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Marine Magnetic Anomaly Timescales for the Cenozoic and Late Cretaceous: A Précis, Critique, and Synthesis

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Anomaly timescales for the last 90 million years, derived from marine magnetic profiles and published prior to mid-1979, are summarized, illustrated for comparison, and critically reviewed. A revised timescale is constructed using calibration points which fix the ages of anomalies 2.3', 5.5, 24, and 29. An equation is presented for converting K-Ar dates that is consistent with the recent adoption of new decay and abundance constants. The calibration points used in the revised timescale are so converted, as are the boundary ages of geologic epochs within the range of the timescale.

INTRODUCTION

A little less than 14 years have passed since the first publication of timescales derived from seafloor spreading magnetic anomalies, and in that time, numerous additions and revisions have been made to them. Biostratigraphic results from the Deep-Sea Drilling Project (DSDP) have confirmed the general accuracy of such timescales and have also been used to calibrate portions of them. Radiometrically determined timescales have better defined the polarity reversal boundary ages for portions of the late Neogene. Core magnetostratigraphic data have been used to increase the resolution of portions of the anomaly timescales and have also been used to calibrate them. Recently, new decay and abundance constants have been adopted for use in potassium-argon dating methods, increasing the accuracy, and to some extent the confusion, of age assignments made using anomaly timescales. Within the last 4 years at least four new versions of Cenozoic marine magnetic anomaly timescales have been published.

This paper resulted from what began as a brief literature review, the object of which was to select an anomaly timescale for use in interpreting the detailed tectonic history of the Rivera and Juan de Fuca plates. In the process of this review it became apparent first that the literature on the topic has become very extensive and second that evidence exists in support of making still further revisions to the general history of the geomagnetic field as it is expressed in the seafloor record.

We review those major papers published since 1966 which provide either tables or formulae for determining boundary ages for anomaly source bodies. We also review certain other papers that offer important criticisms or suggestions concerning anomaly timescales. We do not discuss the development of late Neogene radiometrically determined polarity timescales but do include figures illustrating some of those used to calibrate anomaly timescales (Figures 1 and 3). We refer readers wishing such a review to a paper by *Watkins* [1972].

Our Figure 2 illustrates the marine anomaly timescales discussed and includes the boundary age assignments made by previous workers. We hope it will save others some time and confusion.

We present an equation for converting old K-Ar dates to corrected values consistent with the change in decay and abundance constants and use this equation to convert certain radiometric and biostratigraphic dates necessary in constructing a revised timescale, here named NLC-80. We offer timescale NLC-80 as an up-to-date but temporary synthesis and carefully specify how it was constructed. Finally, we criticize our own timescale and provide some alternative interpretations.

For economy we discuss particular boundary ages for anomaly source bodies, using a convention which distinguishes older from younger. For example, the older boundary of anomaly 29 is designated 29(o), and the younger boundary 29(y). We also refer to published timescales in an abbreviated form. Thus the timescale of *Blakely and Cox* [1972*b*] becomes BC-72, and so on. Also for economy, and to avoid ambiguity, we use the abbreviation MY instead of m.y. or Ma to signify millions of years. We adopt the anomaly numbering scheme employed by *Heirtzler et al.* [1968] in their timescale HDHPL-68 and include the revised numberings of *Blakely* [1974], *Klitgord et al.* [1972, 1975], and *LaBrecque et al.* [1977]. We add certain anomaly numbers in NLC-80 consistent with prior usage.

PREVIOUSLY PUBLISHED MAGNETIC ANOMALY TIMESCALES

PH-66 and V-68

When *Vine and Matthews* [1963] first suggested that seafloor magnetic anomalies might be related to geomagnetic field reversals, they could only offer their hypothesis as speculation, since the available evidence for reversals was extremely limited. At that time the results of *Cox et al.* [1963*a*], which were based upon only nine dated rock samples having determined polarities, were insufficient even to determine which of two proposed and very rudimentary reversal timescales might be most correct (Figure 1, bottom). However, by the following year, *Cox et al.* [1964] had compiled the results of several studies and proposed a more detailed reversal timescale based upon 64 dated samples. This scale was sufficiently detailed such that *Vine and Wilson* [1965] used it to generate synthetic seafloor spreading magnetic anomalies using the Vine and Matthews model. Vine and Wilson compared observed profiles from the Juan de Fuca and Pacific-Antarctic ridges with one another and with synthetic anomaly profiles and demonstrated both their similarity and their individual axial symmetry.

It is noteworthy that Vine and Wilson found certain discrepancies between the observed and synthetic anomalies which they attributed to noncontinuous spreading rates. In fact, the discontinuities were caused by inadequacies in the timescale used. The so-called Jaramillo event (anomaly 1') was not distinguished until the following year by *Doell and Dalrymple* [1966], and Vine and Wilson had mistakenly identified it as the Gilsa event (anomaly 2). Recognition of the

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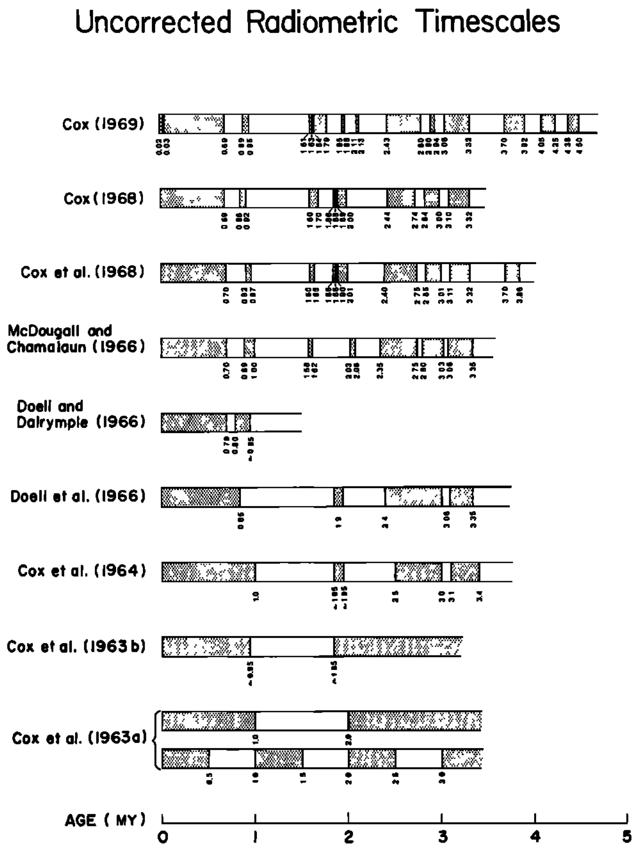


Fig. 1. Radiometrically dated magnetic polarity timescales published between 1963 and 1969. Several have been used to provide calibration points for marine magnetic anomaly timescales as discussed in the text.

Jaramillo event made the error immediately obvious to *Vine* [1966], who pointed out that if he and Wilson had had more faith in the constant spreading assumption, they could have predicted the Jaramillo event using marine and anomaly profiles.

This observation was also apparent to *Pitman and Heirtzler* [1966]. They generated a timescale (PH-66) for the last 10 MY (Figure 2) using profiles from the Pacific-Antarctic Ridge and an assumed half-spreading rate of 4.5 cm/yr, which yielded results consistent with the radiometric timescales published to that time. Pitman and Heirtzler next compared anomalies from the Reykjanes Ridge in the North Atlantic with synthetic anomalies generated using their South Pacific timescale, noted their similarity, and remarked that the spreading rates in the two regions were probably constant over the last 10 MY unless both rates had changed simultaneously and in similar proportion.

Vine [1966] assembled a composite radiometric timescale which was based upon *Cox et al.* [1964] and *Doell and Dalrymple* [1966], though not exactly similar to them, at least with respect to the Gilsa event (anomaly 2). He then used this timescale to determine spreading rates for the Reykjanes, Juan de Fuca, Pacific-Antarctic, northwest Indian, and South Atlantic ridges and again demonstrated their similarity and symmetry. In his paper, Vine generated an extrapolated marine magnetic anomaly timescale for the last 11.5 MY using *Eltanin* cruise 19 data from the Pacific-Antarctic Ridge and a 4.4-cm/yr half-spreading rate. He did not publish a table of the anomaly boundary ages. However, 2 years later the V-68 timescale [*Vine,* 1968] was published in the revised proceedings of a symposium on the history of the earth's crust held in 1966. Using magnetic profiles obtained from the East Pacific Rise at 51°S, the Juan de Fuca Ridge at 48°N, and the Reykjanes Ridge at 60°N, Vine first assumed constant rates of seafloor spreading for each of these three areas and then determined those rates and the reversal ages derived from them by comparison with the detailed radiometric timescale of *Cox et al.* [1968] (Figure 1). Vine next examined an extended magnetic profile (*Eltanin* 19N) obtained from the East Pacific Rise at 51°S (the Pacific-Antarctic Ridge), and by now assuming an overall half-spreading rate of 4.6 cm/yr, he generated an extrapolated marine magnetic anomaly timescale good to approximately 11 MY (just short of anomaly 5A).

Using this South Pacific scale, Vine again went on to demonstrate that the extended pattern of anomalies there was similar in character to that of magnetic profiles obtained from the North and South Atlantic oceans, the Indian Ocean, and the North Pacific Ocean, these differing only in their rates of seafloor spreading. He next generated a block model for magnetic source bodies, in the approximate range of anomalies 21–33, from a central North Pacific Ocean profile and compared synthetic anomalies generated from the model with profiles obtained from the southwest Pacific and northeast Atlantic oceans. The comparison indicated that these also only differed in their respective spreading rates. Following an earlier extrapolation [*Vine,* 1966], these anomalies were estimated to range in age from approximately 50 to 75 MY.

These early results of Vine, Wilson, Pitman, and Heirtzler clearly and quantitatively supported the validity of the Vine and Matthews hypothesis and made it apparent that given sufficient data, an extended magnetic reversal timescale could be constructed using seafloor magnetic anomalies.

HDHPL-68

Without doubt, the magnetic anomaly timescale most widely employed to date has been that of *Heirtzler et al.* [1968]. In a consecutive series of four papers published in the March 1968 edition of the *Journal of Geophysical Research* the authors of HDHPL-68 compared the relative distances to particular marine magnetic anomalies from the crests of spreading ridges in the North and South Pacific, the South Atlantic, and the Indian oceans and used these to select a single long profile to use for generating a continuous, standard magnetic anomaly timescale. The objective, of course, was to choose a profile that was apparently free of any evidence of changes in the rate of seafloor spreading. Heirtzler et al. ruled out an Indian Ocean profile because it only extended to anomaly 16 and a North Pacific profile because the mapped pattern of anomalies was distorted near the Juan de Fuca and Gorda ridges. They also rejected a South Pacific profile because it indicated major accelerations in spreading rates near anomaly 5 and anomaly 24 when compared with both North Pacific and South Atlantic profiles. The South Pacific spreading rate age for anomaly 6 also violated a paleontologically determined age for the base of a sediment core taken in the North Pacific over that anomaly.

