38. GEOCHRONOLOGY OF THE LOWER EOCENE AND UPPER PALEOCENE SEQUENCES OF LEG 81[1]

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ABSTRACT

Data on biostratigraphy, biochronology, magnetostratigraphy, and K-Ar dating of basalts from the lower Eocene and upper Paleocene sequences drilled during Leg 81 are summarized in this chapter. The K-Ar results from Site 555 basalts indicate that the age of marine magnetic Anomaly 24 and adjacent anomalies represents a key problem in the Cenozoic time scale. Three short events of normal polarity in the reversed interval between Anomalies 24B and 25 are interpreted either to represent true physical properties that are detected for the first time in the Leg 81 sequences or to represent overprints of the modern magnetic field direction.

In post-Anomaly 24 times, the sequences are condensed (except part of Site 552) or characterized by hiatuses. Rapid sediment accumulation rates (20–70 cm/1000 yr.) characterize the pre-Anomaly 24B sequences of Hole 553A and Site 555.

INTRODUCTION: THE TIME SCALE PROBLEM

Cenozoic and late Mesozoic time scales are derived from the patterns of marine magnetic anomalies. Absolute ages are determined from a few points that have been dated radiometrically, by assuming linear seafloor spreading rates between or beyond these control points.

One of the most widely used time scales was published by Heirtzler et al. (1968). Heirtzler and his colleagues had a single radiometric control point at Anomaly 2 (Gauss/Gilbert boundary; present estimate 3.40 m.y. ago) and used this to make a linear extrapolation well back into the late Cretaceous. Numerous efforts have since been made to refine this time scale, the most important of which are compared and discussed in the elegant study of Ness et al. (1980). The most recent of these efforts is the comprehensive presentation, partly based on new radiometric age data, of Berggren, Kent, and Flynn (in press). But before that, a major step toward improved radiometric age control was taken in 1979 when Mankinen and Dalrymple provided new K-Ar decay constants.

It has long been assumed that seafloor spreading rates changed on a global scale at around Anomaly 24; consequently, many workers suggested an inflection point at this anomaly during construction of time scales of marine magnetic anomalies (see discussion and review in Ness et al., 1980). Anomaly 24 was until recently bracketed by age-control points tens of millions of years away; thus the slope of the line being extrapolated to Anomaly 24 from the nearest younger age-control point could vary profoundly, depending on which suggested intermediate ages were considered most tenable. This resulted in highly varying ages of the inflection point at Anomaly 24 (see Ness et al., 1980).

Hailwood et al. (1979) utilized several sources (Heirtzler et al., 1968; Talwani et al., 1971; Blakely, 1974; Premoli-Silva et al., 1974; Hardenbol and Berggren, 1978) to construct a time scale used in Volume 48 of the *Initial Reports of the Deep Sea Drilling Project*. Their work was based on pre-1979 K-Ar decay constants.

We had three reasons for using the Hailwood et al. time scale for Leg 81 work. The first was that comparisons between the important, near-identical lower Eocene sequences drilled during Leg 48 and Leg 81 would be more easily made if just one time scale was used. The second reason was that there still existed large uncertainties about the chronostratigraphic position of Anomaly 24 and thus the slope of the time line between Anomaly 24 and nearest younger radiometric age-control point. Finally, the calibrations shown by Hailwood et al. between the biostratigraphic and magnetostratigraphic indications were considered comparatively reliable.

On the basis of these arguments, and particularly in view of the fact that the first had such weight during Leg 81 shipboard work, we chose to adhere to the Hailwood et al. time scale although we were aware of its weak-

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nesses, of which a major one was its use of old K–Ar decay constants.

Knowledge about the chronostratigraphic positon of Anomaly 24 and the calibration of magneto-and biostratigraphic indications in the early Eocene and late Paleocene interval has recently undergone rapid evolution. Apart from the fact that the time scale itself has been improved (see below), work on material from Italy (Monechi and Thierstein, in press), from the Northwest Pacific (Monechi et al., in press; Backman and Shackleton, in prep.), and from the Southeast Atlantic (Backman and Shackleton, in prep.) has established far more accurate calibrations between magnetozones and nannofossil datum events.

