18. MAGNETOSTRATIGRAPHY OF OLIGOCENE TO PLEISTOCENE SEDIMENTS, SITES 558 AND 563[1]

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ABSTRACT

Integrated magnetostratigraphic and biostratigraphic studies of DSDP Sites 563 and 558 (western North Atlantic) show that, except for a short (~2 Ma) early Miocene hiatus, deposition was continuous from time of seafloor formation (Site 563, between Anomalies 12 and 13; Site 558, between Anomalies 13 and 15) through the Miocene at both sites. Several biostratigraphic datum levels, which have been correlated firmly with magnetic polarity chrons elsewhere, allow correlation of the magnetostratigraphy with the geomagnetic polarity time scale. Based upon that calibration, sediment accumulation rates were low to moderate (< 10 m/Ma) in the Oligocene-early Miocene and higher (> 10 m/Ma) in the middle-late Miocene after a short hiatus (Chron C5E is missing at both sites).

The established magnetochronology is used to make direct magnetobiostratigraphic correlations. For the Oligocene-lower Miocene samples, these correlations agree well with previously published first-order correlations. However, our correlations differ from the earlier indirect middle to upper Miocene correlations. In particular, indirect methods were previously used to correlate magnetostratigraphic Chron 11 (= Zone NN9) with marine Anomaly 5A (Chron C5AN). However, Zone NN9 (= Chron 11) and associated Zone N16 occur in a long normal interval at Sites 563 and 558 that best correlates with marine magnetic Anomaly 5. This reassignment (Chron 11 = Anomaly 5 = Chron C5N) requires an approximately 1.5-2 Ma upward shift in nannofossil zonal boundaries NN7/NN8 through NN10/NN11. The stratotype lower upper Miocene (Tortonian) is biostratigraphically linked with Zones NN9-NN11. Because Zone NN9 occurs in magnetic Anomaly 5 correlative (Chron C5N), the middle-upper Miocene boundary (basal Tortonian) is probably near the base of Chron C5N, with an estimated magnetochronologic age of 10.4 Ma.

INTRODUCTION

Recent magnetostratigraphic studies of deep-sea sediments recovered by DSDP (e.g., Kent and Spariosu, 1983; Tauxe et al., 1983; Ogg, 1983) have demonstrated the potential of paleomagnetic techniques for precise stratigraphic control, encouraging further efforts. Such studies greatly improve chronostratigraphic correlation of deep-sea sediments. Biostratigraphy may be correlated with magnetostratigraphy and therefore related to the polarity time scale, providing numerical age limits for biozonal boundaries. A complete stratigraphic sequence suitable for magnetostratigraphic studies has not been recovered often by DSDP because of the problems associated with rotary drilling of soft sediments and the punctuation of the stratigraphic record by numerous hiatuses. Since the advent of hydraulic piston coring (HPC) techniques, most of the stratigraphic sequence can be cored without much sediment disturbance even though HPC has its own limitations and cannot penetrate the deeper and more compact sediments. With this in mind, we attempted to core the sediments of the western North Atlantic on Leg 82 using HPC to the maximum possible extent, and then to core the more consolidated sediments to basement using conventional rotary drilling techniques. Unfortunately, because of time constraints, HPC techniques were used to core only one hole, 558A, and rotary drilling was used to core the sequence of sediments at Holes 558 and 563, after the holes were washed through approximately the upper 150 m of soft sediment.

On-board paleomagnetic studies of these sediments are based on samples collected at 25 to 40 cm intervals and are also confined to the stratigraphic sequence where remanent magnetization was above the noise level of the shipboard Digico spinner magnetometer. More extensive sampling, with intervals of 10 to 40 cm, was done for shore-based studies. Because various degrees of drilling disturbance of the sediment are indicated in the coring logs, sampling was restricted to those portions of the cores that appeared to be more cohesive and less likely to have been adversely affected by the drilling procedures. Even with this attempt to obtain the best material for study, it is difficult to avoid completely the effects of drilling disturbance in the rotary cored sections, and they undoubtedly contribute to the overall scatter of the measured remanent inclinations. Combined with coring gaps and the absence of reliable paleomagnetic data in severely disturbed intervals, these problems add an undesirable but unavoidable element of uncertainty to the interpretation of the magnetic polarity record, particularly in the Miocene where the reversal frequency is high. Nevertheless, we found it possible to construct a provisional magnetobiostratigraphic framework of reasonable resolution at Sites 558 and 563 that is consistent within and between the sites; the more tentative correlations caused by poor or ambiguous data are indicated in the description of the sites below.

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METHODS

Natural remanent magnetization (NRM) of all samples was measured using a Digico spinner magnetometer for on-board studies and a ScT two-axis cryogenic magnetometer for shore-based studies. After measuring the NRM, a few samples were selected for progressive alternating field (AF) demagnetization to observe the stability of remanent magnetization. These samples were subjected to AF treatment generally to 30 mT in intervals of 2.5 to 5 mT; selected samples were subjected to AF treatment up to 80 mT. Remanent magnetization was measured after each step of demagnetization.