Heirtzler et al. selected the South Atlantic, *Vema*-20, profile as standard and calibrated the age of anomaly 2.3′(o) at 3.35 MY, consistent with radiometric age determinations for that boundary made on subaerial basalts by *Doell et al.* [1966] and by *McDougall and Chamalaun* [1966] (Figure 1). They determined a 1.9-cm/yr half-spreading rate for the profile and ex-

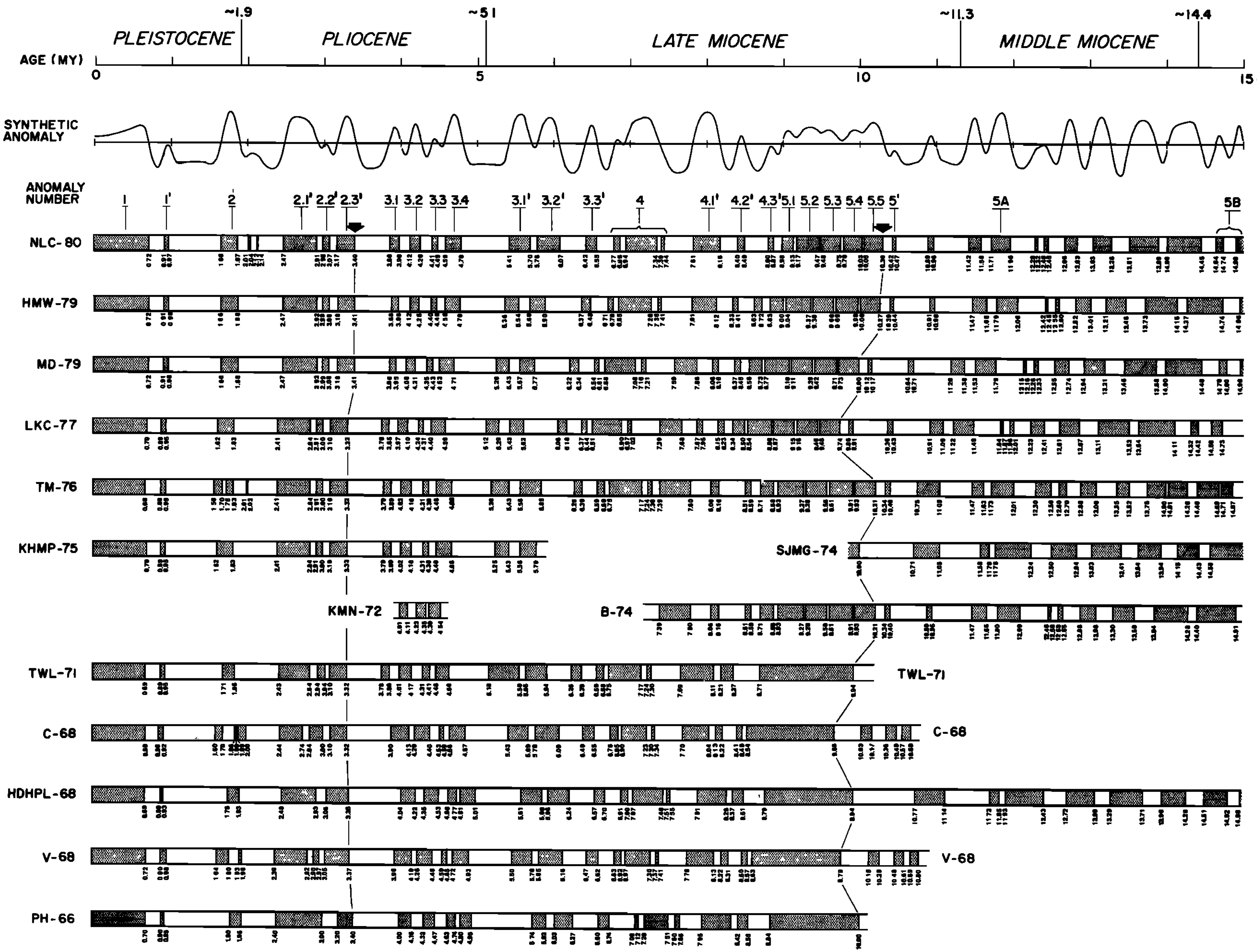
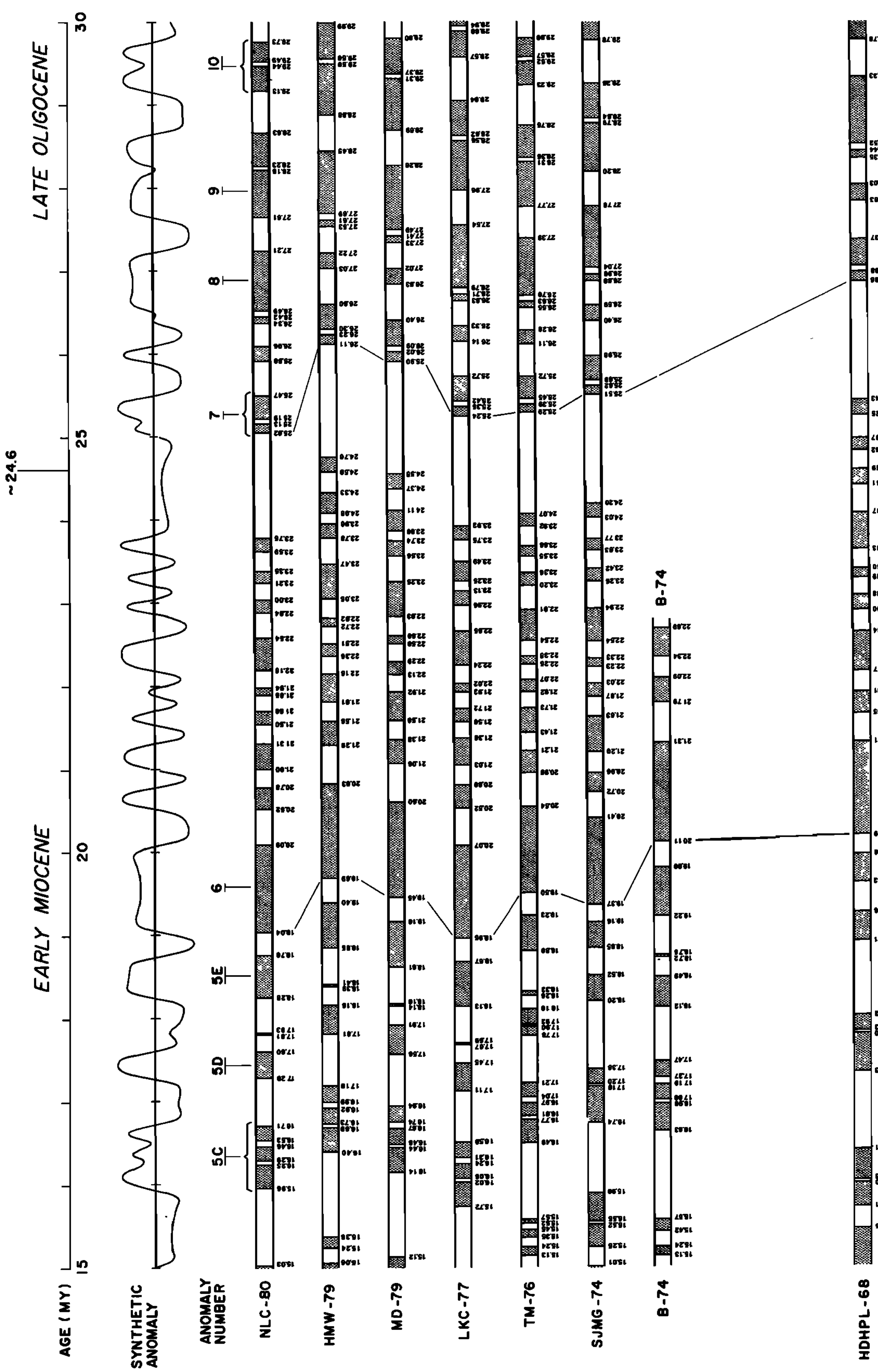


Fig. 2. Late Cretaceous and Cenozoic marine magnetic anomaly timescales. NLC-80, HMW-79, and MD-79 employ new K-Ar decay constants. Arrows on NLC-80 indicate calibration points used on that timescale. Tie lines are drawn for ease of identification between some arbitrarily selected anomaly age boundaries. Geological epoch boundaries are from Table 1. Synthetic anomaly profile is generated from NLC-80, and its shape would be typical of anomalies found in middle latitudes over fast, east-west spreading ridges, measured at the sea surface over an average oceanic water depth of about 3.5 km, generated by source bodies having a thickness of 0.5 km. Each of the six sheets describes 15 MY. (Sheets were designed for assembly into a continuous strip.)



