

A Cretaceous and Jurassic geochronology

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ABSTRACT

An integrated geomagnetic polarity and geologic time-scale for the Jurassic and Cretaceous periods is presented, based on various methods according to the availability of definitive isotopic ages. An age-calibrated sea-floor-spreading model is used to interpolate the ages of the Kimmeridgian to Barremian, and the Campanian to Maastrichtian stages. Numerical age estimates for the Aptian to Santonian stage boundaries follow published isotopic age determinations. The hypothesis of equal duration of ammonite zones is employed as a vernier to apportion time for the Hettangian to Oxfordian stages.

The new scale results in ages of 208 Ma for the base of the Jurassic, 144 Ma for the Jurassic/Cretaceous boundary and 66.5 Ma for the top of the Cretaceous. The integrated biostratigraphic, magnetostratigraphic, and geochronometric record serves as a working hypothesis for geologic correlation of Jurassic and Cretaceous strata.

INTRODUCTION

The derivation of a numerical geological time-scale ultimately depends on the availability of isotopic ages. Given enough stratigraphically meaningful dates, geological stage boundaries may be constrained geochronometrically. Unfortunately, isotopic age data, particularly those derived from high temperature minerals as opposed to authigenic glauconites, are sufficient neither in number nor in their temporal distribution to adequately and directly define the ages of most Jurassic and Lower Cretaceous stage boundaries; more indirect techniques must be utilized. These techniques involve interpolation between geochronometrically well-dated chronostratigraphic tie-points, using biochronology (for example, assuming equal duration of biostratigraphic zones) and magnetochronology. The last method assumes a constant rate of sea-floor spreading over selected increments and requires a well-developed marine magnetic-anomaly record of geomagnetic reversals, chronostratigraphic assignments of the polarity sequence, and geochronometrical control to calculate the spreading rate. Stratigraphic thickness and sedimentation rates can also be used to interpolate stage boundary ages in a similar way, but such information has generally not been compiled to make it of broad use. Figure 1 illustrates the evolution of Jurassic and Cretaceous time-scales over the past few years; this reflects a variety of dating and interpolation methods.

Discussion of our formulation of a Cretaceous and Jurassic geochronology proceeds from youngest (top of Cretaceous) to oldest (base of Jurassic) and is organized by time intervals according to the availability of magneto-geochronological constraints for interpolation of stage boundary ages. The Jurassic and Cretaceous numerical and geomagnetic reversal time-scales are integrated with low- to mid-latitude Atlantic biostratigraphy, using nannofossils, foraminifers, palynomorphs, radiolarians, and

calpionellids. This integrated stratigraphic record serves as a working hypothesis for geologic correlation of Jurassic and Cretaceous strata.

Numerical ages of Jurassic and Cretaceous stage boundaries from this time-scale have been incorporated in the Decade of North American Geology (DNAG) time-scale (Palmer, 1983) and in a summary of Jurassic to Recent chronology prepared for the DNAG volume on the western North Atlantic region (Kent and Gradstein, in press). Here are presented the supportive data and arguments we used in the formulation of this Jurassic and Cretaceous geochronology.

TABLE 1. BOUNDARY AGE ESTIMATES AND DURATIONS FOR SUBDIVISION OF THE CRETACEOUS AND JURASSIC

CRETACEOUS		(144 Ma-66.5 Ma; duration = 77.5 m.y.)		
Late	Maastrichtian		8.0	
	Campanian	74.5	9.5	Berggren and others, 1985
	Santonian	84.0	3.5	Obradovich and Cobban, 1975
	Coniacian	87.5	1	Harland and others, 1982
	Turonian	88.5	1	"
	Cenomanian	91.0	2.5	"
		97.5	6.5	"
Early	Albian		15.5	
	Aptian	113	6	"
	Barremian	119	5	"
	Hauterivian	124	7	this paper
	Valanginian	131	7	"
	Berriasian	138	6	"
		144		"
JURASSIC		(208 Ma-144 Ma; duration = 64 m.y.)		
Late	Tithonian		8	
	Kimmeridgian	152	4	
	Oxfordian	156	7	Armstrong, 1978; Harland and others, 1982
		163		this paper
Middle	Callovian		6	
	Bathonian	169	7	"
	Bajocian	176	7	"
	Aalenian	183	4	"
		187		"
Early	Toarcian		6	
	Pliensbachian	193	5	"
	Sinemurian	198	6	"
	Hettangian	204	4	"
		208		Armstrong, 1982

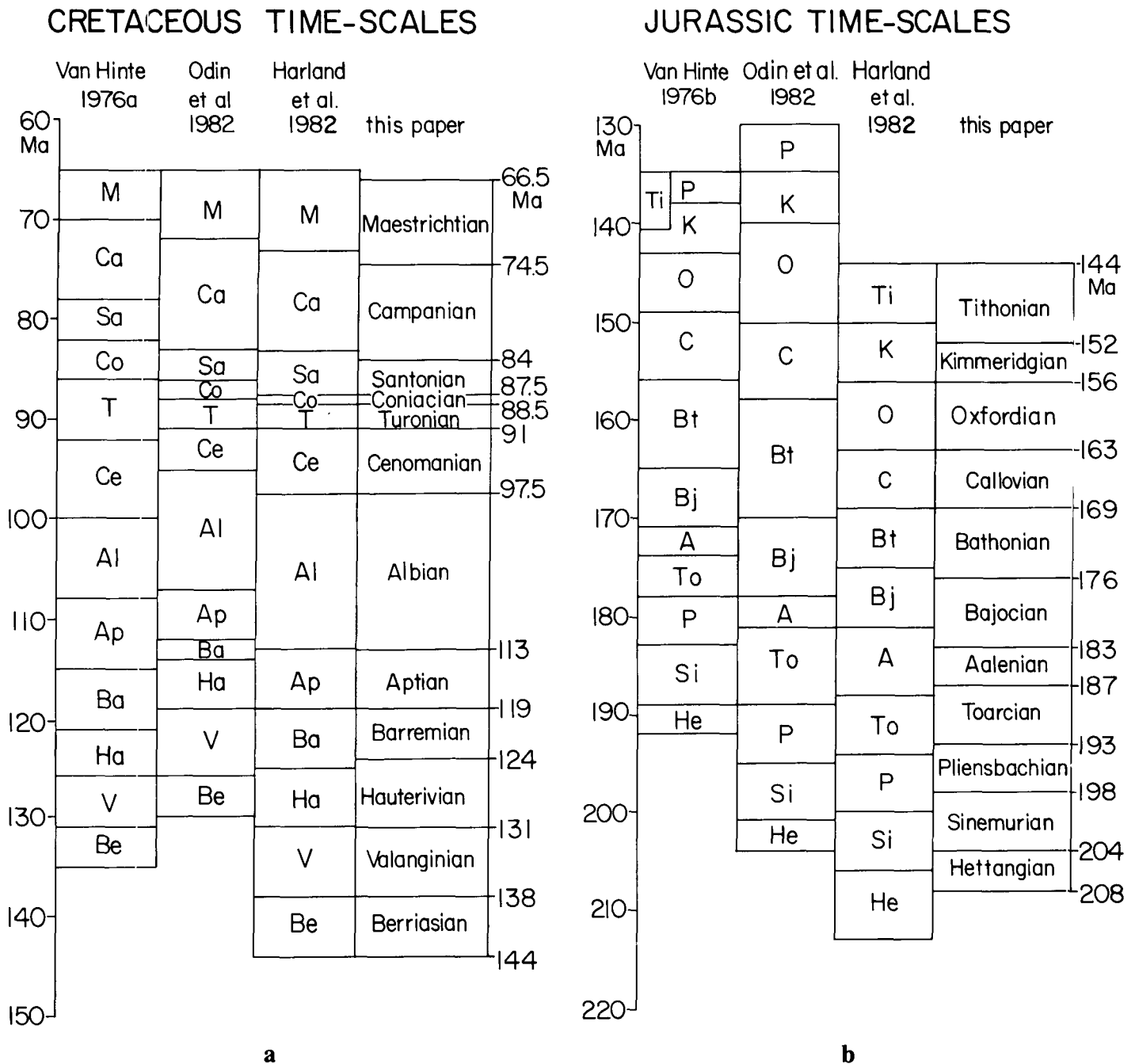


Figure 1. Recently proposed Cretaceous (a) and Jurassic (b) time-scales. Stage boundary ages proposed in this paper are shown next to the column on the right of each set. Stage labeled P in (b) refers to Portlandian. Stage boundary age estimates are based on ICC constants except for Van Hinte (1976a, 1976b).