Typical results of these progressive AF demagnetizations are shown in Figure 1. These results suggest that the remanent magnetization of many of these samples is a composite of a low coercivity component of magnetization that, in most of the samples, is removed by AF treatment of 5 to 10 mT, and a more stable component of magnetization that is isolated after 10-mT treatment. The low coercivity component usually has a downward inclination and may represent a viscous remanence acquired in the present-day magnetic field. Removal of this secondary magnetization reveals a more stable component of magnetization that only decreases in intensity with further AF treatment. This higher coercivity component is considered to represent the original remanent magnetization acquired during the process of deposition of these sediments. All remaining samples were therefore subject to blanket demagnetization at 10 mT, although in some cases they were further subjected to 15-to-20-mT treatments to isolate this more stable component of magnetization. After AF demagnetization, the magnetic polarity of many samples became reversed; magnetostratigraphic study of the sediment sections without demagnetization would have resulted in predominantly normal polarity because of overprinting by secondary magnetization.

Cores are nonoriented in the horizontal, and declinations are consequently not generally useful in determining polarity. Therefore, the values of remanent magnetization inclination after magnetic cleaning are used to establish magnetic polarity stratigraphy. Because all of the drilled holes are located in the northern hemisphere, positive (negative) inclination values are assigned normal (reversed) magnetic polarity. Because of the relatively small amount of apparent polar wander since the early Tertiary documented for the North America plate (Irving and Irving, 1982) on which Sites 558 and 563 are located, the Oligocene to Recent sediments are expected to record inclinations comparable to modern dipole field inclinations of 57° (Site 558) and 53° (Site 563). The stable inclination values are plotted stratigraphically, and a magnetic polarity reversal sequence is established (Figs. 2–4). Based on various age constraints, an attempt is made to correlate the observed normal and reversed magnetozones with the age-calibrated geomagnetic polarity time scale (Fig. 2) of Berggren, Kent, and, Flynn (in press) and Berggren, Kent, and Van Couvering (in press) as described below for each hole.

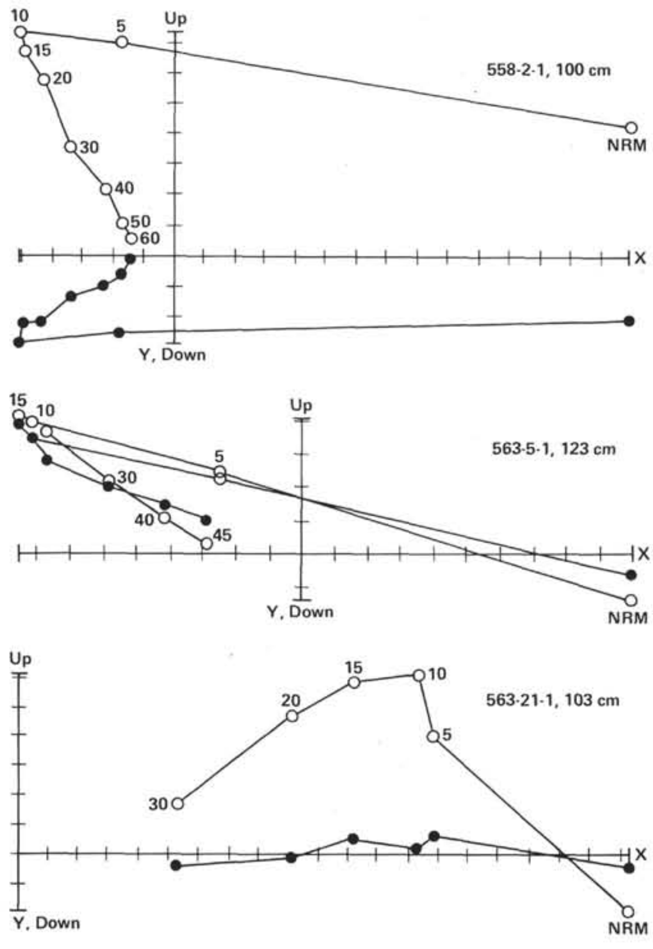

Figure 1. Orthogonal projection diagrams of alternating field demagnetization of the natural remanent magnetization of some representative samples from Holes 558 and 563. Open circles depict projection of remanence vector endpoints on vertical planes; closed circles depict projection of remanence vector endpoints on azimuthally unoriented horizontal planes. Magnetization units on axis in 5 × 10^{-4} A/m; demagnetization levels indicated in m/T.