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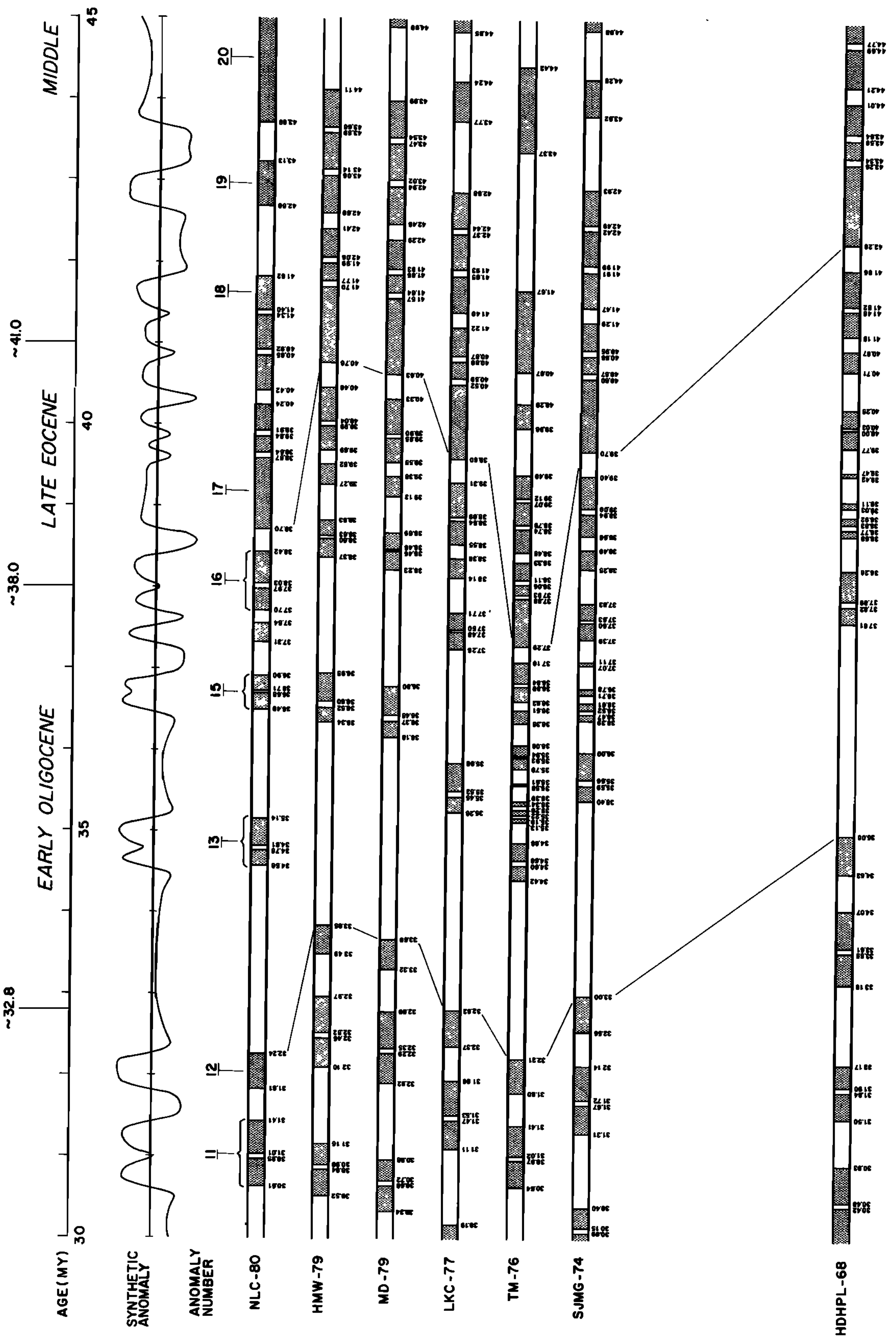

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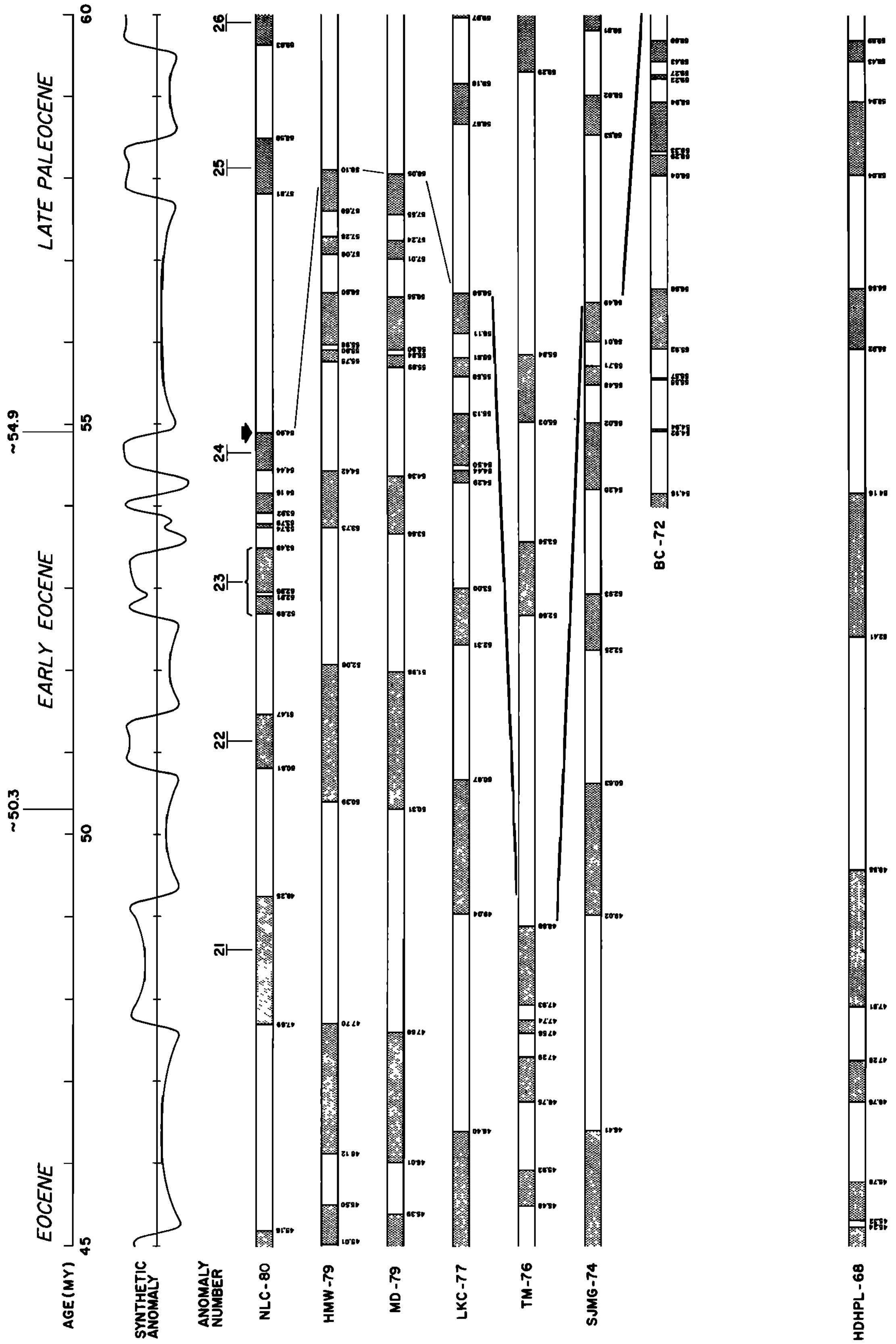

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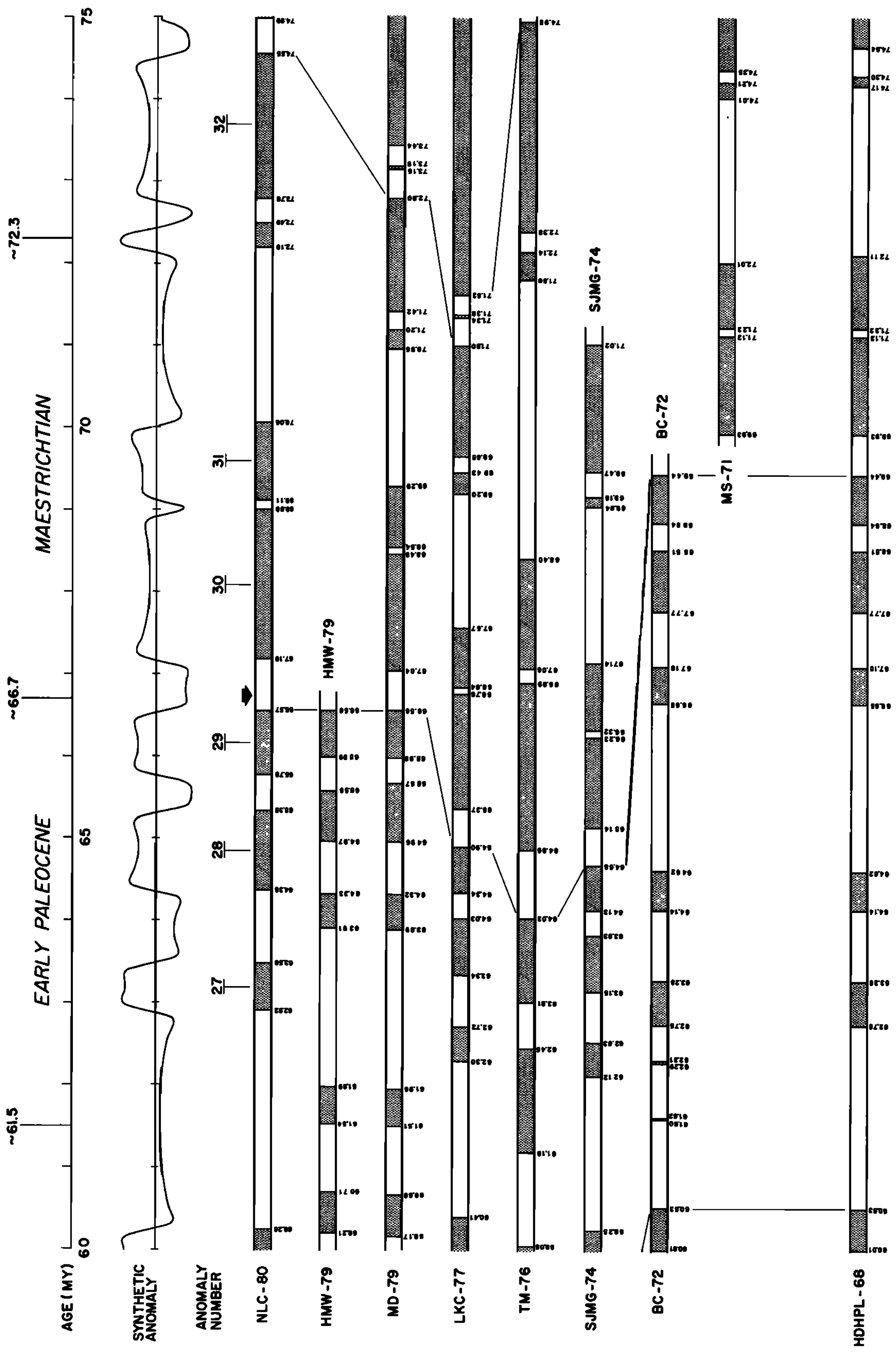