MAGNETO-GEOCHRONOLOGY

Maestrichtian and Campanian

The geochronology and chronostratigraphy of this time interval are drawn directly from Berggren and others (in press) and are based on an assessment of Late Cretaceous calcareous plankton datums directly correlated with magnetic polarity stratigraphy in deep-sea sediment cores and

land sections. Magnetogeochronological estimates are derived from an age-calibration model for the ridge-crest marine magnetic anomalies (see also Berggren and others, 1985, this volume). A derived age of 56.14 Ma for the older end of Anomaly 24 and a tie-point age of 84 Ma for Anomaly 34 or the older end of the Cretaceous Long Normal (Campanian/Santonian boundary; Obradovich and Cobban, 1975; Lowrie and Alvarez, 1977) serve to calibrate the portion of the geomagnetic reversal sequence that extends into the Cretaceous. (Note that the derived ages quoted here

are given to the nearest 10,000 yr to reflect the precision of the extrapolation or interpolation and not to imply a comparable degree of accuracy in the age estimates.) Magnetostratigraphic age estimates derived from this model of 66.4 Ma for the Cretaceous/Tertiary and 74.5 Ma for the Campanian/Maestrichtian boundary agree well with respective estimates of 66.5 Ma and 74–75 Ma obtained from isotopic dates (recalculated to ICC constants; Dalrymple, 1979) in Obradovich and Cobban (1975). A younger estimate (about 72 to 73 Ma) for the Campanian/Maestrichtian boundary, used by Lowrie and Alvarez (1981) via Ness and others (1980) as a calibration tie-point, results from different and less preferred (Berggren and others, in press) biostratigraphic criteria of Obradovich and Cobban (1975).

Santonian to Aptian

The stratigraphic interval from the top of the Santonian to the lower Aptian generally records predominantly normal geomagnetic polarity (Lowrie and others, 1980) which nicely accounts for the Cretaceous Quiet Zone in the oceans. Consequently, there are no well-documented magnetozones or anomalies that can be correlated and used for interpolation. Sufficient isotopic ages are, however, available to allow direct geochronometric age estimates for stage boundaries in this interval. Numerical ages (Table 1) for Santonian to Aptian stage boundaries are therefore taken directly from the geochronometric estimates of Harland and others (1982), which are based largely on assessment of isotopic ages from the list of Armstrong (1978).

Barremian to Kimmeridgian

The older end of the Cretaceous Quiet Zone in the oceans typically is bounded by lineated magnetic anomalies referred to as the "M-sequence." These anomalies are best defined over the higher spreading rate systems in the Pacific, but they are correlatable to the Keathley sequence of the North Atlantic (Larson and Chase, 1972; Larson and Pitman, 1972). The standard magnetic reversal model for the M-sequence (M0 to M25 from youngest to oldest, designating key anomalies which are interpreted to correspond usually to reversed polarity) was derived from the Hawaiian lineations (Larson and Hilde, 1975). The M-sequence has been extended beyond M25 in the Pacific (Cande and others, 1978; PM26 to PM29) and in the Atlantic (Bryan and others, 1980; AM26 to AM28). The pre-M25 anomalies are of small amplitudes, and their designations are not the same in both papers.

The geochronologic control used by Larson and Hilde (1975) was based on biostratigraphic assignments of sediments immediately overlying basement at five Deep Sea Drilling Project (DSDP) holes drilled over identified M-anomalies; numerical ages were referred to the Geological Society of London (1964) time-scale. More exact correlations between magnetostratigraphy and biostratigraphy, primarily from studies of land sections and supported by additional basal sediment ages and magnetostratigraphy in DSDP holes have since become available, and they provide a basis for a more refined geochronology, as discussed below.

According to magnetobiostratigraphic studies in land sections from the Mediterranean region (Lowrie and others, 1980), marine magnetic anomaly M0 is early Aptian, and M3 essentially straddles the Hauterivian/Barremian boundary. We note, however, that preliminary results from a study of pelagic limestones in DSDP Sites 534 and 603 indicate that the Hauterivian/Barremian boundary may be at M5 or even M7 (J. Ogg, 1985, personal commun.). The same study places M10N at the Valanginian/Hauterivian boundary.

From the land-based magnetostratigraphic studies summarized by

Channell and others (1982), M10N also correlates with the Valanginian/Hauterivian boundary, and M14, with the Berriasian/Valanginian boundary. M16, based on the age of basal sediments at DSDP Site 387, occurs at or just below this latter boundary; the dating is supported by magnetostratigraphic correlations at DSDP Sites 534 and 603, which suggest that M16 is about middle Berriasian (Ogg, 1983; 1985, personal commun.). Channell and others (1982) correlate M17 with early Berriasian. The Tithonian/Berriasian boundary is poorly defined, and as a result, there is no consensus on criteria for definition of the Jurassic/Cretaceous boundary by means of ammonites, calpionellids, nannofossils, or magnetic reversals. Ogg and others (1984) found that in southern Spain the boundary (defined at the base of the *Grandis-Jacobi* ammonite Zone) falls between M18 and M19. Nanofossils in the Maiolica limestones in Italy have been used to correlate the boundary close to the older part of M17 (Lowrie and Channell, 1984). The same study places M18 and M19 in the late Tithonian.

The co-occurrence of the benthic foraminifers *Epistomina* aff. *uhligi* and *Lenticulina quenstedti* in sediments immediately above basement of approximately M25 age in DSDP Sites 105 and 367, and correlation of this biostratigraphic occurrence to DSDP Site 534 suggest that M24 and M25 are older than late Kimmeridgian (Sheridan, Gradstein, and others, 1983). Early Kimmeridgian is a minimum age for these magnetochrons on the basis of the palynological age of basal sediments in DSDP Site 105 and their correlation to DSDP Site 534 (Habib and Drugg, 1983). Ogg and others (1984) estimate the Kimmeridgian/Tithonian boundary in deep-water limestones in southern Spain to be at the base of M22; M25, the oldest globally recognized M-sequence magnetic anomaly, is just below, near to the Oxfordian/Kimmeridgian boundary.

Despite the improved correlations between magnetostratigraphy and biostratigraphy, numerical age estimates for Upper Jurassic and Lower Cretaceous stages are still poor due to a lack of sufficient reliable isotopic data. To be consistent with our use of the Harland and others (1982) chronology for the Santonian to Albian, we use their age estimate of 119 Ma for the Barremian/Aptian boundary to calibrate the younger end of the M-sequence. The Barremian/Aptian boundary falls within the M-sequence and is the next (older) boundary from the Aptian/Albian boundary which is considered by Harland and others (1982) and Agterberg (in press) to be the only geochronometrically well-constrained tie-point (113 Ma) in the Lower Cretaceous and the Jurassic. An isochron age of 120 Ma was determined for basalt overlain by lower Aptian sediment at DSDP Hole 417D, which was drilled on anomaly M0 in the western North Atlantic (Ozima and others, 1979). This age is admittedly poor, but it is nevertheless consistent with the 119 Ma age estimate of Harland and others (1982) for the base of the Aptian.

