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Chapter 3

A Jurassic to recent chronology

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INTRODUCTION

We present an integrated geomagnetic polarity and geologic time scale for the Jurassic to Recent interval, encompassing the age range of the modern ocean floor. The time scale is based on the most recent bio-, magneto-, and radiochronologic data available.

The biostratigraphic bases for Jurassic, Cretaceous, and Cenozoic time-scales are discussed extensively elsewhere (e.g., Gradstein, this volume; Van Hinte, 1976b; Hardenbol and Berggren, 1978; Berggren and Van Couvering, 1974; Van Couvering and Berggren, 1977). Emphasis is placed here on magnetochronology and its integration with biochronology in the derivation of an internally consistent geologic time scale. The binary signal of normal and reversed geomagnetic polarity has little intrinsic absolute time value (ordinal scale), but it can be used to measure time according to its radiochronologic calibration (cardinal scale). The standard magnetic reversal sequence has a correlatable, characteristic pattern and is demonstrated to be continuous from numerous marine magnetic anomaly profiles from the world ocean. The reversal sequence is recorded by lateral accretion in sea-floor spreading and vertical accumulation in sedimentary or lava sections, allowing independent checks on the completeness and relative spacing of the reversal sequence as well as the opportunity to apply an assortment of geochronologic data for calibration. Although different phenomena and assumptions are invoked in their derivation, both magneto- and biochronologic time estimates involve indirect assessment according to calculated rates of sea-floor spreading, sedimentation, and biotic evolution. These extend the application of the relatively few reliable radiometric dates available, so that a continuous geologic time scale can be inferred.

The degree of magnetochronologic resolution possible depends on the frequency of geomagnetic reversals and the availability of a well-defined record of the polarity sequence best developed in marine magnetic lineations (Vogt, this volume, Ch. 15). Thus the Campanian to Recent and the latest Oxfordian to early Aptian intervals of frequent reversals, corresponding to the mid-ocean ridge and the M-sequence magnetic lineations, respectively, allow the construction of a precise magnetochronologic framework. In contrast, the early Aptian to Santonian, and the Callovian to late Oxfordian intervals are of predominantly constant geomagnetic polarity. They correspond to the oceanic Cretaceous and Jurassic Quiet Zones, respectively, and magnetochronologic resolution is poor. A Sinemurian to Bathonian interval of frequent reversals has been documented in magnetostratigraphic land sections, primarily from the Mediterranean region. However, oceanic crust that might carry a magnetic anomaly signature of these early and middle Jurassic reversals is apparently not present. Consequently, the detailed sequence of reversals is poorly known for this time interval.

LATE CRETACEOUS AND CENOZOIC

The chronology and chronostratigraphy of this time interval is drawn directly from Berggren and others (1984a, b). In their work, bio- and magnetostratigraphy in some European Paleogene and Neogene stratotype sections are integrated and an assessment of some 200 Cenozoic and Late Cretaceous calcareous plankton datum events are directly correlated with magnetic polarity stratigraphy in deep-sea sediment cores and land sections. The data provide improved identification of the boundaries and durations of chronostratigraphic units in terms of planktic biostratigraphy and geomagnetic polarity chrons.

The geomagnetic polarity time scale is based on the radiometric dates and magnetic polarities on lavas for 0 to 4 Ma (Mankinen and Dalrymple, 1979) and is extended in time by age calibration of the polarity sequence inferred from marine magnetic anomalies. The polarity sequence compiled by LaBrecque and others (1977) is taken as representative of the sea-floor spreading record for the Late Cretaceous and Cenozoic. Six selected high-temperature radiometric ages are used for age calibration in such a way as to minimize apparent accelerations in sea-floor spreading history. These key ages are for Anomalies 2A (3.40 Ma), 5 (8.87 Ma), 12 (32.4 Ma), 13 (34.6 Ma), 21 (49.5 Ma) and 34 (84.0 Ma) (see Berggren and others, 1984a). Calculated ages for magnetic polarity intervals are shown in Table 1. Relative precision of boundaries in the reversal sequence depends

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TABLE 1. REVISED GEOMAGNETIC POLARITY TIME-SCALE FOR OXFORDIAN TO RECENT TIME

