Dolikephalites) gracilis
Bull. bullatus
Clydoniceras (C.) discus
Hecticoceras (P.) retrocostatum
Cado. bremeri
M. morrisi / T. subcontractus
Procerites (P.) progracilis
Pro. aurigerus
Sub. lamplughi
Subcraspedites preplicomphalus
Sub. primitivus
Para. oppressus
T. anguiformis
Ga. kerberus
Ga. okusensis
Gl. glaucolithus
Pro. albani
Virgatopav. fittoni
Pav. rotunda
P. pallasioides
P. pectinatus
P. hudlestoni
P. wheatleyensis
P. scitulus
P. elegans
Aulacostephanus autissiodorensis
Aulacostephanus eudoxus
Aulacostephanoides mutabilis
Rasenia cymodoce
Pictonia baylei
Ringsteadia pseudocordata
Per. cautisnigrae
Perisphinctes pumilus
Pelto. athleta
Ery. coronatum
Kosmo. jason
Sig. calloviense
Proplanulites koenigi
Macro. herveyi
Oxycerites orbis
Pro. hodsoni
A. tenuiplicatus
Gochteodinia villosa
Occisucysta balios
Dichadogonyaulax culmula
Endoscrinium luridum
Cribroperidinium longicorne
Scriniodinium crystallinum
Liesbergia scarburghensis
Leptodinium subtile
Wanaea fimbriata
Wanaea thysanota, Limbodinium absidiatum
Ctenidodinium combazii
Valvaeodinium spinosum
Carpathodinium predae
Gvi
Dpa
Gdi
Elu
Scr
Lsc
Wfi
Wth
Cco
Cse
Calpionellid zones
Calpionella alpina (intermediate spherical variety)
B
A
T. carpathica (smallest variety)
Chitinoidella sp.
Chitinoidella
Smaller Benthic Foraminifera
Haplophragmoides canuiformis
Lenticulina oxfordiana mg S.
Nodosaria plicatilis
L. ectypa costata mg M.
T. agglutinans
Frondicularia molleri
Citharina macilenta, Triplasia bartensteini, Flabellammina althoffi, Frondicularia franconica
A. irregularis
Tristix acutangulum
Nannoconus colomii, steinmannii
Nannoconus steinmanni min.
Stephanolithion atmetros
Conusphaera mexicana (Tethyan)
Rotelapillus helotatus
Hexapodorhabdus cuvillieri
Lotharingius crucicentralis
Stephanolithion bigotii maximum
Ansulasphaera helvetica
Stephanolithion bigotii bigotii
Pseudoconus enigma
Ansulasphaera helvetica
CC1
NJ17
NJ16
NJ15b
NJ15a
NJ14
NJ13
NJ12b
NJ12a
NJ11
Mai Seq
T R

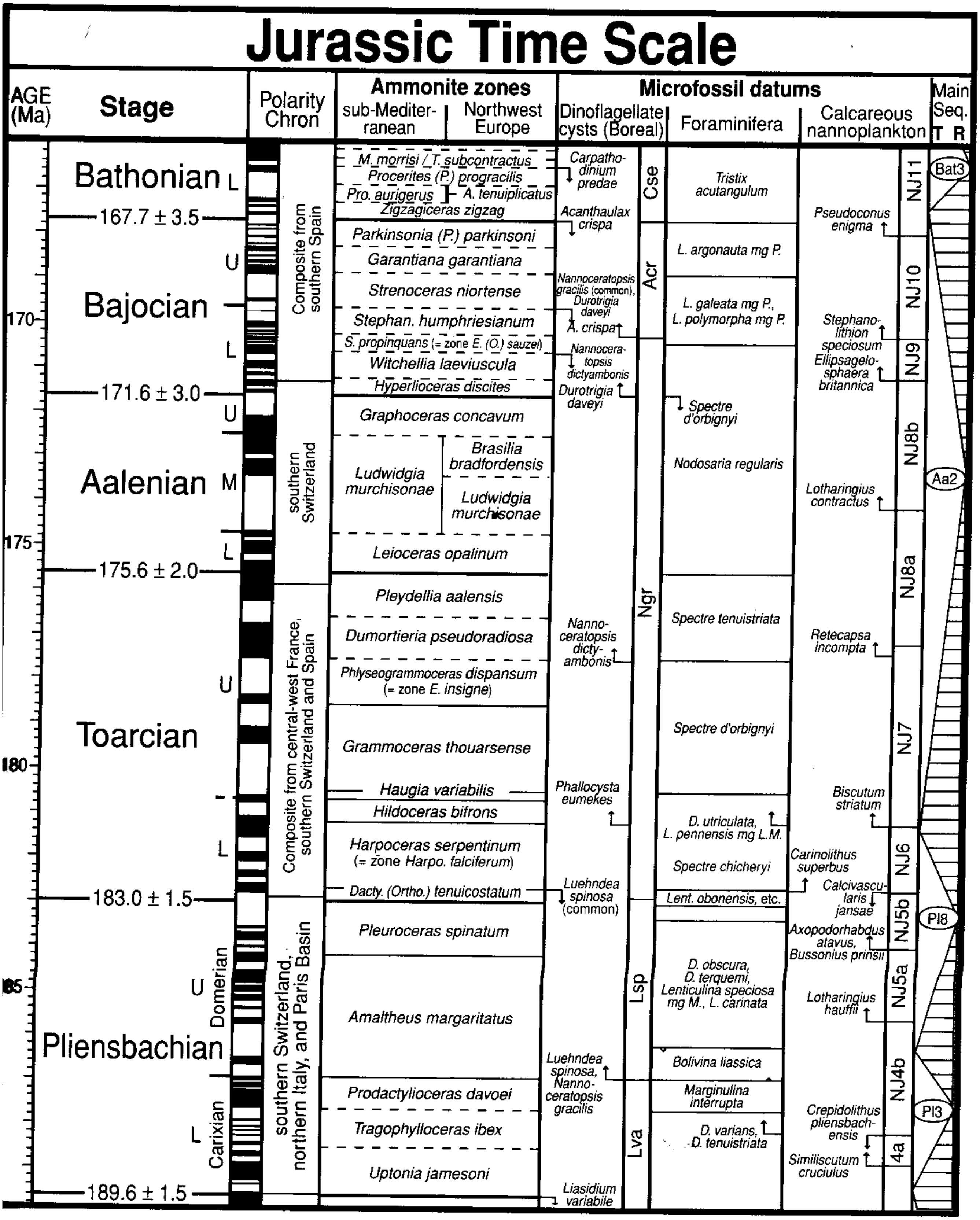


Figure 18.1 (*cont.*)

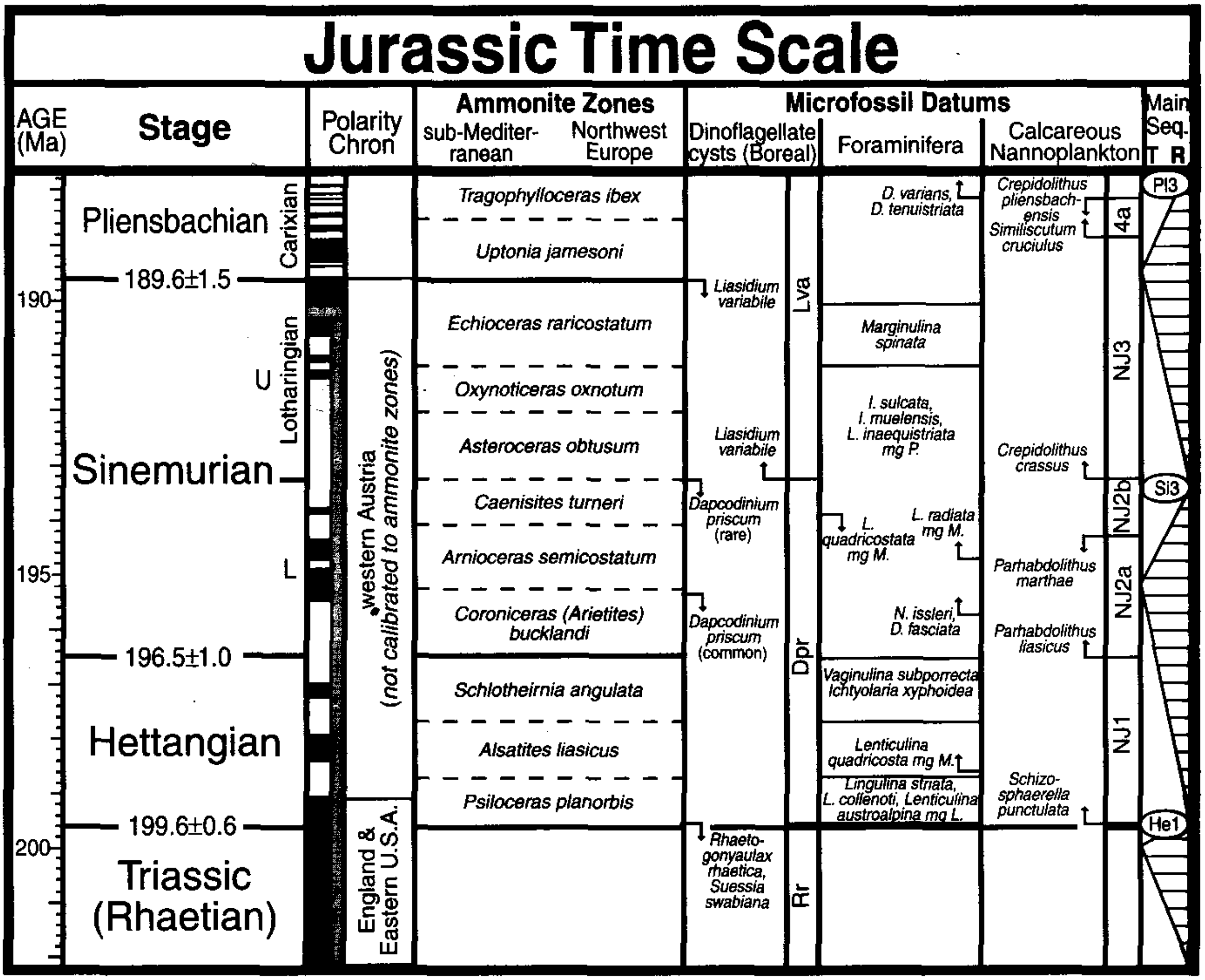


Figure 18.1 *(cont.)*

obtusum Zone (e.g. Krymholts *et al.*, 1982–8; Groupe Français d'Etude du Jurassique, 1997). The lower substage does not have a secondary name, and there is no recommendation for a potential GSSP for the substage boundary.

PLIENSBACHIAN

History, definition, and boundary stratotype The Pliensbachian Stage was proposed by Oppel (1856–8) to replace the Liasian stage of d'Orbigny, which lacked a type locality for its base. The stage was named after the outcrops along the Pliensbach stream near the village of Pliensbach (Geppingen, 35 km southeast of Stuttgart) in the Baden–Württemberg district of Germany. Even though this section lies unconformably on the underlying Sinemurian, the lowest ammonite subzone (*Phricodoceras taylori* subzone of the *Uptonia jamesoni* Zone) in this section is traditionally used as the base of the Pliensbachian Stage (e.g. Dean *et al.*, 1961; Meister, 1999a,b).

At this level, the Psiloceratoidea ammonites, which dominated the Hettangian and Sinemurian, disappear and the Eoderoceratoidea superfamily diversifies and dominates the northeast European fauna of the Pliensbachian Stage (Meister *et al.*, 2003). This faunal event occurs globally, but a stratigraphic gap between the Pliensbachian and Sinemurian sequences is a common feature. Of 27 regions considered by the Pliensbachian boundary working group, only a single candidate in Yorkshire, England, was satisfactory for a potential GSSP (Meister, 1999a,b; Meister *et al.*, 2003). At the clay-rich coastal section of Wine Haven at Robin Hood's Bay, Yorkshire, the GSSP coincides with the lowest ammonite occurrences of *Bifericeras donovani* species and of *Apoderoceras* genera (Table 18.1). section at Aselfingen in the Baden–Württemberg district

Stage	Stage boundary *Substage base*	Status	Location and point	Primary markers	Other correlations	Comments	References (GSSP, correlations)
		Global Boundary Stratotype Section and Point					
Upper Jurassic							
Tithonian	*Upper*	Informal usage within sub-Mediterranean province (Tethyan faunal domain)		Base of *Micracanthoceras microcanthum* ammonite zone.	At this level there is a major turnover in ammonite assemblages and calpionellid microfossils become important in the biostratigraphic correlation of pelagic limestone. Calibrated to base of normal-polarity Chron M20n.		Groupe Français d'Étude du Jurassique, 1997.
	Tithonian/ Kimmeridgian	Candidate sections	Southeastern France – Crussol mountain on the Rhône river just west of Valence, and a quarry at Canjuers – or in Swabia region of southern Germany.	Ammonite, simultaneous lowest occurrence of the ammonites *Hybonoticeras* aff *hybonotum* and *Glochiceras lithographicum* (base of *H. hybonotum* Zone), immediately followed by the lowest occurrence of the *Gravesia* genera.	Base of normal-polarity Chron M22An.	Traditional placement of Kimmeridgian-Tithonian boundary in sub-boreal realm is at base of *Pectinatites (Virgatosphinctoides) elegans* ammonite zone, but this datum is known to be younger than the sub-Mediterranean definition of the boundary.	Atrops, 1982, 1994
Kimmeridgian	*Upper*	Informal usage within sub-Boreal province (Boreal faunal domain)		Base of *Aulacostephanoides mutabilis* ammonite zone.	Probably near the base of normal-polarity Chron M24Bn.	In the sub-Mediterranean realm, the base of an Upper Kimmeridgian substage is typically assigned to the base of the *Aspidoceras acanthicum* Zone. Magnetostratigraphy suggests that this level (lower part of Chron M24r) is about 0.9 myr younger than the sub-Boreal assignment (Ogg, Coe & Atrops, in preparation).	Groupe Français d'Étude du Jurassique, 1997.
	Kimmeridgian/ Oxfordian (traditional Tethyan placement)	Candidate sections	Crussol mountain on the Rhône river just west of Valence, and Châteauneuf d'Oze in the Haute Provence district	Ammonite, base of *Sutneria platynota* Zone.	Just above base of reversed-polarity Chron M25r.	Crussol candidate yielded magnetostratigraphy. Châteauneuf d'Oze candidate did not yield a magnetostratigraphy, but appears more suitable for microfossil biostratigraphy (dinoflagellate cysts) and chemostratigraphy. Magnetostratigraphy, sequence stratigraphy and ammonite constraints indicate that the base of the *S. platynota* zone approximately correlates with the middle of the *Rasenia cymodoce* Zone of the sub-Boreal province (Boreal faunal realm) (Ogg & Coe, in preparation).	Melendez & Atrops, 1999; Atrops, 1994.

(*cont.*)

Table 18.1 (*cont.*)

Stage	Stage boundary *Substage base*	Status	Location and point	Primary markers	Other correlations	Comments	References (GSSP, correlations)
		Global Boundary Stratotype Section and Point					
	Kimmeridgian/ Oxfordian (traditional Boreal placement)	Candidate section	Staffin Bay (Isle of Skye, northwest Scotland)	Ammonite, concident bases of *Pictonia baylei* Zone (Subboreal province) and *Amoeboceras bauhini* Zone (Boreal province)	The base of the *P. baylei* zone is commonly a minor hiatus at a maximum flooding surface (Coe, 1995). In the Staffin Bay section, the Kimmeridgian-Oxfordian boundary is just above the base of a reversed-polarity zone assigned to lower part of polarity Chron M26r (Ogg & Coe, 1997 and in preparation).	Magnetostratigraphy, sequence stratigraphy and ammonite constraints indicate that the base of the *P. baylei* zone approximately correlates with the base of the *Taramelliceras hauffianum* Subzone of uppermost *Epipeltoceras bimammatum* Zone of the sub-Mediterranean province (Tethyan faunal realm) (Ogg & Coe, in preparation).	Melendez & Atrops, 1999; Wright, 1973, 1989; Riding & Thomas, 1997; Wierzbowski, 2002, 2003.
Oxfordian	*Upper*	Informal usage within sub-Boreal province (Boreal faunal domain)		Base of *Perisphinctes cautisnigrae* ammonite zone.		In the sub-Mediterranean province (Tethyan domain), the base of an Upper Oxfordian substage is commonly assigned to the base of the *Perisphinctes (Dichotomoceras) bifurcatus* Zone, and this level is probably slightly older than the Boreal placement. Base of *P. bifucatus* is within a normal-polarity zone that is correlated to magnetic Chron M29n.	Groupe Français d'Étude du Jurassique, 1997.
	Middle	Informal European usage		Base of *Perisphinctes (Arisphinctes) plicatilis* ammonite zone.	Base of *P. plicatilis* Zone is within a brief normal-polarity magnetic zone that is correlated to marine magnetic anomaly M33b(n) (Ogg & Coe, 1997 and in preparation).		Groupe Français d'Étude du Jurassique, 1997.
	Oxfordian/ Callovian	Site of GSSP is undecided.	Leading candidates in Tethyan realm are Thuoux and Savournon near Serres (Provence, Chaines Subalpin) in southeast France. A candidate in Boreal realm is a coastal section (Ham Cliff) near Weymouth (Dorset) in southern England.	Ammonite, *Brightia thuouxensis* Horizon at base of the *Cardioceras scarburgense* Subzone (*Quenstedtoceras mariae* Zone).	Boundary interval is contact of range zone of *Quenstedtoceras mariae* to underlying range zone of *Q. lamberti*. The French candidate section has dinoflagellate markers, but no other macrofossils or microfossils. The boundary in England coincides with a maximum flooding surface (Coe, 1995) and is within a brief normal-polarity magnetic zone that is correlated to M-sequence marine magnetic anomaly M36An (Coe & Ogg, in preparation).	Candidate GSSP sections in France did not preserve a primary magnetostratigraphy, and other faunal groups or chemostratigraphy are not documented.	Melendez, 1999; Fortwengler & Marchand, 1994.