Armstrong (1978) interpolates whole-rock K/Ar ages to arrive at ~156 Ma for the Oxfordian/Kimmeridgian boundary. This is identical to the broadly interpolated age derived by Harland and others (1982), who used the equal duration of stages between the Anisian/Ladinian boundary at 238 Ma and the Aptian/Albian boundary at 113 Ma. From the Sierra Nevada (California) comes additional evidence for a 154–158 Ma age range for the Oxfordian/Kimmeridgian boundary (Schweickert and others, 1984). Numerous igneous intrusions that have been isotopically dated are associated with Late Jurassic strata and Nevadan orogeny structures. The Mariposa Formation, dated by *Buchia concentrica*, *Dichotomosphinctes*, *Discosphinctes*, and *Amoebites* (*Amoeboceras*) to be late Oxfordian–early Kimmeridgian in age (R. W. Imlay in Clark 1964, 1976) is of particular stratigraphic significance. The Mariposa Formation shows a so-called Nevadan-type of regional deformation and is the youngest unit affected by the Nevadan orogeny. Nevadan cleavage and folds affect dikes and plutons as young as 157–159 Ma (Sonora dikes) but do not affect plutons as old as 154 Ma (Haypress Creek granite). The Nevadan orogeny

is therefore confined to the interval 157–159 to 154 Ma, which can be interpreted as an indirect minimum age range for the Mariposa Formation and the Oxfordian-Kimmeridgian boundary.

For these reasons, we have accepted the ages of 119 Ma (Barremian/Aptian boundary) and 156 Ma (Oxfordian/Kimmeridgian boundary) as reasonable tie-points for calibration of the M-sequence. We note, however, that these age estimates are older, by as much as 14–16 m.y. in the case of the Oxfordian/Kimmeridgian boundary, than age estimates of Van Hinte (1976b) and of Odin and others (1982) (Fig. 2), which are more controlled by ages determined on glauconites.

We used the magnetostratigraphic correlations, the assumption of a constant spreading rate on the Hawaiian lineations (Larson and Hilde, 1975), and the above calibration tie-points to derive age estimates for Kimmeridgian to Barremian stage boundaries (Fig. 2) and for the dating of the M-sequence geomagnetic reversals (Table 2). In comparison to the

equal-stage-duration model of Harland and others (1982), the magneto-chronological method also gives approximately equal (~6 m.y.) durations for the oldest four ages of the Early Cretaceous; however, it results in an apparently longer Tithonian (8 m.y.) and a shorter Kimmeridgian (4 m.y.). This factor-of-two ratio in duration of the Tithonian and Kimmeridgian stages is in good agreement with the relative durations inferred from assuming equal duration of ammonite zones (see below). Differences with previously published magnetostratigraphies for the M-sequence vary according to the degree of integration of magnetostratigraphic and biostratigraphic data (see Cox, 1982) and the geologic time-scale used in numerical calibration (Fig. 2).

Oxfordian to Hettangian

The older end of the M-sequence of magnetic polarity anomalies is bounded by the Jurassic Quiet Zone, which is represented by sea-floor

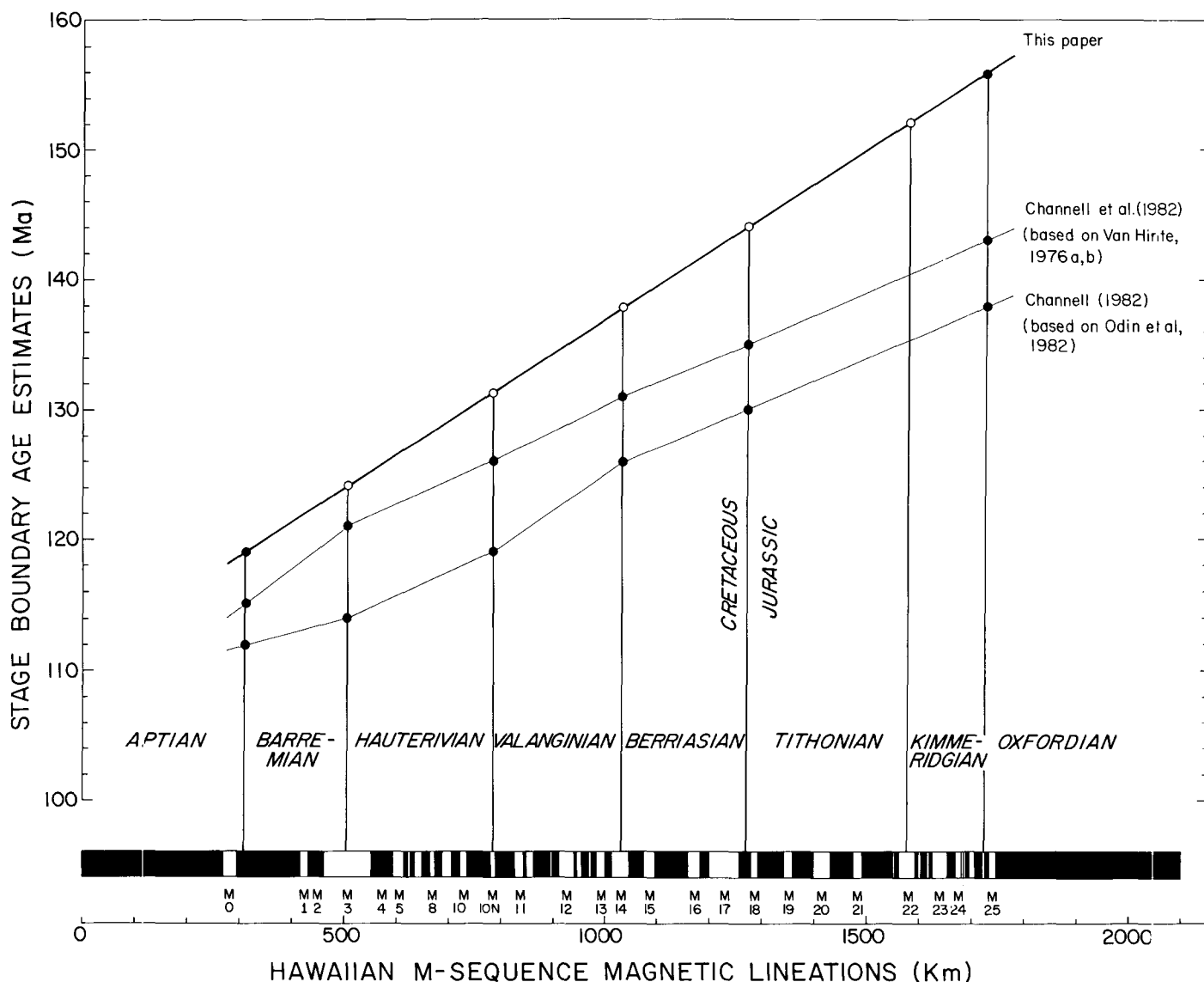


Figure 2. Comparison of age estimates for Late Jurassic and Early Cretaceous stages that have been similarly correlated to standard magnetic M-reversal sequence as derived from Hawaiian lineations (Larson and Hilde, 1975). A constant spreading rate of 3.836 cm/yr is assumed here for the Hawaiian lineations based on age estimates of 119 Ma and 156 Ma for the Barremian/Aptian and Oxfordian/Kimmeridgian boundaries, respectively (solid circles); age estimates of intervening stage boundaries (open circles) are based on interpolation.

areas of subdued magnetic signature. Unlike the generally well-defined boundary with the Cretaceous Quiet Zone, the boundary of the M-sequence with the Jurassic Quiet Zone is typically gradational and indistinct, characterized by a decreasing anomaly amplitude envelope from at least M22 to M25 and complicated by small-scale lineated anomalies extending the sequence to PM29 (*sensu* Cande and others, 1978) or AM28 (*sensu* Bryan and others, 1980).

