Magnetostratigraphic dating of shallow-water carbonates from San Salvador, Bahamas

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ABSTRACT

Magnetostratigraphic results are reported here from a sequence of late Neogene-Quaternary shallow-water carbonate sediments from a continuous core drilled on the island of San Salvador, Bahamas. On the basis of the remanent magnetism of 136 samples from a 91-m measured section of core, the polarity sequence can be correlated with the magnetic polarity time scale from the Gilbert chron (early Pliocene) through the late Brunhes chron (late Pleistocene–Holocene). Magnetic polarities were determined on the basis of relative up-down direction in the unoriented core. Extraction studies of the magnetic particles reveal the presence of single-domain crystals of magnetite resembling those produced by the magnetotactic bacteria and algae. The sequence of reversals provides a minimum of six new major chronostratigraphic markers for the Pliocene-Pleistocene of the Bahamas; it confirms and refines the local timing of both the lithologic change from skeletal to nonskeletal sediments and the disappearance of coral and molluscan species from the Bahamas as upper late Pliocene (between 2.6 and 2.7 Ma). That the primary magnetic remanence is preserved in shallow-water carbonates, including replacement dolomites, suggests that this technique could be used to date similar Tertiary and possibly even older carbonate sequences. The establishment of a reliable magnetostratigraphy provides refined dating of shallow-water carbonates and regional faunal appearances or disappearances, sediment accumulation rates, subsidence, and depositional events.

INTRODUCTION

Magnetostratigraphy, the use of an established reversal pattern of remanent magnetism for dating, is well established for siliciclastic deposits and pelagic carbonates, but there have been few similar applications to shallow-water carbonates. Encouragement for this application has now come from a combination of three developments: (1) superconducting magnetometers capable of accurate determinations of extremely weak magnetic signals, (2) a few reports of remanent magnetism in shallow-water carbonates, and (3) the identification of living magnetite-precipitating bacteria in shallow-water carbonate environments in sufficient number to provide a source for a measurable remanent magnetism. As a first test for the existence of a reversal stratigraphy, we made a pilot study of a continuous core nearly 100 m deep from the Bahamas. Here we report successful results of the study and show how the new magnetostratigraphy adds significantly to the dating of major depositional events in pure carbonates.

Until recently, there were only a few reports of remanent magnetism in shallow-water carbonates (Jowett and Pearce, 1977; Kent, 1979; Smith et al., 1980; Hurley and Van der Voo, 1987; Stolz et al., 1987; Chang et al., 1987). This limited attention stemmed from the general consensus that remanent magnetism required the presence of terrestrial magnetic material that is rare or absent in pure carbonates. The discovery of an indigenous source of single-domain magnetite produced by bacteria (Blakemore, 1975; Kirschvink, 1980a; Kirschvink and Chang, 1984) obviated this limitation. Subsequent research has demonstrated that magnetite produced by bacteria is common in modern shallow-water environments of south Florida (Stolz et al., 1987; J. L. Kirschvink, 1987, personal commun.).

There are several reasons for choosing the late Cenozoic carbonates of the Bahamas as a test case for magnetostratigraphy. First, continuous cores of these young carbonates that have been studied and dated biostratigraphically (Beach, 1982; Williams, 1985) are available; second, these carbonates have no detectable siliciclastic components; and third, although they are young, they have already undergone some major diagenetic changes, including cementation, dissolution, and dolomitization, any or all of which might modify original magnetism.

CORE LOCATION, SAMPLING METHODOLOGY, AND MAGNETIC DATA

A continuous core 8 cm in diameter from the northern end of San Salvador, Bahamas (Fig. 1), was sampled to determine magnetic polarities. The core was drilled in the late 1960s by Peter Supko, who described and interpreted the carbonate rocks recovered (Supko, 1977). The re-