Middle Jurassic							
Callovian	*Upper*	Informal European usage		Base of *Peltoceras (Peltoceras) athleta* ammonite zone*(Kosmoceras (Lobokosmoceras) phaeinum* Subzone).		In the sub-Mediterranean province, the Middle/Upper Callovian boundary is placed at the base of the *Peltoceras (Peltoceras) athleta* Zone*(Hecticoceras (Orbignyiceras) trezeense* Subzone), or approximately a subzone higher than in the sub-Boreal province.	Groupe Français d'Étude du Jurassique, 1997.
	Middle	Informal usage within sub-Boreal province (Boreal faunal domain)		Base of *Kosmoceras (Zugokosmoceras) jason* ammonite zone (at base of *Kosmoceras (Zugokosmoceras) medea* Subzone).	Lower/Middle Callovian substage boundary coincides with a moderate sequence boundary (Call3 of Hardenbol *et al.*, 1998).	In the sub-Mediterranean province, the Lower/Middle Callovian boundary is placed at the base of the *Reineckeia anceps* ammonite zone (*Reineckeia stuebeli* Subzone), which is considered approximately coeval with the sub-Boreal substage boundary placement.	Groupe Français d'Étude du Jurassique, 1997.
	Callovian/ Bathonian	Candidate section	Excavated section of Macrocephalen-Oolith formation in forest preserve "Quellgebiet des Roschbachs" in the upper Eyach valley, about 1 km west of Pfeffingen village in the Albstadt district of the Swabian Alb (30 km south of Tübingen, southwest Germany). *[See footnote a]*	Ammonite, lowest occurrence of the genus *Kepplerites* (Kosmoceratidae), which defines the *Kepplerites (Kepplerites) keppleri* horizon at base of *K. keppleri* Subzone of *Macrocephalites herveyi* Zone in the sub-Boreal province (Great Britain to southwest Germany).	In the sub-Mediterranean province (southern Paris Basin to north Africa and Italy, the basal Callovian zone is the *Bullatimorphites (Kheraiceras) bullatus* Zone defined by the range of the index species. A major latest Bathonian sequence boundary (Bat5 of Hardenbol *et al.*, 1998) is widespread in lower *C. discus* Subzone, and a minor sequence boundary (Call0) coincides with the Bathonian-Callovian boundary level.	The Macrocephalen-Oolith formation, a condensed faciès of iron-oolite-bearing clay to marly limestone, is easily eroded, therefore the complete "Roschbachs" section is only exposed by escavation, then reburied after sampling to prevent removal of its rich ammonite fauna by amateur fossil collectors. The flat-lying section is similar to the profile of Macrocephalen-Ooliths diagrammed by Dietl (1994, fig. 4), but the relative thicknesses are different. *[See footnote a]*	Dietl, 1994; Callomon, 1999; Callomon & Dietl, 2000
Bathonian	*Upper*	Informal usage within sub-Mediterranean province (Tethyan faunal domain)		Base of *Hecticoceras (Prohecticoceras) retrocostatum* ammonite zone.	Approximately coincides with minor sequence boundary (Bat4 of Hardenbol *et al.*, 1998) in NW European basins.	In the Northwest European province (Boreal domain), a substage boundary is commonly assigned to the base of the *Procerites (Procerites) hodsoni* Zone, which is a significantly older level. This level is just above a major sequence boundary (Bat3 of Hardenbol *et al.*, 1998, see Figure 12.1) in NW European basins.	Groupe Français d'Étude du Jurassique, 1997.
	Middle	Informal European usage		Base of *Procerites progracilis* ammonite zone.			

(cont.)

Table 18.1 (*cont.*)

Stage	Stage boundary *Substage base*	Status	Location and point	Primary markers	Other correlations	Comments	References (GSSP, correlations)
		Global Boundary Stratotype Section and Point					
	Bathonian/ Bajocian	Proposed in 1988, but may not be suitable for GSSP.	Ravin du Bès-Bas Auran near Digne, 4 km west of Barrême, Basses-Alpes, southeast France. Proposed GSSP was base of Bed 23 of Sturani (1967) in section of interbedded limestone and marl. Another candidate GSSP is at Cabo Mondego, Portugal.	Ammonite, base of the *Zigzagiceras zigzag* Zone (base of *Parkinsonia (Gonolkites) convergens* Subzone) as marked by the lowest occurrence of *Parkinsonia (G.) convergens*, *P. (P.) pachypleura* and *Morphoceras parvum*.	Just prior to the peak of a major transgression trend in NW Europe	Strata at proposed GSSP did not preserve a primary magnetostratigraphy, are barren of dinoflagellate cysts, and the uppermost Bajocian (*Parkinsonia (Parkinsonia) bomfordi Subzone*) may be absent. A nearby auxiliary GSSP section of La Palud near Castellane places the *P. bomfordi–P. convergens* subzone boundary at Bed 44 (rather than Bed 39, as placed in Innocenti *et al.*, 1988) (Mangold, 1999).	Mangold, 1999; Innocenti *et al.*, 1988.
Bajocian	*Upper*	Informal European usage		Base of *Strenoceras (Strenoceras) niortense* ammonite zone.	Major turnover of ammonite genera occurs at this level as *Teloceras* disappear, and Perisphinctaceae, *Leptosphinctes*, *Strenoceras* and *Garantiana (Orthogarantiana)* appear with some overlap.		Krymholts *et al.*, 1982/1988; Groupe Français d'Étude du Jurassique, 1997.
	Bajocian/ Aalenian	Ratified 1996	Cabo Mondego, Portugal (Murtinheira coastal section at the foot of Cabo Mondego cliff, southwest of the village of Murtinheira, 40 km west of Coimbra and 7 km north of Figueira da Foz). GSSP is base of Bed AB11 (section of Henriques *et al.*, 1988, which corresponds to Bed M337 of Henriques *et al.*, 1994) at 77.8 m level as measured from the base of the coastal section in rhythmic alternations of gray limestone and marl.	Ammonite, lowest occurrence of the genus *Hyperlioceras* (*Toxolioceras*), which defines the base of the *Hyperlioceras discites* Zone.	The GSSP is just below the lowest occurrences of calcareous nannofossils *Watznaueria communis* and *W. fossacincta*. The GSSP at Capo Mondego coincides with the boundary between a reversed-polarity zone in the uppermost Aalenian to a normal-polarity zone spanning the lowermost *H. discites* Zone (Henriques *et al.*, 1994), which is consistent with a composite magnetic pattern derived from other Aalenian–Bajocian studies (e.g., compilation by Ogg, 1995, shown in Figure 12.1). Boundary is near a major sequence boundary (Bj1 of Hardenbol *et al.*, 1998) in NW European basins.	Auxiliary Stratotype Point is at Bearreraig Bay, about 10 km north of Portree on the eastern coast of the Isle of Skye in western Scotland. The boundary level is at the base of Bed U10 in the lower Udairn Shale Member, 12.4 m above the base of the section as revised by Morton (in Pavia *et al.*, 1995). Base of the Bajocian in this section is marked by radiation of gonyaulacacean dinoflagellate cysts, is within the NJ8b nannofossil Subzone, and is just above the lowest occurrence of inoceramid bivalve *Mytiloceramus polyplocus*.	Henriques *et al.*, 1994; Pavia & Enay, 1997; enhanced CD-ROM from M.H. Henriques (hhenriq@cygnus.ci.uc.pt)
Aalenian	*Upper*	Informal		Base of *Graphoceras concavum* ammonite zone.	Transgression above major lowstand (Aa2) in NW European basins		

	Middle	Informal European usage		Base of *Ludwigia murchisonae* ammonite zone.	Just above a major sequence boundary (Aa1 of Hardenbol *et al.*, 1998) in NW European basins.		
	Aalenian/ Toarcian	Ratified 2000	Fuentelsalz at Nuevalos, Spain, in central sector of the Castelian Branch of the Iberian Range, about 170 km ENE of Madrid and 30 km north of Molina de Aragon). GSSP is base of calcareous Bed 107 within an expanded uppermost Toarcian-lowermost Aalenian succession of flat-lying rhythmic alternations of marl and limestone.	Ammonite, lowest occurrence of genus *Leioceras* (base of *Leioceras opalinum* Zone), which evolved from *Pleydellia*.	Evolution of the ammonite Subfamily Grammoceratinae and Leioceratinae. Boundary interval is within a normal-polarity magnetozone which, with the underlying reversed-polarity magnetozone in the lower part of the *Pleydellia aalensis* zone (uppermost zone of Toarcian). Diversity changes are recorded by brachiopods, bivalves, benthic foraminifera, ostracods and calcareous nannofossils in the Fuentelsaz section; although the most significant faunal events generally take place in the uppermost Toarcian before the boundary (Goy *et al.*, 1996). The boundary interval is the lower part of a minor trangressive systems tract (Hardenbol *et al.*, 1998).	Wittnau at Freiburg in south Germany was the other main GSSP candidate (Ohmert, 1996).	Goy *et al.*, 1994, 1996; Cresta *et al.*, 2001.
Lower Jurassic							
Toarcian	*Upper*	Informal European usage		Base of *Grammoceras thouarsense* ammonite zone.		An alternate two-fold subdivision of Toarcian places an Upper/Lower substage boundary at the base of the *Haugia variabilis* ammonite zone.	Groupe Français d'Étude du Jurassique, 1997
	Middle	Informal European usage		Base of *Hildoceras bifrons* ammonite zone.	Major maximum flooding surface in NW European basins.		Groupe Français d'Étude du Jurassique, 1997
	Toarcian/ Pliensbachian	Location and global correlation debated.	Main candidate profile for the GSSP is Ponte da Trovã-Cruz dos Remedios secton at Peniche, Portugal. Another candidate is at Aït Moussa in the Middle Atlas of Morocco.	Ammonite, lowest occurrence of a diversified *Eodactylites* fauna (Simplex horizon, sensu Goy *et al.*, 1997) with the association *Paltarpites-Tiltoniceras-Eodactylites*, which correlates with the northwest European *Palterpites paltus* horizon/subzone.	Toarcian-Pliensbachian boundary interval is marked by a massive surge of Dactylioceratide (*Eodactylites*) and Hildoceratide ammonite families of Tethyan origin and extinction of Boreal amaltheid family. Base of Toarcian is an important maximum flooding surface above a major sequence boundary (Pl8) and minimum in seawater strontium-isotope ratios.	Widespread condensation or gaps at the base of the Toarcian strata (*Dactylioceras tenuicostatum* ammonite zone) necessitated selection of candidate GSSPs in the Mediterranean region where gaps in the succession are less pronounced	Elmi, 1999, 2003.
Pliensbachian	*Upper (Carixian substage)*	Informal European usage		Base of *Amaltheus margaritatus* ammonite zone.	Appearance of the *Amaltheus* ammonite genera (typically *Amaltheus stokesi*).	The Domerian is the informal name for the lower substage of Pliensbachian.	Colloque du Jurassique à Luxembourg 1962 (1964)

(*cont.*)

Table 18.1 (*cont.*)

Stage	Stage boundary *Substage base*	Global Boundary Stratotype Section and Point: Status	Location and point	Primary markers	Other correlations	Comments	References (GSSP, correlations)
	Pliensbachian/ Sinemurian	ICS voting 2003	Wine Haven section of claystone, Robin Hood's Bay, Yorkshire, England. GSSP is at base of clay Bed 73b, 6 cm above a thin calcareous nodule Bed 72 of Hesselbo and Jenkyns (1995).	Ammonite, lowest occurrences of *Bifericeras donovani* and of genera *Apoderoceras* and *Gleviceras.*	Lowest occurrences of ammonites *Apoderoceras nodogigas, A. leckenbyi, Tetraspidoceras quadrarmatum,* and *P. taylori.* Uppermost Sinemurian has the disappearance of the Echioceratidae ammonite family. Dinoflagellate cysts are absent, microfauna studies have not been published, and magnetostratigraphy is unavailable. The potential boundary level displays a seawater 87Sr/86Sr ratio of 0.707425 and oxygen isotopes from belemnites suggest a local seawater temperature drop of about 5 C (Hesselbo *et al.*, 2000; Meister, 2001). This level is just below a maximum flooding surface in British sections (Hesselbo & Jenkyns, 1998).	Of 27 regions considered by the Pliensbachian boundary working group, only a single candidate in Yorkshire, England, appeared to be satisfactory for a potential GSSP. A section at Aselfingen in the historical area in southwest Germany is condensed limestone and clay with rare ammonites, but allows calibration of secondary markers in ostracods and dinocysts (Meister, 1999a). Boundary corresponds to Strontium 87/86 ratio of 0.707425 ± 0.000021.	Meister, 1999a,b, 2001; Hesselbo *et al.*, 2000, Meister *et al.*, 2003.
Sinemurian	*Upper (Lotharingian substage)*	Informal European usage		Base of *Asteroceras obtusum* ammonite zone.	Just above a major sequence boundary (Si3) in NW European basins.	Lower substage of Sinemurian does not have a secondary informal name.	Krymholts *et al.*, 1982/1988; Groupe Français d'Étude du Jurassique, 1997
	Sinemurian/ Hettangian	Ratified 2000	East Quantoxhead section of interbedded limestone and claystone at the coastal exposures 500m north of court house of village of Quantock's Head, 6 km east of Watchet, southern coast of the Bristol Channel, West Somerset, England. Within a bituminous shale between calcareous claystone Beds 145 and	Ammonite, lowest occurrence of arietitid genera *Metophioceras s. str.*, and *Vermiceras* (base of *Metophioceras conybearoides* subzone of *Coroniceras (Arietites) bucklandi* ammonite zone). Just below the highest occurrence of the genera *Schlotheimia* that is characteristic of the uppermost Hettangian.	Sinemurian-Hettangian boundary is within a transgressive episode following a latest Hettangian lowstand in British sections (Hesselbo & Jenkyns, 1998). Foraminifer *Lingulina tenera* plex (latest Hettangian) and appearance of *Planularia inaequistriata* and the *Frondicularia terquemi* plexus group (basal Sinemurian). There are no conspicuous changes in ostracods, palynology, pelecypods or brachiopods across the boundary interval, and magnetostratigraphy was not successful.	This turnover of ammonite genera is a world-wide event that marks the boundary interval (Sinemurian Boundary Working Group, 2000).	Page *et al.*, 2000; Sinemurian Boundary Working Group, 2000; Bloos & Page, 2002.

recommended substages						
Hettangian/ Rhaetian (= base of Jurassic)	Debated criteria and location	Four main candidates: (1) Chilingote, Peru on the west side of the Utcubamba Valley (Hillebrandt, 1997, 1994), (2) southeast shore of Kunga Island, Queen Charlotte Islands, British Columbia, Canada (Tipper *et al.*, 1994; Carter *et al.*, 1998), (3) New York Canyon area, Gabbs Valley Range, Nevada (Guex *et al.*, 1997; Guex, 1995), and (4) St. Audrie's By, Somerset, England (Warrington *et al.*, 1994; Page and Bloos, 1998).	Ammonite, first occurrence of the smooth *planorbis* group within the ammonite genus *Psiloceras*.	Extinction of conodonts. Radiolarian assemblages (top of the latest Triassic *Globolaxtorum tozeri* zone and base of earliest Hettangian *Conoptum merum* zone) (e.g., Carter *et al.*, 1998). Earliest stage of transgression after major eustatic lowstand.	The *Planorbis* ammonite group is described under several names *(planorbis, tilmanni, pacificum, calliphyllum,* etc.), which probably characterize local morphologic varieties of a single species or closely related coeval species (Guex *et al.*, 1997). Peru and Nevada sections contain ammonite assemblages of both the uppermost Rhaetian and lowermost Hettangian. Only the uppermost Triassic of the Somerset section has a published magnetic polarity stratigraphy (Briden and Daniels, 1999), but an expanded bio-magnetostratigraphy for that section is forthcoming (cited by Warrington and Bloos, 2001). Age of the Triassic–Jurassic boundary is constrained by a U-Pb zircon age of 199.6 ± 0.3 Ma on a tuff layer in the uppermost Rhaetian (top of Triassic) at the Kunga Island (British Columbia) section (Pálfy *et al.*, 2000a).	Bloos, 1999; Warrington, 1999; Page & Bloos, 1998; Pálfy *et al.*, 2000a.