There appear to be conflicting interpretations of polarity history during the Oxfordian and Callovian. Magnetostratigraphic studies summarized by Channell and others (1982) on sedimentary land sections from Franconia in southern Germany, the southern Alps, the Umbrian Apennines, and Sicily delimit an interval of normal polarity in the Callovian and most of the Oxfordian. In contrast, magnetostratigraphic studies on land sections in Spain and Poland, summarized by Ogg and Steiner (1985), indicate frequent magnetic reversals in this time interval. The Jurassic Quiet Zone most likely falls within the Oxfordian and Callovian stages and may therefore record a time of reduced geomagnetic intensity, accounting for the very small amplitude lineations (Cande and others, 1978).

From preliminary magnetostratigraphic work on Middle and Lower Jurassic land sections primarily from the Mediterranean area, there is more of a consensus that the Bathonian to Sinemurian stages are characterized by frequent geomagnetic reversals, even though correlation of magnetozones between sections is difficult (Channell and others, 1982; Steiner and Ogg, 1983). No marine magnetic anomalies record this interval of frequent reversals at the older end of the Jurassic Quiet Zone, suggesting that the present Atlantic ocean crust is of post-Bathonian age (younger than ~169 Ma).

For pre-Kimmeridgian Jurassic geochronology, the general lack of correlatable lineated magnetic anomalies means that it is not possible to utilize magnetostratigraphy to calibrate the time-scale as we did for the Kimmeridgian to Aptian interval. We therefore apply biochronometric and geochronometric methods for age estimation of Oxfordian to Hettangian stages, according to the following arguments.

We start with the age estimate of 156 Ma for the Oxfordian/Kimmeridgian boundary. The chronograms of Harland and others (1982) show that few isotopic dates exist to allow geochronometric estimates of the ages of the stage boundaries between the base of the Kimmeridgian and the base of the Jurassic. However, according to Armstrong (1982), at least part of the Sinemurian should be older than 203 Ma and some part of the Toarcian should fall in the age bracket of 185–189 Ma.

The age of the Triassic/Jurassic boundary is inferred from another series of whole-rock cooling ages from Triassic and Jurassic beds in volcanogenic and sedimentary complexes in British Columbia, Canada (Armstrong, 1982). Armstrong, taking into account all world data, suggests that the best available evidence places the base of the Jurassic at 208 Ma. This figure is just within the 200–208 Ma range of Odin and Letolle (1982) that is also based on high-temperature-mineral isotopic dates. Harland and others (1982) estimate an age of 213 Ma for the Triassic/Jurassic boundary based on the interpolation between Middle Triassic and middle Cretaceous, using equal duration of stages; however, the 208 Ma estimate preferred by us is within the geochronometric uncertainty they calculate.

The Jurassic chronology is then built on the isotopic age constraints of 208 Ma for the Jurassic/Triassic boundary and an Oxfordian/Kimmeridgian boundary age of 156 Ma. We use an interpolation mechanism that also was adopted by Van Hinte (1976b), the equal duration of biozones, but we use the updated ammonite zonation advocated by Hallam (1975). There are 50 biozones between the base of the Hettangian (208 Ma) and the top of the Oxfordian (156 Ma), which is 1.04 Ma per biozone. The equal-zone-duration method is, in our opinion, less crude a vernier than the equal-duration of stages used by Harland and others (1982). In fact,

TABLE 2. REVISED GEOMAGNETIC POLARITY TIME-SCALE FOR EARLY CRETACEOUS-LATE JURASSIC TIME (M-SEQUENCE)

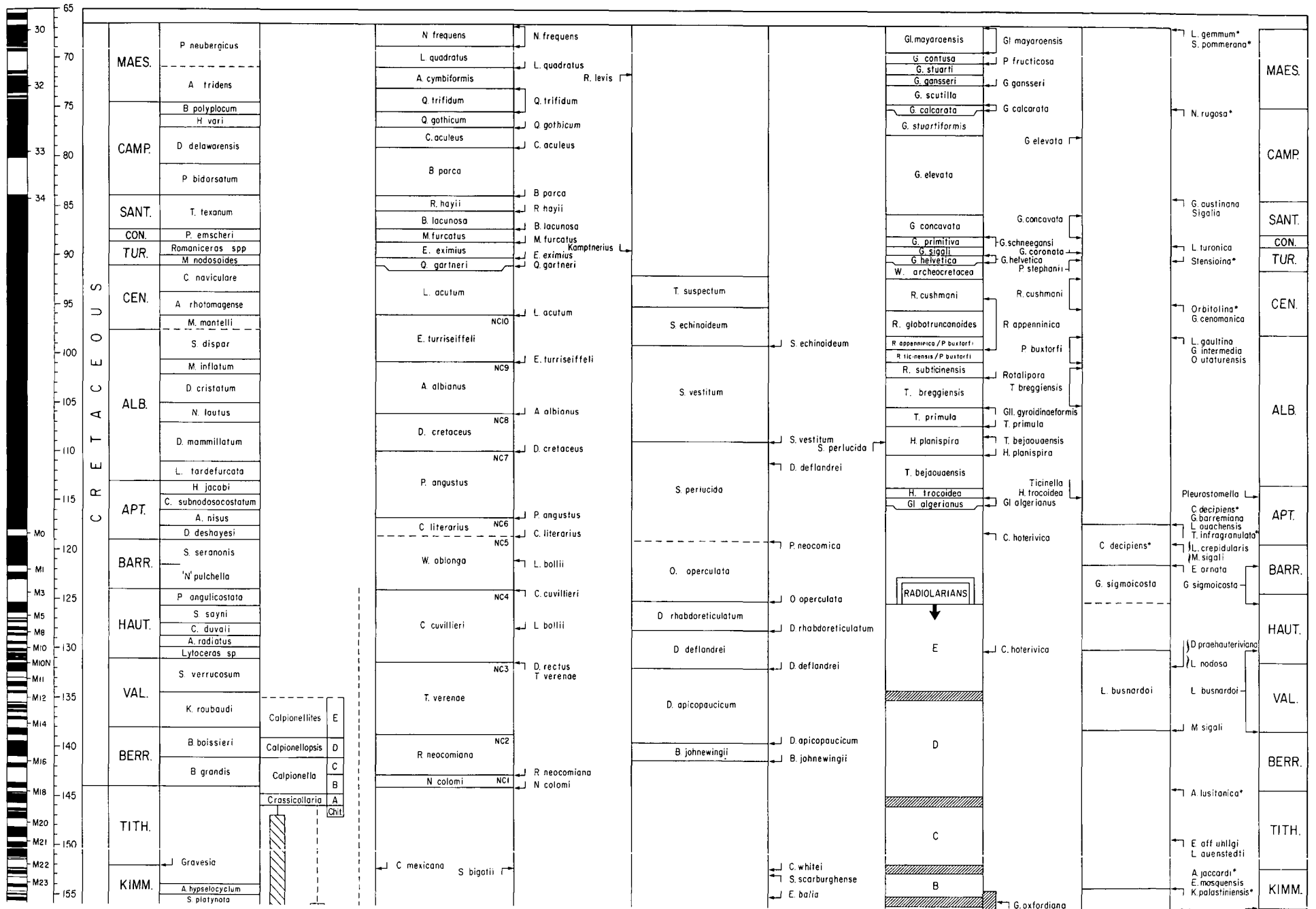
Anomaly (Reversed polarity)	NORMAL POLARITY INTERVAL (Ma)		Anomaly (Normal polarity)
	84.00 – 118.00		Cretaceous Quiet Zone
M0	118.70 – 121.81		
M1	122.25 – 123.03		M2
M3	125.36 – 126.46		M4
M5	127.05 – 127.21		
M6	127.34 – 127.52		
M7	127.97 – 128.33		
M8	128.60 – 128.91		
M9	129.43 – 129.82		
M10	130.19 – 130.57		
	130.63 – 131.00		
	131.02 – 131.36		
M10N	131.65 – 132.53		
M11	133.03 – 133.08		
M11	133.50 – 134.01		
	134.42 – 134.75		
M12	135.56 – 135.66		
	135.88 – 136.24		
	136.37 – 136.64		
M13	137.10 – 137.39		
M14	138.30 – 139.01		
M15	139.58 – 141.20		
M16	141.85 – 142.27		
M17	143.76 – 144.33		
M18	144.75 – 144.88		
	144.96 – 145.98		
M19	146.44 – 146.75		
	146.81 – 147.47		
M20	148.33 – 149.42		
M21	149.89 – 151.46		
	151.51 – 151.56		
	151.61 – 151.69		
M22	152.53 – 152.66		
	152.84 – 153.21		
	153.49 – 153.52		
M23	154.15 – 154.48		
	154.85 – 154.88		
M24	155.08 – 155.21		
	155.48 – 155.84		
	156.00 – 156.29		
M25	156.55 – 156.70		
	156.78 – 156.88		
	156.96 – 157.10		
	157.20 – 157.30		
	157.38 – 157.46		
	157.53 – 157.61		
	157.66 – 157.85		
PM26	158.01 – 158.21		
PM27	158.37 – 158.66		
PM28	158.87 – 159.80		
PM29	160.33 – (169.00)		Jurassic Quiet Zone