Normal Polarity Interval (Ma)	Anomaly	Normal Polarity Interval (Ma)	Anomaly	Anomaly (Reversed)	Normal Polarity Interval (Ma)	Anomaly (Normal)
					- 118.00	Cretaceous Quiet Zone
0.00 - 0.73	1	24.04 - 24.21	6C	M0	118.70 - 121.81	
0.91 - 0.98		25.50 - 25.60	7	M1	122.25 - 123.03	M2
1.66 - 1.88	2	25.67 - 25.97	7	M3	125.36 - 126.46	M4
2.47 - 2.92	2A	26.38 - 26.56	7A	M5	127.05 - 127.21	
2.99 - 3.08	2A	26.86 - 26.93	8	M6	127.34 - 127.52	
3.18 - 3.40	2A	27.01 - 27.74	8	M7	127.97 - 128.33	
3.88 - 3.97	3	28.15 - 28.74	9	M8	128.60 - 128.91	
4.10 - 4.24	3	28.80 - 29.21	9	M9	129.43 - 129.82	
4.40 - 4.47	3	29.73 - 30.03	10	M10	130.19 - 130.57	
4.57 - 4.77	3	30.09 - 30.33	10		130.63 - 131.00	
5.35 - 5.53	3A	31.23 - 31.58	11		131.02 - 131.36	
5.68 - 5.89	3A	31.64 - 32.06	11	M10N	131.65 - 132.53	
6.37 - 6.50		32.46 - 32.90	12	M11	133.03 - 133.08	
6.70 - 6.78	4	35.29 - 35.47	13	M11	133.50 - 134.31	
6.85 - 7.28	4	35.54 - 35.87	13		134.42 - 134.75	
7.35 - 7.41	4	37.24 - 37.46	15	M12	135.56 - 135.66	
7.90 - 8.21	4A	37.48 - 37.68	15		135.88 - 136.24	
8.41 - 8.50	4A	38.10 - 38.34	16		136.37 - 136.64	
8.71 - 8.80		38.50 - 38.79	16	M13	137.10 - 137.39	
8.92 - 10.42	5	38.83 - 39.24	16	M14	138.30 - 139.01	
10.54 - 10.59		39.53 - 40.43	17	M15	139.58 - 141.20	
11.03 - 11.09		40.50 - 40.70	17	M16	141.85 - 142.27	
11.55 - 11.73	5A	40.77 - 41.11	17	M17	143.76 - 144.33	
11.86 - 12.12	5A	41.29 - 41.73	18	M18	144.75 - 144.88	
12.46 - 12.49		41.80 - 42.23	18		144.96 - 145.98	
12.58 - 12.62		42.30 - 42.73	18	M19	146.44 - 146.75	
12.83 - 13.01	5AA	43.60 - 44.06	19		146.81 - 147.47	
13.20 - 13.46	5AB	44.66 - 46.17	20	M20	148.33 - 149.42	
13.69 - 14.08	5AC	48.75 - 50.34	21	M21	149.89 - 151.46	
14.20 - 14.66	5AD	51.95 - 52.62	22		151.51 - 151.56	
14.87 - 14.96	5B	53.88 - 54.03	23		151.61 - 151.69	
15.13 - 15.27	5B	54.09 - 54.70	23	M22	152.53 - 152.66	
16.22 - 16.52	5C	55.14 - 55.37	24		152.84 - 153.21	
16.56 - 16.73	5C	55.66 - 56.14	24		153.49 - 153.52	
16.80 - 16.98	5C	58.64 - 59.24	25	M23	154.15 - 154.48	
17.57 - 17.90	5D	60.21 - 60.75	26		154.85 - 154.88	
18.12 - 18.14	5D	63.03 - 63.54	27	M24	155.08 - 155.21	
18.56 - 19.09	5E	64.29 - 65.12	28		155.48 - 155.84	
19.35 - 20.45	6	65.50 - 66.17	29		156.00 - 156.29	
20.88 - 21.16	6A	66.74 - 68.42	30	M25	156.55 - 156.70	
21.38 - 21.71	6A	68.52 - 69.40	31		156.78 - 156.88	
21.90 - 22.06	6AA	71.37 - 71.65	32		156.96 - 157.10	
22.25 - 22.35	6AA	71.91 - 73.55	32		157.20 - 157.30	
22.57 - 22.97	6B	73.96 - 74.01			157.38 - 157.46	
23.27 - 23.44	6C	74.30 - 80.17	33		157.53 - 157.61	
23.55 - 23.79	6C	84.00 -118.00	34		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