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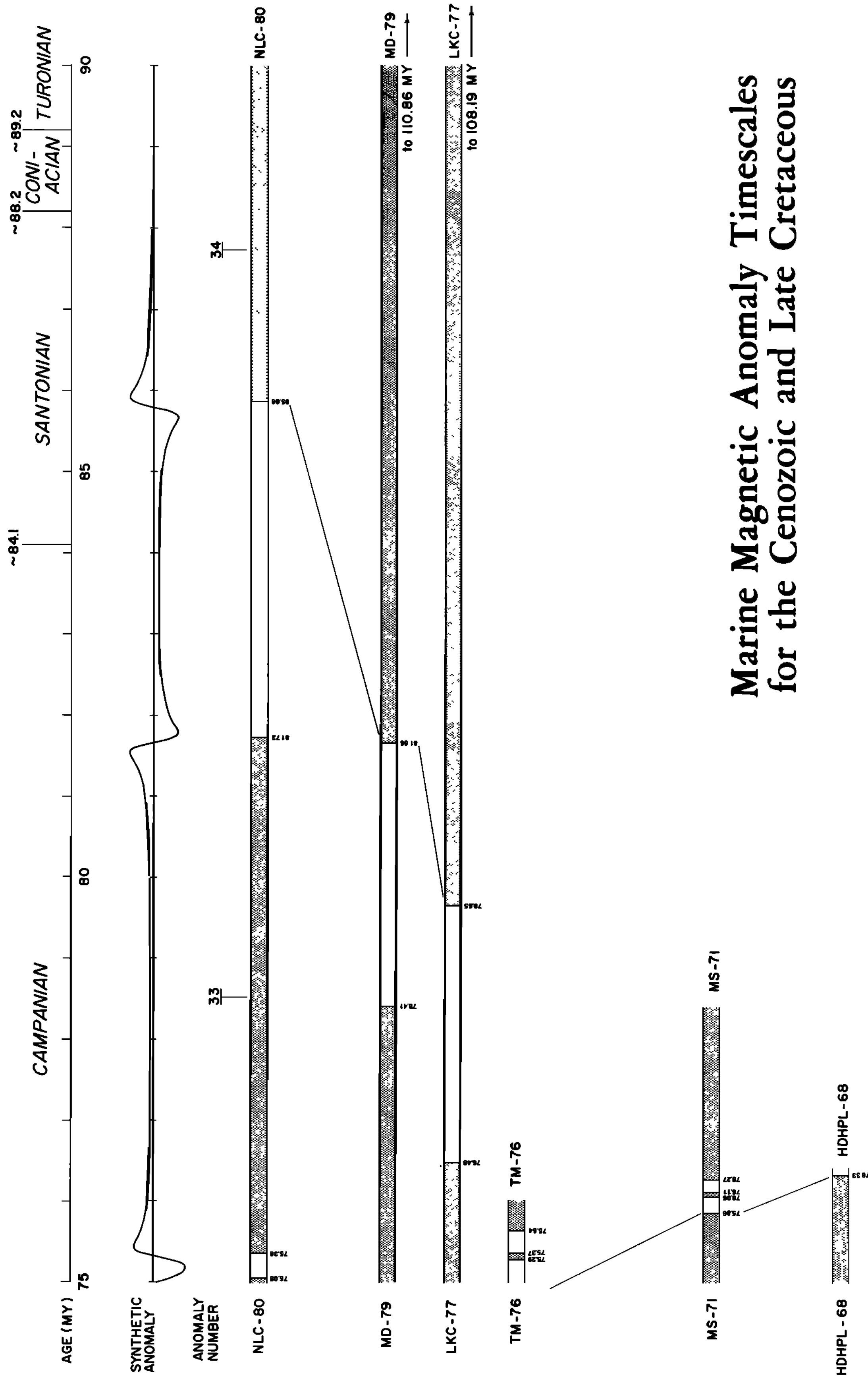

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Fig. 2. (continued)

trapolated the spreading rate versus distance relationship to approximately 80 MY, beyond anomaly 32. This timescale was consistent with the Cretaceous age determination of a sediment core from the South Atlantic near anomaly 31 and also in close agreement with the earlier estimate made for the age of that anomaly by *Vine* [1966].

The remarkable 80-MY extrapolation made by *Heirtzler et al.* [1968] from a calibration date of 3.35 MY was supported at the time it was made by only the most tenuous of evidence, a single Late Cretaceous core. Yet, for the most part, magnetic anomaly timescales published after HDHPL-68 are only modest revisions, additions, or recalibrations of it, and the general plate tectonics reconstructions made using that scale as a time base are still valid. Today, however, greater resolution and accuracy are required for understanding both the finer scale phenomena of plate motions and the short-period behavior of the earth's field. The disadvantage in HDHPL-68 is that it was generated from a single sinuous profile obtained from the relatively slow spreading South Atlantic Ridge. This affected both its resolving power and its accuracy. Note, for example, that it fails to resolve anomaly 2.2′ and anomaly 4.3′ source blocks, while timescale V-68, which was generated from fast-ridge data, resolved both.

C-68

In a paper devoted primarily to a statistical study of the length of polarity intervals, *Cox* [1968] constructed a hybrid timescale of radiometric, core magnetostratigraphic, and marine anomalies. From 0 to 3.2 MY the scale was based on radiometric ages from *Cox et al.* [1968] and on studies of the paleomagnetism of deep-sea sediment cores. Beyond anomaly 2.3′(o), at 3.32 MY, the V-68 scale of Vine was compressed by a ratio of 3.32/3.37. To our knowledge this scale was never used in any tectonic reconstructions.

TWL-71

From a comprehensive survey of the Reykjanes Ridge south of Iceland, which employed satellite navigation techniques, *Talwani et al.* [1971] generated timescale TWL-71. Average distances between the ridge crest and prominent anomalies were determined along 12 closely spaced profiles made perpendicular to the ridge. Then, assuming that the HDHPL-68 age for anomaly 5(o) of 9.94 MY was correct and that spreading on the Reykjanes Ridge had been constant since that time, a residual distance versus time curve was constructed comparing measured distances with distances predicted using HDHPL-68. The residuals were considered to represent errors in the timescale of *Heirtzler et al.* [1968]. A new hybrid scale was constructed using radiometric age data from *Cox* [1969] (modified by core magnetostratigraphic information) to anomaly 2.3′(o) at 3.32 MY. Anomaly 3.1′(y) was fixed at 5.18 MY as a compromise between residual distance data which indicated a corrected age of 5.31 MY and a date of 5.06 MY assigned by *Foster and Opdyke* [1970] using core magnetostratigraphy. Beyond anomaly 3.1′(y) the residual distance data alone were used to correct HDHPL-68. The advantage of TWL-71 over HDHPL-68 is that many closely spaced and parallel profiles were used in its construction. This technique reduces noise and eliminates questions about the ideal two-dimensionality of the seafloor spreading anomalies. The disadvantages in TWL-71 are first that it was generated from profiles obtained over a slow spreading ridge, which limits its resolution, and second that it is a hybrid, compromise scale and therefore difficult to put to certain kinds of use without risking circularity.

MS-71

From an analysis of shipboard and aeromagnetic profiles obtained in the Indian Ocean, *McKenzie and Sclater* [1971] proposed modifications and additions to HDHPL-68 beyond anomaly 30. A determination was made of the average distances between particular anomalies in the range of anomalies 22 to 33. This information was then compared with similar data from the North Pacific Ocean at 40°N from a study by *Raff* [1966] and from the South Atlantic Ocean using the *Vema* 20 data from *Dickson et al.* [1968]. In this anomaly range, the South Atlantic distance data were found to be linearly proportional to the North Pacific distance data, at least as far back as anomaly 30. *McKenzie and Sclater* [1971] therefore assumed that variations in the Indian Ocean distance data were due to changes in Indian Ocean spreading rates occurring near the times of anomalies 23 and 31. North Pacific distance data were then used to generate MS-71; however, no details of these data were presented in the paper.

BC-72

Blakely and Cox [1972*b*], using the same signal-enhancing techniques applied in an earlier paper [*Blakely and Cox*, 1972*a*], analyzed six magnetic profiles from the northeast Pacific Ocean in order to resolve short-term magnetic polarity events within the range of anomalies 21 to 29. Profiles were first reduced to the pole to eliminate asymmetry, then stretched to a common spreading rate by fitting major anomalies to HDHPL-68. The profiles were then algebraically averaged to attenuate noise. Six short-polarity intervals were recognized and included in BC-72 as modifications to HDHPL-68. Subsequently, three-component magnetometer data were obtained from a low-altitude aeromagnetic profile over the original survey area [*Blakely et al.*, 1973]. These data supported the two-dimensionality of the source bodies associated with the two longest of the six previously determined polarity intervals and indicated the possible presence of an additional new polarity interval. The data were too noisy, however, to confirm the presence of the other four short intervals in question.

Cande and LaBrecque [1974] pointed out that very short polarity intervals are virtually indistinguishable from large, single-polarity, geomagnetic intensity fluctuations, when observed from the ocean surface. The issue of distinguishing intensity fluctuations from true polarity reversals is significant for those studies concerning the origin and behavior of the field. However, our original purpose in conducting this review was to adopt or to construct a marine magnetic anomaly timescale for use in making detailed plate tectonic reconstructions. Therefore to the extent that a particular anomaly is a common feature of appropriate magnetic profiles, it is a useful time marker and should be included in the timescale. Features of short duration are particularly useful in distinguishing between anomalies when dealing with relatively short magnetic profiles. Strictly, the determination of whether or not a particular short-duration anomaly truly represents a field reversal requires independent paleomagnetic confirmation. Practically, in plate tectonics applications it is not required. Logically, the burden of proof appears to be on those who would argue that any particular two-dimensional, marine magnetic anomaly is not due to a geomagnetic field reversal. Anomaly polarity timescales are essentially identical to radiometric polarity timescales, at least for the last 3.5 MY. To accept this and then argue without proof that any older two-dimensional anomaly is not due to a field reversal is inconsistent. Moreover, short-polarity events are documented, but intensity fluctuations of the type needed to produce single-polarity wiggles are not.

In constructing the NLC-80 timescale we include only the two longer events of BC-72, whose presence was supported by the subsequent three-axis magnetometer study of *Blakely et al.* [1973]. It is worth noting that the four events of BC-72 which are omitted from NLC-80 are of normal polarity and their duration is only of the order of 0.02 MY.

KMN-72

Using a deep-tow magnetometer and a bottom transponder navigation system, *Klitgord et al.* [1972] conducted two separate surveys, 6 months apart, of the seafloor off of the southern tip of Baja California. Magnetic observations from both surveys were used to determine the average spatial distribution of anomalies 3.2, 3.3, and 3.4. This information was then used to generate a revised timescale, for the interval studied, by fixing anomaly 3.2(y) at 4.01 MY, the TWL-71 age for that boundary, and by applying an overall 3.15-cm/yr half-spreading-rate value to the distance information. The spreading rate was determined by the regression of anomaly distances, from the nearby ridge crest, onto the TWL-71 timescale.