those writers justified their equal-stage-duration criterion by evolutionary turnover; thus it might be better to assume equal duration of biozones, which are the shortest biostratigraphic building blocks.

From this information, we derive boundary age estimates for Jurassic stages as shown in Figures 1 and 3; numerical values are listed in Table 1. The age of the lower boundary of the Sinemurian (204 Ma) just falls within the age constraint of Armstrong (1982) noted earlier, and at least part of the Toarcian (193–187 Ma) is in Armstrong's 185–189 Ma range. According to our equal-biozone-duration method of interpolation, Jurassic stages vary in duration by a factor of 2, even though the average duration of the 11 Jurassic stages (5.8 m.y.) must be very close to the average (~6 m.y.) assumed by Harland and others (1982) in their interpolation. Our age estimates of the Jurassic stage boundaries therefore tend to differ from those of Harland and others (1982) by at most 5 m.y. (at the Triassic/Jurassic boundary), and are usually within 2 m.y. Recently, Westermann (in press) has scaled the Jurassic stages based on equal duration of subzones, also using the isotopic tie-points favored in this study. The main difference is that the Aalenian (Middle Jurassic) starts about 4 m.y. later.

Above the Oxfordian, the ammonite zonation is less well established, particularly because latitudinal provincialism creates more of a problem

CRETACEOUS AND JURASSIC GEOCHRONOLOGY



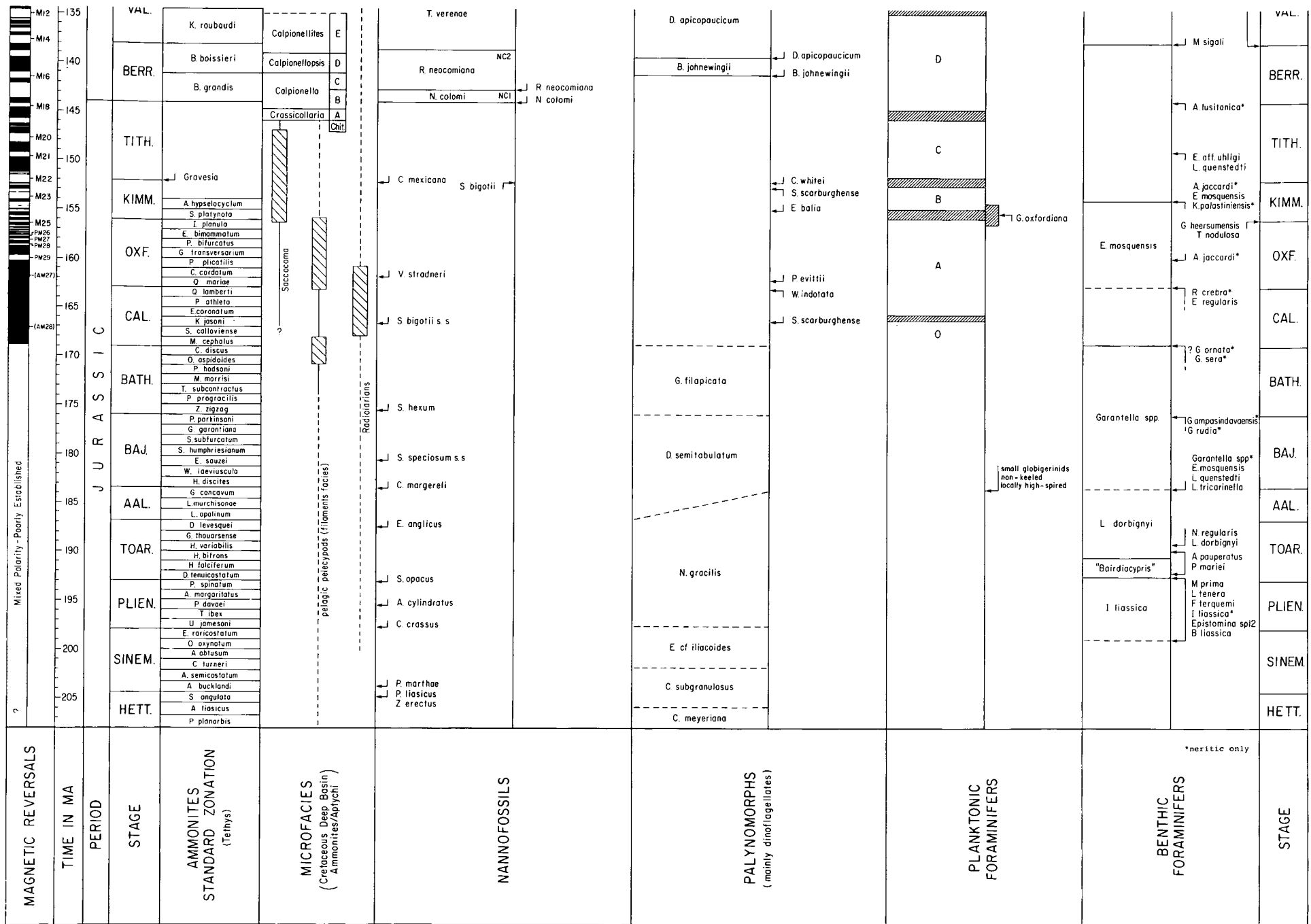


Figure 3. Stratigraphic and chronologic relationship of Jurassic and Cretaceous ammonite and microfossil zonation, and the geomagnetic reversal sequence. See text and Table 1 for sources of information. (Note: some overlap is provided in center of figure.)

for correlation. The Kimmeridgian may have 4–6 zones, however, and the Tithonian, 7–9 zones (Hallam, 1975); this ostensibly requires a Tithonian stage twice as long as the Kimmeridgian and is consistent with the magneto-chronological estimate given above. The question of what accuracy in time the new scale achieves will be answered only when many more well-spaced and stratigraphically meaningful isotopic ages become available.