HOLE 558

The geophysical survey (see site chapter, this volume) showed that Site 558 is located between marine magnetic Anomalies 13 and 15, but is closer to magnetic Anomaly 13. According to the geomagnetic polarity time scale of Berggren, Kent, and Flynn (in press), the younger end of Anomaly 15 is assigned an age of 37.24 Ma. Based upon the position of the site relative to identified Anomalies 13 and 15, Site 558 is estimated to be located on ocean crust not older than 36.5 Ma, providing a maximum age for the overlying sediments. Preliminary biostratigraphic work suggests assignment of basal sediments to nannofossil Zone CP16a/b (Parker et al., this volume) and planktonic foraminiferal Zone P18 (Echols, this volume). According to numerical age estimates for these biostratigraphic zones (Berggren, Kent, and Flynn, in press), these data suggest that deposition began shortly (approximately <1 Ma) after seafloor formation. Based upon this corroborated bottom-hole age, the observed magnetic polarity reversal sequence is correlated with the geomagnetic polarity time scale (Fig. 3). The validity of the magnetostratigraphic correlation is indicated by the ease with which the observed magnetic polarity reversal sequence can be correlated with the standard geomagnetic polarity sequence (Fig. 2) and is further strengthened by the following biostratigraphic data.

1. The last occurrence (= LO) of *Pseudohastigerina* spp. occurs between 558-26-1, 93 cm and 558-25-4, 85 cm within a reversed magnetozone correlated with marine magnetic Anomaly 12 (= Magnetochron C12R, chron terminology of LaBrecque et al., 1983; Berggren, Kent, and Flynn, in press) in agreement with magnetobiostratigraphic correlations elsewhere (Berggren et al., 1983).

2. The LO of *Chiloguembelina* spp. occurs within a normal interval correlated with magnetochron C10N (Core 558-22), in close agreement with the results from Legs 72 (Pujol, 1983) and 73 (Poore et al., 1983). The last occurrence of this taxon can be used to recognize the lower/upper Oligocene boundary (Berggren, Kent, and Flynn, in press). Together with the bottom-hole age estimate,