The accuracy of KMN-72 is questionable. Since no common transponders were used between the two survey sections, one survey was adjusted to the other by using bathymetric features yielding 'a final relative position accuracy of less than 200 m.' However, absolute positioning was with radar and therefore 'only accurate to within a few kilometers.' Both estimates seem optimistic, particularly since the mapped orientation of anomalies 3.2, 3.3, and 3.4 is about 35°, while the strike of the ridge crest is about 21° and the strike of anomaly 5 is more nearly north-south. The authors themselves noted the discrepancy and suggested that it could have been due either to survey orientation errors, which raises the question of navigational accuracy, or to the existence of unmapped fracture zones, which casts doubt upon the matching of bathymetric features. The survey area has undergone large-scale tectonic reorientations since at least anomaly 5 time.

B-74

Blakely [1974], using the same signal-enhancing techniques employed in generating BC-72, analyzed 14 parallel and closely spaced magnetic profiles from the northeast Pacific Ocean, west of the Juan de Fuca and Gorda ridges, in the range of anomalies 4.1′ to 6A. The 14 profiles were selected from an area where mapped anomalies were extraordinarily regular and apparently free from distortions due to tectonic complications. The survey, conducted by the National Oceanic and Atmospheric Administration in 1971, was based on satellite navigation.

These profiles were again reduced to the pole, adjusted to a constant spreading rate with respect to 17 points in HDHPL-68, and stacked. Several new short-wavelength anomalies were recognized. The stacked North Pacific profile was then compared to stacked South Pacific profiles (*Eltanin* 20E and 20W) and stacked Indian Ocean profiles (*Eltanin* 41N and 41S). The newly recognized anomalies were again found. Anomaly 5 of *Heirtzler et al.* [1968] was interpreted to consist of five shorter-polarity events. Anomalies 4.3′ and 5′, which were apparent in V-68 but not in HDHPL-68 or TWL-71, were confirmed, again demonstrating the advantage of constructing anomaly timescales from profiles obtained over fast spreading ridges.

As a by-product of adjusting the spreading rates of the original profiles to 17 points in HDHPL-68, information was obtained on local spreading rates for 16 time intervals. Radical, short-term changes in spreading rates were implied. For example, a deceleration of 3.19 cm/yr/MY apparently occurred at approximately 19 MY, and nearly identical, synchronous accelerations were recognized in South Pacific and Indian ocean data. Blakely concluded that it would be most reasonable to assume that continuous spreading occurred in the North and South Pacific and Indian oceans during the time interval studied. The local accelerations could then be explained either as artifacts of discontinuous spreading in the South Atlantic implicit in HDHPL-68 or as inaccuracies in HDHPL-68 caused by the fact that it was generated from a single sinuous profile, the only kind of data available to Heirtzler et al. in 1968. A constant spreading rate, northeast Pacific timescale was then constructed by fixing anomaly 5.1(y) at the 8.71-MY age from TWL-71 and anomaly 6(o) at the 21.31-MY age from HDHPL-68. Fine scale biostratigraphic calibration points were considered but rejected owing to the large potential errors involved.

Blakely's [1974] choice of 8.71 MY as a calibration point merits discussion. *Talwani et al.* [1971] used a 9.94-MY date from HDHPL-68 to fit the older end of their timescale TWL-71. In a similar fashion, *Blakely* [1974] chose to fix anomaly 6(y) to an HDHPL-68 date but then went on to register his scale to TWL-71 at anomaly 5.1(y) instead of using a corresponding HDHPL-68 date. There were two reasons for doing so. First, the character of anomaly 5 in B-74 is very different from that in HDHPL-68. Second, if he had selected anomaly 5.5(o) as a calibration point, the younger end of his timescale, by extrapolation, would have seriously disagreed with all previously published timescales. His choice of 8.71 MY as a calibration point was a compromise between fixing B-74 to readily identifiable anomalies and minimizing radical spreading rate discontinuities introduced as artifacts, in the time range of anomalies 2.3′(o) to 5.1(y). This last problem has been approached by later workers, and one of the conclusions of this review is that the time range in question is still very poorly constrained.

SJMG-74

At the same time that Blakely was working on modifications to the younger end of HDHPL-68, *Sclater et al.* [1974] proposed a recalibration near the older end. For four DSDP drilling sites having good sediment to basement contacts on identifiable magnetic anomalies older than anomaly 13, they noted that the biostratigraphic age determinations of the basal sediments were consistently 5–8 MY younger than the ages of magnetic anomalies 21, 24, 26, and 30 determined by using HDHPL-68. This prompted a further examination using similar evidence from a total of 13 DSDP sites that were thought to be located on or close to identifiable magnetic anomalies and had good sediment to basement contacts. Five of these sites were rejected by using various criteria. A comparison was then made of magnetic ages with paleontologic ages by using the absolute age assignments for geological epochs of *Berg-*

gren [1972]. Paleontologic ages were found to be consistently equal to or younger than magnetic ages.

An adjustment to HDHPL-68 was then proposed to bring the older portion of it into agreement with biostratigraphic ages. Anomaly 30(o) was assigned a biostratigraphic age of about 66 MY, and the HDHPL-68 scale was assumed to be correct at 10 MY. This compressed HDHPL-68 such that the 65-MY Cretaceous-Paleogene boundary was located between anomalies 29 and 30 instead of between 26 and 27.

In their paper, *Sclater et al.* [1974] stated that they were not proposing a formal revision of the magnetic timescale but instead were developing 'their own relationship' between magnetic anomalies and geological ages. They stated that such a revision should await the results from later DSDP legs, more detailed analyses of older anomalies, and a careful consideration of the ages given to reversals dated on land and in DSDP cores.

It should also be noted that Sclater et al. did not attempt any fine scale adjustments to the magnetic timescale in an effort to remove all discrepancies with biostratigraphic age determinations. An examination of their Figure 2 shows that some biostratigraphic age determinations, based on different fossil groups (e.g., calcareous nannoplankton versus foraminifera), are ambiguous by as much as 6 or 7 MY. In particular, the biostratigraphic age determinations for DSDP sites 16 and 36 could be used to argue that anomaly 5 is younger than anomaly 4. The two age estimates also differ by a maximum range of approximately 10 MY, and this is with respect to anomalies whose absolute ages are thought to be less than 10 MY.

We concur with Sclater et al. in their decision to make only a single, conservative biostratigraphic adjustment to the anomaly timescale. In timescale NLC-80 we will propose that a similar adjustment be made to HDHPL-68 at anomaly 24. The biostratigraphic evidence available today could perhaps be used to support three such adjustments [*Berggren et al.*, 1978]. We choose to make only one adjustment that will approximately satisfy all of the available evidence without risking the possible introduction of additional spreading accelerations as timescale artifacts.

KHMP-75

Deep-tow magnetic profiles obtained from six different areas of the Pacific basin (or five separate plate boundaries including the Pacific-Juan de Fuca, the Pacific-Gorda, the Pacific-Rivera, the Cocos-Nazca, and the Pacific-Antarctic) were used by *Klitgord et al.* [1975] to determine the ratios of spreading velocities for various combinations of ridge pairs. Spreading half rates were first determined using calibration points at 0.70, 2.41, and 3.32 MY and the assumption of continuous spreading on both the west flank of the Pacific-Antarctic Ridge from 0 to 6 MY and on the Pacific-Rivera from 3 to 6 MY. The magnetic anomaly boundary ages along each profile were then determined by inversion and averaged between the six profiles providing timescale KHMP-75. Because of the frequent use of calibration points, the resulting boundary ages are quite similar to those of TWL-71, particularly with respect to anomalies 3.1, 3.2, 3.3, and 3.4. However, they are quite different with respect to anomalies 3.1′ and 3.2′, which may reflect on the validity of the constant spreading assumption for the age range of 5–6 MY.

Since widely separated ridges may possess unique spreading histories, real distinctions in magnetic anomaly profiles might be lost in averaging anomaly boundary ages. In addition, three of the ridges involved, the Juan de Fuca, the Gorda, and the Rivera, have rotated in a clockwise sense since anomaly 5 time; therefore single-profile determinations of their spreading velocities are unconvincing. In spite of our objections, however, KHMP-75 closely corresponds to the radiometric timescale of *Cox* [1969] to anomaly 2.3′(o), and with the anomaly scale TWL-71 to anomaly 3.4(o). Also since KHMP-75 was constructed without using fine scale biostratigraphic or core-magnetostratigraphic adjustments, we employ part of it in timescale NLC-80.

TM-76

Tarling and Mitchell [1976] proposed a revised Cenozoic polarity timescale generally based on 'compromise solutions' between core magnetostratigraphy and marine magnetic anomaly records. For Neogene time the number of reversals in their proposed sequence was based preferentially upon the sedimentary record, while the durations of events were based upon those compromise solutions. The entire Cenozoic geological timescale was recalibrated by using the European, glauconite-dated, continental stratigraphy of *Odin* [1975]. Particularly large adjustments were made in the Paleogene, based upon those isotopic dates. The authors also made a major adjustment to the age of anomaly 24 based upon an isotopic age determination (48–49 MY) of reversely magnetized east Greenland basalts interpreted by *Tarling and Mitchell* [1976] to be somewhat older than anomaly 24.

The Tarling and Mitchell timescale was critically reviewed, even 'rejected,' in a strongly worded paper by *Berggren et al.* [1978]. Central to their objections was a criticism of the reliability of dating glauconite by the potassium-argon method. The Paleogene ages determined by *Odin* [1975] were thought to be much too young and 'scarcely warrant immediate, uncritical acceptance nor [do] the modifications to the Paleogene part of the Cenozoic timescale that *Tarling and Mitchell* [1976] have made, based on them.' A second objection was to associating the eastern Greenland Blossville Group basalts with the initial opening of the North Atlantic and therefore to thinking them to be correlated with anomaly 24. This same objection was raised by *LaBrecque et al.* [1977], who noted that there is no close age correspondence between marginal extrusive events and the initiation of rifting. They cited as examples the Deccan Traps in India and basalts in western Greenland and Baffin Island as having been extruded well after rifting.

After discussing the difficulties inherent in dating glauconites, *Berggren et al.* [1978] pointed out that the Paleogene portion of an earlier *Berggren* [1972] timescale depended in large part upon K-Ar determinations on glauconites (many of them by *Odin* [1975]). They then went on to make a detailed reexamination of glauconite, biotite, and sanidine K-Ar ages determined for continental stratigraphic sequences and of continental biostratigraphic correlations with their marine equivalents. They reached the following conclusions:

1. The early-middle Eocene boundary occurred at about 49.5 MY rather than 44 MY as accepted by *Tarling and Mitchell* [1976], a significant difference of more than 5 MY.
2. The age of anomaly 21 is approximately 48 MY instead of 44 MY.
3. The age of anomaly 24 is approximately 53 MY instead of 48 MY.
4. The age of anomaly 26 is approximately 57–58 MY instead of 55.5 MY.