We can also place age constraints with our time-scale on the pre-M25, small-amplitude magnetic anomalies. PM29 (*sensu* Cande and others, 1978) has an age estimated by extrapolation from the M-sequence of ~160 Ma (Table 2) which should place it within the mid-Oxfordian (Fig. 3). AM26 (*sensu* Bryan and others, 1980) probably corresponds to PM29 *sensu* Cande and others (1978). A minimum age for AM27 (*sensu* Bryan and others, 1980) may be derived from the pinch-out of seismic reflector D on basement at AM27 in the Blake Bahama Basin. Drilling at DSDP Site 534 (Sheridan, Gradstein, and others, 1983) showed D to be approximately early Oxfordian in age, and AM27 is thus no younger than early Oxfordian (~162 Ma). As also shown by Site 534 drilling on crust at anomaly AM28 (*sensu* Bryan and others, 1980), this anomaly is likely to be of early or middle Callovian age or ~168 Ma (Fig. 3).

BIOCHRONOLOGY

There exists a large body of Jurassic and Cretaceous biostratigraphic information for the (western) Atlantic Ocean and margin, integrated by Gradstein (in press). This biostratigraphic framework has been related to the new Jurassic and Cretaceous numerical and geomagnetic reversal time-scales (Fig. 3).

We have used Hallam's (1975) standard Jurassic ammonite zonation. The Tithonian lower boundary is based on the appearance of *Gravesia*, which leads to the short Kimmeridgian. Probably as a result of increasing geographic differentiation of morphologies and ranges, Late Jurassic and particularly Cretaceous ammonite zonations become more complex and more latitudinally distinct. For reference see Hallam (1975), Van Hinte (1976a), Sigal (1977) and Robaszynski and others (1979).

There is a first order correlation between the ranges of Early Jurassic (Pliensbachian-Toarcian) foraminifers in Portugal and the ammonite zones. Moreover, the Lower Jurassic foraminiferal record of Portugal and the Grand Banks shows good agreement (Exton and Gradstein, 1984). The *Garantella* datums which may be neritic are from the Grand Banks (Gradstein, 1977). The Late Jurassic (Oxfordian-Tithonian) foraminiferal datums are also known from the Canadian passive margin and, to some extent, from Tethys in southern Europe and North Africa. Few taxa are, however, exclusive of neritic biofacies. Increasing provincialism since Late Jurassic time precludes recognition of many of the datums in higher latitudes, although along the western Atlantic, strong Tethyan influences extended to the northern limit of the marine Jurassic and Early Cretaceous realm.

The Middle Jurassic development of planktonic foraminifera is recorded on the Grand Banks; the ancestral forms may have appeared in Aalenian-Bajocian time. The record in Atlantic pelagic biofacies is sparse, to say the least, and it is confined to some specimens in Upper Jurassic (Oxfordian) strata (Gradstein, 1977, 1983). Until Barremian time, the planktonic foraminifera were essentially confined to epicontinental seas and ocean margin basins.

The Cretaceous planktonic foraminifera zonation (as adapted from Sigal, 1977; Van Hinte, 1976a; and P. Marks, 1983, personal commun.) applies in the Atlantic. There is, however, the Upper Cretaceous condensed or unfossiliferous sequence in the bathyal and abyssal Atlantic realm. Also, the Albian *Ticinella bejaouaensis* and *Hedbergella planispira* zones, the Turonian *Whiteinella archeocretacea* zone, and Maestrichtian

Globotruncana scutilla and *G. stuarti* zones are difficult to recognize, if at all, in the Atlantic region.

The stratigraphic distribution of Cretaceous benthic foraminifera datums largely follows studies by Moullade (1966), Van Hinte (1976a), Ascoli (1977), Gradstein (1978 and unpub. data), and Drushtchiz and Gorbatschik (1978). Good summaries of eastern Atlantic Cretaceous foraminiferal datums are in Butt (1982) and Sliter (1980).

Biostratigraphic determinations using the Early and early Middle Jurassic biostratigraphic zonation of organic-walled microfossils (Bujak and Williams, 1977) on the western Atlantic margin are in reasonable agreement with those using foraminifers (see Gradstein, 1978). The foraminiferal biostratigraphy has been tied to that of the ammonite succession shown in Figure 3. For the younger Jurassic and the Cretaceous stratigraphic sections, the organic-walled microfossil biostratigraphy (dir. of flagellates) was developed for the pelagic realm by Habib (1977) and Habib and Drugg (1983). An attempt was made to relate this biostratigraphy to ammonite zonations and stratotypes. The biostratigraphy of the dinoflagellate zonation shown is in reasonable agreement with the chronostratigraphic assessments of Roth and others (1983) and Roth (1978), using nannofossils in parts of the same Deep Sea Drilling sections. Adequate regional criteria for recognition of Oxfordian, Kimmeridgian, lower Tithonian, Hauterivian, and Aptian Stages are still not settled upon. Jurassic nannofossil datums and their relation to ammonite zones, as shown, follows a literature evaluation by Roth and others (1983) and D. Watkins (1984, personal commun.).

The Late Cretaceous nannofossil zonation is that developed on the northwestern Atlantic margin and adapted from Tethyan standard zonations (Doeven and others, 1982; Doeven, 1983). It has been tied to the foraminiferal record of the Grand Banks. The calpionellid zonation is applicable to Jurassic/Cretaceous boundary beds and extends into the western Atlantic (Remane, 1978, 1983; Jansa and others, 1980). The cephalopod (small ammonites and aptychi) correlation scheme in the pelagic biofacies is that of Renz (1983). It was developed in the western Atlantic. The quantitative Tethyan radiolarian zonation which extends into DSDP Site 534, Blake Bahama basin, is that of Baumgartner (1983).

CONCLUSIONS

Boundary-age estimates and durations for Cretaceous and Jurassic stages are summarized in Table 1. A numerical chronology of geomagnetic polarity reversals for Early Cretaceous and Late Jurassic time (M-sequence) is shown in Table 2. Some general implications of this revised time-scale are:

1. An apparently systematic discrepancy exists in the geochronology of the Jurassic and Cretaceous between glauconite-based age estimates and those relying more heavily on high-temperature minerals. Berggren and others (in press) emphasize such a difference in the Paleogene, and we find also that the glauconite-based age estimates tend to be about 10% younger. For example, the Oxfordian/Kimmeridgian boundary is 140 Ma in Odin and others (1982), whereas a 156 Ma age is indicated by Armstrong (1978), Harland and others (1982), and by additional arguments cited here (Fig. 2). The cause of the disparity is not clear, although the numerical age differences are large enough to suggest that they cannot be attributed simply to analytical or even stratigraphic uncertainties.

2. Compared to the geomagnetic reversal time-scales used by Larson and Pitman (1972) and Larson and Hilde (1975) in the analysis of global sea-floor spreading rates, the time-scale presented here increases the duration of the Cretaceous Quiet Zone by ~25% and decreases the duration of the M-sequence reversals by a similar percentage. These changes in duration result primarily from making M0 (lower Aptian and base of Cretaceous Long Normal) about 10 m.y. older. Global sea-floor spreading rates

are thereby reduced in the Cretaceous Quiet Zone and increased in the M-sequence by comparable percentages. The high sea levels previously calculated for the Cretaceous Quiet Zone interval of faster sea-floor spreading on the basis of an increase in ridge-crest volumes (Hays and Pitman, 1973; Pitman, 1978) would also be significantly reduced. The effect of our time-scale on such sea-level calculations corresponds closely to that analyzed by Kominz (1984; with what that author referred to as the "BIO scale").

3. Finally, we again call attention to the obvious paucity of isotopic age data in the Early Cretaceous and Jurassic which inhibits the construction of a more constrained geochronology. At present, the precision of correlation based on magnetostratigraphy or biostratigraphy far exceeds temporal accuracy in this interval.