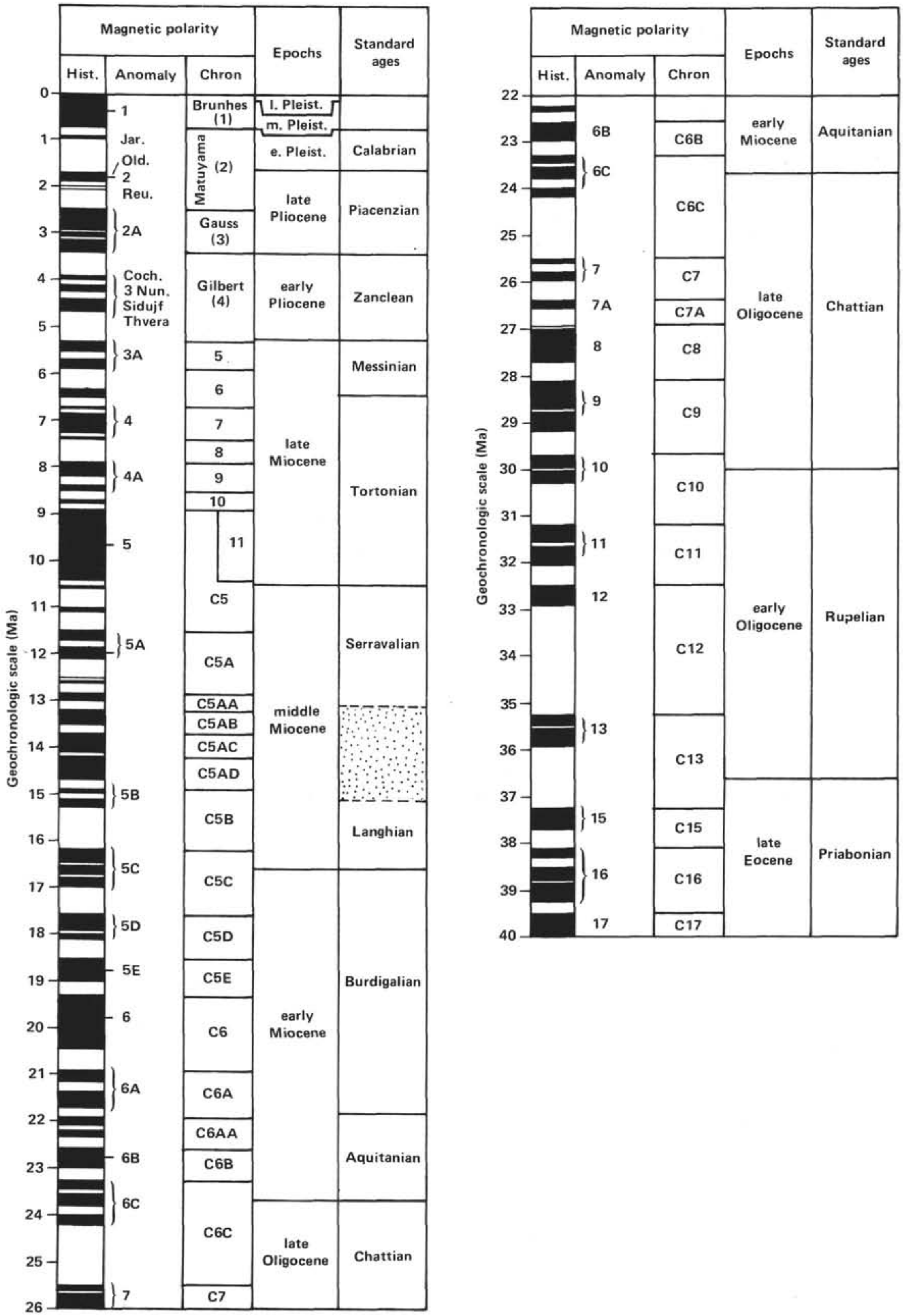

Figure 2. Geomagnetic polarity and geologic time scale from Berggren, Kent, and Flynn, in press; and Berggren, Kent, and Van Couvering, in press. In History (Hist.) column, normal is indicated by black, reversed by white. Jar. = Jaramillo; Old. = Olduvai; Reu. = Reunion; Coch. = Cochiti; Nun. = Nunivak.

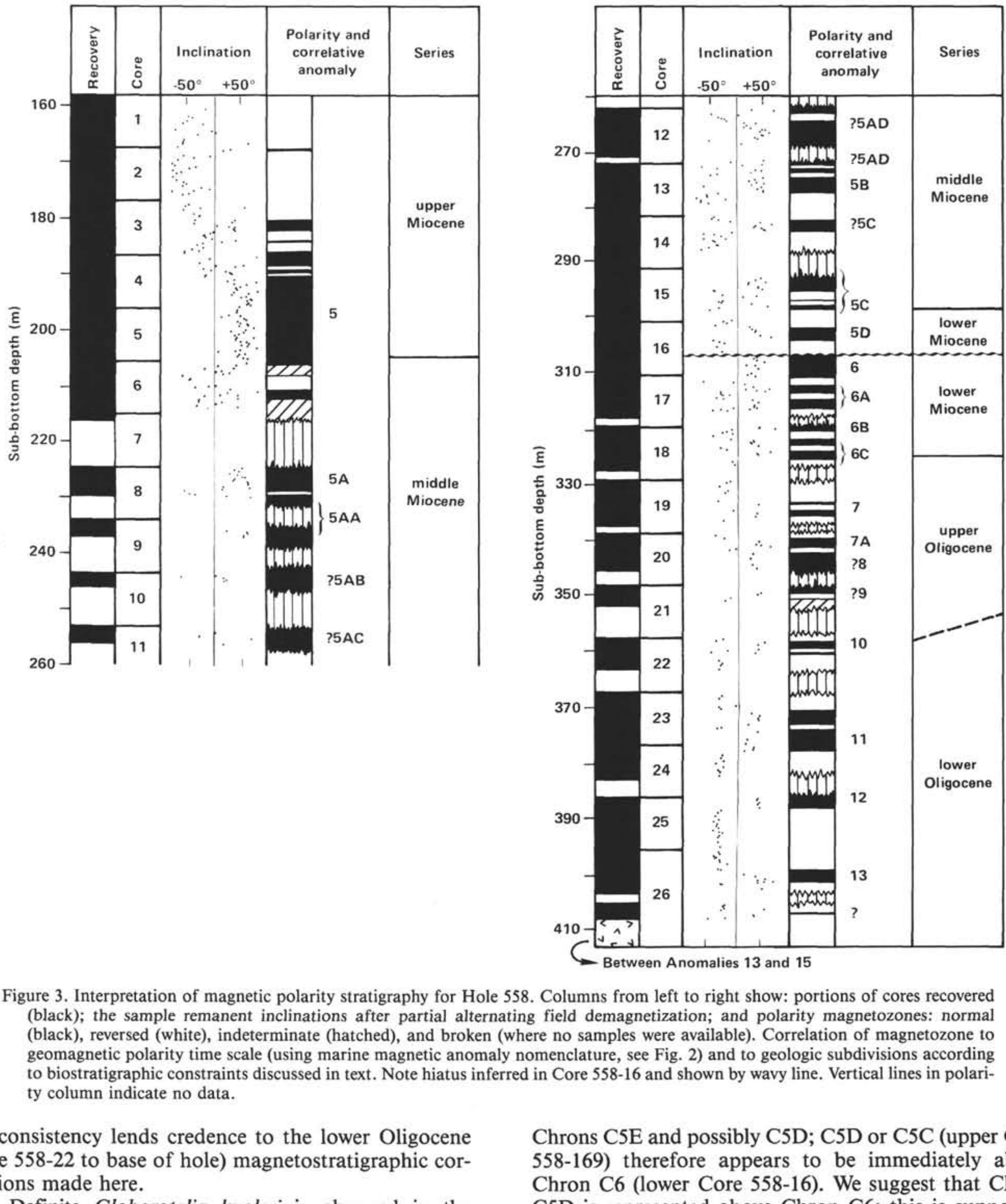

Figure 3. Interpretation of magnetic polarity stratigraphy for Hole 558. Columns from left to right show: portions of cores recovered (black); the sample remanent inclinations after partial alternating field demagnetization; and polarity magnetozones: normal (black), reversed (white), indeterminate (hatched), and broken (where no samples were available). Correlation of magnetozone to geomagnetic polarity time scale (using marine magnetic anomaly nomenclature, see Fig. 2) and to geologic subdivisions according to biostratigraphic constraints discussed in text. Note hiatus inferred in Core 558-16 and shown by wavy line. Vertical lines in polarity column indicate no data.