Footnotes:

[a] *[Callovian/Bathonian candidate GSSP]* Most of the *K. keppleri* Subzone (basal Callovian) is encompassed within 70 cm and overlies a 8-cm-thick bed of uppermost Bathonian (the *hockstetteri* horizon (var. *hockstetteri* of *Clydoniceras discus)* of the *C. discus* Subzone. The boundary stratigraphic interval is bounded by unconformities – the basal Callovian *keppleri* Subzone is overlain by the *Kepplerities (Gowericeras) gowerianus* Subzone of the *Proplanulites koenigi* Zone implying omission of the two upper subzones of the *M. herveyi* Zone, and the uppermost Bathonian *hockstetteri* Horizon overlies the *Hecticoceras (Prohecticoceras) blanazense* Subzone of the *Oxycerites orbis* Zone implying omission of the majority of the *C. discus* Zone. Preliminary magnetostratigraphy of the candidate GSSP section at Roschbachs (Ogg and Dietl, unpublished) suggests significant omission surfaces where polarity zone and ammonite biozone boundaries coincided, including the Bathonian–Callovian contact, although the main polarity pattern may provide a useful secondary correlation tool for the boundary interval into other provinces.

Germany comprises condensed limestone and clay with rare ammonites, but allows calibration of secondary markers in ostracods and dinocysts (Meister, 1999a,b).

Pliensbachian substages The Pliensbachian has two substages. The lower substage of Carixian was named by Lang (1913) after Carixia, the Latin name for Charmouth, France. The upper stage was named Domerian by Bonarelli (1894, 1895) after the type section in the Medolo formation at Monte Domaro in the Lombardian Alps of northern Italy.

The Colloque du Jurassique à Luxembourg 1962 (1964) assigned the boundary between the Carixian and Domerian substages to the base of the *Amaltheus margaritatus* ammonite zone, at the appearance of the *Amaltheus* genera (typically *Amaltheus stokesi*). This level is just below the sequence boundary ("Pl5" of Hardenbol *et al.*, 1998) in British sections (Hesselbo and Jenkyns, 1998; Fig. 18.1).

TOARCIAN

History, definition, and boundary stratotype candidates The Toarcian Stage was defined by d'Orbigny (1842–51, 1852) at the Vrines quarry, 2 km northwest of the village of Thouars (Toarcium in Latin) in the Deux-Sévres region of west-central France. The thin-bedded succession of blue-gray marl and clayey limestone spans the entire Toarcian with 27 ammonite horizons grouped into eight ammonite zones (Gabilly, 1976).

The Toarcian–Pliensbachian boundary interval marks a major extinction event in western Europe among rhynchonellid brachiopods, ostracod fauna, benthic foraminifera, and bivalves, and turnover in ammonites and belemnites, but the extinction event appears to be a phenomenon of regional, not global, extent (Hallam, 1986). The base of the Toarcian is marked by a massive surge of Dactylioceratide (*Eodactylites*) ammonites and extinction of the Boreal amaltheid family. Seawater strontium isotope ratios, which had been declining since the Hettangian, reach a minimum in the latest Pliensbachian.

The base of the Toarcian strata at Thouars, and throughout northwest Europe, is an important maximum flooding surface and associated condensation or gaps above a major sequence boundary (Pl8 in Fig. 18.1) in the *Dactylioceras tenuicostatum* ammonite zone. This widespread hiatus necessitates selection of candidate GSSPs in the Mediterranean region where gaps in the succession are less pronounced (Elmi, 1999). The primary marker of the Toarcian GSSP will be the lowest occurrence of a diversified *Eodactylites* ammonite fauna (Simplex horizon, *sensu* Goy *et al.*, 1996; Table 18.1). The best profile currently available is in Peniche, Portugal, where the Tethyan *Eodactylites* fauna is succeeded by an "English" *Orthodactylites* succession (Elmi, 2003).

Toarcian substages There is no agreement on the number of substages of the Toarcian. A binary subdivision following that by Oppel (1856–8) places a substage boundary at the base of the *Haugia variabilis* ammonite zone, at the appearance of abundant Phymatoceratinae group of ammonites, particularly the *Haugia* genus (e.g. Krymholts *et al.*, 1982–8; Burger, 1995). An alternate three-substage division (e.g. Groupe Français d'Etude du Jurassique, 1997) groups the *Haugia variabilis* and underlying *Hildoceras bifrons* Zones into a Middle Toarcian, and places the limit of an Upper Toarcian at the base of the *Grammoceras thouarsense* Zone. There are no recommendations for a potential GSSP(s) for the substage boundary(s).

18.1.3 Middle Jurassic

The black clays that are typical of the Early Jurassic (*Schwarzer Jura*) are overlain in southwestern Germany by strata containing clayey sandstone and brown-weathering ferruginous oolite. Therefore, these strata were grouped as the Brown Jurassic (*Brauner Jura*) by von Buch (1839), and this lithologic change has been retained in the assignment of the base of the Middle Jurassic (the base of the Aalenian). This Middle Jurassic interval is characterized by shallow-marine carbonates and siliciclastics in southern England, which comprised the Lower Oolite group of Conybeare and Phillips (1822) or the expanded "Bathonian Stage" of d'Omalius d'Halloy (1868, p. 470). The lower portion (Lower Oolite or Dogger strata) of the "Bathonian" of southern England was classified as a separate Bajocian Stage by d'Orbigny (1842–51, 1852). In turn, Mayer-Eymar (1864) separated the lower portion of d'Orbigny's "Bajocian" into a distinct Aalenian Stage.

The upper limit of the Middle Jurassic or Dogger of Oppel (1856–8) was placed at the base of the Kellaway Rock, England, hence at the base of the associated Callovian Stage of d'Orbigny (1842–51, 1852). The Colloque du Jurassique à Luxembourg 1962 (Maubeuge, 1964) reassigned the Callovian Stage into the Middle Jurassic series as preferred by Arkell (1956).

The bases of the Aalenian and Bajocian stages (and probably soon the Bathonian) have been marked by GSSPs in expanded sections of rhythmic alternations of limestone and marl. The placement of a base for the Callovian Stage has been hindered by a ubiquitous condensation or hiatuses in strata of northwest Europe.

AALENIAN

History, definition, and boundary stratotype The Aalenian Stage was proposed by C. Mayer-Eymar (1864) for the lowest part of the "Braunjura" in the vicinity of Aalen at the northeastern margin of the Swabian Alb (southwestern Germany) where iron ore was mined from the associated ferruginous oolite sandstones (Dietl and Etzold, 1977; Rieber, 1984). His lithologic-based definition truncated the Bajocian Stage of d'Orbigny (1842–51, 1852) at the base of the *Sonninia sowerbyi* ammonite zone.

The biostratigraphic recognition of the base of the Middle Jurassic was traditionally assigned to the evolution of the ammonite subfamily Grammoceratinae and Leioceratinae, in particular the first occurrence of species of the genus *Leioceras*, which evolved from *Pleydellia*. The Aalenian GSSP in the Fuentelsaz section in Spain corresponds to this ammonite marker (Goy *et al.*, 1994, 1996; Cresta *et al.*, 2001; Table 18.1). This section of alternating marl and limestone yielded a magnetostratigraphy that could be correlated to a composite magnetic pattern derived from other sections in Europe. A secondary reference section for the base of Aalenian is at Wittnau, near Freiburg, south Germany (Ohmert, 1996).

Aalenian substages The four ammonite zones of the Aalenian are grouped into three substages: the Lower Aalenian is equivalent to the *Leioceras opalinum* Zone, the Middle Aalenian comprises the *Ludwigia murchisonae* and *Brasilia bradfordensis* Zones, and the Upper Aalenian is the *Graphoceras concavum* Zone.

BAJOCIAN

History, definition, and boundary stratotype The Bajocian Stage was named by d'Orbigny (1842–51, 1852) after the town of Bayeux, Normandy (Bajoce in Latin). The abandoned quarries from which the stage was first described are now overgrown, and the nearby coastal cliff section of Les Hachettes indicates that most of the lower Bajocian is a hiatus and erosional surface, and the upper Bajocian is largely condensed in a 5-cm-thick layer (Rioult, 1964). Ammonite lists of d'Orbigny indicate that he erroneously assigned species of the upper Toarcian to the lower Bajocian and vice versa. This confusion was the reason why Mayer-Eymar (1864) distinguished the Aalenian Stage for the deposits between the Toarcian and Bajocian.

The Colloque du Jurassique à Luxembourg 1962 (Maubeuge, 1964) defined the Bajocian Stage to begin at the base of the *Sonninia sowerbyi* ammonite zone and to extend to the top of the *Parkinsonia parkinsoni* Zone. However, the holotype of the *Sonninia sowerby* index species was later discovered to be a nucleus of a large Sonniniidae (*Papilliceras*) from the overlying *Otoites sauzei* Zone (Westermann and Riccardi, 1972). Therefore, the basal ammonite zone of the Bajocian was redefined as the *Hyperlioceras discites* Zone, with the zonal base marked by the lowest occurrence of the ammonite genus *Hyperlioceras* (*Toxolioceras*), which evolved from *Graphoceras* (both in ammonite family Graphoceratidae).

Two sections recorded this ammonite datum with supplementary biostratigraphic and magnetostratigraphic data: Murtinheira at Cabo Mondego, Portugal (selected for the GSSP), and Bearreraig Bay on the Isle of Skye, Scotland (selected as an auxiliary stratotype point), (Pavia and Enay, 1997). The GSSP at coastal Cabo Mondego (Table 18.1) comprises rhythmic alternations of gray limestone and marl (Henriques, 1992; Henriques *et al.*, 1994), and was ratified in 1996 (Pavia and Enay, 1997).

Bajocian substages The base of the Upper Bajocian is the base of the *Strenoceras (Strenoceras) niortense* ammonite zone. (In older literature, the base was assigned as the base of the "*Strenoceras*" *subfurcatum* Zone, until it was recognized by Dietl (1981) that the holotype of the index species belongs to *Garantiana* and had originated from the overlying zone, therefore this zone became invalid.) A major turnover of ammonite genera occurs at this level (Table 18.1).

BATHONIAN

History, definition, and proposed boundary stratotype The former Bathonian Stage of d'Omalius d'Halloy (1843) was named after the town of Bath in southern England, where strata characterized by oolitic limestone are exposed in a number of quarries, but these are incomplete and lack adequate characterization by ammonites (Torrens, 1965). The lower half of the originally "Bathonian" exposed in Normandy was reclassified as the Bajocian Stage in the system of d'Orbigny (1842–51, 1852), but he did not specify a revised stratotype for the shortened Bathonian, nor provide an unambiguous lower boundary. Indeed, d'Orbigny's description suggests that he included the present "Lower Bathonian" substage within his Bajocian (Rioult, 1964). A century of confusion ended when the base of the Bathonian Stage was defined by the Colloque du Jurassique à Luxembourg 1962 (Maubeuge, 1964) as the base of the *Zigzagiceras zigzag* ammonite zone.

The basal-Bathonian is well developed in southeastern France. A GSSP was suggested within inter-bedded limestone and marl at Ravin du Bès-Bas Auran, near Digne, Basses-Alpes (Innocenti *et al.*, 1988; Table 18.1). However, the strata do not preserve a primary magnetostratigraphy and are barren of dinoflagellate cysts (Mangold, 1999). In addition, the uppermost Bajocian (*Parkinsonia (Parkinsonia) bomfordi* subzone) may be absent, indicating that the proposed GSSP level is a hiatus (Dietl, 1995, as reported by Mangold, 1997). Another GSSP candidate is Cabo Mondego, Portugal, the same section that defines the base of the underlying Bajocian, but its uppermost Bajocian zone is poorly preserved (Fernández-López, 2003).

Bathonian substages The Bathonian is generally divided into three substages, with the base of the Middle Bathonian placed at the base of the *Procentes progracilis* ammonite zone.

A divergence of ammonite assemblages in the upper Middle Bathonian has resulted in different bases of an Upper Bathonian substage in each province. In the sub-Mediterranean province (Tethyan domain), a Middle–Upper Bathonian boundary is assigned to the base of the *Hecticoceras (Prohecticoceras) retrocostatum* Zone. In the northwest European province (Boreal domain), a substage boundary is commonly assigned to the base of the *Procerites (Procerites) hodsoni* Zone, which is a significantly older level (Groupe Français d'Etude du Jurassique, 1997).

CALLOVIAN

History, definition, and proposed boundary stratotype The Callovian Stage was named by d'Orbigny (1842–51, 1852) after the village of Kelloway, Wiltshire, England, 3 km northeast of Chippenham. The "Kelloways Stone" contains abundant cephalopods, including *Ammonites calloviensis* (*Sigaloceras calloviensis* in current taxonomy), and d'Orbigny considered "*Calloviens*" to be a derivative of Kelloway. Oppel (1856–8) placed the base of his "Kelloway gruppe" at the base of the *Macrocephalites macrocephalus* Zone, or at the lithologic contact of the Upper Cornbrash with the underlying Forest Marble Formation (currently the upper part of the *Clydoniceras discus* subzone of uppermost Bathonian). At this contact, ammonites of the genus *Macrocephalites* replace *Clydoniceras*, but much of the upper Cornbrash is condensed and/or a deposit "representing but a fraction of the time-intervals involved" (Cope *et al.*, 1980a).

Callomon (1964, 1999) noted that the base of the *Macrocephalites macrocephalus* subzone in "standard chronostratigraphy" was initially defined by Arkell (1956) as the base of Bed 4, at the Sutton Bingham section, near Yeovil, Somerset, England; therefore, this served as the de facto GSSP for the base of the Callovian Stage. However, the lowest occurrence of *Macrocephalites* genera was later discovered to be in strata equivalent to the Upper Bathonian (Dietl, 1981; Dietl and Callomon, 1988), therefore the "standard" *Macrocephalites macrocephalus* Zone was abandoned, and the base of the Callovian was assigned to the lowest occurrence of the genus *Kepplerites* (Kosmoceratidae), which defined a basal horizon of *Kepplerites (Kepplerites) keppleri* (base of *K. keppleri* subzone of *Macrocephalites herveyi* Zone) in the sub-Boreal province (UK to southwest Germany). The uppermost Bathonian is the *hockstetteri* horizon (var. *hockstetteri* of *Clydoniceras discus*) of the *C. discus* subzone, *C. discus* Zone.

A continuous transition between the uppermost Bathonian and basal-Callovian is rarely preserved. A proposed GSSP with an apparently complete boundary at the resolution level of ammonite successions is in the Albstadt district of the Swabian Alb, southwest Germany (Dietl, 1994; Callomon and Dietl, 2000; Table 18.1). The Macrocephalen-Oolith Formation (Unit ε of the Brown Jura facies) is a condensed facies of iron-oolite-bearing clay to marly limestone, and the compact Bathonian–Callovian boundary interval is bounded by unconformities and may contain minor hiatuses (Table 18.1). Therefore, this suggested GSSP has not yet been adopted by the International Stratigraphic Commission.

In the sub-Mediterranean province (southern Paris Basin to north Africa and Italy), the basal-Callovian zone is the *Bullatimorphites* (*Kheraiceras*) *bullatus* Zone defined by the range of the index species (Groupe Français d'Etude du Jurassique, 1997). Strong ammonite biogeographic differences require these two regions to have distinct and poorly correlated zonations until the middle of the Callovian.

Callovian substages The Callovian Stage is generally divided into three substages. The substage boundaries correspond to two important changes in ammonite fauna, but ammonite provincialism and utilization of different faunal successions lead to different placements within each realm that do not necessarily coincide (Groupe Français d'Etude du Jurassique, 1997).

In the sub-Boreal province, the Lower–Middle Callovian boundary is placed at the base of the *Kosmoceras* (*Zugokosmoceras*) *jason* Zone (base of *Kosmoceras* (*Zugokosmoceras*) *medea* subzone), above the *Sigaloceras* (*Sigaloceras*) *calloviense* Zone (*Sigaloceras* (*Catasigaloceras*) *enodatum* subzone). In the sub-Mediterranean province, the Lower–Middle Callovian boundary is placed at the base of the *Reineckeia anceps* Zone (*Reineckeia stuebeli* subzone), above the *Macrocephalites* (*Dolikephalites* *gracilis* Zone (*Indosphinctes patina* subzone). These two levels are considered approximately coeval.