on the spatial resolution of the magnetic anomaly data and on the assumption that the compiled reversal sequence represents a linear and continuous record over time intervals of at least tens of million years (but see Vogt, this volume, Ch. 24). The accuracy of the reversal chronology ultimately depends on the radiometric age data set used for calibration. Remarkably, the first extended magnetochronology proposed by Heirtzler and others (1968), based on a simple extrapolation from Anomaly 2A (Gauss/Gilbert boundary), gives age estimates for magnetochrons that are within 10 percent of the absolute age estimates summarized here and based on more extensive magnetobiostratigraphic correlations and radiometric date calibration data. This agreement indicates that the constant-spreading rate-assumption applied to selected areas of the world ocean is a very good first-order approximation in the derivation of a geomagnetic reversal chronology.

The age-calibrated magnetic reversal sequence can then be used as a vernier (analogous to use of age-calibrated stratigraphic thickness) to obtain precise age estimates for various boundaries in accordance with magnetobiostratigraphic correlations. Numerical ages on the Late Cretaceous and Cenozoic geologic timescale (Fig. 1; Plate 1, in pocket inside back cover) are therefore based on the revised magnetochronology summarized above.

MID-CRETACEOUS

The stratigraphic interval from the lower Aptian to the top of the Santonian records predominantly normal geomagnetic polarity; this nicely accounts for the Cretaceous Quiet Zones in the oceans (Lowrie and others, 1980). Consequently, there are no well-documented magnetozones or anomalies that can be correlated (Vogt, this volume, Ch. 15). Fortunately, abundant radiometric dates are available for this interval; numerical ages for stage boundaries (Fig. 1; Plate 1B) are therefore taken directly from the chronometric estimates of Harland and others (1982).

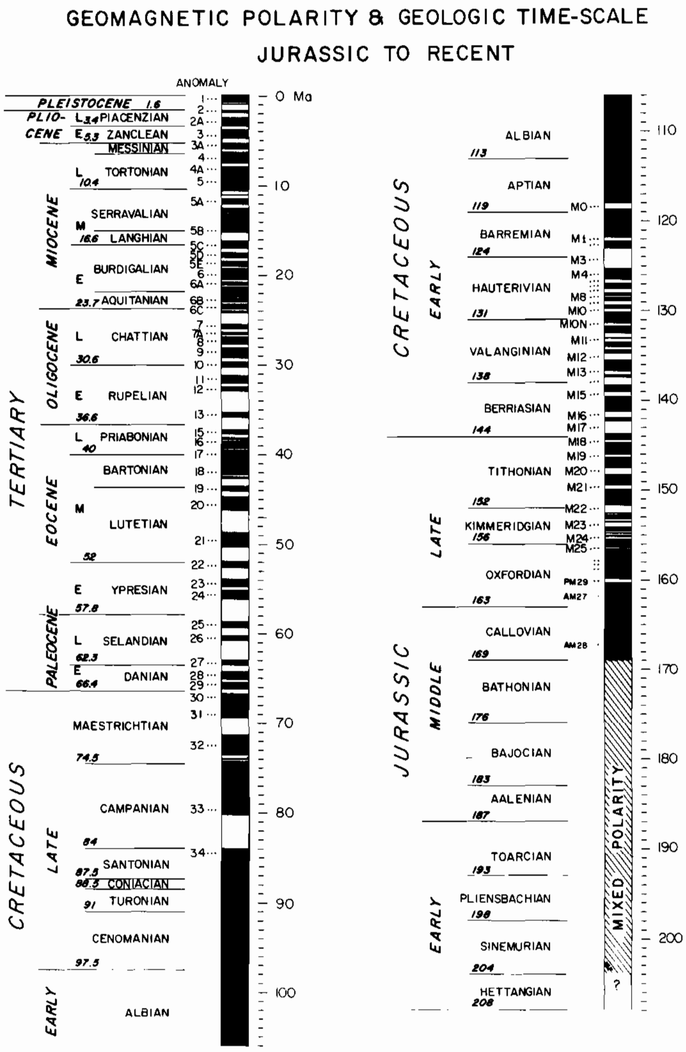

Figure 1. Geomagnetic polarity and geologic time scale for the Jurassic to recent. Methods of construction and sources of information are discussed in the text. Numerical ages of stage boundaries are indicated in millions of years (Ma).