TABLE 1. Boundary Ages for Late Cretaceous, Paleogene, and Neogene Epochs and Ages Corrected for New Potassium-Argon Decay Constants

	Uncorrected Age, MY	Source*	Corrected Age, MY	Value Used in NLC-80
Pleistocene				
Pliocene	1.8	1	1.85	1.9
Late Miocene	5.0	1	5.13	5.1
Middle Miocene	11.0	1	11.29	11.3
Early Miocene	14.0	1	14.37	14.4
Late Oligocene	24.0	2	24.63	24.6
Early Oligocene	32.0	2	32.84	32.8
Late Eocene	37.0	2	37.96	38.0
Middle Eocene	40.0	2	41.04	41.0
Early Eocene	49.0	2	50.26	50.3
Late Paleocene	53.5	2	54.88	54.9
Early Paleocene	60.0	2	61.53	61.5
Maestrichtian	65.0	2	66.66	66.7
Campanian	70.5	3	72.29	72.3
Santonian	82.0	3	84.06	84.1
Coniacian	86.0	3	88.16	88.2
Turonian	87.0	3	89.18	89.2
Cenomanian	89.5	3	91.74	91.7
Albian	94.0	3	96.34	96.3

Sources are 1, *Berggren and van Couvering* [1974]; 2, *Hardenbol and Berggren* [1978]; and 3, *Obradovich and Cobban* [1975].

It should be emphasized that these revised ages for anomalies 21, 24, and 26 are about 2.0–3.5 MY younger than those given in SJMG-74, and so the disagreement between *Berggren et al.* [1978] and *Tarling and Mitchell* [1976] is to some extent one of degree, at least in effect. We favor the revised Paleogene geologic timescale of *Hardenbol and Berggren* [1978] and agree that sufficient biostratigraphic evidence exists from DSDP results to justify revising the age of anomaly 24. We do so in timescale NLC-80 but only adjust it to the Paleocene-Eocene boundary of Hardenbol and Berggren, which is here corrected for new K-Ar constants to be 54.9 MY (Table 1). This adjustment is similar in kind to that made for anomaly 30 by *Sclater et al.* [1974], and it approximately satisfies the three adjustments to anomaly ages proposed by *Berggren et al.* [1978]. To some extent it is also consistent with the sense of the anomaly 24 revision proposed by *Tarling and Mitchell* [1976] on different grounds.

Beyond agreeing with the criticisms by Berggren et al. we feel in addition that Tarling and Mitchell placed excessive emphasis on fine scale biostratigraphic and magnetostratigraphic age determinations in constructing TM-76. The sedimentary record is subject to numerous complications including variations in sedimentation rate, compaction, erosion, reworking, chemical changes, magnetic instability, etc., and biostratigraphic age determinations are frequently questionable, as the previously discussed results from DSDP sites 16 and 36 indicate. Yet, although it is not made clear by Tarling and Mitchell, as many as eight and possibly more calibration points or adjustments may have been used in constructing that portion of TM-76 younger than anomaly 6. Moreover, it is difficult to determine the specific reason for many of the compromise ages which they selected. Some examples follow.

Although a 0.68-MY age for anomaly 1(o) is certainly an acceptable choice within the existing uncertainties, *Tarling and Mitchell* [1976] provide no reason for preferring that particular age to the then published values of 0.69, or 0.70 MY, obtained either from K-Ar dating (Figure 1) or seafloor spreading scales (Figure 2). The source for the boundary ages of anomaly 2 is not stated. Boundary ages for anomalies 1′, 2′, 3, 3.1′(o), and 3.2′(y) were apparently taken from KHMP-75 (Figure 2). The boundary age of anomaly 3.1′(y) is a compromise between one unstated source and a biostratigraphic age; TWL-71 boundary ages seem to have been used for anomalies 3.3′(o) and 4, but it is not clear how the boundary ages for 3.2′(o) and 3.3′(y) were obtained. B-74 was evidently used for anomalies 4′ through 5′. For the older segments of anomaly 5 there is an unrecognizable mix of B-74 and stratigraphic ages, including two isotopically dated ash horizons in sedimentary cores at 11.2 and 12.3 MY. DSDP results are used as a stratigraphic tie for anomaly 6(y).

These apparent calibration points come from a variety of sources including biostratigraphy, magnetostratigraphy, radiometric age determinations, and various seafloor spreading timescales, each of which is subject to its own uncertainties and sources of error. Thus TM-76, particularly in the range younger than anomaly 6, is neither fish nor fowl, and we wonder at the number of artificial spreading rate changes that would be introduced by this kind of fine scale stretching and compressing of the anomaly timescale. At the very least we lack confidence in the use of TM-76 for tectonic reconstructions.

Instead, we feel that the relative constancy of seafloor spreading rates has been conclusively demonstrated in the linear relationships found in anomaly distance versus distance plots which compare numerous ridge pairs, bounding numerous lithospheric plates, from numerous oceans, for numerous intervals of the past. This has been illustrated many times, and we urge skeptical co-workers to review such figures as are found in the work of *Pitman et al.* [1968], *Dickson et al.* [1968], *Le Pichon and Heirtzler* [1968], *Heirtzler et al.* [1968], and *Blakely* [1974]. If TM-76 were applied to the distance information presented in such figures, the resulting inference would necessarily be that all of the lithospheric plates were subject to simultaneous, short-term, high-magnitude accelerations. We do not deny this possibility, but we do consider it to be very unlikely.

LKC-77

LaBrecque et al. [1977] incorporated into their anomaly timescale parts of previously published scales including HDHPL-68, TWL-71, MS-71, BC-72, B-74, and KHMP-75. They limited their selection to those studies which provided increased resolution to parts of the Heirtzler et al. scale and which were based exclusively on marine magnetic anomalies. To some extent, TWL-71 used core magnetostratigraphic data, but the section interpolated into LKC-77 was derived exclusively from anomalies. Their scale was fixed at 3.32 MY for anomaly 2.3′(o) from KHMP-75, 7.39 MY for anomaly 4.1′(y) from B-74, and 64.90 MY for anomaly 29(o) on the basis of the relative position of that anomaly with respect to the 65-MY Cretaceous-Paleogene boundary expressed in a sedimentary section in Gubbio, Italy [*Alvarez et al.*, 1977]. This last calibration point is essentially identical to the anomaly 29–30 and Cretaceous-Paleogene boundary relationship proposed earlier by *Sclater et al.* [1974], using DSDP results.

LaBrecque et al. [1977] eliminated anomaly 14, since it is not found in most marine magnetic profiles. The positions of anomalies 4.2′ and 4.3′ were arbitrarily adjusted for better correspondence with anomaly patterns in the southeast Indian and South Pacific oceans. The relative spacings of anomalies

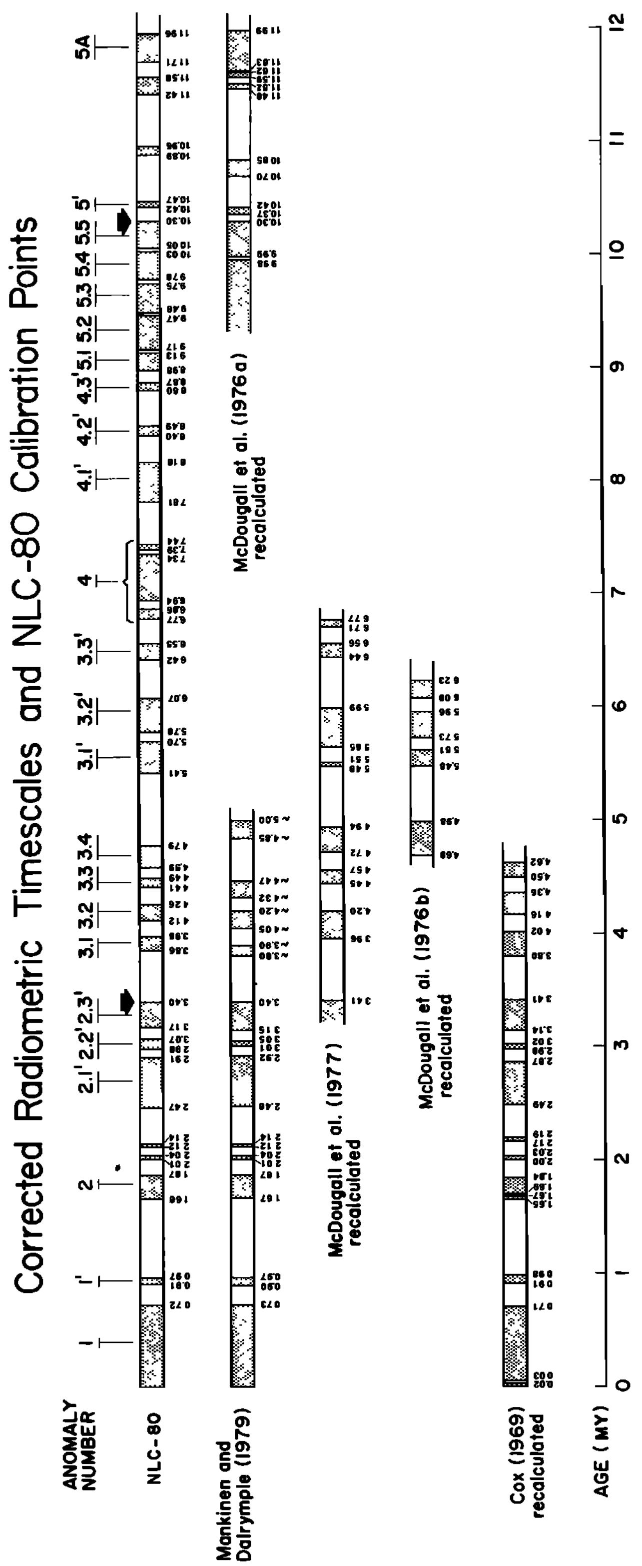

Fig. 3. NLC-80 boundary ages compared with recently published radiometric timescales.