The time scale of Berggren, Kent, and Flynn (in press) is characterized by three distinct improvements over many previous time scales: (1) it relies predominantly on first-order correlations between magnetozones and radiometric age determinations; (2) it does not mix K–Ar dates from different types of sources; that is, all K–Ar ages are derived from high-temperature minerals; and (3) it provides three new age-control points between Anomalies 5 and 24, which more accurately determine the slope of the time line in the relevant interval.

It appears not unlikely that future, unambiguous radiometric dating of Anomaly 24, as well as surrounding anomalies, may change the position of the inflection point and also change the absolute ages of Paleocene and early Eocene marine magnetic anomalies. Before this is achieved, however, the time scale proposed by Berggren and his colleagues is considered to display a tenable chronostratigraphic record of the Cenozoic and late Mesozoic.

In order to surmount the time-scale problem, we made a diagram (Fig. 1) showing the calibration between the time scales of Hailwood et al. (1979) and Berggren, Kent, and Flynn (in press). The nannofossil zonal boundaries of Martini (1971) are also shown, together with their newly established ages (references above), as well as the ages these boundaries would have if defined according to the Hailwood et al. time scale. These biochronologic properties are also listed in Table 1.

Several Leg 48 sites were drilled at virtually the same locations as Leg 81 sites. A chief purpose of the Leg 81 drilling program was to penetrate deeper than Leg 48 sites did—into the "dipping reflector" sequence, in order to determine its nature and describe its geological development. Our drilling program held the promise of increasing our insight about those tectonic phases related to the breaking apart of continental crust and the formation of new seafloor. A critical aspect of the problem is to establish a chronostratigraphy of the sequences drilled. It is the intention of this chapter to summarize the relevant bio-

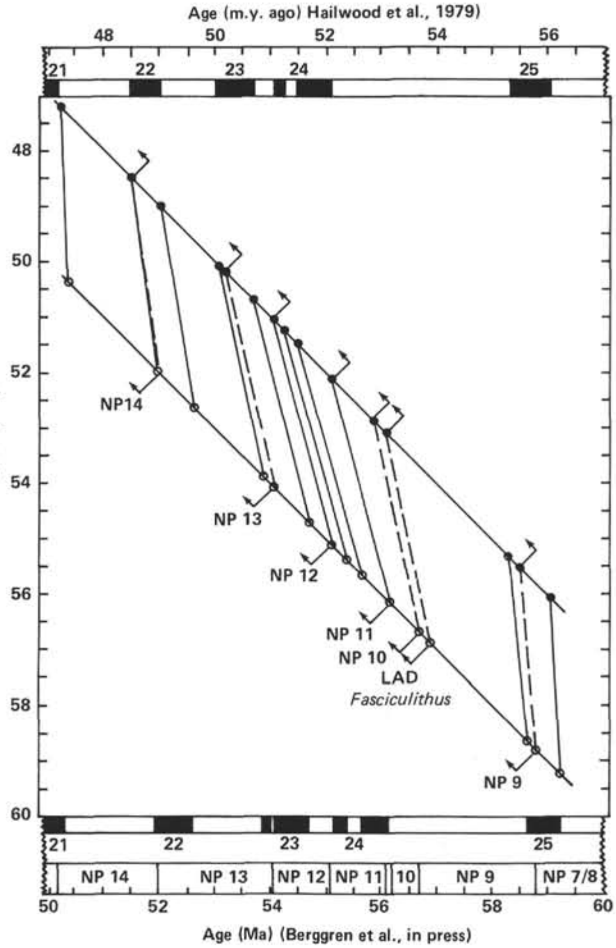

Figure 1. Calibration of the time scales suggested by Hailwood et al. (1979) and Berggren, Kent, and Flynn (in press). Magnetic polarity history, anomaly numbers, and nannofossil zones (Martini, 1971) are also shown.