LATE JURASSIC AND EARLY CRETACEOUS

The older end of the Cretaceous Quiet Zones in the oceans is bounded typically 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 that are interpreted to correspond usually to reversed polarity) was derived from the Hawaiian lineations that are assumed to have formed at a constant rate of sea-floor spreading (Larson and Hilde, 1975). The M-sequence has been extended beyond M25 in the Pacific (Cande and others, 1978; PM26 to PM29 in Fig. 1 and Plate 1B) and in the Atlantic (Bryan and others, 1980; AM26 to AM28); the anomaly designations are not the same in both papers.

The chronologic control used by Larson and Hilde (1975) was based on biostratigraphic assignments of basal sediments of five DSDP holes drilled over identified M-anomalies; numerical ages were referred to the Geological Society of London (1964) time-scale. More exact magnetobiostratigraphic correlations have since become available (Heller, 1977; Lowrie and others, 1980; Channell and others, 1982; Ogg, 1983; Gradstein and Sheridan, 1983; Lowrie and Channell, 1984; Gradstein, this volume) and they provide a basis for a more refined chronology. The correlation of Late Jurassic and Early Cretaceous stage boundaries with the M-sequence geomagnetic reversal record (Figs. 1 and 2; Plate 1B) is based on the work cited above and is discussed in Kent and Gradstein (submitted).

Despite the improved magnetobiostratigraphic correlations, numerical age estimates for Late Jurassic and Early Cretaceous stages are still poor due to a lack of reliable radiometric dates. Harland and others (1982) adopted the "equal duration of stages concept" to interpolate between chronometrically determined age calibration tie-points at the Aptian/Albian boundary (113 Ma) and the Ladinian/Anisian boundary (238 Ma). To be consistent with our use of the Harland and others (1982) chronology for the Santonian to Albian, and to avoid an artificial discontinuity, we use their age estimates of 119 Ma for the Barremian/Aptian boundary and 156 Ma for the Oxfordian/Kimmeridgian boundary to calibrate the M-sequence.

The Barremian/Aptian falls within the M-sequence; it is the next (older) boundary from the Aptian/Albian which is considered by Harland and others (1982) to be the only chronometrically well-constrained tie-point (113 Ma) in the Early 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 MO in the western North Atlantic (Ozima and others, 1979). This date is admittedly poor, but it nevertheless is 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 dates to arrive at an age of approximately 156 Ma for the Oxfordian/Kimmeridgian boundary. This is identical to the broadly interpolated age derived by Harland and others (1982). Additional evidence for a 154–158 Ma age range for this boundary is found in the Sierra Nevada (California) (Schweickert and others, 1984).

For these reasons, we have accepted the age interpolations of 119 Ma (Barremian/Aptian) and 156 Ma (Oxfordian/Kimmeridgian) as reasonably well-defined tie-points for calibration of the M-sequence. We note, however, that these age estimates based largely on high-temperature mineral dates are older, by as much as 14–16 Ma in the case of the Oxfordian/Kimmeridgian boundary, than age estimates in Van Hinte (1976a, b) and Odin and others (1982); the discrepancy is principally in the fact that their age estimates are much more controlled by glauconite dates.