The Middle–Upper Callovian boundary in the sub-Boreal province is assigned to the base of the *Peltoceras* (*Peltoceras*) *athleta* Zone (*Kosmoceras* (*Lobokosmoceras*) *phaeinum* subzone), above the *Erymnoceras coronatum* Zone (*Kosmoceras* (*Zugokosmoceras*) *grossouvrei* subzone). The Middle–Upper Callovian boundary in the sub-Mediterranean province is assigned to the base of the *Peltoceras* (*Peltoceras*) *athleta* Zone (*Hecticoceras* (*Orbignyiceras*) *trezeense* subzone), above the *Erymnoceras coronatum* Zone (*Rehmannia* (*Loczyceras*) *rota* subzone), or approximately a subzone higher than in the sub-Boreal province (Groupe Français d'Etude du Jurassique, 1997).

18.1.4 Upper Jurassic

The brownish-weathering deposits of the Middle Jurassic (*Brauner Jura*) in southwestern Germany are overlain by units dominated by calcareous claystone and limestone. Therefore, these carbonates were grouped as the White Jurassic (*Weisser Jura*) by von Buch (1839), and the base of the current Upper Jurassic (the base of the Oxfordian) coincides approximately with this lithologic change. This Upper Jurassic interval, or former "Malm," is approximately equivalent to the Middle and Upper Oolite group of Conybeare and Phillips (1822) in England. Both the White Jurassic of southwest Germany and the English strata undergo a shallowing upward in the latest Jurassic, and are erosionally truncated or are overlain by non-marine deposits. Southern England provided the reference sections when d'Orbigny (1842–1851, 1852) subdivided the Upper Jurassic into four stages (Oxfordian, Corallian, Kimmeridgian, and Portlandian), and designated the base of the Cretaceous as the Purbeck Stage, followed by the Neocomian Stage. Oppel (1856–1858) eliminated d'Orbigny's Corallian and Portlandian Stages, and extended the Kimmeridgian to the base of the Purbeckian (also considered to be Cretaceous). Oppel left an interval "unassigned" between his Oxfordian and Kimmeridgian groups (his *Diceras arietina* Zone, approximately equivalent to the Upper Calcareous Grit Formation of Dorset, England). Later, Oppel (1865) created a new uppermost Jurassic stage, the Tithonian, in the Mediterranean region that encompassed the upper part of his previous "Kimmeridgian group" and extended to the base of the Neocomian Stage. However, Oppel did not specify the limits or reference sections for the Tithonian Stage concept. The situation was further distorted when the "Berriasian" Stage of Coquand (1871) came into common use to designate the lowermost Cretaceous, even though it overlapped with the original concept of the Tithonian Stage.

The combination of (1) the shuffling of Upper Jurassic stage nomenclature coupled with imprecise definitions, (2) a pronounced faunal provincialism during the majority of the Upper Jurassic that precluded precise correlation even within northwest Europe, and (3) widespread hiatuses in the reference sections resulted in a proliferation of regional stage and substage nomenclature. Finally, after a century of debate, the Colloque du Jurassique à Luxembourg 1962 (1964) voted to "return to the original sense of this stage [Oxfordian] as defined by A. d'Orbigny and given precision by W. J. Arkell" and to discontinue regional usage of a "Purbeckian" Stage, because it was primarily a local facies. However, the controversy over other Upper Jurassic stage definitions or the placement of the Jurassic–Cretaceous boundary led the Collogue to "refer the question back for consultation among interested specialists." During the 1980s and 1990s, the International Subcommission on Jurassic Stratigraphy established that the Upper Jurassic consists of the Oxfordian, Kimmeridgian, and Tithonian stages. Through a fortunate episode of biogeography, an inter-regional biostratigraphic definition of the base of the Oxfordian is well established with ammonites. However, it has proven difficult to correlate potential definitions for the bases of the Kimmeridgian and Tithonian stages, and long-held traditions of regional equivalence have proven to be erroneous.

OXFORDIAN

History, definition, and boundary stratotype candidates The Oxfordian Stage of d'Orbigny (1842–51, 1852) was named after the town of Oxford, Oxfordshire, England, with reference to the Oxford Clay Formation, and was overlain by his "Coralline Stage." Oppel (1856–8) incorporated the majority of the "Corallian Stage" into his expanded Oxfordian group. Oppel assigned the base of his "Oxfordian Stage" to both the contact between the Oxford Clay Formation and the underlying Kelloway Rock in Yorkshire (now considered to be approximately the Lower–Middle Callovian boundary) and to the top of the *Peltoceras athleta* ammonite zone (now considered to be middle of the Upper Callovian). He also left "unassigned" a suite of strata between his "Oxfordian" and overlying "Kimmeridgian Stage."

Ammonites across the Callovian–Oxfordian boundary interval were studied by Arkell (1939, 1946), who placed the boundary at the contact of the range zones of *Vertumniceras mariae* (now placed in the *Quenstedtoceras* genus) above *Quenstedtoceras lamberti*, or the base of the Oxford Clay Formation in Yorkshire. This is consistent with the historical usage in southwest Germany, where the Upper or "White" Jurassic begins just above the Lamberti Knollen bed. The Colloque du Jurassique à Luxembourg 1962 (Maubeuge, 1964) selected Arkell's biostratigraphic definition for the base of the Oxfordian Stage. The Colloque also assigned the upper limit of the Oxfordian as the top of the *Ringsteadia pseudocordata* ammonite zone in the Boreal realm.

The ammonite succession across the *Q. lamberti–Q. mariae* interval has been studied in expanded dark clay sections in southeast France (e.g. Fortwengler and Marchand, 1994) and two complementary sections were recommended as basal-Oxfordian GSSPs (Melendez, 1999; Table 18.1). The basal-Oxfordian was proposed as the *Brightia thuouxensis* Horizon at base of the *Cardioceras scarburgense* subzone (*Quenstedtoceras mariae* Zone), above the uppermost Callovian *Cardioceras paucicostatum* Horizon. However, except for dinoflagellates, these French sections have not yet proved suitable for other stratigraphic correlation methods, therefore the GSSP proposal was suspended (e.g. Melendez, 2002, 2003). A coastal section near Weymouth (Dorset, southern England) is in a facies suitable for magnetostratigraphy, where the base of the Oxfordian is correlated to a brief normal-polarity marine magnetic anomaly M36An (Coe and Ogg, unpublished), and is being considered as a reference section for the Callovian–Oxfordian boundary in the Boreal domain (Melendez, 1999; Table 18.1).

Oxfordian substages Traditionally, the base of the Middle Oxfordian substage is placed at base of the *Perisphinctes* (*Arisphinctes*) *plicatilis* Zone.

Beginning with the Middle Oxfordian, faunal differentiation in separate basins became more pronounced and has inhibited standardization and correlation of regional ammonite zones. In addition, even though regional zonal nomenclatures have commonly remained constant, the assigned boundaries of biostratigraphic units have undergone re-definition (e.g. Glowniak, 1997; Groupe Français d'Etude du Jurassique, 1997).

In the sub-Mediterranean province (Tethyan domain), the base of an Upper Oxfordian substage is commonly assigned to the base of the *Perisphinctes* (*Dichotomoceras*) *bifurcatus* Zone. In the sub-Boreal province (Boreal domain), this substage boundary is assigned to the base of the *Perisphinctes cautisnigrae* Zone. These two levels may be approximately synchronous (Groupe Français d'Etude du Jurassique, 1997).

KIMMERIDGIAN

History, revised definition, and boundary stratotype candidates The Kimmeridgian Stage was named by d'Orbigny (1842–51, 1852) after the coastal village of Kimmeridge in Dorset, England, where the spectacular cliffs of dark gray Kimmeridge Clay expose a continuous record of that interval. Oppel (1856–8) expanded the Kimmeridgian downward by incorporating a portion of d'Orbigny's former Corallian Stage, but, rather than assign a boundary between the Oxfordian and Kimmeridgian, he left the intervening Upper Calcareous Grit Formation "unassigned." Oppel initially indicated that the Kimmeridgian "group" would continue upward to the base of the Purbeck (his base of the Cretaceous), but later, Oppel (1865) inserted a Tithonian Stage as the uppermost Jurassic stage. Therefore neither boundary of the Kimmeridgian Stage was adequately defined.

The Oxfordian–Kimmeridgian boundary was defined by Salfeld (1914) after studying the Perisphinctidae ammonite succession from the boundary interval. He proposed that the boundary should be placed between the *Ringsteadia anglica* Zone (now called *Ringsteadia pseudocordata* Zone) in the uppermost Oxfordian and the appearance of *Pictonia* at the base of the Kimmeridgian. The Colloque du Jurassique à Luxembourg 1962 (Maubeuge, 1964) fixed the base of the Kimmeridgian as the base of the *Pictonia baylei* Zone. However, due to faunal provincialism that began in the middle Oxfordian, the ammonite zonation of England (Boreal domain) could not be correlated to the sub-Mediterranean province (Tethyan domain). The Colloque du Jurassique à Luxembourg 1962 (Maubeuge, 1964) indicated that this level was equivalent to the base of the *Sutneria platynota* Zone of the sub-Mediterranean province.

However, this presumed equivalence was later demonstrated to be incorrect from comparisons of dinoflagellate cyst assemblages (Brenner, 1988; Melendez and Atrops, 1999) and rare incursions of ammonites from the Boreal domain into the sub-Mediterranean successions in Poland and the Swabian Alb (Atrops *et al.*, 1993; Matyja and Wierzbowski, 1997; Schweigert and Callomon, 1997). The chain of logic from ammonite assemblages is (1) ammonite *Pictonia densicostata* (Salfeld) occurs in the lower *Pictonia baylei* Zone, which is the basal zone of the "Kimmeridgian" Stage as currently used in sub-Boreal province, in Dorset; (2) *Pictonia densicostata* occurs with *Amoeboceras bauhini* (Oppel) in South Ferriby in eastern England and on the Isle of Skye in northwest Scotland; and (3) *Amoeboceras bauhini* occurs in the *Taramelliceras hauffianum* subzone of the *Epipeltoceras bimammatum* Zone (middle of the "upper Oxfordian" as currently used in the sub-Mediterranean province) in southwest Germany and in Poland. Assuming a narrow and synchronous range of *A. bauhini* among these localities, then the current placement of the base of the "Kimmeridgian" Stage in Britain is significantly younger (approximately one-and-a-half ammonite zones, or about 1 myr) than the base of the "Kimmeridgian" Stage as used in the sub-Mediterranean province (Fig. 18.1). This biostratigraphic conclusion is supported by comparing magnetostratigraphy and sequence stratigraphy patterns of the UK with different regions in the sub-Mediterranean province (Ogg and Coe, 1997, and in prep.).

This temporal offset has created a dilemma in selecting a GSSP for the base of the Kimmeridgian Stage, because an initial choice must be made between faunal provinces and the corresponding definition of the Oxfordian–Kimmeridgian boundary (reviewed in Atrops, 1999; Melendez and Atrops, 1999; and Wierzbowski, 2001).

In the Boreal realm, the leading candidate for a GSSP is the coincident base of the *Pictonia baylei* Zone (sub-Boreal province) and *Amoeboceras bauhini* Zone (Boreal province) in a succession of medium-gray clays at Staffin Bay (Isle of Skye, northwest Scotland) containing abundant ammonites and dinoflagellate cysts (Wright, 1973, 1989; Riding and Thomas, 1997; Melendez and Atrops, 1999; Wierzbowski, 2002, 2003). At this Staffin Bay section, the base of the *P. baylei* Zone is just above the base of a reversed-polarity zone assigned to lower Chron M26r (Ogg and Coe, 1997, and in prep.).

In the sub-Mediterranean province, southwestern France has two main candidates for a GSSP at the base of the *S. platynota* Zone in inter-bedded limestone and marl: Crussol mountain on the Rhône river just west of Valence (Atrops, 1982, 1994) and Châteauneuf d'Oze in the Haute Provence district (Atrops, 1994; Melendez and Atrops, 1999). The base of the *S. platynota* Zone at Crussol is just above the base of reversed-polarity zone M25r (Ogg and Atrops, in prep.). Châteauneuf d'Oze did not yield a magnetostratigraphy, but appears more suitable for microfossil biostratigraphy (dinoflagellate cysts) and chemostratigraphy.

Kimmeridgian substage The dichotomy in defining the base of the Kimmeridgian Stage among paleogeographic faunal realms precludes standardizing substages. Traditional usage places a base of an Upper Kimmeridgian substage in the sub-Boreal realm at the base of the ammonite *Aulacostephanoides mutabilis* Zone, whereas in the sub-Mediterranean realm it is typically assigned to the base of the *Aspidoceras acanthicum* Zone. Magnetostratigraphy suggests that the sub-Mediterreanean substage base is about 0.9 myr younger than the sub-Boreal assignment (Ogg *et al.*, in prep.).

TITHONIAN

History and revised definition In an enlightened departure from the stratotype concept, Oppel (1865) defined the Tithonian Stage solely on biostratigraphy. In mythology, Tithon is the spouse of Eos (Aurora), goddess of dawn, and Oppel used this name in a poetic allusion to the dawn of the Cretaceous. He referenced characteristic Tithonian sections in western Europe from Poland to Austria.

The base of Oppel's Tithonian was placed at the top of the Kimmeridgian *Aulacostephanus eudoxus* ammonite zone, which can be recognized in both the sub-Boreal and sub-Mediterranean realms. Later, Neumayr (1873) established the *Hybonoticeras beckeri* Zone above the *A. eudoxus* in the sub-Mediterranean realm and also assigned it to the Kimmeridgian Stage.

Neumayr's revised placement of the Tithonian–Kimmeridgian boundary corresponded closely with the boundary between the "Portlandian" and Kimmeridgian stages as initially assigned by Alcide d'Orbigny (1842–51, 1852), who had assigned "des *Ammonites giganteus* et *Irius*" as Portlandian index fossils. However, d'Orbigny did not visit England, and he inadvertently combined fossil assemblages from outcrops at Bologna in Italy with a name derived from a "type section" on the Isle of Portland in England. The "*Ammonite irius*" is one representative of the *Gravesia* genera, which have a lowest occurrence in the basal *Hybonoticeras hybonotum* Zone of the revised Tithonian. Accordingly, the *Gravesia gravesiana* ammonite zone was assigned as the basal zone of the British Portlandian (Tithonian) Stage by Salfeld (1913). Following Salfeld's oral presentation to the Geological Society of London, it was noted that the chronostratigraphic term "Kimmeridgian" only partially encompassed the "Kimmeridgian Clay" Formation, therefore it was recommended that Salfeld "should invent a dual nomenclature – one for the stratigraphical and another for the zoological sequence" and replace 'Kimmeridgian Stage" with a new name (in Salfeld, 1913). Unfortunately, this enlightened recommendation was not pursued, and a confusing equivalence of a "Kimmeridgian" Stage with the "Kimmeridge Clay" Formation and associated lifting of the base of d'Orbigny's "Portlandian" Stage became common usage in England, but a lower Tithonian–Kimmeridgian boundary was used elsewhere in Europe. The Kimmeridge Clay Formation was arbitrarily subdivided into a lower and upper member at the approximate Kimmeridgian–Tithonian boundary level at the lowest occurrence of *Gravesia gravesiana* at the "Maple Ledge" bed (reviewed in Cox and Gallois, 1981).

The "Tithonian" was formally adopted as the name of the uppermost stage of the Jurassic by a vote of the International Commission on Stratigraphy in September 1990.

The Second Colloquium on the Jurassic System, held in Luxembourg in 1967, recommended that the top of the Kimmeridgian be assigned to the base of the *Gravesia gravesiana* Zone (Anonymous, 1970). However, Cope (1967) subdivided the lowermost Tithonian portion of the Upper Kimmeridge Clay into several ammonite zones based on successive species of his reconstituted *Pectinatites* genera and abandoned Salfeld's two *Gravesia* Zones. Cope raised the upper limit of the uppermost Kimmeridgian *Aulacostephanus autissiodorensis* Zone to the base of his new *Pectinatites* (*Virgatosphinctoides*) *elegans* Zone, thereby effectively lifting the associated biostratigraphic division between Lower and Upper Kimmeridge Clay. Cox and Gallois (1981) note that the top of the international Kimmeridgian Stage now falls within the middle of Cope's expanded *A. autissiodorensis* Zone in the sub-Boreal realm, therefore, they suggest reinstating a truncated *Gravesia gravesiana* Zone below the *P.* (*V.*) *elegans* Zone.

Boundary stratotype candidates The Tithonian–Kimmeridgian boundary interval in the Tethyan faunal realm is marked by the simultaneous lowest occurrence of the ammonites *Hybonoticeras* aff. *hybonotum* and *Glochiceras lithographicum* (the base of the *H. hybonotum* Zone), immediately followed by the lowest occurrence of the *Gravesia* genera. Candidate sections in southeast France for the GSSP include thick pelagic limestone outcrops at Crussol mountain on the Rhône river just west of Valence (Atrops, 1982, 1994) and at a quarry at Canjuers (Var district, southeast; France; Atrops *et al.*, in prep.). The base of *H. hybonotum* Zone is at the base of normal-polarity Chron M22An at Crussol (Ogg and Atrops, in prep.). The Canjuers quarry did not yield a magnetostratigraphy, but its ammonite succession is better established. Other potential GSSP sections are in the Swabian region of southern Germany.