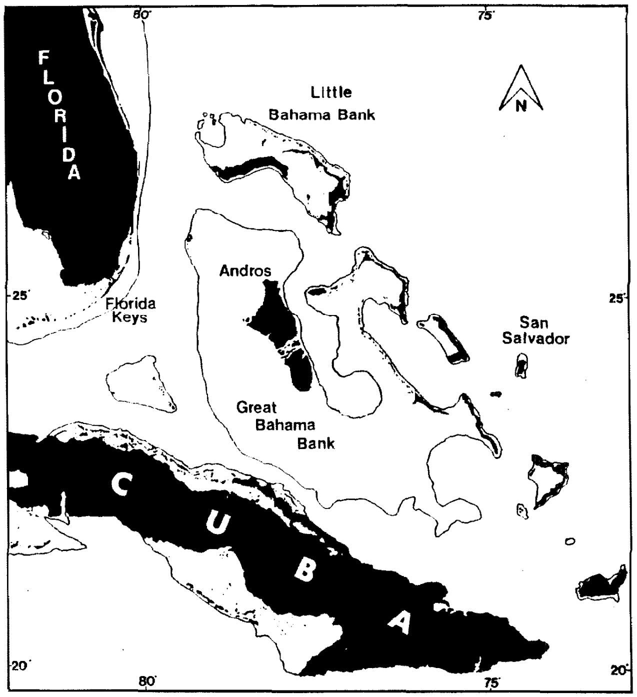

Figure 1. Regional location map of Bahamas archipelago. Core was collected from northern end of San Salvador.

covered core section is nearly complete except for the very top 2 m and small (<1 m) intervals which were very friable. The upper 91 m of the 168-m core was used for this study. From this section, a total of 174 samples were taken, averaging 1 per 0.5 m. The actual sampling interval varied depending on the condition of core sections and the presence of a geopetal structure confirming the up-down orientation.

Each sample for paleomagnetic analysis was a plug about 3 cm long and 2 cm in diameter, drilled from the core with a hollow, nonmagnetic diamond-studded drill bit mounted on a standard drill press. Orientation was marked by a small saw-cut groove on the top of the plug. All samples were briefly submerged in 25% hydrochloric acid and rinsed to remove residual metallic particles from the drill or core barrel.

The remanent magnetism of the samples was measured with a SQUID (Superconducting Quantum Interference Device) moment magnetometer (Fuller et al., 1985). After measuring natural remanent magnetism (NRM), all samples were demagnetized by using alternating fields (AF 2.5, 5.0, 7.5, 10.0, and 12.5 mT) and thermal demagnetization (150, 200, 233, 266, and 300 °C) to isolate characteristic components of remanent magnetization. Magnetic polarities were determined on the basis of relative up-down directions in the core.

The paleomagnetic results used for the polarity sequence included 136 of the 174 samples. The results from 38 samples were omitted because of extremely weak and unstable remanent magnetism ($<1.0 \times 10^{-9}$ A m^2/kg).

Because the core was not oriented with reference to magnetic north, only the inclination could be used to identify periods of normal and reversed polarity. Polarity interpretations were not made on samples with very shallow inclinations (<10°). The true inclination for normal and reversed samples of 32.4° (α_{95} = 12.1°) (calculated by using the inclination-only method of Kono, 1980) is slightly shallower, but still comparable to the expected geocentric axial dipole inclination of 46.3° at the sampling site. The inclination angles from the San Salvador core have a modal class between 35° and 40°. Of the 136 samples used, 83 had a normal polarity and 53 reversed.

The demagnetization steps were plotted as Zijderveld diagrams (Zijderveld, 1967), and a least-squares analysis of the data was used to estimate average remanence direction Kirschvink, 1980b). As demagnetization progressed, measurements not reproducible to within 15° were not included from estimates of the characteristic remanence direction. Typical thermal demagnetization ceased at 300 °C because most samples became too weak to measure accurately (Fig. 2). NRM intensities ranged from 1.63×10^{-9} to 1.99×10^{-7} A m^2/kg, with a mean intensity of 2.75×10^{-8} A m^2/kg. Most NRM values fell within the 6.0×10^{-9} A m^2/kg to 6.2×10^{-8} A m^2/kg range from the top of the core through 56 m. From 56 to 83 m, a zone of lower intensity was encountered (Fig. 3).

Sampling deficiencies in this study, which include irregular sampling intervals and single-point reversals, are often controlled by core recovery. Poor core recovery is evidenced by the decreased sampling interval in the lower section of the core. The single-point reversals in this study are preliminary and need verification by additional analyses.

RESULTS

Reversal Chronology

The chronology of reversals is based on the comparison of the measured sequence of polarities with the dated geomagnetic polarity time scale, fixed by a biostratigraphic datum. Boundaries for magnetic polarity zones reported here for the core have been approximated on the basis of mid-point distance between two adjacent samples of opposite polarity and are usually constrained in position to within 1 m. To match these polarity zones with the standard geomagnetic polarity time scale (Harland et al., 1982), we used a well-established late Pliocene biostratigraphic datum (disappearance of Bowden assemblage molluscs and coral *Stylophora affinis*) as the starting point for age determinations (Beach and Ginsburg, 1980; Beach, 1982; Williams, 1985). On the basis of the biostratigraphic age and the presence of this datum in a normal zone, we interpret this to be the upper part of the Gauss normal chron. This interpretation implies that the major reversed section above the datum is the Matuyama chron. By extrapolation, the four major magnetic zones recognized throughout the sampled core include the normal Brunhes chron, the reversed Matuyama, the normal Gauss, and the upper part of the reversed Gilbert chron (Fig. 3).