Table 1. Comparisons of ages of nannofossil datum events using two different time scales.

Event	Species	Zonal boundary	Age (m.y. ago)[a]	Age (m.y. ago)[b]
FAD	*Discoaster sublodoensis*	Base NP14	52.00	48.51
LAD	*Tribrachiatus orthostylus*	Base NP13	54.05	50.17
FAD	*Discoaster lodoensis*	Base NP12	55.10	51.02
FAD/LAD	*Tribrachiatus orthostylus* *Tribrachiatus contortus*	Base NP11	56.15	52.11
FAD	*Tribrachiatus contortus*	—	56.50	52.56
FAD	*Tribrachiatus nunnii*	Base NP10	56.70	52.82
FAD	*Discoaster diastypus*	—	56.70	52.82
LAD	*Fasciculithus* spp.	—	56.90	53.07
FAD	*Discoaster multiradiatus*	Base NP9	58.80	55.50

[a] Berggren, Kent, and Van Couvering (in press) and Berggren, Kent, and Flynn (in press).
[b] Hailwood et al., 1979.

stratigraphic and magnetostratigraphic results of this leg in order to apply these in terms of time control of syn- and post-rift development.

K–Ar DATING OF HOLE 553A AND SITE 555 BASALTS

Two basalt samples from Hole 553A (Cores 46 and 49, respectively) and five Site 555 basalt samples (two from Core 69, one each from Cores 76, 90, and 96) were dated by K–Ar analyses (Macintyre and Hamilton, this volume). Problems were encountered with low potassium contents and extraneous argon components. A first exploratory series of analyses of the uppermost basalt sample from Hole 553A and the uppermost two samples from Site 555 gave a mean age of 59.0 ± 3.1 m .y. ago. A second series of analyses was performed in order to "investigate more fully the nature and origin of the extraneous argon." In this set of analyses the sample weights were "significantly increased." The ages vary from 52.3 to 397 m.y. ago. Macintyre and Hamilton (this volume) argue that only two samples in the second set of analyses provide reliable results, namely those from Sections 555-69-2 and 555-69-4. These give a mean age of 53.4 ± 1.3 m.y. ago.

The biochronologic data indicate (see below) that approximately 0.7–0.8 m.y. separate the Core 555-69 basalts from the base of Anomaly 24B in the Site 555 sequence, suggesting that the base of Anomaly 24B could be as young as 52.6–52.7 m.y. ago. Berggren, Kent, and Flynn (in press) suggest an age of 56.14 m.y. ago for this reversal boundary. It follows that if Macintyre and Hamilton's age of 52.6–52.7 m.y. ago proves to be correct, then the Berggren et al. time scale will have to be compressed somewhere above Anomaly 24B. The problem is accentuated when one considers that Berggren et al. derived a K–Ar age of 49.5 m.y. ago for the younger side of Anomaly 21; this suggests that the envisaged compression of approximately 3.5 m.y. has to take place between the top of Anomaly 21 and the base of Anomaly 24B. This in turn suggests that the entire early Eocene has a duration of roughly 2.5 m.y., in contrast to the Berggren et al. estimate of 5.8 m.y.

We conclude that age control of the history of early Eocene magnetic polarity still represents a key problem in the Cenozoic time scale. The problem can be satisfactorily settled only if more accurate dating becomes possible.

MAGNETOSTRATIGRAPHY

Site 552 is the only site with a comparatively extended lower Eocene sequence above nannofossil Zone NP10, that is, in the interval from above magnetic Anomaly 22 to the base of Anomaly 24B. In the other Leg 81 sites, this interval is condensed or is characterized by gaps. As a consequence, it appears less meaningful to seek to identify magnetic Anomalies 22 through 24A in Sites 553, 554, and 555. Site 554 was drilled on Anomaly 24 age seafloor, and the lowest nannofossiliferous sediments are of normal polarity, which, according to the nannofossil biostratigraphy (Backman, this volume), should represent Anomaly 24B. The level of the basalt/sediment contact at Site 552 is of reversed polarity and appears to represent the reversed polarity interval between Anomalies 24A and 24B (see later).