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REFERENCES CITED

- Agterberg, F. P., 1985, Quality of time scales—A statistical appraisal, in Merriam, D. F., ed., *Computers and geology* 5: Oxford, England, Pergamon Press (in press).
- Armstrong, R. L., 1978, Pre-Cenozoic Phanerozoic time scale—Computer file of critical dates and consequences of new and in-progress decay-constant revisions, in Cohee, G., Glaessner, M., and Hedberg, H., eds., *Contributions to the geologic time scale*: Tulsa, Oklahoma, American Association of Petroleum Geologists, p. 73–91.
- 1982, Late Triassic–Early Jurassic time-scale calibration in British Columbia, Canada, in Odin, G. S., ed., *Numerical dating in stratigraphy*: New York, John Wiley & Sons Ltd., p. 509–513.
- Ascoli, P., 1977, Foraminiferal and ostracod biostratigraphy of the Mesozoic–Cenozoic, Scotian Shelf, Atlantic Canada, in *International Symposium on Benthonic Foraminifera, 1st, 1975, Proceedings, part B, Maritime sediments, Special Publication no. 1*: Halifax, Nova Scotia, p. 653–771.
- Baumgartner, P. O., 1983, Summary of Middle Jurassic–Early Cretaceous radiolarian biostratigraphy of DSDP Site 534 (Blake Bahama basin) and correlation to Tethyan sections, in Sheridan, R. E., Gradstein, F. M., and others, *Initial reports of the Deep Sea Drilling Project, Volume 76*: Washington, D.C., U.S. Government Printing Office, p. 569–573.
- Berggren, W. A., Kent, D. V., and Flynn, J. J., 1985a, Paleogene chronology and chronostratigraphy: Geological Society of London (in press).
- Berggren, W. A., Kent, D. V., Flynn, J. J., and Van Couvering, J. A., 1985b, Cenozoic geochronology: Geological Society of America Bulletin, this volume.
- Bryan, G. M., Markl, R. G., and Sheridan, R. E., 1980, IPOD site surveys in the Blake-Bahama basin: *Marine Geology*, v. 35, p. 43–63.
- Bujak, J. P., and Williams, G. L., 1977, Jurassic palynostratigraphy of offshore eastern Canada, in Swain, E. M., ed., *Stratigraphic micropaleontology of the Atlantic basin and borderlands*: New York, Elsevier, p. 321–339.
- Butt, A., 1982, Micropaleontological bathymetry of the Cretaceous of western Morocco: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 37, p. 235–275.
- Cande, S. C., Larson, R. L., and LaBrecque, J. L., 1978, Magnetic lineations in the Pacific Jurassic Quiet Zone: *Earth and Planetary Science Letters*, v. 41, p. 434–440.
- Channell, J.E.T., 1982, Mesozoic–Cenozoic time scale, in Odin, G. S., ed., *Numerical dating in stratigraphy*: New York, John Wiley and Sons, Ltd., p. 97.
- Channell, J.E.T., Ogg, J. G., and Lowrie, W., 1982, Geomagnetic polarity in the Early Cretaceous and Jurassic: *Royal Society of London Philosophical Transactions*, v. A306, p. 137–146.
- Clark, L. D., 1964, Stratigraphy and structure of part of the western Sierra Nevada metamorphic belt, California: *U.S. Geological Survey Professional Paper* 410, p. 1–70.
- Clark, L. D., 1976, Stratigraphy of the northern half of the western Sierra Nevada metamorphic belt, California: *U.S. Geological Survey Professional Paper* 923, p. 1–26.
- Cox, A. V., 1982, Magnetic reversal time-scale, in Harland, W. B., and others, eds., *A geologic time scale*: Cambridge, England, Cambridge University Press, 128 p.
- Dalrymple, G. B., 1979, Critical tables for conversion of K–Ar ages from old to new constants: *Geology*, v. 7, p. 558–560.
- Doeven, P. H., 1983, Cretaceous nannofossil stratigraphy and paleoecology of the northwestern Atlantic: *Canada Geological Survey Bulletin*, v. 356, 69 p.
- Doeven, P. H., Gradstein, F. M., Jackson, A., Agterberg, F. P., and Nel, L. D., 1982, A quantitative nannofossil range chart: *Micropaleontology*, v. 28, p. 85–92.
- Drushtchitz, V. V., and Gorbatschik, T. N., 1978, Zonengliederung der Unteren Kreide der südlichen USSR nach Ammoniten und Foraminiferen, in *Aspekte der Kreide Europas*, International Union of Geological Sciences, ser. A, Volume 6: p. 107–116.
- Exton, J., and Gradstein, F. M., 1984, Early Jurassic stratigraphy and micropaleontology of the Grand Banks and Portugal, in Westermann, G. E., ed., *Jurassic and Cretaceous biochronology and biogeography of North America: Geological Association of Canada Memoir*, p. 13–30.
- Geological Society of London, 1964, *Geological Society Phanerozoic time scale 1964*: Geological Society of London Quarterly Journal, v. 120, p. 260–262.
- Gradstein, F. M., 1977, Biostratigraphy and biogeography of Jurassic Grand Banks foraminifera, in *International Symposium on Benthonic Foraminifera, 1st, 1975, Proceedings, Part B, Maritime sediments Special Publication, no. 1*: Halifax, Nova Scotia, 1975, p. 557–583.
- 1978, Biostratigraphy of Lower Cretaceous Blake Nose and Blake-Bahama basin foraminifera, DSDP Leg 44, western North Atlantic Ocean, in Benson, W. E., and others, *Initial reports of the Deep Sea Drilling Project, Volume 44*: Washington, D.C., U.S. Government Printing Office, p. 663–703.
- Gradstein, F. M., 1983, Paleocology and stratigraphy of Jurassic abyssal foraminifera in the Blake Bahama basin, Deep Sea Drilling Project Site 534, in Sheridan, R. S., and others, *Initial reports of the Deep Sea Drilling Project, Volume 76*: Washington, D.C., U.S. Government Printing Office, p. 537–561.
- 1985, Northwestern Atlantic Mesozoic biostratigraphy, in Tucholke, B. E., and Vogt, P. R., eds., *The geology of North America: The western Atlantic region, Volume M*: Geological Society of America (in press).
- Habib, D., 1977, Comparison of Lower and Middle Cretaceous palynostratigraphy zonations in the western North Atlantic, in Swain, F. M., ed., *Micropaleontology of the Atlantic basin and borderlands*: New York, Elsevier Publishing Co., p. 341–367.
- Habib, D., and Drugg, W. S., 1983, Dinoflagellate age of Middle Jurassic–Early Cretaceous sediments in the Blake Bahama basin, in Sheridan, R. E., and others, *Initial reports of the Deep Sea Drilling Project, Volume 76*: Washington, D.C., U.S. Government Printing Office, p. 623–639.
- Hallam, A., 1975, *Jurassic environments*: London, Cambridge University Press, 269 p.
- Harland, W. B., Cox, A. V., Llewellyn, P. G., Pickton, C.A.G., Smith, A. G., and Walters, R., 1982, *A geologic time scale*: Cambridge, Cambridge University Press, 128 p.
- Hays, J. D., and Pitman, W. C. III, 1973, Lithospheric plate motion, sea level changes and climatic and ecological consequences: *Nature*, v. 246, p. 18–22.
- Jansa, L. F., Remane, J., and Ascoli, P., 1980, Calpionellid and foraminiferal–ostracod biostratigraphy at the Jurassic–Cretaceous boundary, offshore eastern Canada: *Rivista Italiana di Paleontologia*, v. 86, p. 67–126.
- Kent, D. V., and Gradstein, F. M., 1985, A Jurassic to Recent chronology, in Tucholke, B. E., and Vogt, P. R., eds., *The western Atlantic region, Vol. M, The geology of North America: The Geological Society of America (in press)*.