We used the magnetostratigraphic correlations, the assumption of a constant spreading rate on the Hawaiian lineations

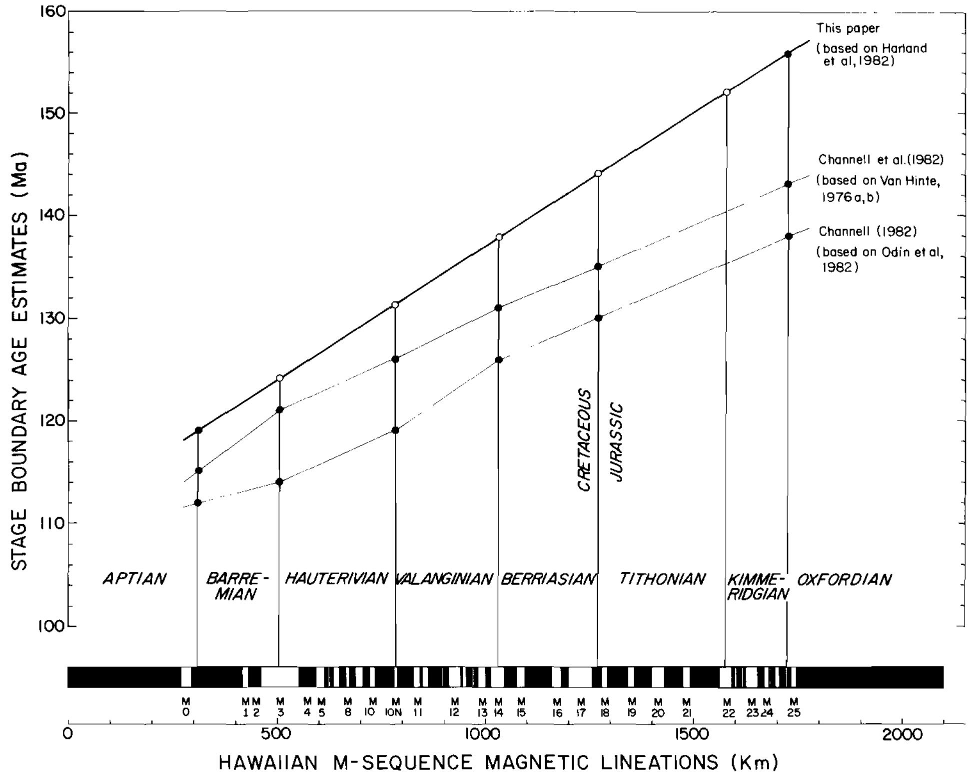

Figure 2. Three sets of age estimates for late Jurassic and early Cretaceous stages that have been similarly correlated to standard magnetic M-reversal sequence as derived from Hawaiian lineations (Larson and Hilde 1975). A constant spreading rate of 3.836 cm/yr is assumed here for the Hawaiian lineations based on age estimates (from Harland and others 1982) of 119 Ma and 156 Ma for the Barremian/Aptian and Oxfordian/Kimmeridgian boundaries, respectively; age estimates of intervening stage boundaries (open circles) are based on interpolation. In comparison, age calibration data used by Channell and others (1982) are from Van Hinte (1976a, b), and those used by Channel (1982) are from Odin and others (1982).

(Larson and Hilde, 1975), and the above calibration tie-points to derive age estimates for Kimmeridgian to Barremian stage boundaries (Fig. 2; Plate 1B) and for the M-sequence geomagnetic reversals (Table 1). This is simply another case of using the magnetic reversal sequence as a vernier to estimate ages of correlated boundaries between points of known or assumed age. In comparison to the equal-stage-duration model of Harland and others (1982), the magnetochronological method also gives approximately equal (ca. 6 m.y.) durations for the oldest four stages 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 relative duration of the Tithonian and Kimmeridgian stages is in good agreement with the relative duration inferred from assuming equal duration of ammonite zones (see below). Differences with previously published magnetochronologies for the M-sequence vary according to the degree of magnetobiostratigraphic data incorporated (e.g. Cox, 1982) and the geologic time-scale used in calibration (Fig. 2).

JURASSIC (PRE-KIMMERIDGIAN)

The older end of the M-sequence of anomalies is bounded by the Jurassic Quiet Zone that is represented by sea-floor areas of subdued magnetic signature. The boundary of the M-sequence with the Jurassic Quiet Zone is typically gradational or 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 (Cande and others, 1978) or AM28 (Bryan and others, 1980).