When compared to the standard reversal time scale, however, differences in relative thickness of the chrons are likely the result of variations in the amount of subaerial exposure and rates of accumulation (Fig. 4). The Matuyama reversed

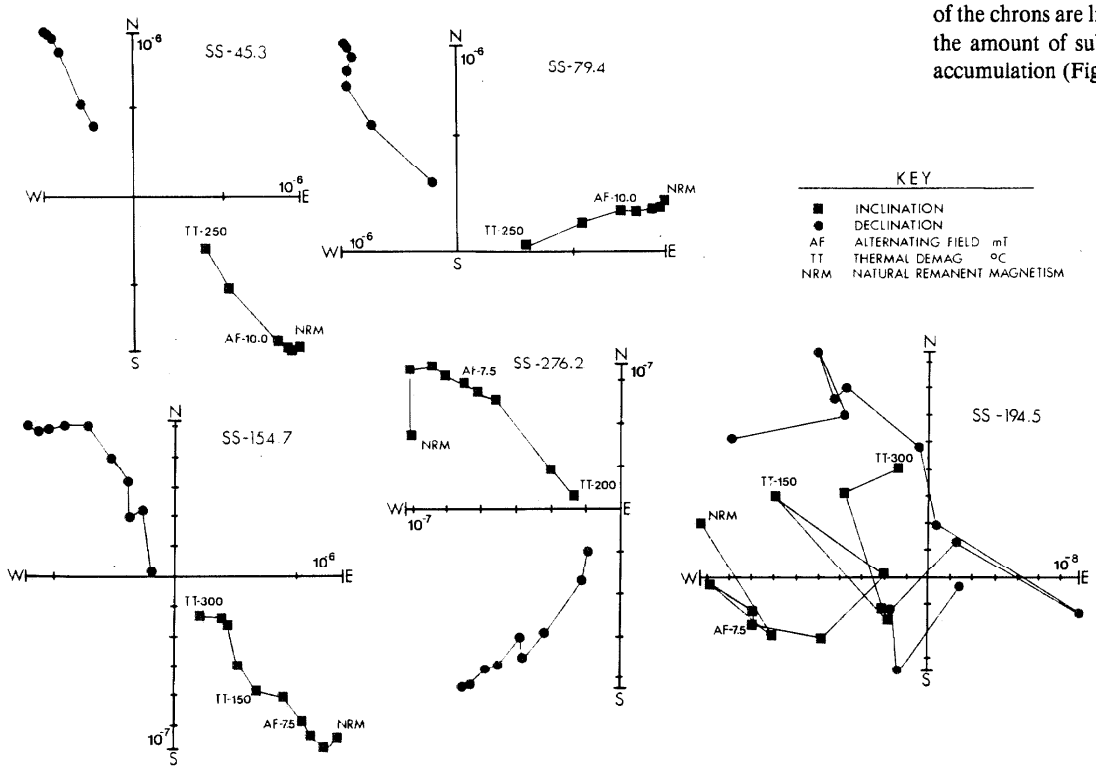

Figure 2. Typical Zijderveld plots from San Salvador core. Sample SS-45.3 (13.8 m depth) is from normal Brunhes chron; SS-79.4 (24.2 m depth) is from reversed Matuyama chron; SS-154.7 (47.2 m depth) is part of normal Gauss chron; SS-276.2 (84.3 m depth) is from Gilbert chron. Sample SS-194.5 (59.3 m depth) is typical of unusable sample exhibiting extremely weak and unstable remanent magnetism.