The magnetic polarity history below the nannofossil zonal boundary NP10/NP11, which approximates the base of Anomaly 24B, is not unambiguous. Zone NP10 is of long stratigraphic extension in both Hole 553A and Site 555 because of high sediment-accumulation rates. The most conspicuous magnetostratigraphic characteristic in that zone is the presence of three normals. During the shipboard work these were labeled RA, RB, and RC, respectively, because the biostratigraphy indicated that neither of these normals could be associated with Anomaly 25.

It appears possible that the normals RA, RB, and RC represent true physical properties observed for the first time in Leg 81 sequences when one takes the following into account:

1. Seafloor magnetic profiles derived from the North Pacific (Pitman et al., 1968) and from the Gulf of Alaska (Pitman and Hayes, 1968) show at least two clearly visible minor excursions ("bumps") in the reversed interval between Anomalies 24B and 25.
2. The sediment accumulation rate in the critical intervals of Hole 553A and Site 555 are high (approximately 50 cm/1000 yr.).
3. We lack highly resolved magnetostratigraphic studies of continuous sequences representing the reversed interval between Anomalies 24B and 25.

On the other hand, these normals are associated with conspicuously low magnetic intensities, and the intensity changes occur exactly at the reversal boundaries. This is particularly obvious in the Site 555 sequence. We cannot, therefore, exclude the possibility that these normals may represent an overprint of the modern magnetic field direction. The three normals RA, RB, and RC have durations ranging from about 0.02 to 0.1 m.y. according to the established sediment accumulation rates (see below). Thus, the question of whether these normals exist in the reversed polarity intervals below Anomaly 24B can only be answered through future studies of continuous sequences where sample intervals do not exceed about 0.01 m.y.

DINOFLAGELLATE CYST BIOSTRATIGRAPHY

The existing biostratigraphic zonation system for dinoflagellate cysts of the lower Eocene and upper Paleocene is largely based on the work of Costa and Downie (1976, 1979). First-order correlations between the zonal boundaries and the magnetic polarity history have yet to be established. Costa and Müller (1978) attempted to calibrate dinoflagellate cyst zones with those of the calcareous nannofossils. Of particular importance was the suggestion that the base of the *Wetzeliella astra* Zone equates with the base of nannofossil Zone NP10. Morton et al. (1983) demonstrated, however, that this calibration is untenable.

Brown and Downie (this volume) studied the dinoflagellate cyst biostratigraphy of the lower Eocene and upper Paleocene deposits of Leg 81. Their results corroborate the view that large biostratigraphic uncertainties are still associated with this group of microfossils, problems which in part probably stem from the strong facies dependency the group seems to exhibit.

Apart from observing *Wetzeliella astra* itself, Brown and Downie also noticed a form referred to as *Wetzeliella* cf. *astra*. According to R. Harland (pers. comm., 1983) this latter form should be regarded as *W. astra*. Nevertheless, the *Wetzeliella* cf. *astra* was observed in Core 87 of Site 555, which belongs to Zone NP9 (*Discoaster multiradiatus* and *Fasciculithus* spp. co-occur) in nannofossil zonation.

We conclude that the biochronologic value of dinoflagellate cyst index species around the Paleocene/Eocene boundary will be restricted until first-order correlations to magnetostratigraphic records are established and until problems of diachroneity/synchroneity of datum events used for short distance correlations are more fully investigated.

CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY

In sediments representing open ocean depositional environments, quantitative techniques allow high precision when one determines the series of nannofossil datum events in the lower Eocene and upper Paleocene interval. It is not, however, considered meaningful to apply such techniques to the corresponding part of the stratigraphic column at Hole 553A and Site 555 for the following reasons. The nannofossils are consistently rare, if not absent, in these sequences. Two long sedimentary intervals are barren of nannofossils at each site. A third interval in one of sites (555) contains extremely few nannofossils.