Magnetostratigraphic studies on land-sections (summarized by Channel and others, 1982) indicate an interval of predominantly normal geomagnetic polarity for the Callovian and most of the Oxfordian. Thus reversed polarity magnetozones that might correlate to anomalies older than M25 have not yet been confidently identified in magnetostratigraphic sections. Whether this reflects inadequate magnetostratigraphic sampling or means that the small-amplitude, pre-M25 anomalies are not due to geomagnetic reversals is not yet clear.

Preliminary magnetostratigraphic work on Middle and Lower Jurassic land sections, primarily from the Mediterranean area, suggests that the Sinemurian to Bathonian 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 oldest end of the Jurassic Quiet Zones, suggesting that the present oceanic crust is of post-Bathonian age (ca <169 Ma). However, at least in the Atlantic, this crust is deeply buried by sediment and any magnetic lineations would most likely already be low-amplitude and poorly developed.

For pre-Kimmeridgian Jurassic geochronology, the general lack of correlatable, lineated magnetic anomalies means that it is not possible to effectively use magnetochronology to calibrate the time-scale as we did for the Kimmeridgian-Aptian interval. We therefore apply bio-and radiochronologic methods for Early and Middle Jurassic stage age estimation, according to the following arguments.

We proceed from the age estimate of 156 Ma for the Oxfordian/Kimmeridgian boundary. The chronograms of Harland and others (1982) show that few radiometric dates exist to allow radiochronologic estimates of 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 Triassic/Jurassic boundary age 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 radiometric 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 that we prefer is within the chronometric uncertainty they calculate. We therefore accept 208 Ma as a reasonable estimate for the Triassic/Jurassic boundary.

The Jurassic chronology is then built on the radiometric 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 zones, but we use the updated ammonite zonation advocated by Hallam (1975). There are 50 zones between the base of the Hettangian (208 Ma) and the top of the Oxfordian (156 Ma), which is 1.04 m.y. per zone. Skeptics will point to the uncertainties in this number, which is only an average, but we believe it is less crude a means for apportioning time than the equal duration of stages assumed by Harland and others (1982). In fact, Harland and others (1982) justify their equal-duration criterion by evolutionary turnover; thus it may be better to assume equal duration of zones, which are the shortest (bio) stratigraphic building blocks.

Above the Oxfordian the ammonite zonation is less well established, particularly because latitudinal provincialism creates more of a problem in correlation. However, the Kimmeridgian may have four to six zones and the Tithonian seven to nine zones (Hallam, 1975); this ostensibly requires a Tithonian stage twice as long as the Kimmeridgian and is consistent with the magnetochronological estimates given above.

From this information, we derive boundary age estimates for Jurassic stages as shown in Figure 1 and Plate 1B. The older age limit of the Sinemurian (204 Ma) falls just 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-zone-duration method of interpolation, Jurassic stages vary in duration by a factor of 2, but of course the average duration of the 11 Jurassic stages (5.7 m.y.) is still very near the average (ca. 6 m.y.) assumed by Harland and others (1982) in their interpolation. Our Jurassic stage-boundary age estimates therefore tend to differ at most by 5 m.y. (at the Triassic/Jurassic boundary) from Harland and others (1982) and usually they fall within 2 m.y. The question of what accuracy in time the new scale achieves will be answered only when many more well spaced and stratigraphically meaningful radiometric dates become available. At the moment time resolution, although not accuracy, is going to be far better when a biochronologic and magnetochronologic framework is used rather than radiochronology alone.

As a final note, we place age constraints with our time-scale on the pre-M25 small-amplitude magnetic anomalies. PM29 (Cande and others, 1978) has an age estimated by extrapolation from the M-sequence of ca. 160 Ma (Table 1) which should place it within the mid-Oxfordian (Fig. 1; Plate 1B). AM26 (Bryan and others, 1980) probably corresponds to PM29 (Cande and others, 1978). A minimum age for AM27 (Bryan and others, 1980) may be derived from the pinch-out of seismic reflector D on basement at AM27. Drilling at DSDP Site 534 (Sheridan and others 1983) shows D to be approximately early Oxfordian in age. AM27 is thus no younger than early Oxfordian. As also shown by Site 534 drilling on crust at anomaly AM28, this anomaly is likely to be of early or middle Callovian age.

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