- Kominz, M. A., 1984, Oceanic ridge volumes and sea-level change—an error analysis, in Schler, J., ed., *International unconformities and hydrocarbon accumulation*: American Association of Petroleum Geologists, Memoir 36, p. 109–127.
- Larson, R. L., and Chase, C. G., 1972, Late Mesozoic evolution of the western Pacific: *Geological Society of America Bulletin*, v. 83, p. 3627–3644.
- Larson, R. L., and Hilde, T.W.C., 1975, A revised time scale of magnetic anomalies for the Early Cretaceous and Late Jurassic: *Journal of Geophysical Research*, v. 80, p. 2586–2594.
- Larson, R. L., and Pitman, W. C. III, 1972, Worldwide correlation of Mesozoic magnetic anomalies, and its implications: *Geological Society of America Bulletin*, v. 83, p. 3645–3662.
- Lowrie, W., and Alvarez, W., 1977, Upper Cretaceous–Paleocene magnetic stratigraphy at Gubbio, Italy. III. Upper Cretaceous magnetic stratigraphy: *Geological Society of America Bulletin*, v. 88, p. 374–377.
- 1981, One hundred million years of geomagnetic polarity history: *Geology*, v. 9, p. 392–397.
- Lowrie, W., and Channell, J.E.T., 1984, Magnetostratigraphy of the Jurassic–Cretaceous boundary in the Maiolica Limestone (Umbria, Italy): *Geology*, v. 12, p. 44–47.
- Lowrie, W., Channell, J.E.T., and Alvarez, W., 1980, A review of magnetic stratigraphic investigations in Cretaceous pelagic carbonate rocks: *Journal of Geophysical Research*, v. 89, p. 3597–3605.
- Moullade, M., 1966, Etude stratigraphique et micropaleontologique du Cretace inferieur de la 'Fosse Vocontienne': Documents des Laboratoires de Geologie de la Faculte des Sciences de Lyon, no. 15, fasc., 1, 2, 369 p.
- Ness, G., Levi, S., and Couch, R., 1980, Marine magnetic anomaly time scales for the Cenozoic and Late Cretaceous: A precis, critique, and synthesis: *Revue de Geophysique Space Physics*, v. 18, p. 753–770.
- Obradovich, J. D., and Cobban, W. A., 1975, A time-scale for the Late Cretaceous of the western interior of North America: *Geological Association of Canada Special Paper* 13, p. 31–45.
- Odin, G. S., Curry, D., Gale, N. H., and Kennedy, W. J., 1982, The Phanerozoic time scale in 1981, in Odin, G. S., ed., *Numerical dating in stratigraphy*: New York, John Wiley & Sons, Ltd., p. 957–960.
- Odin, G. S., and Letolle, R., 1982, The Triassic time scale in 1981, in Odin, G. S., ed., *Numerical dating in stratigraphy*: New York, John Wiley & Sons, Ltd., p. 523–533.
- Ogg, J. G., 1983, Magnetostratigraphy of Upper Jurassic and Lower Cretaceous sediments, DSDP Site 534, western North Atlantic, in Sheridan, R. E. and others, *Initial Reports of the Deep Sea Drilling Project, Volume 76*: Washington, D.C., U.S. Government Printing Office, p. 685–699.
- Ogg, J. G., and Steiner, M. B., 1985, Jurassic magnetic polarity time scale—current status and compilation, in Gichelson, O., and Zeiss, A., eds., *Jurassic stratigraphy: Special publication of the Danish Geological Survey*, p. 1–16.
- Ogg, J. G., Steiner, M. B., Oloriz, F., and Tavera, J. M., 1984, Jurassic magnetostratigraphy, 1. Kimmeridgian–Tithonian of Sierra Gorda and Carcabuey, southern Spain: *Earth and Planetary Science Letters*, v. 71, p. 147–162.
- Ozima, M., Kaneko, I., and Yanagisawa, M., 1979, ⁴⁰Ar/³⁹Ar geochronological studies of drilled basalts from leg 51 and 52, in Donnelly, T., Francheteau, J., Robinson, P., Flower, M., and Salisbury, M., eds., *Initial Reports of the Deep Sea Drilling Project, Volumes 51, 52, 53*: Washington, D.C., U.S. Government Printing Office, p. 1127–1128.
- Palmer, A. R., 1983, The Decade of North American Geology 1983 geologic time scale: *Geology*, v. 11, p. 503–504.
- Pitman, W. C. III, 1978, Relationship between eustasy and stratigraphic sequences of passive margins: *Geological Society of America Bulletin*, v. 89, p. 1389–1403.
- Remane, J., 1978, Calpionellids, in Haq, B. U., and Boersma, A., eds., *Introduction to marine micropaleontology*: New York, Elsevier, p. 161–170.
- 1983, Calpionellids and the Jurassic–Cretaceous boundary in Deep Sea Drilling Project Site 534, western North Atlantic, in Sheridan, R. E., and others, *Initial reports of the Deep Sea Drilling Project, Volume 76*: Washington, D.C., U.S. Government Printing Office, p. 561–569.
- Renz, O., 1983, Early Cretaceous Cephalopoda from the Blake-Bahama basin (DSDP Leg 76, Site 534A) and their correlation in the Atlantic and southwestern Tethys, in Sheridan, R. E., and others, *Initial reports of the Deep Sea Drilling Project, Volume 76*: Washington, D.C., U.S. Government Printing Office, p. 639–645.
- Robaszynski, F., Caron, M., and others, 1979, Atlas of Mid-Cretaceous planktonic foraminifera: *Cahiers de Micropaleontologie*, part 1 (1979), p. 1–184; part 2 (1979), p. 1–181.
- Roth, P. H., 1978, Cretaceous nanoplankton biostratigraphy and oceanography of the northwestern Atlantic Ocean, in Benson, W. E., and others, *Initial reports of the Deep Sea Drilling Project, Volume 44*: Washington, D.C., U.S. Government Printing Office, p. 731–761.
- Roth, P. H., Medd, A. W., and Watkins, D. K., 1983, Jurassic calcareous nanofossil zonation, an overview with new evidence from DSDP Site 534, in Sheridan, R. E., and others, *Initial reports of the Deep Sea Drilling Project, Volume 76*: Washington, D.C., U.S. Government Printing Office, p. 573–581.
- Schweickert, R. A., Bogen, N. L., Girty, G. H., Hanson, R. E., and Merguerian, C., 1984, Timing and structural expression of the Nevada orogeny, Sierra Nevada, California: *Geological Society of America Bulletin*, v. 95, p. 967–979.
- Sheridan, R. E., Gradstein, F. M., and others, 1983, *Initial reports of the Deep Sea Drilling Project, Volume 76*: Washington, D.C., U.S. Government Printing Office, 947 p.
- Sigal, J., 1977, Essai de zonation du Cretace mediterraneen a l'aide des foraminiferes planctoniques: *Geologie Mediterranee*, v. 4, p. 99–108.
- Sliter, W. V., 1980, Mesozoic foraminifera and deep-sea benthic environments from Deep Sea Drilling Project Sites 415 and 416, eastern North Atlantic, in Lancelot, Y., and others, *Initial reports of the Deep Sea Drilling Project, Volume 50*: Washington, D.C., U.S. Government Printing Office, p. 353–427.
- Steiner, M. B., and Ogg, J. G., 1983, Jurassic magnetic polarity time scale [abs.]: *EOS (American Geophysical Union Transactions)*, v. 45, p. 689.
- Van Hinte, J. E., 1976a, A Cretaceous time scale: *American Association of Petroleum Geologists Bulletin*, v. 60, p. 498–516.
- 1976b, A Jurassic time scale: *American Association of Petroleum Geologists*, v. 60, p. 489–497.
- Westermann, G.E.G., 1985, Duration of Jurassic ammonite zones and stages based on scaled-equal subzone method, in *International Symposium on Quantitative Stratigraphy*, Kharagpur, India, 1983, Proceedings: Hyderabad, Association of Eapl. Geophysicists (in press).

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