This situation probably results from a number of interacting factors, such as (1) dilution caused by high accumulation rates of abiogenous sediment; (2) the paleoecological requirements of organisms producing the nannofossils; (3) the development of transgressions and regressions in the study area, and (4) diagenetic effects.

As a consequence, we have to rely on qualitatively gathered information and sporadic occurrences of critical species rather than precisely determined first appearances/last occurrences. It should be stressed, however, that the series of nannofossil biostratigraphic indications identified at Hole 553A and Site 555 follows the progressive development of datum events as recognized from open ocean strata. Thus, we can put certain constraints on possible depth-age relationships in the sequences at Hole 553A and Site 555, from above magnetic Anomaly 22 to below Anomaly 24B.

NANNOFOSSIL BIOCHRONOLOGY AND SEDIMENT ACCUMULATION RATES

One of our chief interests is to describe the pre-Anomaly 24B development of Hole 553A and Site 555 in terms of chronology. Calcareous nannofossil biochronology is the single available means for achieving this. The biochronologic contents of the critical species used are derived from the work of Monechi and Thierstein (in press), Monechi et al. (in press), and Backman and Shackleton (in prep.), who all used the time scale of Berggren, Kent, and Flynn (in press).

Because of the time scale problem in the early Eocene interval, the absolute ages established for the datum events employed may eventually prove to be erroneous. Consequently, durations of intervals separating individual datum events may also have to be changed in the future; if that happens, the sediment accumulation rates shown below will change. One implication of Macintyre and Hamilton's (this volume) suggestion of a comparatively young age of Anomaly 24B would be that the accumulation rates represent maximum rates in the pre-Anomaly 24B interval and minimum rates in the post-Anomaly 24B interval. (The pre-Anomaly 24B accumulation rates presented below may be approximately 25% too high if, for example, the base of Anomaly 24B is given an age of 52.65 m. y. ago and an age of 66.74 m.y. ago is retained for the top of Anomaly 30).

The accumulation rates for Sites 552, 553A, and 555 are shown in Figure 2, using the Berggren, Kent, and Flynn (in press) time scale. Site 554 is omitted from Figure 2 because only a few meters of datable lower Eocene sediment were recovered. The accumulation rates in Figure 2 depict a simplified chronology, since we may safely assume that the different segments showing constant rates are in reality variable.

By combining the stratigraphic ranges of the critical calcareous nannofossil species (Backman, this volume) with the chronologic estimates shown in Table 1, sediment accumulation rates can be determined (Fig. 2).

At Site 552, magnetic anomalies were identified and used together with nannofossil markers to determine accumulation rates. At Site 555, box H (presence of *Rhomboaster* spp.) is based on renewed nannofossil studies of the sequence. These forms were observed in Samples 555-59-4, 74 cm and 555-60-3, 139 cm. The pre-Anomaly 24B data from Site 555 suggest that the basalt present from about 670 to 820 m may have been formed during only a few tens of thousands of years, assuming that the occurrence of *Fasciculithus* spp. below the basalt is close to the extinction age of this genus. On the other hand, *Ericsonia robusta*, which has an extinction age of approximately 57.8 m.y. ago, was not observed in the Zone NP9 interval below the basalt. Consequently one may argue that the sediment below the basalt represents an age just younger than the extinction age of *E. robusta*. This provides a maximum estimate of roughly 0.9 m.y. for the formation of the overlying basalt.

The pre-Anomaly 24B accumulation rates of Hole 553A are better controlled than those in the corresponding interval from Site 555. By inferring a change in rate between marker events D and E in the Site 555 sequence, rates may be obtained that are identical to those of Hole 553A (20–70 cm/1000 years); still, this would fit all available data at Site 555.