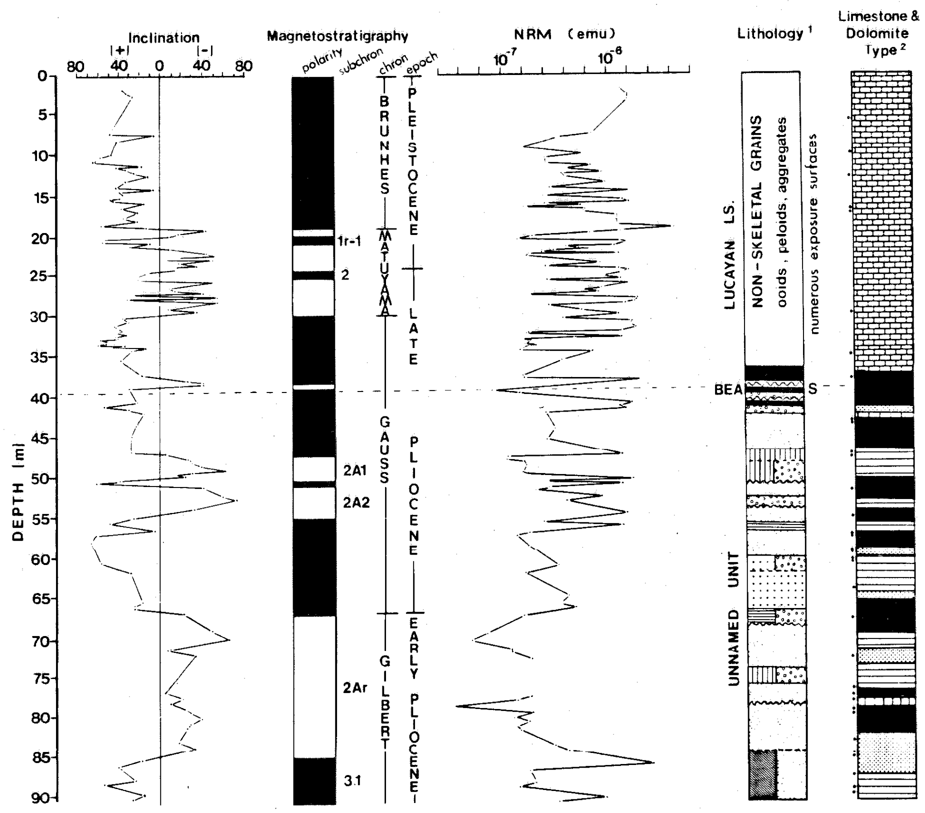

Figure 3. Summary of paleomagnetic, stratigraphic, and lithologic data from San Salvador. No direct correlation exists between polarity sequence, remanent magnetic intensity, textural type, and dolomite replacement type.

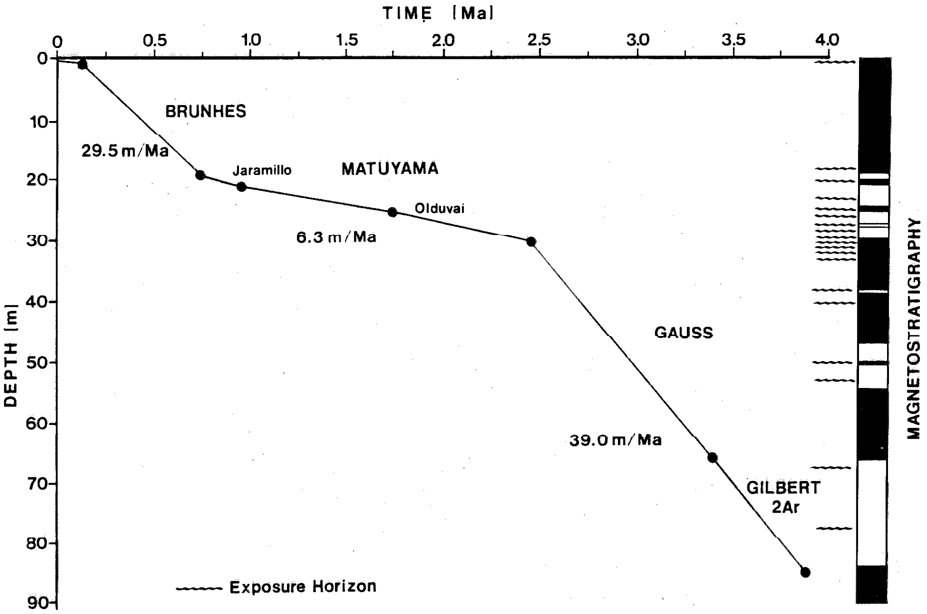

Figure 4. Age/depth curve for 91-m San Salvador core based on magnetostratigraphy (Harland et al., 1982). Matuyama reversed zone in core is relatively short, most likely result of prolonged subaerial exposure during late Pliocene and early Pleistocene. Increased frequency of subaerial exposure horizons during this period is consistent with estimated global eustatic lowering of sea level.

zone is particularly short, but the unrecorded time could easily have been lost in the several exposure horizons that were recognized previously (Fig. 3) (Supko, 1977; Dawans and Swart, 1987).