Tithonian substages In the Tethyan faunal domain, the base of an Upper Tithonian substage is traditionally assigned to a major turnover in ammonite assemblages at the base of the *Micracanthoceras microcanthum* Zone. This level is approximately where calpionellid microfossils become important in the biostratigraphic correlation of pelagic limestone and is at the base of normal-polarity Chron M20n.

In the Boreal realm, the boundary between Lower and Middle "Volgian" regional substages assigned at the base of the *Dorsoplanites panderi* ammonite zone may be approximately coeval. However, in the sub-Boreal faunal province in Britain, the base of the "Portlandian" regional stage is traditionally placed at the base of the *Progalbanites albani* ammonite zone, at the base of the Portland Sand Formation, which may be significantly higher.

Bolonian–Portlandian and Volgian regional stages of Europe The century of controversy over the subdivision and nomenclature for the uppermost Jurassic and lowermost Cretaceous stages, coupled with markedly distinct ammonite assemblages in different regions of Europe, led to extensive usage of regional stages (see Fig. 19.2).

Though the Portlandian was used in Russia, the Volgian Stage was later established in western Russia by Nikitin (1881), capped by a Ryazanian horizon (Bogoslovsky, 1897), and extended downward so as to equate with the Tithonian (Resolution, 1955; reviewed in Krymholts *et al.*, 1982–8). The Volgian is zoned by continuous ammonite assemblages (but generally containing several stratigraphic breaks) that are extensively distributed in the Boreal faunal realm, therefore it became another widely used standard in the northern high latitudes outside of Britain. In 1996, the Russian Interdepartmental Stratigraphic Committee resolved to equate the Lower and Middle Volgian (*Ilowaiskya klimovi* through *Epivirgatites nikitini* ammonite zones) to the Tithonian Stage, assign the Upper Volgian (*Kachpurites fulgens* through *Craspedites nodiger* ammonite zones) to the lowermost Cretaceous, and use only Tithonian and Berriasian as chronostratigraphic units in the Russian geological time scale (Rostovtsev and Prozorowsky, 1997).

The "Bolonian" and "Portlandian" have been promoted as "secondary standard stages" of a Tithonian "superstage" for usage in English and French regional geology, especially in Dorset (e.g. Cope 1993, 1995, 2003; Taylor *et al.*, 2001). The "Bolonian" is equivalent to the upper Kimmeridgian Clay Formation between the Tithonian–Kimmeridgian boundary and the base of the Portland Sand, or *Pectinatites* (*Virgatosphinctoides*) *elegans* through *Virgatopavlovia fittoni* ammonite zones. The overlying "Portlandian" is traditionally equivalent to the Portland Group in Dorset, or *Progalbanites albani* through the *Titanites anguiformis* ammonite zones.

18.2 JURASSIC STRATIGRAPHY

The ammonite successions of Europe have historically served as the global primary standard for the Jurassic. Biostratigraphic, magnetostratigraphic, chemostratigraphic, and other events are typically calibrated to these standard European ammonite zones. However, especially during the middle Oxfordian through Tithonian, different faunal assemblages occur in the various paleogeographic realms, such as Boreal (Arctic and northernmost Europe), sub-Boreal (northern Europe), sub-Mediterranean (southern Europe), and Tethyan (southernmost Europe and margins of the former Tethys seaway). An extensive compilation and inter-correlation of Jurassic stratigraphy of European basins was coordinated by Hardenbol *et al.* (1998), and Fig. 18.1 is a summary of a portion of their comprehensive chart series. These European basins contain the majority of the proposed GSSP sites and alternative sites for the chronostratigraphic framework of the Jurassic.

18.2.1 Macrofossil zonations

Ammonites dominate the historical zonation of the Jurassic. Brachiopod and bivalve assemblages provide important regional markers. Terrestrial biostratigraphy of dinosaurs and palynology has a less-precise calibration to the marine stratigraphy.

AMMONITES

Alfred Oppel (1856–8) developed the concept of a biostratigraphic zone, and used ammonites to define two-thirds of his 33 Jurassic zones. Jurassic ammonite zonations have undergone constant revision since Oppel, and the Jurassic is currently subdivided into 70–80 zones and typically has 160–170 subzones in each faunal realm. Reviews of the development, definitions, and inter-correlation of European ammonite zonations are presented in Thierry (in Hardenbol *et al.*, 1998, pp. 776–777 plus correlation charts), Krymholts *et al.* (1982–8), and Groupe Français d'Etude du Jurassique (1997). Correlation of the regional ammonite zones of western North America to the northwest European standard is summarized in Pálfy *et al.* (2000a).

In contrast to standard biostratigraphic usage and most Cretaceous ammonite zones, the "index" or "name" species of some Jurassic ammonite zones is not always an indicator of the definition of those zones. The biostratigraphic range of an index species, such as *Aulacostephanoides mutabilis*, can be entirely independent of the limits of the designated "*mutabilis* zone" (Callomon, 1985, 1995). Partly to alleviate the resulting confusion, several British workers have advocated designating "standard chronozones" with regional equivalents of GSSPs to replace the former associated ammonite zones (e.g. see tables in Cox, 1990). It was believed that the evolutionary rates of the ammonites were relatively fast that so there was no practical difference between an ammonite-based biostratigraphy (zonation) and chronostratigraphy. Therefore, a standard Eudoxus Chronozone (capitalized, non-italics, no genus designation) of the Kimmeridgian in southern England has a base defined at bed E1 at a quarry near Westbury, Wiltshire (Birkelund *et al.*, 1983), and continues to the base of the Autissiodorensis Chronozone, which is assigned as the top of Flats Stone Band bed at beach exposures of the Kimmeridge Clay near Kimmeridge village, Dorset (Cox and Gallois, 1981; Cox, 1990). However, the base of the "Eudoxus" ammonite assemblage zone, as independently used in France has been assigned to the lowest occurrence of *Orthaspidoceras orthocera*, which is significantly lower than the base of the Eudoxus Chronozone of England (Ogg *et al.*, in prep.), and neither is delimited by the observed range (biozone) of *Aulacostephanus eudoxus*. Both systems – the nomenclature of Jurassic ammonite assemblage zones and the regional designation of standard chronozones – have defenders (mainly Jurassic ammonite specialists) and critics. For clarity in the chart in Fig. 18.1 (see also Table 18.2), we have included the genera of the ammonite "index" species, but with caution that these are not always the "guide" species of the named zone.

OTHER MARINE MACROFAUNA

Brachiopod zonations for northwest Europe and for the northern part of the Tethyan province provide important markers within individual basins and approach the resolution of ammonite zones in some stages of the Jurassic (e.g. Alméras *et al.*, 1997; Laurin, 1998). The correlation potential of brachiopods and the slower-evolving successions of bivalves and gastropods are compromised by their benthic habits which can be reflected in ecological-facies associations and provincialism (reviewed in Cope *et al.*, 1980b). Belemnite zones within the Jurassic can provide correlation to the stage or substage level (e.g. Combemorel, 1998).

Ostracodes are small (0.2–1.5 mm) crustaceans with bivalved, calcified shells, which are a major constituent of shallow-marine and brackish benthic fauna. Ostracode datums can approach the resolution of ammonite zones, especially within portions of the Lower and Middle Jurassic (e.g. see reviews by Cox, 1990; Colin, 1998).

DINOSAURS AND OTHER VERTEBRATES

Dinosaurs are the most famous Jurassic fauna. This summary of major trends is from Lucas (1997). Dinosaurs dominated the land herbivores and carnivores during the Early and Middle

Table 18.2 *Jurassic time scale for ammonite zones*[a]

Stage	Zone: Boreal (or Cosmopolitan for early Jurassic)	Method	Calibration	Age (base of zone) (Ma)	Comments	Zone: Tethyan (sub-Mediterranean)	Method	Calibration	Age (base of zone) (Ma)	Comments
Berriasian						*Berriasian*				
	Subcraspedites (Volgidiscus) lamplughi	magstrat	M18n.2 (±0.5)	144.5		*Berriasella jacobi*	magstrat	M19n.2n.55 (±0.05)	144.5	
JURASSIC (Tithonian) *(top)*				**145.5**	Base of *B. jacobi* Zone	**JURASSIC (Tithonian)** *(top)*			**145.5**	
	Subcraspedites (S.) preplicomphalus	magstrat	M19n.3 (±0.2)	145.6						
	Subcraspedites (Swinnertonia) primitivus	magstrat	M19r.8 (±0.5, hiatus)	146.0						
	Paracraspedites oppressus	magstrat	M20n.1n.5 (±0.5, est.)	146.3	Base Oppressus = Base of Lulworth Beds (Purbeck) in Dorset; but usefulness of this zone is disputed	*Durangites*	magstrat	M19r.1 (±0.2)	146.1	Base *Calpionellid* Zone A2 is base of *Durangites* Zone
	Titanites anguiformis	magstrat	M20n.2n.7 (±0.2)	146.7	Anguiformis = Portland Freestone Member in Dorset					
	Galbanites (Kerberites) kerberus	magstrat	M20n.2n.2 (±0.2)	147.0	Kerberites = Upper Cherty Beds in Dorset					
	Galbanites okusensis	magstrat	M20r.6 (±0.1)	147.4	*Okusensis–Glaucolithus* = West Weare "sandstone" (dolomite) and overlying Lower Cherty Member in Dorset					
	Glaucolithites	magstrat	M20r.1	147.7						

Progalbanites albani	**magstrat**	**M21n.7 (±0.1)**	**148.0**	**Albani = basal-Portland** Sand = Black Noire and Exogyra Bed in Dorset, hiatus is common	*Micracanthoceras microcanthum* (lower subzone is *Simplisphinctes* and upper is *Paraulacosphinctes transitorius*)	magstrat	base M20n (±0.1)	147.2	Base *Calpionellid* Zone A1 is just above base of *Microcanthum* Zone
Virgatopavlovia fittoni (top of Kimmeridge Clay formation)	magstrat	M21n.3 (± 0.1)	148.3	Base of *V. fittoni* = top of Kimmeridge Clay formation in Dorset	*Micracanthoceras ponti–Burckhardticeras*	magstrat	M20r.5 (±0.1)	147.5	
Pavlovia rotunda	magstrat	M21r.8 (±0.3, est.)	148.6						
Pavlovia pallasioides	magstrat	M22n.95 (±0.1)	149.0		*Simoceras admirandum–Simoceras biruncinatum*	magstrat	M21n.4 (±0.1)	148.2	Base *Chitinoidella* is near top of *Admirandum* Zone
Pectinatites (P.) pectinatus	magstrat	M22n.7 (±0.1)	149.3		*Richterella richteri*	magstrat	M22n.95 (±0.05)	149.0	
Pectinatites (Arkellites) hudlestoni	magstrat	M22n.45 (±0.1)	149.6		*Semiformiceras semiforme* (= zone of *Haploceras (Volanites) verruciferum*)	magstrat	M22n.6 (±0.1)	149.4	
Pectinatites (Virgatosphinctoides) wheatleyensis	magstrat	M22n.2 (±0.1)	150.0		*Semiformiceras darwini* (= zone of *Virgatosimoceras albertinum*)	magstrat	M22n.25 (±0.05)	149.9	
Pectinatites (Virgatosphinctoides) scitulus	magstrat	M22r.8 (±0.2, est)	150.3						
Pectinatites (Virgatosphinctoides) elegans	magstrat	M22r.2 (±0.2, est)	150.6	Projects to middle of M22r	*Hybonoticeras hybonotum*	magstrat	base M22An (±0.1)	150.8	
Kimmeridgian (top)			**150.8**		*Kimmeridgian (top)*			**150.8**	
Aulacostephanus autissiodorensis	magstrat (for zone base)	M23n.5 (±0.5, est.)	151.2		*Hybonoticeras beckeri*	magstrat	M23r.2r.1 (±0.05)	152.2	
Aulacostephanus eudoxus	magstrat	M24n.5	152.4		*Aulacostephanus eudoxus*	magstrat	M24r.1r.8 (±0.1)	152.6	
					Aspidoceras acanthicum	magstrat	M24r.2r.6 (±0.1)	153.1	

(cont.)

Table 18.2 (*cont.*)

Stage	Zone: Boreal (or Cosmopolitan for early Jurassic)	Method	Calibration	Age (base of zone) (Ma)	Comments	Zone: Tethyan (sub-Mediterranean)	Method	Calibration	Age (base of zone) (Ma)	Comments
	Aulacostephanoides mutabilis	magstrat	base M24Bn (±0.3) (estimate)	153.9		*Crussoliceras divisum*	magstrat	M24Ar.7 (±0.1)	153.4	
						Ataxioceras (A.) hypselocyclum	magstrat	M25n.8 (±0.1)	154.1	
						Sutneria platynota	magstrat	M25r.1 (±0.1)	154.5	
	Rasenia cymodoce	magstrat	base M25An.3n (±0.1)	155.0		*Oxfordian* (sub-Mediterranean usage) *(top)*			**154.5**	
	Pictonia baylei	magstrat	M26r.2 (±0.2)	155.7	Marine anomaly model is uncertain for M26 subchrons	*Subnebrodites planula*	magstrat	base M26n.3n (±0.1)	155.4	Marine anomaly model is uncertain for M26 subchrons
Oxfordian (sub-Boreal usage) *(top)*				**155.7**						
	Ringsteadia pseudocordata	magstrat	base M28Bn (estimate)	156.8		*Epipeltoceras bimammatum*	magstrat	base M28Cn (±0.1)	157.0	
	Perisphinctes cautisnigrae	magstrat	base M28Dn (estimate)	157.2		*Perisphinctes (Dichotomoceras) bifurcatus*	magstrat	M29n.1n.1 (±0.2)	157.4	
	Perisphinctes pumilus	magstrat	M31r.5 (±0.2)	158.6	Assumed to be same as base of *Transversarium*	*Gregoryceras transversarium*	magstrat	M31r.5 (±0.2)	158.6	
	Perisphinctes (Arisphinctes) plicatilis	magstrat	M33Bn.3 (±0.2)	159.5		*Perisphinctes (Arisphinctes) plicatilis*			159.5	
	Cardioceras (C.) cordatum	magstrat	M34Bn.1r.3 (±0.3)	160.6		*Cardioceras (C.) cordatum*			160.6	
	Quenstedtoceras (Q.) mariae	magstrat	base M36An (±0.3)	161.2		*Quenstedtoceras (Q.) mariae*			161.2	

Callovian (top)		Callovian = 18 subzones	**161.2**		*Callovian (top)*	**161.2**
Quenstedtoceras (Lamberticeras) lamberti	magstrat	M37.2n.3 (±0.2)	**162.0**	Lamberti (2 subzones) base set by magstrat. Rest of Callovian zones proportioned to subzones (16 subzones)	*Quenstedtoceras (Lamberticeras) lamberti*	162.0
Peltoceras (P.) athleta	equal subzones		162.5	*Athleta–Coronatum* zonal boundary in Boreal zonation is placed one subzone lower than in Tethyan	*Peltoceras (P.) athleta*	162.3
Erymnoceras coronatum	equal subzones		162.9		*Erymnoceras coronatum*	162.9
Kosmoceras (Zugokosmoceras) jason	equal subzones		163.2		*Reineckeia anceps*	163.2
Sigaloceras (S.) calloviense	equal subzones		163.5			
Proplanulites koenigi	equal subzones		164.2		*Macrocephalites (Dolikephalites) gracilis*	164.4
Macrocephalites herveyi	equal subzones		164.7		*Bullatimorphites (Kheraiceras) bullatus*	164.7
Bathonian (top)		Bathonian = 15 subzones	**164.7**	Bajo–Bath–Callov zones are proportionally scaled according to their component subzones	*Bathonian (top)*	
Clydoniceras (C.) discus	equal subzones		165.1		*Clydoniceras (C.) discus*	165.1
Oxycerites orbis	equal subzones		165.5		*Hecticoceras (Prohecticoceras) retrocostatum*	165.7
Procerites (P.) hodsoni	equal subzones		166.1		*Cadomites (C.) bremeri*	166.1
Morrisiceras (M.) morrisi	equal subzones		166.3		*Morrisiceras (M.) morrisi*	166.3
Tulites (T.) subcontractus	equal subzones		166.5		*Tulites (T.) subcontractus*	166.5
Procerites (P.) progracilis	equal subzones		166.9		*Procerites (P.) progracilis*	166.9

(cont.)