this consistency lends credence to the lower Oligocene (Core 558-22 to base of hole) magnetostratigraphic correlations made here.

3. Definite *Globorotalia kugleri* is observed in the lower part of Core 558-18 in association with the lower of two normals correlated with marine magnetic Anomaly 6C (Chron 6CN). This first occurrence (=FO) is quite consistent with correlations compiled by Berggren, Kent, and Flynn (in press) and supports the magnetostratigraphic correlations of the upper Oligocene (lower Core 558-18 to upper Core 558-22).

4. Nannofossils indicate the absence of Zone NN3 and most of Zone NN2 (M.-P. Aubry, pers. comm., 1984). A hiatus is therefore inferred for the time interval of Chrons C5E and possibly C5D; C5D or C5C (upper Core 558-169) therefore appears to be immediately above Chron C6 (lower Core 558-16). We suggest that Chron C5D is represented above Chron C6; this is supported by the LO of *Catapsydrax dissimilis* and the FO of *Globoratalia praescitula* in Sections 558-16-3 and 558-16-5, respectively; these datum levels have been reported as occurring in Chron C5D by Berggren, Kent, and Van Couvering (in press).

5. The FO of *Orbulina* spp. in Core 558-14 is associated with the lower part of a normal interval interpreted as C5BN; this is in excellent agreement with the correlations at Site 563 (this study) and Site 521 (Poore et al., 1983).

6. *Globigerina nepenthes* first appears in Core 558-7 above a level of poor recovery (Cores 558-7 through 558-11) and therefore of questionable magnetostratigraphic value. This poorly recovered section may, however, be correlated with the interval of Chrons C5AN to C5ADN. A long normal polarity magnetozone noted in Cores 558-4 to 558-6 (approximately 190 to 205 m sub-bottom) should therefore correspond to the prominent long interval of normal geomagnetic polarity represented by marine magnetic Anomaly 5. Here and at Site 563 (see below), this Anomaly 5 correlative is found to be associated with Zone NN9 (M.-P. Aubry, pers. comm., 1984), whereas the FO of *Neogloboquadrina acostaensis* occurs at the base of this normal magnetozone (Sample 558-5-5, 110–115 cm). These correlations at Sites 558 and 563 suggest that Anomaly 5 is equivalent to the magnetostratigraphic Chron 11 of Foster and Opdyke (1970) and is not equivalent to Chron 9 as suggested by Theyer and Hammond (1974) and Ryan et al. (1974) (see further discussion in Hole 563 section and in Miller et al., in press; Berggren, Kent, and Van Couvering, in press).

HOLE 558A

Hole 558A was piston cored to recover the upper part of the sediment section because Hole 558 was washed to 158 m sub-bottom. However, because of technical problems, Hole 558A was cored only to a depth of 132 m and an overlapping stratigraphic sequence was not cored. The observed magnetic polarity reversal sequence of Hole 558A is shown in Figure 4. The magnetostratigraphic correlation is limited by preliminary shipboard biostratigraphic data (site report, Site 558; Parker et al.; and Echols, all this volume).

The downcore normal-to-reversed polarity change at 14 m can be correlated to the Brunhes/Matuyama boundary and the normal polarity interval between 16.2 and 19.8 m to the Jaramillo Subchron. A short magnetozone present below the Jaramillo (at ~22.5 m) has also been detected elsewhere—for example, in the Siwalik group rocks of Pakistan (Khan and Opdyke, 1981); Site 502 (Kent and Spariosu, 1983); and Hole 552A (Shackleton et al., 1984). This magnetozone is correlated with the 1.1 Ma Cobb Mt. Subchron reported by Mankinen et al. (1978). Where recovered, the sediment sequence form 22.5 to 61.7 m has dominantly reversed polarity and probably represents the Matuyama Chron. An exception is the upper two sections of Core 558A-5 (29 to 32 m) with positive but scattered inclinations that may either represent the Olduvai Normal Subchron or, more likely, secondary magnetic overprints associated with core disturbance. If the latter is accepted, the Olduvai is not detected in this hole. The normal polarity intervals between 61.5 and 65 m and between 70 and 71.5 m presumably record part of the Gauss Normal Chron. Complicating magnetostratigraphic correlation below Core 558A-9 is the presence of an apparent hiatus within the lower Pliocene indicated by the calcareous nannoplankton stratigraphy (Parker et al., this volume). Most, if not all, of the Gilbert Chron may therefore be missing; Core 558A-10 contains Miocene (pre-Gilbert) sediments. The magnetic polarity zonation below Core 558A-9 cannot be interpreted until further biostratigraphic studies are finished.