29 to 34, based on then unpublished data from the North Pacific, were extrapolated by assuming that spreading in the North Pacific was continous from anomalies 23 to 34. Although the authors referred to the radiometric age dating of part of anomaly 5 done by *McDougall et al.* [1976*a*] on Icelandic basalts, they chose not to calibrate LKC-77 near the end of anomaly 5. They also mentioned the systematically young DSDP biostratigraphic dates found in the Paleogene and suggested that they were probably due to small errors in HDHPL-68 but made no adjustment. The big shift in anomaly 24 age made by *Tarling and Mitchell* [1976] was not accepted. Moreover, *LaBrecque et al.* [1977] reversed the emphasis and adjusted several biostratigraphic age boundaries to their revised seafloor spreading timescale using the core magnetostratigraphic and biostratigraphic results of *Ryan et al.* [1974] and *Alvarez et al.* [1977]. They developed a Late Cretaceous to Recent geological timescale based on those correlations and upon the scale of *van Eysinga* [1975]. We support their effort and applaud their courage.

Renewing an older argument, *LaBrecque et al.* [1977] discussed 'tiny wiggles' in marine magnetic anomaly records and expressed concern that these short-wavelength anomalies were becoming accepted as records of full scale reversals. In a pictorial presentation of their paleomagnetic polarity scale they omitted seven events from the B-74 scale including the four reversed polarity events within anomaly 5 proposed by *Blakely* [1974]. However, these events were included in their numerical table of boundary ages. As stated previously, the authors also omitted most of the short-polarity events from BC-72. In our scale, NLC-80, we include the B-74 events, believing that these have been essentially confirmed by the work of *McDougall et al.* [1976*a*]. We also include the so-called Reunion events by interpolation from the radiometric scale of *Mankinen and Dalrymple* [1979]. We agree with the emphasis placed on seafloor magnetics by *LaBrecque et al.* [1977] in their construction of LKC-77. Our timescale NLC-80 is structurally very similar to theirs, except that we include a few more events, fix two additional calibration points, and convert the absolute ages of all calibration points to corrected ages using new K-Ar decay constants.

MD-79

In 1977 the Subcommission on Geochronology of the International Union of Geological Sciences recommended the adoption of new atomic abundance and decay constants used in potassium-argon dating. *Mankinen and Dalrymple* [1979], using the new constants and 354 K-Ar dated igneous rock samples with determined magnetic polarities, compiled a new radiometric polarity timescale for the interval 0–5 MY (Figure 3). It is noteworthy that from anomaly 1 to anomaly 2.3′ the revised timescale is very similar to the earlier radiometric scale of *Cox* [1969] when it is corrected for new K-Ar constants. The boundary ages assigned to anomalies 3.1 through 3.4 were considered less certain by Mankinen and Dalrymple.

Mankinen and Dalrymple also converted the marine magnetic anomaly timescale LKC-77, which is here called MD-79. We emphasize that MD-79 is essentially the scale of *LaBrecque et al.* [1977] expanded nonlinearly to correct it for the change in K-Ar constants. *Dalrymple* [1979] published a table for converting western (non-Russian) K-Ar ages, and we present an equation for the same purpose that provides a precision of 10^{-2} MY, using the constants provided in the Mankinen and Dalrymple paper:

$$t_{\mathrm{new}} = 1804.1 \ln (1.0728 e^{t_{\mathrm{old}}/1885} - 0.0728) \qquad (1)$$

We use this equation to convert the two biostratigraphic calibration points used in NLC-80, the boundary ages (Table 1) of Cenozoic epochs from *Berggren* [1972] and *Hardenbol and Berggren* [1978], the boundaries of Late Cretaceous ages from *Obradovich and Cobban* [1975], the Icelandic radiometric polarity scales of *McDougall et al.* [1976*a*, *b*, 1977], and the timescale of *Cox* [1969].

HMW-79

The radiometrically determined polarity timescales illustrated in Figure 1 are composite scales generated by integrating K-Ar dated polarity data obtained from widely separate locations throughout the world. Beyond about 3.5 MY the precision of the K-Ar method begins to approach the average duration of individual polarity events, and the determination of boundary ages becomes increasingly ambiguous. The problem becomes apparent in comparing the various published estimates for the boundary ages of anomalies 3.1 through 3.4. The radiometric scales differ among themselves and are also quite different from marine magnetic anomaly scales (Figure 2), which assume constant local rates of seafloor spreading. K-Ar age determinations made on oceanic basalts are subject to large errors because of hydrothermal alteration and weathering. It is because of this problem, of course, that the older portions of polarity timescales were determined by extrapolating marine magnetic anomaly data.

In Iceland, thick stratigraphic sequences of subaerial lava flows, thought to have extruded at a fairly regular rate, allow the relative age and polarity of lava members to be unambiguously determined. Regression analysis of K-Ar ages onto stratigraphic height data have resulted in the generation of radiometric polarity timescale sections discontinuously ranging from 3.5 to 12 MY. Three of these scales by *McDougall et al.* [1976*a*, 1977], corrected here for new K-Ar decay constants, are illustrated in Figure 3. The problem of correlating polarity events between the scales of various workers persists, however, as an examination of the various estimates for anomaly 3 and anomaly 3′ boundary ages will reveal.

Harrison et al. [1979] integrated the data from several such stratigraphic sections in both eastern and western Iceland. The K-Ar ages ranged over an interval of from about 3 to almost 13 MY. They calculated the difference between the average K-Ar age determinations of particular polarity events and their ages as given by the seafloor spreading timescale MD-79. They found that the K-Ar ages were predominantly greater by about 0.2–0.3 MY. As a result of this analysis, Harrison et al. recalibrated MD-79 at 8.5 and 13 MY.

We agree that the combined paleomagnetic stratigraphy and K-Ar dating on Iceland indicate that the MD-79 boundary ages for magnetic anomalies 3 through 5A should be increased. However, because of scatter in the K-Ar determinations and the noncontinuous nature of the extrusion process and because there are no lavas exposed on Iceland older than about 13 MY, we feel that the data more readily justify a single recalibration of the marine magnetic anomaly timescale. Accordingly, in NLC-80 we fix anomaly 5.5(o) at 10.30 MY (Figures 2 and 3), consistent with the recalculated radiometric timescale of *McDougall et al.* [1976*a*]. This accomplishes the purpose of *Harrison et al.* [1979], within the resolution indicated in their Figure 6, and does not risk introducing an artifical spreading rate change at 13 MY as a timescale artifact.

THE ANOMALY 24 PROBLEM

A graphical summary of oceanic crustal ages determined using biostratigraphic evidence from DSDP sites is presented by *LaBrecque et al.* [1977, Figure 4]. Sites 19, 38 M, 39, and 213 yield basal sediments with biostratigraphic ages covering about a 12-MY period in the late Paleocene through late and middle Eocene. Although the precision of these estimates ranges from about 2 to about 6 MY, the ages are all younger by about 2–5 MY than ages predicted by using timescale LKC-77. LaBrecque et al. noted these discrepancies and suggested that the continuous South Atlantic spreading assumption of *Heirtzler et al.* [1968] may require revision in the Paleogene. However, since there may be systematic errors in Paleogene biostratigraphy, they made no such adjustments.

Tarling and Mitchell [1976] proposed large adjustments to the geologic timescale, as previously discussed. Their revised Paleocene-Eocene boundary is about 5 MY younger than that of *Berggren* [1972], and anomaly 24 was tied to that adjusted boundary by using biostratigraphic evidence from DSDP site 39 published by *Sclater et al.* [1974] and by the stratigraphic position and isotopic ages of basalts in east Greenland. *Berggren et al.* [1978] chose not to adjust the age of the Paleocene-Eocene boundary but did adjust anomaly 24 to comply with the site 39 evidence, making its age about 3.5 MY younger than did *Berggren* [1972].

There is evidence, independent of biostratigraphy, in support of a younger age for anomaly 24. A comparison of the distances from ridge crests to particular anomalies in the North and South Pacific and South Atlantic oceans (Figure 4*a*) indicates that in relation to the assumption of constant spreading in the South Atlantic Ocean, large spreading accelerations occurred in the North Pacific about the time of anomaly 6 and in the South Pacific about the times of anomalies 5 and 24.

It was this comparison that originally led *Heirtzler et al.* [1968] to reject the South Pacific distance data as a possible base for developing a standard anomaly timescale. It is important to recognize that at the time that HDHPL-68 was developed, it was necessary to assume that at least one such profile represented the record of a constantly spreading ridge. No convincing, additional calibration points were available apart from the late Neogene radiometric scales published to that time. Since then an important revision to HDHPL-68 has been made by adjusting anomaly 29 to be younger than the Cretaceous-Paleogene boundary. The obvious point is that the assumption of 90 MY of continuous spreading in the South Atlantic Ocean no longer holds. If anomalies 2.3′ and 5 are fixed to radiometric scales, and if anomaly 29 is adjusted, then corresponding accelerations are implied in the spreading history of the South Atlantic Ocean.

If anomaly 24 is adjusted, in order to conform with DSDP biostratigraphic results, to the Paleocene-Eocene boundary of *Hardenbol and Berggren* [1978], an additional acceleration is introduced into the South Atlantic (Figure 4*c*).

We find it interesting that if anomaly 24 is further adjusted to the age given the Paleocene-Eocene boundary by *Tarling and Mitchell* [1976], then the spreading record in the South Pacific becomes constant from anomalies 5 to 29 and beyond (Figure 4*d*). Our problem then becomes one of making the choice of possible adjustments to anomaly 24. While we admit to being intrigued by the possibility of continuous South Pacific spreading prior to 10 MY, we recognize that it is not required. It seems quite possible that if major, long-term spreading rate changes occur at the boundary of a large plate pair, these changes in motion could (or perhaps even should) be reflected eventually in the motions of other large plates, either by coupling across adjacent plate boundaries or perhaps by some sort of worldwide responses to changes in mantle convection rates. However, since the entire topic of plate-driving mechanisms is still speculative, we do not presume that this effect be required.

We select the more conservative adjustment and fix anomaly 24 at about 55 MY, consistent with the findings of *Hardenbol and Berggren* [1978]. This provides relatively good agreement between timescales NLC-80, radiometric dates, and other anomaly timescales over the interval of 3.4–12 MY. Adjustments to anomaly 24 affect this portion of the timescale by extrapolation and interpolation.

Presently, *Butler and Lindsay* [1979] are compiling the magnetic stratigraphy of Paleocene and lower Eocene continental deposits in the Big Horn Basin of Wyoming. They have clearly identified anomalies 25 and 26 in the Paleocene and a long reversed interval younger than anomaly 25 that extends at least into the lowermost Eocene. Thus the biostratigraphic age of anomaly 24 would appear to be at least as young as the Paleocene-Eocene boundary—the value to which we adjusted it. It may even result that the absolute age for anomaly 24 proposed by Tarling and Mitchell is right but for what we consider to be wrong reasons. Continuing work on the problem, both in Wyoming and in the Italian sections, will be watched with interest.