Table 18.2 (*cont.*)

Stage	Zone: Boreal (or Cosmopolitan for early Jurassic)	Method	Calibration	Age (base of zone) (Ma)	Comments	Zone: Tethyan (sub-Mediterranean)	Method	Calibration	Age (base of zone) (Ma)	Comments
	Asphinctites tenuiplicatus	equal subzones		167.1		*Procerites (Siemiradzkia) aurigerus*			167.3	
	Zigzagiceras (Z.) zigzag	equal subzones		167.7		*Zigzagiceras (Z.) zigzag*			167.7	
Bajocian (top)			Bajocian = 20 subzones	**167.7**		*Bajocian (top)*				
	Parkinsonia (P.) parkinsoni	equal subzones		168.3		Tethyan zones are the same as Boreal zones from Hettangian through Bajocian				
	Garantiana (G.) garantiana	equal subzones		168.9						
	Strenoceras (S.) niortense	equal subzones		169.6						
	Stephanoceras (S.) humphriesianum	equal subzones		170.2						
	Sonninia propinquans (= former zone of *Emileia (Otoites) sauzei*)	equal subzones		170.6						
	Witchellia laeviuscula	equal subzones		171.2						
	Hyperlioceras (H.) discites	equal subzones		171.6						
Aalenian (top)			Total duration of Aalenian set by cycle stratigraphy as 4 myr	171.6						

Table 18.2 *(cont.)*

Stage	Zone: Boreal (or Cosmopolitan for early Jurassic)	Method	Calibration	Age (base of zone) (Ma)	Comments
	Graphoceras concavum	equal subzones		172.5	
	Brazilia bradfordensis	equal subzones		173.4	
	Ludwigia murchisonae	equal subzones		174.7	
	Leioceras opalinum	equal subzones		175.6	
Toarcian (top)			Duration of Toarcian is set by cycle stratigraphy	**175.6**	
	Pleydellia aalensis	equal subzones		176.6	
	Dumortieria pseudoradiosa	equal subzones		177.6	
	Phlyseogrammoceras dispansum	equal subzones		178.5	
	Grammoceras thouarsense	equal subzones	Control on upper Toarcian equal-subzone scale	**180.5**	
	Haugia variabilis	Linear Sr isotope trend		180.7	
	Hildoceras bifrons	Linear Sr isotope trend		181.2	
	Harpoceras serpentinum (= former zone of *Harpoceras falciferum*)	Linear Sr isotope trend		182.7	
	Dactylioceras (Orthodactylites) tenuicostatum	Linear Sr isotope trend		183.0	
Pliensbachian (top)			Cycle-scaled linear Sr isotope trend	**183.0**	
	Pleuroceras spinatum	Linear Sr isotope trend		184.2	
	Amaltheus margaritatus	Linear Sr isotope trend	Control on lower Pliensbachian equal-subzone scale	**187.0**	
	Prodactylioceras davoei	equal subzones		187.7	
	Tragophylloceras ibex	equal subzones		188.5	
	Uptonia jamesoni	equal subzones		189.6	
Sinemurian (top)			Cycle-scaled linear Sr isotope trend	**189.6**	
	Echioceras raricostatum	equal subzones		191.2	
	Oxynoticeras oxnotum	equal subzones		192.0	
	Asteroceras obtusum	equal subzones		193.3	
	Caenisites tuneri	equal subzones		194.1	
	Arnioceras semicostatum	equal subzones		195.3	
	Coroniceras (Arietites) bucklandi	equal subzones		196.5	
Hettangian (top)			Cycle-scaled linear Sr isotope trend	**196.5**	
	Schlotheimia angulata	equal subzones		197.7	
	Alsatites liasicus	equal subzones		198.8	
	Psiloceras planorbis	equal subzones		199.6	
TRIASSIC (Rhaetian) *(top)*			Radiometric age	**199.6**	

[1] Methodology for deriving each age for primary ammonite zones and associated stage boundaries are given with summary of computational details. For ammonite zones that are scaled using relative numbers of subzones, these subzonal counts are from compilation by J. Thierry (in Gradstein *et al.*, 1994a, 1995, and illustrated in Hardenbol *et al.*, 1998).

Jurassic, but left only a sketchy record. In contrast, rich fossil deposits of the Late Jurassic document the evolution of the largest land animals that ever lived. Plant eaters included huge sauropods, large stegosaurids, and moderate-sized ornithopids (iguanodontids and hypsilophodontids). The kings of the carnivores were allosaurid theropods.

18.2.2 Microfossil zonations

Major microfossil biostratigraphic zonations for the Jurassic incorporate dinoflagellate cysts, calcareous nannoplankton, benthic foraminifera, calpionellids, and radiolaria.

DINOFLAGELLATE CYSTS

Organic-walled cysts of dinoflagellates are an important correlation tool for the North Sea, and the datums are correlated directly to ammonite zones of the Boreal realm (e.g. Woollam and Riding, 1983; Riding and Ioannides, 1996). A few selected markers and associated dinoflagellate zones for the Boreal realm are shown in Fig. 18.1 (extracted from Ioannides *et al.*, 1998). Several of these markers also occur in the Tethyan realm, but the ranges and correlation to ammonite zones are not as well established (Habib and Drugg, 1983; Ioannides *et al.*, 1998). Independent dinocyst zonations have been developed for the Jurassic of Australia (Helby *et al.*, 1987), for the Upper Jurassic of New Zealand (Wilson, 1984), and for other basins.

CALCAREOUS NANNOFOSSILS

The beginning of the major transgression during the late Triassic coincides with the earliest known calcareous nannofossils. The major radiation of Jurassic placolith coccoliths (plates from coccolithophorid algae) took place during the late Sinemurian to Pliensbachian (reviewed in de Kaenel *et al.*, 1996). A major re-organization of Tethyan nannofossil assemblages took place in the late Tithonian, followed by the initiation of the nannofossil-rich limestone that characterizes the pelagic realm in the Cretaceous. Jurassic nannofossil zonations and markers in the Boreal–sub-Boreal realm are calibrated to ammonite zones in northwestern Europe (e.g. Bown *et al.*, 1988; Bown, 1998), and the generalized scale in Fig. 18.1 is modified from the compilation by von Salis *et al.* (1998). Nannofossil datums in the Tethyan–sub-Mediterranean realm are partially calibrated to ammonite zones (de Kaenel *et al.*, 1996) and to latest Jurassic magnetic polarity zones (e.g. Bralower *et al.*, 1989).

FORAMINIFERA AND CALPIONELLIDS

Planktonic foraminifera did not evolve until the Middle Jurassic and are localized in occurrence, therefore Jurassic foraminifera assemblages are dominated by calcareous and agglutinated benthic forms. Compilations of foraminifer zonations and events are available for the British and North Sea region (e.g. Copestake *et al.*, 1989), for larger benthic foraminifera in the Tethyan domain (Peybernes, 1998b), and generalized for smaller benthic foraminifera in European basins (Ruget and Nicollin, 1998). The benthic foraminifer zonation in Fig. 18.1 is generalized from the later compilation.

Calpionellids are vase-shaped pelagic microfossils of uncertain origin, which appeared in the late Tithonian and continued until the middle of the Early Cretaceous (Remane, 1985). They provide important correlation markers, especially in pelagic carbonates of the Tethyan–Atlantic seaway (reviewed by Remane, 1998).

RADIOLARIA

Siliceous radiolaria are a major component of Jurassic pelagic sediments deposited under high-productivity conditions, but their tests are rarely preserved jointly with aragonitic ammonite shells. Detailed radiolarian zonations for the Middle and Late Jurassic have been developed for the western margin of North America (e.g. Pessagno *et al.*, 1993), for Japan (Matsuoka and Yao, 1986; Matsuoka, 1992), for the former Tethyan seaways exposed in Europe (Baumgartner, 1987; INTERRAD Jurassic–Cretaceous Working Group, 1995; De Wever, 1998) and for the North Sea (Dyer and Copestake, 1989; Dyer, 1998). These zonations can be partially correlated to each other (e.g. Pessagno and Meyerhoff Hull, 1996).

However, calibration of the radiolarian assemblages to standard geological stages and reference ammonite scales of Europe has been challenging and controversial. An example is the divergent correlations for the radiolarian assemblage overlying basalt at Ocean Drilling Program (ODP) Site 801, which provided a key age control on the Callovian–Oxfordian portion of the marine magnetic anomaly M-sequence and global spreading rates. The basal sediment assemblages were originally interpreted as "late Bathonian–early Callovian" (Shipboard Scientific Party, 1990; Matsuoka, 1992; reviewed in Ogg *et al.*, 1992), interpreted as equivalent to the "middle Oxfordian" of western North America by Pessagno and Meyerhoff Hull (1996), and assigned to "Bajocian" in the zonal calibration developed by the INTERRAD Jurassic–Cretaceous Working Group (1995) for the Mediterranean region (Bartolini *et al.*

2000; Bartolini and Larson, 2001). Possible contributing factors to this divergence are diachroneity of radiolarian or ammonite datums and ranges among basins, errors in taxonomy assignments, imprecise correlation of radiolarian markers to regional ammonite stratigraphy, and miscorrelation of ammonite assemblages among paleogeographic provinces (Pessagno and Meyerhoff Hull, 1996).

18.2.3 Physical stratigraphy

MAGNETOSTRATIGRAPHY

The M-sequence of marine magnetic anomalies is the template for calibrating magnetostratigraphy from Upper Jurassic fossiliferous sections. Several high-resolution studies of Kimmeridgian and Tithonian strata have correlated ammonites, calpionellids, and calcareous nannofossils from the sub-Mediterranean faunal province and DSDP cores from the central Atlantic to polarity chrons M25 through M18 (e.g. Bralower *et al.*, 1989: syntheses in Ogg, 1988; Ogg *et al.*, 1991a; Ogg and Atrops, in prep.). Calibration of Boreal sections to this magnetic time scale has been partially achieved for the Tithonian (Ogg *et al.*, 1994) and the middle Kimmeridgian (Ogg and Coe, in prep.). (Based upon magnetostratigraphy of coastal sections along the French side of the English Channel (Ogg and Wimbledon, in prep.), the reversed-polarity interval of the *Progalbanites albani* ammonite zone at the base of the Portland Sand is now assigned as Chron M20r, instead of M21r as interpreted by Ogg *et al.* (1994).) The suite of calibrations shown in Fig. 18.1 is scaled to a variable spreading model of the Pacific M-sequence during the Kimmeridgian through lower Cretaceous (see Chapters 5 and tables therein). These calibrations constrain the relative duration of each ammonite zone within the Kimmeridgian and Tithonian stages.

The oldest magnetic anomaly that is documented in all ocean basins is M25, which has been correlated to the base of the *Sutneria platynota* Zone, which is the base of the Kimmeridgian as traditionally assigned in the sub-Mediterranean province (Ogg *et al.*, 1984; Ogg and Atrops, in prep.). Magnetic profiles over pre-M26 oceanic crust in the Pacific (Handschumacher *et al.*, 1988) have been supported and extended by deep-tow surveys (Sager *et al.*, 1998), thereby indicating a possible set of between 50 and 100 polarity chrons within the Callovian and Oxfordian stages. In contrast to the well-resolved major magnetic anomalies younger than M25, it is uncertain how many of the modeled short-duration, low-amplitude polarity intervals in the deep-tow data are paleomagnetic intensity fluctuations rather than actual geomagnetic reversals. An array of magnetostratigraphic studies in Oxfordian strata with sub-Mediterranean ammonite zonation in Spain and Poland yielded reversal patterns that were consistent with the extended Pacific model (e.g. Steiner *et al.*, 1986; Juárez *et al.*, 1994, 1995; Ogg and Gutowski, 1996). The magnetostratigraphy of a suite of overlapping sections in Great Britain with sub-Boreal and Boreal ammonite zones, coupled with a revised correlation of the Oxfordian–Kimmeridgian boundary interval between the sub-Mediterranean and Boreal provinces, enabled construction of a complete Oxfordian magnetic polarity time scale for the combined Boreal and Tethyan faunal realms and correlation to the main features of the Pacific magnetic anomaly pattern from M25 through M36 (Ogg and Coe, 1997; Ogg and Coe, in prep.). This calibrated M-sequence scale for the Oxfordian is illustrated in Fig. 18.1 with ammonite zones of both faunal realms scaled to a spreading-rate model for M25 through M41 (see Chapter 5). Minor divergences of the magnetostratigraphic pattern (right-hand scale) with the modeled deep-tow signature (left-hand scale) are generally consistent with uncertainties in the marine magnetic model (Sager *et al.*, 1998).

The magnetostratigraphy of the Upper Callovian in European sections is also consistent with the simple marine magnetic anomaly pattern of M36 through M38. However, the marine magnetic profiles of the presumed Callovian portion of the "Jurassic Quiet Zone" older than M38 display a very low-amplitude short-wavelength oscillation of magnetic intensity of uncertain origin (Sager *et al.*, 1998). Magnetographic investigations of Lower and Middle Callovian strata in England, France, and Poland (e.g. Ogg *et al.*, 1991b; Belkaaloul *et al.*, 1995, 1997; Ogg with Garcia, Coe, and Dietl, unpublished) are generally dominated by normal polarity with only a few correlative reversed-polarity intervals, mainly within the *Macrocephalites (Dolikephalites) gracilis* and *Clydoniceras discus* ammonite zones. Therefore, it remains to be demonstrated that the modeled short-wavelength fluctuations over Pacific crust older than Late Callovian are a reliable indicator of the history of the geomagnetic field. Figure 18.1 displays the tentative common polarity pattern derived from French and English sections scaled to equal-duration ammonite subzones.

The Early and Middle Jurassic magnetic polarity patterns are primarily compiled from ammonite-bearing sections in Europe. A suite of Bathonian and Bajocian sections in Spain displays a rapidly changing magnetic polarity pattern (Steiner *et al.*, 1987), but this has not yet been fully verified elsewhere.

The Aalenian, Toarcian, and Pliensbachian polarity pattern is primarily derived from a detailed study in southern Switzerland (Horner, 1983; Horner and Heller, 1983). This pattern has been consistent with later magnetostratigraphy work across the base-Bajocian GSSP at Cabo Mondego, Portugal (Henriques *et al.*, 1994; Pavia and Enay, 1997), the base-Aalenian GSSP at Fuentelsaz, Spain (Goy *et al.*, 1996; Cresta, 1999), and the relatively condensed type Toarcian section at Thouars, France (Galbrun *et al.*, 1988, using the inter-province ammonite zone correlation in Hardenbol *et al.*, 1998). The Pliensbachian portion has been enhanced and recalibrated using boreholes in the Paris Basin (Moreau *et al.*, 2002; Fig. 18.1).

The Hettangian and Sinemurian stages have not yet yielded a verified magnetostratigraphy. The Sinemurian and Hettangian appear to be dominated by reversed polarity (Steiner and Ogg, 1988; Gallet *et al.*, 1993), with perhaps several minor normal-polarity zones (Yang *et al.*, 1996), and the basal-Hettangian may be dominated by normal polarity (Kent *et al.*, 1995; Yang *et al.*, 1996; Posen *et al.*, 1998; Kent and Olsen, 1999). Only a possible schematic pattern, not correlated to biostratigraphy, is shown in Fig. 18.1.

Polarity chrons prior to the Callovian do not have a corresponding marine magnetic anomaly sequence to provide an independent nomenclature or scaling system. A compilation by Ogg (1995) suggested using abbreviations derived from the corresponding ammonite zones or stage. However, until the polarity pattern spanning each stage has been adequately verified, a standardized nomenclature system is not possible.

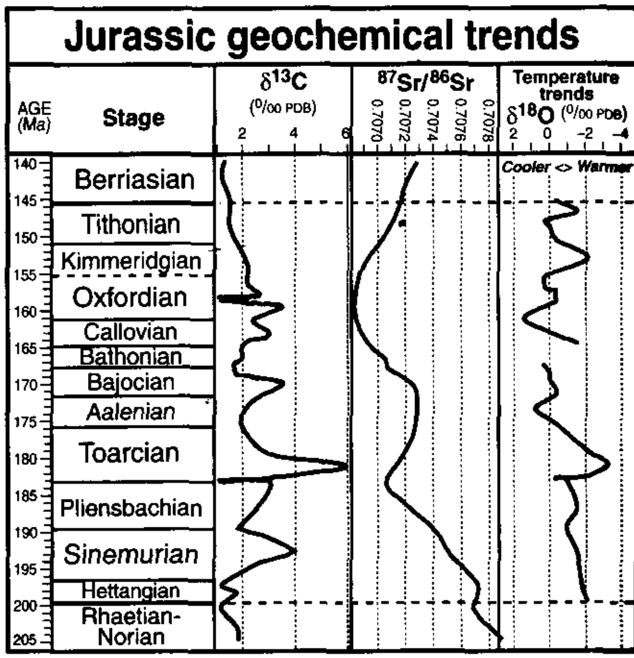


Figure 18.2 Smoothed trends and excursions in carbon and oxygen stable isotopes and in marine $^{87}Sr/^{86}Sr$ ratio during the Jurassic. The schematic carbon isotope curve is generalized from the compilations in Bartolini *et al.* (1996) and Jenkyns *et al.* (2002), with details on the complex Toarcian and the Oxfordian excursions from McArthur *et al.* (2000) and Padden *et al.* (2001), respectively. The strontium isotope curve is a LOWESS fit to data from several sources – see text and Chapter 7. The schematic oxygen isotope curve is mainly from belemnites from Europe, but the main trends are also observed in New Zealand (late Jurassic) and Canada (middle Jurassic) (from Jenkyns *et al.*, 2002). Overall global shifts to higher oxygen-18 values in carbonates are generally interpreted as cooler seawater, but there are many other contributing factors. The data for these schematic carbon and oxygen isotope curves have significant scatter and should be considered as only general indications of the trends.