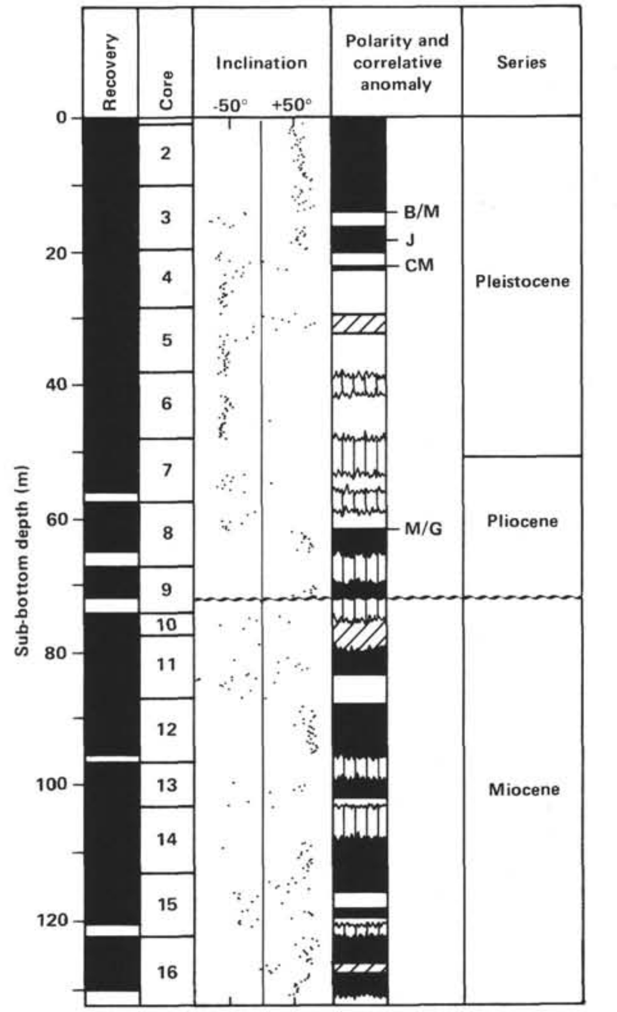

Figure 4. Magnetic polarity stratigraphy for Hole 558A. See Fig. 3 for explanation of columns, except for magnetozone correlation (B/M = Brunhes/Matuyama, J = Jaramillo, CM = Cobb Mt., and M/G = Matuyama/Gauss chrons, boundaries, or subchrons). Geologic subdivisions from preliminary biostratigraphy (Parker et al., this volume); note hiatus inferred near base of Core 558A-9. Vertical lines in polarity column indicate no data.

HOLE 563

According to the geophysical survey (site report, Site 563; Cande et al., both this volume), Site 563 is located between magnetic Anomalies 12 and 13, very close to magnetic Anomaly 13. The geomagnetic polarity time scale of Berggren, Kent, and Flynn et al. (in press) suggests that the younger end of magnetic Anomaly 13 is 35.29 Ma old, which provides a maximum age for the ocean crust and overlying sediments cored at Hole 563. Therefore, the long reversed polarity magnetozone observed in the basal part of the magnetic polarity reversal sequence established for this hole is correlated with Chron C12R. This interpretation agrees closely with biostratigraphic studies showing that the basal part of the sediments from this hole belongs to Zone NP21 and to Zone P18 (Parker et al., this volume, Echols, this volume; Miller and Fairbanks, 1983; Miller et al., in press). Extrapolation of sediment accumulation rates between biostratigraphic datums (Miller and Fairbanks, 1983), together with the assignment to Zone NP21, suggests that basal sediment ages should be older than 34.5 Ma. Sedimentation apparently began a short time (estimated as less than 0.8 Ma) after crustal formation, suggesting that bottom-hole ages are good indicators of crust age.

When the basal magnetostratigraphy has been established, the rest of the observed magnetic polarity reversal sequence can be correlated with the magnetic polarity time scale shown in Figure 5. These magnetostratigraphic assignments are supported by the following biostratigraphic correlations (see also Miller and Fairbanks, 1983; Miller et al., in press).

1. The LO of *Pseudohastigerina* spp. occurs in the base of Core 563-21, in a reversed polarity interval interpreted as Chron C12R. This observation is consistent with the fact that the last appearance datum (= LAD) of *Pseudohastigerina* spp. occurs between the correlatives of magnetic Anomalies 12 and 13 at other locations (Berggren, Kent, and Flynn, in press).