CONSTRUCTION OF MAGNETIC ANOMALY TIMESCALE NLC-80

1. From anomaly 1 to anomaly 3.4(o) we use timescale KHMP-75 and fix anomaly 2.3′(o) at 3.40 MY, consistent with the new radiometric age determination for that polarity reversal boundary made by *Mankinen and Dalrymple* [1979]. The conversion equation is

$$t = \left[\frac{3.40}{3.32} K\right] \tag{2}$$

where K is the age given in KHMP-75. Thus anomalies 3.1 through 3.4 are extrapolated beyond 3.40 MY on the assumption of constant seafloor spreading. The Réunion events of *Mankinen and Dalrymple* [1979] are added by interpolation between anomalies 2 and 2.1′.

2. From anomaly 24(o) to anomaly 29(o) we fix anomaly 24(o) at the Eocene-Paleocene boundary of *Hardenbol and Berggren* [1978], recalculated for new K-Ar constants at 54.9 MY. We next recalculate the Cretaceous-Paleogene boundary of *Hardenbol and Berggren* [1978] to be 66.7 MY and assume the same relative position for that boundary with respect to anomalies 29(o) and 30(y) in timescale HDHPL-68 as that used by *LaBrecque et al.* [1977] in timescale LKC-77. HDHPL-68 is then interpolated between 24(o) and the Cretaceous-Paleogene boundary using the conversion equation

$$t = \left[\frac{H - 60.53}{(69.54 - 60.53)}\right](66.7 - 54.9) + 54.9 \tag{3}$$

where H is the age given in HDHPL-68. Those polarity reversals from the study of *Blakely and Cox* [1972*a*] supported

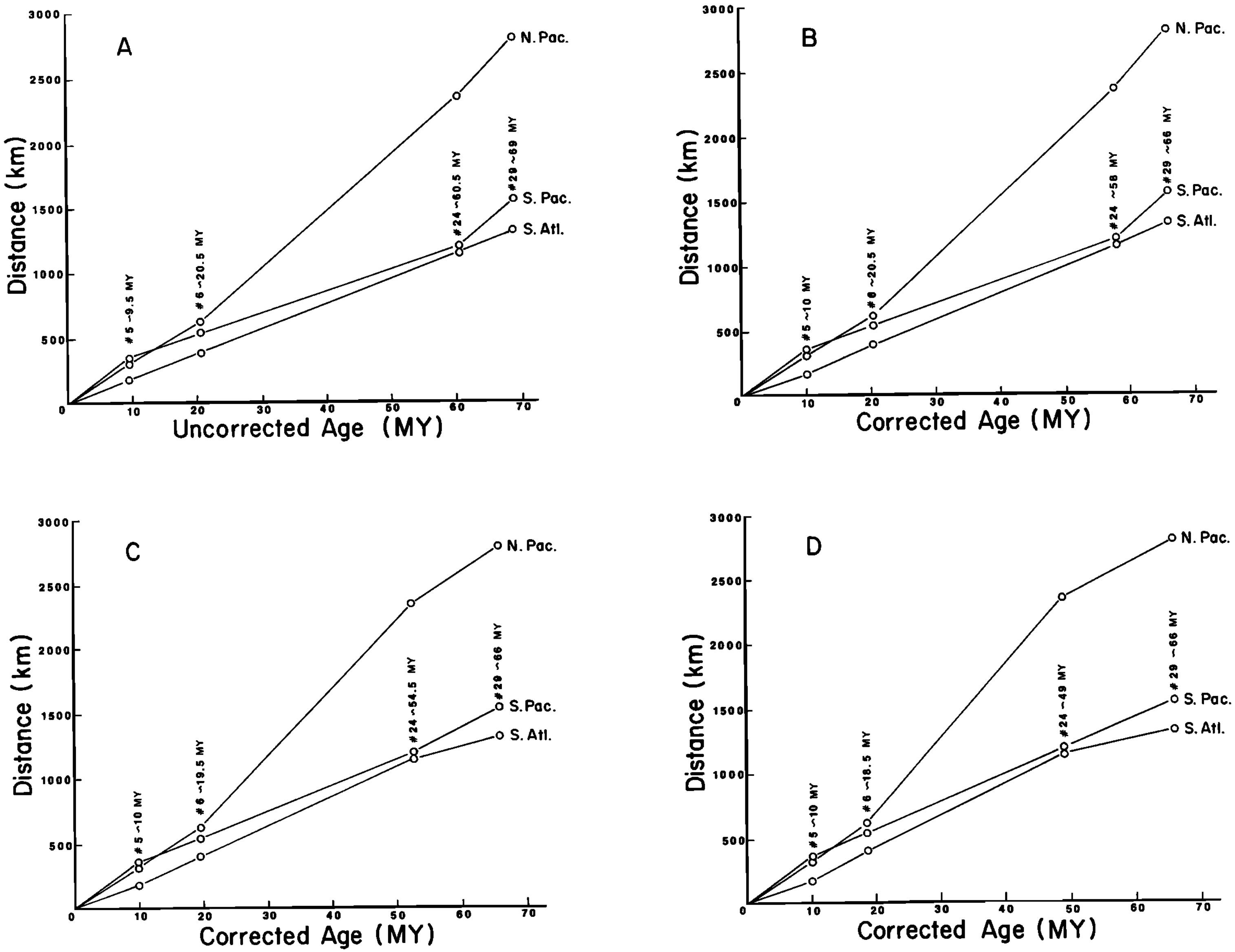

Fig. 4. North Pacific, South Pacific, and South Atlantic age-distance data pertinent to the discussion of adjusting anomaly 24. (*a*) Original data estimated from *Heirtzler et al.* [1968]. (*b*) Anomaly 5 and 29 ages are fixed using NLC-80 values, and corrected ages are used. (*c*) Anomaly 24 is fixed at 54.5 MY. Anomaly 6 is interpolated. (*d*) Anomaly 24 is fixed at 49.0 MY. Anomaly 6 is interpolated.

by the three-axis magnetometer study of *Blakely et al.* [1973] are interpolated into this portion of the recalibrated scale.

3. From anomaly 4.1′(y) to anomaly 24(o) we tie anomaly 5.1(y) from timescale B-74 to the corresponding date used in HDHPL-68 so that no artificial acceleration is introduced near anomaly 6A. B-74 is fit to HDHPL-68 using the equation

$$B' = \left[\frac{B - 8.71}{(21.31 - 8.71)}\right](21.31 - 8.79) + 8.79 \qquad (4)$$

where B is the age given in B-74. This yields an interim age for anomaly 5.5(o) of 10.28 MY (uncorrected for new K-Ar constants). We then fix anomaly 5.5(o) at 10.30 MY using the radiometric age for that polarity reversal boundary determined by *McDougall et al.* [1976*a*] here corrected for new K-Ar constants (see Figure 3). The B' values from anomaly 4.1′(y) to anomaly 6A(o) and the HDHPL-68 timescale from anomaly 6A(o) to anomaly 24(o) are then calculated using the equation

$$t = \left[\frac{B'(\text{or } H) - 10.28}{(60.53 - 10.28)}\right](54.9 - 10.30) + 10.30 \qquad (5)$$

Anomaly 14 is omitted, consistent with *LaBrecque et al.* [1977].

4. Between anomalies 3.4(o) and 4.1′(y) we interpolate HDHPL-68 using the conversion equation

$$t = \left[\frac{H - 5.01}{(7.91 - 5.01)}\right](7.81 - 4.79) + 4.79 \qquad (6)$$

5. From anomalies 29(o) to 34(y) we extrapolate the timescale LKC-77 from relocated anomaly 23(y), at 52.69 MY, to beyond the Cretaceous-Paleogene boundary at 66.7 MY, consistent with the procedure used by *LaBrecque et al.* [1977]. The conversion equation is

$$t = \left[\frac{L - 65.0}{(65.0 - 54.29)}\right](66.7 - 52.69) + 66.7 \qquad (7)$$

where L is the age given in LKC-77.

CONCLUSIONS

Timescale NLC-80 is at best of temporary utility. We anticipate that further, more precise adjustments to the age of anomaly 24 are justified and will soon be suggested by several groups of workers. This in turn may require that the age of anomaly 34(y) be fixed, so that its newly extrapolated spreading age will not radically violate its biostratigraphic age. Ironically, this may result in the introduction of an artificial spreading rate change at anomaly 29 time. There is, in addition, some evidence that suggests that the age of anomaly 6 may require adjustment. This in turn will affect by extrapolation those portions of the timescale between anomalies 2.3′ and 5.5, and while we have carefully tried to avoid both circular reasoning and the introduction of artificial spreading rate changes in the construction of NLC-80, we still lack confidence in its accuracy, particularly between anomalies 2.3′ and 5.5, where most of the cutting and splicing have been done.

Timescale NLC-80 is also at best a critical reshuffling of some very old cards from some very different decks. Its accuracy, or the accuracy of any anomaly timescale, is ultimately limited by the quality of the anomaly versus distance data used to make it up. Most of these data were acquired prior to the so-called 'geologic revolution,' from ship tracks which were set out for other purposes and which were sailed using low-accuracy navigation systems. Thus detailed, fine scale calibrations of anomaly timescales may be meaningless unless the quality of the data base itself is improved first.

Within the last decade, very accurate navigation systems have become available to the marine science community. Knowledge of the various structural features of the seafloor has greatly increased. Geometrical methods for determining and describing plate motions have become more powerful. New signal-enhancing techniques have been applied to the analyses of marine magnetic data. New radiometric techniques have been developed that may be of great utility in determining the absolute ages of submarine basalts, and deep sea drilling hole reentry and continuous sampling capabilities have been developed, all of which now make it possible to reexamine completely the general problem of marine magnetic anomalies by initiating a field program specifically and exclusively designed to develop a new, high-precision magnetic anomaly timescale.

The results of such a program would have valuable, fundamental application to many diverse fields of research including plate tectonic reconstructions, core magnetostratigraphy, biostratigraphy, geomagnetic field reversal frequency studies, oceanic age-depth relationships, crustal evolution studies, ridge processes, and multiplate geometrical studies.

We feel that such a program is not only desirable but necessary. First-generation anomaly timescales have successfully served their purpose but are nearing the ultimate limit of their accuracy. Second-generation tectonics analyses will require a second-generation timescale. Unfortunately, such a program, if properly organized, would be an expensive, multiocean, multiship, multiinstitution cooperative effort. Such a project can only be initiated with the broad support of the geological community.

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