CHEMICAL STRATIGRAPHY

A comprehensive review of Jurassic chemostratigraphy trends and excursions is compiled by Jenkyns *et al.* (2002). Only the major features are summarized below.

Stable isotopes of carbon Two major negative excursions in carbon isotopes, accompanied by an abundance of organic-carbon-rich sediments, are recognized in the Jurassic in the Toarcian and Oxfordian, and lesser anomalies occur in other intervals (reviewed in Jenkyns *et al.*, 2002; Fig. 18.2).

Lower Toarcian pelagic limestone in the upper *Harpoceras serpentinus* ammonite zone (also known as upper *Harpoceras falciferum* ammonite zone) display a major positive carbon-13 excursion (e.g. Jenkyns and Clayton, 1986, 1997). High-resolution isotope stratigraphy (McArthur *et al.*, 2000) suggests that the positive excursion consists of multiple oscillations, but identification of global trends may be compromised by superimposed local and basinal effects (Jiménez *et al.*, 1996). This carbon isotope excursion in carbonates follows a widespread occurrence of organic-carbon-rich marine deposits, such as the Posidonienschiefer of Germany and the Jet Rock of England, that are associated with a major transgression during the upper *Dactylioceras tenuicostatum* and lower *serpentinus* Zones (e.g. Hallam, 1981b; Jenkyns, 1988). The organic-rich sediments are associated with pronounced negative carbon-13 excursions in both organic and carbonate components, which is one of the largest of the Phanerozoic (e.g. Hesselbo *et al.*, 2000b, 2003; Schouten *et al.*, 2000). This early Toarcian "oceanic anoxic event" at approximately 183 Ma persisted for only about 0.5 myr (McArthur *et al.*, 2000). T event seems to have been coincident with the eruption of the Karoo–Ferrar flood basalts across South Africa and Antarctica (Kerr, 2000; Pálfy and Smith, 2000) and a methane release from undersea destabilization of frozen methane hydrates may have contributed to this excursion (Hesselbo *et al.*, 2000b; Cohen *et al.*, 2004).

Middle Oxfordian pelagic sediments indicate a broad peak in carbon-13 (Jenkyns, 1996) that contains a pair of brief (50 kyr) major negative excursions within the upper *Gregoryceras transversarium* ammonite zone (Padden *et al.*, 2001, 2002). Other major features are a negative excursion in carbon-13 near the Sinemurian–Pliensbachian boundary, and generally low values in the Bathonian–Bajocian boundary interval and Tithonian (Jenkyns *et al.*, 2002). Excursions in this general trend in carbon isotope are reported within the Triassic–Jurassic boundary interval (e.g. Pálfy *et al.*, 2001; Hesselbo *et al.*, 2002; see Chapter 17), and in the lower Bajocian and upper Bathonian to lower Callovian pelagic sediments in Italy (Bartolini *et al.*, 1996, 1999; Morettini *et al.*, 2002). However, these postulated excursions have not yet been calibrated to ammonite zones. The Jurassic–Cretaceous boundary interval lacks any carbon isotope excursions to aid in global correlation of the system boundary (Weissert and Channell, 1989).

Stable isotopes of oxygen and temperature trends The Jurassic is generally considered as an interval of sustained warmth without any documented glacial deposits. Oxygen isotope records of oceanic temperature trends are patchy and heavily biased toward records from Europe and Russia (e.g. Veizer *et al.*, 2000; Jenkyns *et al.*, 2002). These suggest an overall warm period (lighter oxygen-18 values) from Hettangian to Toarcian, cooler temperatures during Aalenian through Oxfordian (but with potential anomalies), and moderate temperatures during the Kimmeridgian and Tithonian (Fig. 18.2). Except for the implied "cold snap" during the Callovian–Oxfordian from the isotope compilation, these general temperature trends are consistent with other paleoclimate indicators (Jenkyns *et al.*, 2002).

Strontium and osmium isotope ratios The curve of marine $^{87}Sr/^{86}Sr$ through the Jurassic is a broad valley centered on the early Oxfordian, with a subordinate trough in latest Pliensbachian time (Fig. 18.2). Both minima broadly coincide with major carbon isotope excursions. Except within the Aalenian and the Oxfordian, the rapidly changing ratios enable global correlation at high resolution (McArthur *et al.*, 2001).

At the end of the Triassic, an abrupt downturn in marine $^{87}Sr/^{86}Sr$ from the latest Triassic peak (0.707 95) coincided with major flood basalt outpouring of the "Central Atlantic Magmatic Province" along the future Central Atlantic seaway (McArthur *et al.*, 2001). The strontium isotope ratio continued a steady decline through the Early Jurassic to a trough (0.707 08) in the latest Pliensbachian (Jones *et al.*, 1994a; McArthur *et al.*, 2000; Jones and Jenkyns, 2001). By assuming that this decrease was linear through the Hettangian, Sinemurian, and Pliensbachian stages, and scaling the slope with cycle stratigraphy in the lower Pliensbachian, Weedon and Jenkyns (1999) estimated that the minimum duration of these three stages was 2.86, 7.62, and 6.67 myr, respectively, for a total of 17.15 myr. A similar calculation using an expanded Lower Jurassic database (McArthur *et al.*, 2001) yields 3.10, 6.90, and 6.60 myr, respectively, for a total of 16.90 myr.

Strontium isotope ratios progressively rose during the Toarcian to a sustained plateau (0.707 30) through the Aalenian. If the Pliensbachian fall and Toarcian rise are assumed to be linear segments, then a high-resolution time scale can be constructed for scaling ammonite subzones and carbon isotope excursions (McArthur *et al.*, 2000). Strontium isotope ratios again decreased through the Bajocian to middle Callovian, with a shoulder spanning the Bajocian–Bathonian boundary (Jones *et al.*, 1994b; M. Engkilde, unpublished) that may be real or may be an artifact of differential rates of sedimentation and the imposed time scale.

During the early Oxfordian, marine $^{87}Sr/^{86}Sr$ reached its lowest ratio (0.706 86) throughout the entire Phanerozoic (McArthur *et al.*, 2001). This pronounced episode may indicate a major pulse of seafloor hydrothermal activity (Jones *et al.*, 1994b; Jones and Jenkyns, 2001), which is supported by interpretations of other geochemical, deep-sea sediment, and spreading-rate evidence (e.g. Ogg *et al.*, 1992). From the middle Oxfordian, the strontium isotope ratio began a long-term increase that peaked in the *P. elegans* ammonite zone of the Barremian Stage of Early Cretaceous.

As with Sr, the $^{187}Os/^{188}Os$ value of marine Os reflects competing fluxes of Os from the input of ^{187}Os-rich fluids, from continental weathering, and of non-radiogenic ^{188}Os-rich fluids from hydrothermal alteration of oceanic crust and from dissolution of extraterrestrial material from meteorites, but with a shorter residence time (about 40 kyr). Jurassic $^{187}Os/^{188}Os$ ratios have been derived from organic-rich shales in southern England (Cohen *et al.*, 1999). The extremely non-radiogenic $^{187}Os/^{188}Os$ ratio of 0.15 in the basal-Hettangian (*Psiloceras planorbis* ammonite zone) is similar to the anomalous end-Cretaceous excursion produced by the ^{188}Os-rich bolide impact, but is interpreted as hydrothermal activity associated with the eruption of the Central Atlantic Magmatic Province (Cohen *et al.*, 1999; Cohen and Coe, 2002). In contrast to the descending strontium trend, the $^{187}Os/^{188}Os$ ratio progressively rises through the Hettangian and Sinemurian, and attains a ratio of 0.8 in the lower Toarcian. The average upper Kimmeridgian and lower Tithonian ratio is about 0.6.

CYCLE STRATIGRAPHY AND ESTIMATES OF STAGE DURATIONS

Period oscillations in composition or physical properties within several marine successions in the Jurassic have been interpreted as Milankovitch orbital-climate cycles. Sudden shifts in the relative dominance of obliquity (37–38 kyr in Jurassic) and precession (20 kyr) within Jurassic cyclostratigraphy sections in England and Italy (30°–35° N paleolatitude) can be associated with times of significant global environmental change (e.g. Hinnov and Park, 1999; Weedon *et al.*, 1999).

Hettangian and Sinemurian Obliquity-dominated cyclicity in the Blue Lias Formation of southern England yields minimum durations of 1.29 myr for the Hettangian Stage and 0.34 myr for the *Arietites bucklandi* ammonite zone of lowest Sinemurian, but these estimates incorporate known stratigraphic breaks (Weedon *et al.*, 1999). Assuming that marine $^{87}Sr/^{86}Sr$ had a linear decrease through this interval identical to the precession-cycle-scaled trend of the lower Pliensbachian (−0.000 042 per myr), this yields minimum durations of 2.86 myr for the Hettangian Stage and 7.62 myr for the total Sinemurian Stage (Weedon and Jenkyns, 1999), or 3.10 and 6.90 myr using the LOWESS-fit Sr-curve of McArthur *et al.* (2001).

Pliensbachian Precession-dominated cyclicity in the Belemnite Marls of southern England, combined with linear strontium isotope trends and cyclostratigraphic data from Robin Hood's Bay, northeast England (van Buchem *et al.*, 1994), and Breggia Gorge, southern Switzerland (Weedon, 1989), indicate a minimum duration of 6.67 myr for the Pliensbachian Stage (Weedon and Jenkyns, 1999). This is consistent with the minimum estimate of 5 myr derived from precession-dominated strata in northern Italy (Hinnov and Park, 1999).

Toarcian and Aalenian Obliquity-dominated cyclic carbonates of the Sogno Formation in northern Italy yielded a combined duration of 11.37 ± 0.05 myr for the Toarcian and Aalenian stages (Hinnov and Park, 1999; Hinnov *et al.*, 1999). A mid-Toarcian date of 181.4 ± 0.6 Ma (1-sigma; Pálfy *et al.*, 1997) is projected to fall 132 obliquity cycles (4.9 myr) below the Aalenian–Bajocian boundary, implying an age for the boundary of 176.5 ± 0.6 Ma (Hinnov and Park, 1999). This age estimate for the Aalenian–Bajocian boundary is identical to an earlier statistical fit of combined radiometric ages and biozones by Gradstein *et al.* (1995).

Kimmeridgian and Tithonian Lithologic and magnetic-susceptibility variations within the Kimmeridge Clay Formation of southern England appear to be associated with obliquity with perhaps minor contributions from precession (e.g. Waterhouse, 1995; Weedon *et al.*, 1999). Tuning all susceptibility peaks to a fixed 38-kyr obliquity cycle implies that the *Aulacostephanus autissiodorensis* ammonite zone of the uppermost Kimmeridgian Stage spans 1.35 myr and the overlying *Pectinatites (Virgatosphinctoides) elegans* Zone of basal-Tithonian spans 0.55 myr (Weedon *et al.*, 1999). However, if this obliquity tuning is applied to all overlying susceptibility peaks, then the upper portion of the Kimmeridgian Clay (*P. elegans* through *Virgatopaviovia fittoni* ammonite zones) spans a minimum of ~4.3 myr (Weedon, 2001; Weedon *et al.*, 2004). If verified, this cycle tuning would imply that the "Upper Kimmeridgian" regional stage of classical usage in England coincides with the entire Tithonian Stage of the sub-Mediterranean (Tethyan) faunal realm. This equivalency has not been incorporated in our Jurassic time scale (Fig. 18.1), pending satisfactory consistency with other correlation constraints.

SEQUENCE STRATIGRAPHY

Jurassic sea-level trends have been compiled for different basins (e.g. Partington *et al.*, 1993; Coe, 1996; Sahagian *et al.*, 19[illegible]; Gygi *et al.*, 1998; Hesselbo and Jenkyns, 1998) and on a global scale (e.g. Hallam, 1978, 1981b, 1988, 2001; Haq *et al.*, 19[illegible]; Hardenbol *et al.*, 1998).

The main Jurassic sea-level trend is a progressive transgression from the latest Triassic until the late Kimmeridgian. A major regressive trend begins in the Tithonian and reaches a minimum in the late Berriasian.

Superimposed on these main cycles are several [illegible] sequences (especially a lesser regressive trend during [illegible]dle Toarcian and Aalenian). The larger-scale deepening [illegible] shallowing trends compiled by Hardenbol *et al.* (1998) are summarized in Fig. 18.1. Assignments of small-scale sequences depend on interpretation models for the response of sediment facies (other than obvious relative sea-level falls or flooding surfaces) to relative sea-level changes, therefore interpretations vary among stratigraphers for assigning small-scale sequences within a given region (e.g. comparison charts within Hesselbo and Jenkyns, 1998; Newell, 2000; and Taylor *et al.*, 2001).

OTHER MAJOR STRATIGRAPHIC EVENTS

Large igneous provinces The Central Atlantic Magmatic Province has ages centered on 200 Ma (Olsen *et al.*, 2003), and probably peaked just before the Triassic–Jurassic boundary as recognized in the marine realm (Pálfy *et al.*, 2000b), and may be the largest known flood basalt (e.g. Marzoli *et al.*, 1999; Hames *et al.*, 2000). (This major volcanic outpouring is summarized in Chapter 17.)

The majority of the Karoo flood basalts in South Africa and the Farrar volcanics in Antarctica erupted at 183 ± 2 Ma (Pálfy and Smith, 2000). This large igneous province coincides with major geochemical anomalies, organic-rich strata, and faunal extinctions within the earliest Toarcian (e.g. Jones and Jenkyns, 2001; Wignall, 2001; Cohen and Coe, 2002; Pálfy *et al.*, 2002b).

Large impact events The Puchezh–Katunki crater in Russia, with an apparent diameter of 80 km, has an age reported as $\sim 167 \pm 3$ Ma, implying a large impact within the Bathonian–Bajocian interval.

A modest iridium anomaly has been reported from near the palynology-defined Triassic–Jurassic boundary in eastern USA, and associated features, such as a fern spike and apparent suddenness of the terrestrial extinctions suggest a possible impact relationship (Olsen *et al.*, 2003).

18.3 JURASSIC TIME SCALE

The time scale for the Jurassic Period and the scaling of events within each geological stage combines many types of stratigraphic information: a selection of key radiometric dates, constraints on durations from cycle stratigraphy, applying linear trends to strontium isotopic variation within certain intervals, proportional scaling of some ammonite zone successions according to their subzonal numbers, and applying the M-sequence magnetic polarity time scale derived from estimates of Pacific seafloor-spreading rates. Table 18.2 summarizes the scaling methods and assumptions for each stage and each component ammonite zone.

18.3.1 Selection of radiometric ages

Suites of high-precision U–Pb and $^{40}Ar/^{39}Ar$ ages from ammonite-zoned strata have largely rendered obsolete Jurassic time scales published before 1996, which had incorporated ages from less precise K–Ar and Rb–Sr methods. Pálfy (1995) critiqued the databases and methodology of previous Jurassic time scales, and his team began a systematic effort to establish a detailed Early and Middle Jurassic age array from U–Pb analysis of zircons from volcaniclastics inter-bedded with ammonite-zoned strata in British Columbia and Alaska (Pálfy *et al.*, 1997, 1999, 2000b,c; Pálfy and Smith, 2000). A series of studies have calibrated North American ammonite zones or specific ammonite datums to the standard northwest European zones and associated definition of geological stages (summarized in Pálfy *et al.*, 2000a). This effort required re-evaluation of biostratigraphic material (e.g. Pálfy *et al.*, 1997, observed that there were approximately 25% erroneous identifications of Toarcian ammonites at the species level in other reference biostratigraphic sections).

Pálfy *et al.* (2000a) compiled a database of 55 latest Triassic through Tithonian ages that were derived solely from U–Pb and $^{40}Ar/^{39}Ar$ methods, of which only 12 were from publications of pre-1995 vintage. Their detailed analysis of the stratigraphic control and radiometric behavior of each item (Appendix 1 in Pálfy *et al.*, 2000a) is partially summarized in Table 17.1.

Ten other U–Pb and $^{40}Ar/^{39}Ar$ ages from the Jurassic that had been used in Harland *et al.* (1990), and hence also incorporated into Gradstein *et al.* (1994a, 1995), did not meet the more rigorous standards for radiometric behavior or stratigraphic control of Pálfy *et al.* (2000a, their Appendix 1). They also excluded all previous high-temperature-mineral ages derived by the K–Ar (and Rb–Sr) method, which are considered less reliable and do not easily allow detection of a geochemical error, in which loss of radiogenic daughter isotopes produces a younger apparent age (e.g. see comparisons in Pálfy, 1995). Unexpectedly, after rejecting all K–Ar ages in favor of a select U–Pb and $^{40}Ar/^{39}Ar$ database, their statistical estimates of all Jurassic stage boundaries (Pálfy *et al.*, 2000a) are systematically shifted to younger ages relative to the previous all-inclusive fit by Gradstein *et al.* (1994a, 1995). This result suggests that some K–Ar ages may provide useful age approximations, albeit with greater analytical uncertainties, of stratigraphic units.