2. The LO of *Chiloguembelina* spp. occurs between 563-19-1, 12 cm and 563-18-5, 23 cm and should coincide with the middle of Chron C10N (Berggren et al., 1983). Chrons C10 and C11 are not observed at Site 563 because of poor recovery and the lack of suitable paleomagnetic samples from Core 563-19 and part of Core 563-18. Nevertheless, this LO can be used to indicate that the normal polarity interval found in Core 563-18 and the lower part of Core 563-17 is younger than Chron C10.

3. The LO of *Globorotalia opima opima*, associated with the younger part of Chron C9 (Berggren et al., 1983), occurs in Section 563-18-1. This supports the interpretation of the normal polarity interval in Cores 563-17 and 563-18 as formed by the concatenation of Chrons C8N and C9N, because Section 563-18-1 forms the middle part of this normal polarity interval.

4. The FO of *Globorotalia kugleri*, correlated elsewhere with Chron C6C (Berggren et al., 1983; Site 558 section of this chapter), occurs in the uppermost part of Core 563-16 in association with the lower of two normal intervals indentified here as correlative with Anomaly 6C. This assignment is also supported by the observation that the FO of *Globoquadrina dehiscens* occurs between 563-15-5, 117 cm and 563-15-2, 117 cm (the stratigraphic interval correlated with Chron C6BR). This agrees with the observation that the FO of *G. dehiscens* occurs in the older part of Chron 6B (Berggren et al., 1983). A similar correlation of *G. dehiscens* and Chron C6BR occurs at Sites 558 (this study), 522 (Poore et al., 1983), and 516 (Berggren et al., 1983). The correlation of the Oligocene/Miocene boundary, as recognized by the FO of *Globorotalia kugleri* (Berggren, Kent, and Flynn, in press; Berggren, Kent, and Van Couvering, in press) or the FO of *Globoquadrina dehiscens* (Kennett and Srinivasan, 1983) can thus be very closely associated with marine magnetic Anomaly 6C, which is equivalent at both Sites 563 and 558.

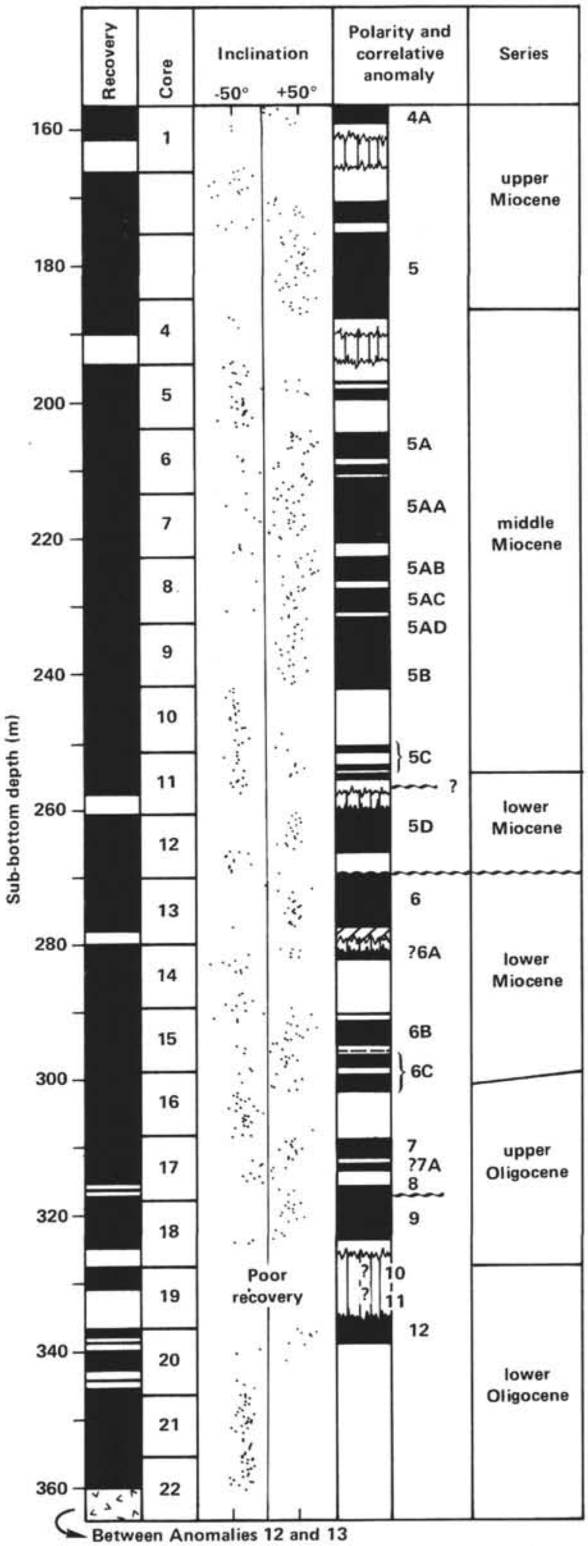

Figure 5. Interpretation of magnetic polarity stratigraphy for Hole 563. See Fig. 3 for explanation for columns. Note hiatus (wavy line) inferred near base of Core 563-12. Vertical lines in polarity column indicate no data.