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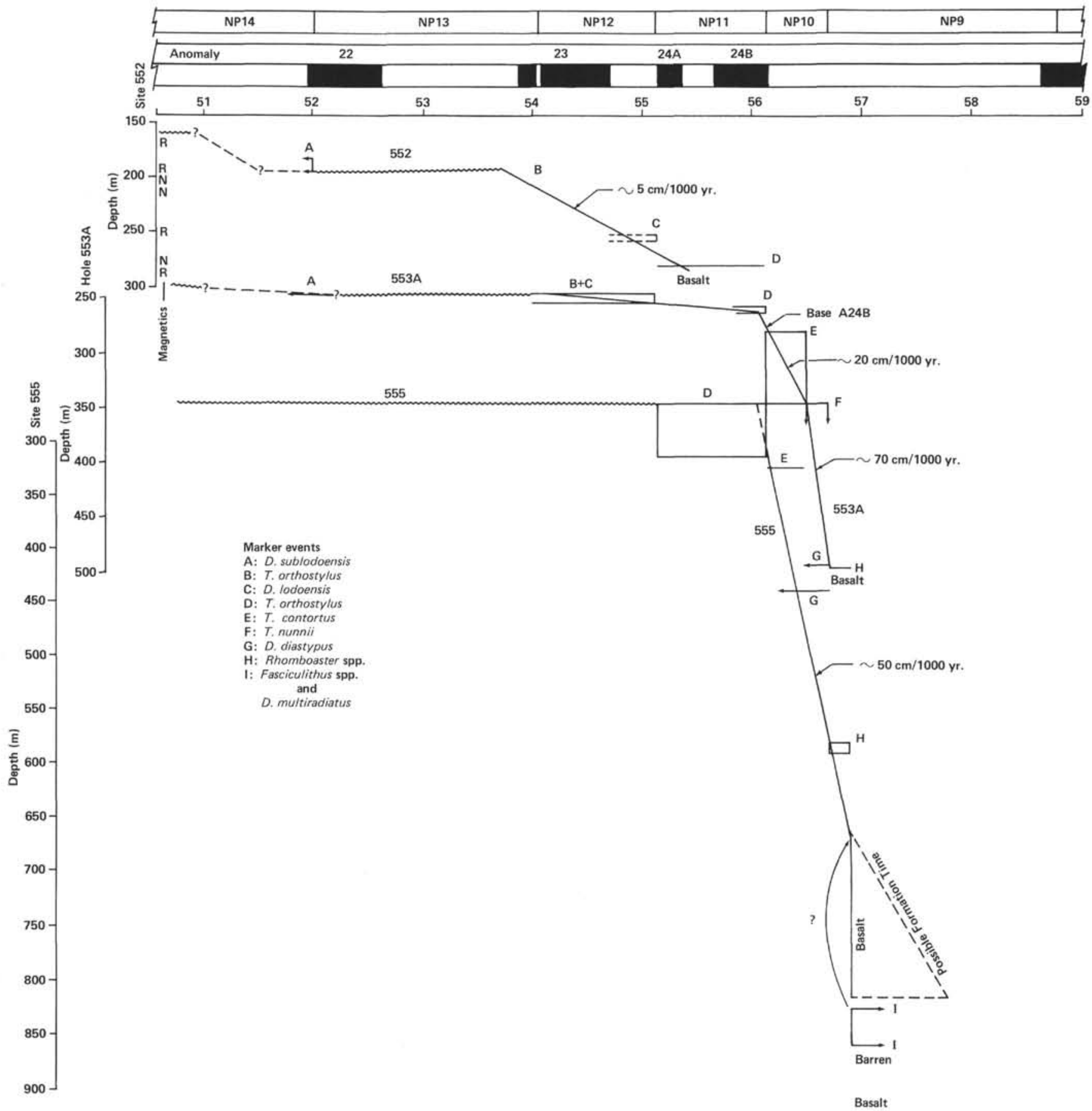

Figure 2. Sediment accumulation plots of Site 552, Hole 553A, and Site 555. The vertical axis represents depth in meters. The horizontal axis shows Martini's (1971) nannofossil zones, magnetic anomaly numbers, polarity history (black represents normals and white reversals), and ages in million years. The Berggren, Kent, and Flynn (in press) time scale is applied.