With these caveats, our selected ages for constructing the Jurassic time scale are summarized in Table 17.2. This suite was selected from a larger compilation of published ages on the basis of both stratigraphic and radiometric precision.

18.3.2 Hettangian through Aalenian

The Early Jurassic time scale integrates radiometric ages with cycle stratigraphy, linear trends in strontium isotope ratios, and relative numbers of ammonite subzones. In most cases, this integrated stratigraphy yields estimates for the stage boundaries that are close to a statistical fit of U–Pb age dates by Pálfy *et al.* (2000a), but our procedure also yields a high-resolution scaling of component ammonite zones within some stages.

The *base of the Jurassic* (*base of the Hettangian*) is tightly constrained by a U–Pb age of *199.6* ± 0.3 Ma (95% confidence limits) from zircons in a tuff directly below the Triassic–Jurassic boundary in British Columbia (Pálfy *et al.*, 2000b). This is currently the only well-documented U–Pb zircon age with narrow 95% confidence limits (2-sigma) that directly constrains a stage boundary within the Jurassic! The Hettangian spans 3.1 myr according to the cycle-scaled Sr trend (Weedon and Jenkyns, 1999, applied to LOWESS fit of McArthur *et al.*, 2001). Therefore, the *base of the Sinemurian* is at *196.5 Ma*. The three Hettangian ammonite zones are proportionally scaled relative to subzones (Table 18.2).

The Sinemurian spans 6.90 myr according to the cycle-scaled Sr trend (Weedon and Jenkyns, 1999, applied to LOWESS fit of McArthur *et al.*, 2001). Therefore, the *base of the Pliensbachian* is at *189.6 Ma*. The six Sinemurian ammonite zones are proportionally scaled relative to subzones.

The Pliensbachian spans 6.60 myr according to the cycle-scaled Sr trend (Weedon and Jenkyns, 1999, applied to LOWESS fit of McArthur *et al.*, 2001). Therefore, the *base of the Toarcian* is at *183.0 Ma*. This is only slightly younger, but within the narrow error bars, than the 183.6 Ma (+1.7/−1.1 myr) estimate from a statistical fit of U–Pb age dates (Pálfy *et al.*, 2000a). Cycle stratigraphy implies that the lower Pliensbachian spans 2.65 myr; and we have proportionally scaled the durations of its three ammonite zones relative to their subzones. The two ammonite zones of the upper Pliensbachian (spanning 3.95 myr) are proportions scaled according to their placement along a linear Sr trend (McArthur *et al.*, 2000; Table 18.2): *Amaltheus margaritatus* = 2.75 myr, *Pleuroceras spinatum* = 1.20 myr.

Zircons from strata of British Columbia that are equivalent to the lower part of the *Haugia variabilis* ammonite zone of the upper Middle Toarcian yield a U–Pb age of 181.4 ± 1.2 Ma (95% confidence limits; Pálfy *et al.*, 1997). The younger limit (~180.5 Ma) of the standard deviation on this age was used to scale the four ammonite zones (14 subzones) of the Early and Middle Toarcian according to their relative proportions along a linearly increasing Sr curve (McArthur *et al.*, 2000; Table 18.2): *Dactylioceras tenuicostatum* = 0.3 myr, *Harpoceras falciferum* = 1.5 myr, *Hidoceras bifrons* = 0.5 myr, and *Haugia variabilis* = 0.2 myr.

The combined Toarcian and Aalenian spans 11.37 ± 0.05 myr according to obliquity-cycle stratigraphy (Hinnov and Park, 1999; Hinnov *et al.*, 1999), which projects the Aalenian–Bajocian boundary as ~171.6 Ma. This assignment is younger, but within the large uncertainty of the estimated 174.0 Ma (+1.2/−7.9 myr) from a statistical fit of U–Pb age dates (Pálfy *et al.*, 2000a). Cycle stratigraphy in pelagic strata from a former seamount at Bugarone, central Italy, suggests that the Aalenian spans only 4 myr (L. Hinnov, pers. comm., 2001). Therefore, the *base of the Aalenian* is estimated as *175.6 Ma*. Durations of the four Late Toarcian and the four Aalenian ammonite zones are proportionally scaled relative to equal subzones.

(Note: Pálfy *et al.* (2000a) estimated the base of the Aalenian as 178.0 Ma (+1.0/−1.5 myr), but this estimate was mainly constrained by a U–Pb date from a possible late Aalenian volcanic unit in British Columbia of 177.3 ± 0.8 Ma (95% confidence limits), of which only one of the four samples yielded a concordant analysis.)

18.3.3 Bajocian through Callovian

The Callovian, Bathonian, and Bajocian stages are poorly constrained by radiometric dates. The Toarcian–Aalenian cycle stratigraphy implies that the *base of the Bajocian* is at *171.6 Ma*. The M-sequence calibration of the ammonite zones within the Oxfordian Stage, coupled with the age model for the corresponding magnetic anomalies in the Pacific (see Chapter 5) imply that the base of the Oxfordian is approximately 161.1 Ma. Therefore, the Callovian, Bathonian, and Bajocian stages span 10.5 myr.

Durations of the seven Bajocian, eight Bathonian, and seven Callovian ammonite zones are scaled proportional to their subzones in the selected standard zonation (e.g. see diagrams in Hardenbol *et al.*, 1998; Table 18.2). Using this simplistic assumption of equal average subzones, the Bajocian (20 subzones) spans 3.9 myr. The *base of the Bathonian* is therefore estimated as *167.7 Ma* (which is within the estimate of 166.0 Ma (+3.8/−5.6 myr) by Pálfy *et al.*, 2000a), and this stage spans 3.0 myr (15 subzones).

The *base of the Callovian* is therefore assigned as *164.7 Ma*, and the Callovian (18 subzones) spans 3.5 myr. Pálfy *et al.*

(2000a) assigned a much younger age of 160.4 Ma (+1.1/−0.5 myr) to the base of the Callovian, which was largely derived from a reported U–Pb date of 160.5 ± 0.3 Ma (95% confidence limits) from the equivalent of the Bathonian–Callovian boundary in Argentina (Odin *et al.*, 1992). However, it is difficult to reconcile this Bathonian–Callovian boundary age with the age model for the Oxfordian through Callovian M-sequence magnetic anomalies in the Pacific, which is constrained by an Ar–Ar age on oceanic crust at Pacific ODP Site 801.

18.3.4 Oxfordian through Tithonian

The Late Jurassic time scale is based on the magnetostratigraphic correlation of Tethyan and Boreal ammonite zones to the M-sequence polarity time scale. The radiometric age constraints and associated assignment of absolute ages to the M-sequence magnetic anomaly pattern in the Pacific is explained in detail in Chapter 5.

There are no high-precision ages obtained directly on volcanogenic units within middle Callovian through Tithonian marine sediments. Volcanic ash horizons within the continental facies of the upper Morrison Formation of western USA have several $^{40}Ar/^{39}Ar$ ages spanning the 148–151 Ma interval (Kowallis *et al.*, 1998), and palynology, ostracode, and charophyte assemblages are interpreted as Kimmeridgian to early Tithonian (Litwin *et al.*, 1998; Schudack *et al.*, 1998). The Morrison Formation has several magnetostratigraphic studies (e.g. Steiner *et al.*, 1994), but unambiguous correlation and associated age control on the M-sequence has not yet been possible (F. Peterson, pers. comm., 2001).

The ages of the Oxfordian through Tithonian stages are determined by the calibration of their magnetostratigraphy. The *base of the Oxfordian* (base of polarity Chron M36An; Ogg and Coe, 1997, and in prep.) is at *161.2 Ma*. The *base of the Kimmeridgian* as currently assigned in *Boreal* realm ammonite stratigraphy (lower part of polarity Chron M26r; Ogg and Coe, 1997, and in prep.) is at *155.65 Ma*, whereas its base as currently assigned in *Tethyan* (sub-Mediterranean) stratigraphy (base of polarity Chron M25r; Ogg *et al.*, in prep.) is at *154.55 Ma*. This base-Kimmeridgian age agrees with an independent statistical estimate of 154.7 Ma (+3.8/−3.3) for the Oxfordian–Kimmeridgian boundary derived from a radiometric age database by Pálfy *et al.* (2000c).

The *base of the Tithonian* (base of polarity Chron M22An; Ogg and Atrops, in prep.) is at *150.8 Ma*. Oxfordian, Kimmeridgian, and Tithonian ammonite zones are scaled according to their calibration to the magnetic polarity time scale (Table 18.2). The *Jurassic–Cretaceous boundary* or the base of the Berriasian, which is assigned here as the base of *Berriasella jacobi* ammonite zone (middle of polarity Chron M19n.2n), is at *145.5 Ma*.

18.3.5 Estimated uncertainties on stage ages and durations

A variety of methods were applied to estimate Jurassic stage boundaries, and each of these has different degrees of imprecision. In general, owing to a dearth of verified high-precision radiometric ages between the Aalenian and the Albian, the Jurassic age assignments are the least accurate for any portion of the Phanerozoic time scale. In the following discussion, the uncertainties are expressed as 2-sigma (95% confidence limits).

The Early Jurassic scale merged high-precision radiometric ages, Milankovitch cycle tuning, and linear strontium isotope segments, therefore the precision of the interpolated stage ages are approximately the same as the radiometric constraints – from ±0.6 myr for base-Hettangian (after increasing the cited ±0.3 myr uncertainty on the U–Pb age to incorporate potential systematic errors) increasing to ±1.5 myr for base-Toarcian. The early part of the Middle Jurassic is scaled by cycle stratigraphy relative to the base-Toarcian age, but these duration estimates have not yet been verified in independent sections, therefore a conservative uncertainty of ±2 myr was applied to the base-Aalenian age and ±3 myr for the base-Bajocian age.

The choice of spreading-rate model for the synthetic profile of the M-sequence magnetic anomaly lineations, coupled with the uncertainties on the two constraining ages on Chron M26n (155 ± 6 Ma) and Site 801 (167.7 ± 1.4 Ma; see Chapter 5), implies that the magnetostratigraphic calibration of the Oxfordian through Tithonian stage boundaries have a high degree of uncertainty (estimated as ±4 myr), which is the highest uncertainty on the age of any stage boundary within the Phanerozoic (see Chapter 23). The choice of a spreading model will also affect the durations by expanding or contracting the reference scale. We conservatively estimate this uncertainty on durations as being ±35% for a realistic range of spreading models (Table 18.3).

The base-Bathonian and base-Callovian are proportionally scaled according to their component ammonite subzones between the calculated ages for the base-Bajocian (from cycle stratigraphy) and base-Oxfordian (from the spreading model), and therefore have equivalent or greater uncertainties.

Table 18.3 *Ages and duration of Jurassic stages (see footnote)*

Boundary	Stage	Age (Ma)	*Estimated uncertainty on age (2-sigma)*	Duration (myr)	*Estimated uncertainty on duration (2-sigma)*	Status; primary marker	Calibration and comments
	CRETACEOUS (Berriasian)						
Top of JURASSIC (base of Berriasian)		145.5	*4.0*			Not defined. Base of Cretaceous (base of Berriasian) placed here as the leading candidate of the base of *Berriasella jacobi* ammonite zone or base of Calpionellid Zone B; which is calibrated as Chron M19n.2n(0.55)	Chron ages and duration of Tithonian through Oxfordian stages depend upon selected *Pacific spreading rate model*. Not well constrained. A slower spreading rate would yield a longer duration.
	Tithonian			5.3	*1.8*		Uncertainties on Tithonian through Oxfordian durations are assigned as 35% of duration, which is probable range of realistic spreading models.
Base of Tithonian		150.8	*4.0*			Not defined, but candidate marker is the lowest occurrence of ammonite *Hybonoticeras aff hybonotum*, which is at base of Chron M22An.	Computed from M-sequence spreading model.
	Kimmeridgian			3.8 *or* 4.9	*~1.5 myr*		Duration of Kimmeridgian depends on eventual decision for Kimm/Oxf boundary definition.
Base of *Kimmeridgian* (Tethyan)		154.6	*4.0*			Traditional usage is base of *Sutneria platynota* Zone, which is just above base of Chron M25r.	Computed from M-sequence spreading model.
Base of Kimmeridgian (Boreal)		155.7	*4.0*			Traditional usage is base of *Pictonia baylei* Zone, which is lower part of polarity Chron M26r.	Computed from M-sequence spreading model.
	Oxfordian			5.5 *or* 6.6	*~2 myr*		Duration of Oxfordian depends on eventual decision for Kimm/Oxf boundary definition.
Base of Oxfordian		161.2	*4.0*			Not defined, but candidate marker is *Quenstedtoceras mariae* ammonite zone, which is correlated to base of Chron M36An.	*Computed from* M-sequence spreading model.
	Callovian			3.5	*1.0*		Equal subzones in Bajo-Bath-Callov (53 subzones span 10.5 myr). Callovian has 18 subzones.
Base of Callovian		164.7	*4.0*			Not defined, but candidate marker is base of *Macrocephalites herveyi* ammonite zone	Scaled according to equal-subzones from computed ages for base-Bajocian and base-Oxfordian.
	Bathonian			3.0	*1.0*		Equal subzones in Bajo-Bath-Callov (53 subzones span 10.5 myr). Bathonian has 15 subzones.
Base of Bathonian		167.7	*3.5*			Not defined, but candidate marker is base of *Zigzagiceras zigzag* ammonite zone.	Scaled according to equal-subzones from computed ages for base-Bajocian and base-Oxfordian.
	Bajocian			3.9	*1.0*		Equal subzones in Bajo-Bath-Callov (53 subzones span 10.5 myr). Bathonian has 20 subzones.
Base of Bajocian		171.6	*3.0*			GSSP; lowest occurrence of the ammonite genus *Hyperlioceras (Toxolioceras)*.	Age derived from cycle-scaling from mid-Toarcian U-Pb dates.

Table 18.3 *(cont.)*

Boundary	Stage	Age (Ma)	Estimated uncertainty on age (2-sigma)	Duration (myr)	Estimated uncertainty on duration (2-sigma)	Status; primary marker	Calibration and comments
	Aalenian			4.0	*1.0*		Total duration of Aalenian is estimated as 4.0 myr from cycle stratigraphy.
Base of Aalenian		175.6	*2.0*			GSSP; lowest occurrence of the ammonite genus *Leioceras.*	Age derived from cycle-scaling from mid-Toarcian U-Pb dates.
	Toarcian			7.4	*1.0*		Total duration of Toarcian is estimated as ~7.4 myr from cycle stratigraphy.
Base of Toarcian		183.0	*1.5*			Not defined, but candidate marker is lowest occurrence of the diversified *Eodactylites* ammonite fauna.	Age derived from cycle-scaling from basal-Jurassic and mid-Toarcian U-Pb dates.
	Pliensbachian			6.6	*0.8*		Total duration of Pliensbachian is estimated as 6.6 myr from assumed linear Sr trend, scaled by cycle stratigraphy.
Base of Pliensbachian		189.6	*1.5*			GSSP pending; lowest occurrence of the ammonite species *Bifericeras donovani* and *Apoderoceras* genera.	Age derived from cycle-scaling from basal-Jurassic and mid-Toarcian U-Pb dates.
	Sinemurian			6.9	*0.8*		Total duration of Sinemurian is estimated as 6.9 myr from assumed linear Sr trend, scaled by cycle stratigraphy.
Base of Sinemurian		196.5	*1.0*			GSSP; lowest occurrence of the ammonite genera *Vermiceras* and *Metophioceras.*	Age derived from cycle-scaling from basal-Jurassic U-Pb date.
	Hettangian			3.1	*0.4*		Total duration of Hettangian is estimated as 4.1 myr from assumed linear Sr trend, scaled by cycle stratigraphy.
Base of JURASSIC (base of Hettangian)		199.6	*0.6*			Not defined, but traditionally assigned to the first occurrence of the smooth *planorbis* group within the ammonite genus *Psiloceras.*	U-Pb age on tuff near candidate GSSP level is 199.6 ± 0.3 Ma(2-sigma); increased to ± 0.6 (2-sigma) to incorporate potential external errors.
	TRIASSIC (Rhaetian)						

For stages that lack a ratified definition (as of Nov 2004), the computed age is for the indicated primary marker. See text for discussion of derivation of uncertainty estimates.

18.3.6 Summary of the Jurassic time scale

The Jurassic spanned 54 myr, between 199.6 ± 0.6 and 145.5 ± 4.0 Ma. The Early, Middle, and Late Jurassic segments lasted 24, 14.4, and 15.7 myr, respectively. Ages for the Middle and Late Jurassic segments are relatively uncertain. An improved time scale for the Jurassic would require additional high-precision radiometric ages with reliable stratigraphic control, especially a data set that can be used to calibrate the Late Jurassic magnetic polarity scale, and application of Milankovitch cycle stratigraphy to upper Jurassic deposits.