5. As at Site 558, some section or sections are missing in the lower Miocene. The unconformity is difficult to place (either between Cores 563-12 and 563-13 or near the base of Core 563-11 or possibly at both levels), and the magnetostratigraphy in this interval is therefore uncertain. However, nannofossil Zone NN3 is apparently absent between Cores 563-12 and 563-13 (M.-P. Aubry, pers. comm., 1984), resulting in an unconformity at this level. This suggests that the hiatus represents the time between Chrons C6N and C5D to possibly C5CR (at least C5E was removed (approximately 1 Ma; age range, 18–19 Ma). This interpretation results in similar hiatuses at both Sites 558 and 563 and also is supported by the similarity in magnetic pattern and biostratigraphy above and below the unconformity at both sites. Chron C5D may be represented in Core 563-12 above Chron 6. This is supported by the LO of *Catapsydrax dissimilis* in the reversed interval at the base of Core 563-11 and the FO of *Globorotolia praescitula* in the reversed interval at the base of Core 563-12; these datums have been associated with Chron C5DN at Site 516 (Berggren, Kent, and Van Couvering, in press). From the planktonic foraminiferal data, we deduce a short hiatus or condensed interval occurring between Chrons C5CN and C5DN (i.e., part of C5CR may be missing), because Zone N7 is very short or absent. (There is virtually no section between the LO of *C. dissimilis* and the FO of *Praeorbulina* spp.; A. Melillo, pers. comm. 1984).

6. The FO of *Orbulina* spp. (base of Core 563-9) occurs at the base of a normal magnetozone correlated with Anomaly 5B, in precise agreement with Sites 521 (Poore et al., 1983) and 558 (this study).

7. The FO *Globigerina nepenthes* occurs at the base of Core 563-5 just above a normal magnetozone that we correlate with Anomaly 5A. This is considered to be the first reliable first-order magnetobiostratigraphic correlation of this taxon.

8. The middle/upper Miocene boundary, based on the FO of *Neogloboquadrina acostaensis*, occurs at the top of Core 563-4 at the base of a long normal polarity magnetozone. This normal magnetozone most likely correlates with the long marine magnetic Anomaly 5 that Ryan et al. (1974) correlated with magnetostratigraphic Chron 9 at RC12-65. Nannofossil studies (M.-P. Aubry, pers. comm., 1984; Miller et al., in press) show that Zone NN9 occurs in the upper part of this long normal polarity magnetozone at Site 563. Yet, Zone NN9 has been found with Chron 11 at RC12-65 (Ryan et al., 1974). This suggests that Chron 11 is equivalent to marine magnetic Anomaly 5 or Chron C5N (Khan et al., 1984; Miller et al., in press; Berggren, Kent, and Van Couvering, in press).

CONCLUSIONS

Oligocene and lower Miocene direct magnetobiostratigraphic correlations at Sites 558 and 563 are in good agreement with those made elsewhere as noted above. Despite the various uncertainties in the interpretation of the magnetobiostratigraphic sequence (most importantly, those uncertainties caused by coring gaps and degradation of magnetic data by drilling disturbance), the records at Sites 558 and 563 are of special importance for refining previous indirect correlations in the middle and upper Miocene. Of particular significance is the documentation that magnetostratigraphic Chron 11 (= Zone NN9), rather than Chron 9, should be correlated with the normal polarity equivalent of marine magnetic Anomaly 5 or Chron C5N. According to magnetochronology, this reassignment necessitates an approximately 1.5–2 Ma upward shift in nannofossil zonal boundaries NN7/NN8 through NN10/NN11 (Khan et al., 1984; Miller et al., in press; Berggren, Kent, and Van Couvering, in press). The stratotype lower upper Miocene (Tortonian) is biostratigraphically linked with Zones NN9–NN11 (Martini, 1971). Because Zone NN9 occurs in the magnetic Anomaly 5 correlative (Chron C5N) at Site 563 and Hole 558 (M.-P. Aubry, pers. comm., 1984), the middle/upper Miocene boundary (basal Tortonian) will be above that previously estimated (Ryan et al., 1974). We estimate that the middle/upper Miocene boundary is associated with the base of Chron C5N, with a magnetochronologic age of about 10.4 Ma (see discussion in Berggren, Kent, and Van Couvering, in press).

We expect that these proposed realignments of magnetobiostratigraphic correlations will be corroborated in other Miocene sections. However, to avoid further confusion in magnetostratigraphic polarity nomenclature, we suggest that the chron terminology adapted from marine magnetic anomaly identification (Cox, 1982; LaBrecque et al., 1983) be used in future magnetostratigraphic work and that the magnetostratigraphic numbering scheme of Hays and Opdyke (1967), Theyer and Hammond (1974), and Opdyke et al. (1974) be avoided, at least for correlations older than Chron 11 (= Chron C5N).

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