These new magnetic results seem to permit a detailed correlation with the standard magnetic time scale (Harland et al., 1982). The top of the core has a normal polarity that we have equated to the Brunhes chron. The underlying Matuyama chron is punctuated by two normal-polarity units from about 20.1 to 21.3 m and 24.7 to 25.6 m, possibly representing the Jaramillo and Olduvai events, respectively. At 27.4 and 28.4 m, normal polarity was encountered in single samples from the same section of core containing reversed polarity. These thin polarity reversals may represent part of the Reunion (2r-1 and 2r-2) events, although we realize that these events are of short duration and are rarely encountered in magnetostratigraphic sections. The Gauss chron exhibits a long normal section from about 30.2 to 66.4 m. Within the Gauss, the two reversed sections can be correlated to the 2A1 and 2A2 subchrons. A long reversed section measured in the core from 66.4 to 84.7 m is matched to the upper section of the Gilbert chron (2Ar).

Source of Remanent Magnetization

Examination of the magnetic mineral separates from a typical sample at 20.1 m below the top of the core was made with the transmission electron microscope (TEM) and revealed crystals about 0.05–0.3 μm in diameter (Fig. 5). X-ray and electron diffraction studies on these particles showed that they are composed of magnetite or maghemite; the black color suggests that mainly magnetite is present. Kirschvink and Chang (1984), Petersen and von Dobeneck (1986), and Stolz et al. (1987) have shown that biogenic magnetites, especially those from magnetotactic bacteria, can be recognized on the basis of particle size and crystal morphology. The magnetite crystal dimensions were plotted on a grain-size stability diagram (Butler and Banerjee, 1975). The crystals measured are within the single-domain field (Fig. 6), similar in size and morphology to those produced by a variety of magnetotactic organisms. In particular, there are two distinct types of single-domain magnetite present: (1) teardrop-shaped particles, shown in Figure 5B and plotted as the triangle of Figure 6, which match those from the magnetotactic algae (Torres de Araujo et al., 1986), and (2) cuboidal, plotted as a small cross in Figure 6. It is important to note that we did not observe any of the large framboidal magnetite spheres that are often linked to the presence of secondary magnetite components in organic-rich sediments (e.g., McCabe et al., 1987; Elmore et al., 1987).

Although the Curie temperature of magnetite is near 580 °C, well above the 300 °C level within the range of measurement. The preservation of remanent magnetism established during deposition, despite the significant diagenetic modifications, is quite remarkable and, if reproduced elsewhere, will indicate that dissolution, recrystallization, and even pervasive dolomitization can proceed at such a fine scale as to not reorient the original remanent magnetism.

APPLICATIONS OF MAGNETOSTRATIGRAPHY

The magnetostratigraphy confirms and refines the dating of two major events in the Pliocene-Pleistocene history of the Bahamas archipelago: a change in depositional facies and the local extinction of bivalves and a common coral. Beach and Ginsburg (1980) used biostratigraphy to date (boundary between early and late Pliocene, ca. 3.4 Ma) the base of their Lucayan Formation, which marks both the disappearance of a distinctive coral and a change from skeletal to nonskeletal limestones. Williams (1985) identified the upper limit of a diagnostic molluscan assemblage equivalent to that of the Bowden Formation in Jamaica at 39.6 m in the San Salvador core. This biostratigraphic datum further refined the timing of the faunal and lithologic change to the middle of the late Pliocene. By using the magnetostratigraphy (Fig. 3), these events can now be dated at between 2.6 and 2.7 Ma.

The refined dating of the major changes in lithology and fauna in the Bahamas may also be applied to the regional mass extinction of bivalves from the southeastern United States and Caribbean discussed by Stanley (1986). The last appearance of the molluscan assemblage (2.6 to 2.7 Ma) on San Salvador is perhaps correlative with oceanic cooling in the late Pliocene and subsequent early Pleistocene cooling pulses (Shackleton, 1985).

The reversals provide a minimum of six new chronostratigraphic markers for the Bahamas which can be used to calculate island subsidence. The age/depth curve (Fig. 4) shows significant variations in the rate of subsidence that may be related to hydro-isostatic effects. Rates of accumulation are variable, slow periods corresponding to an increased frequency of subaerial exposure horizons. The age/depth curve in Figure 4 is similar to age-depth curves from periplatform sediments cored in Exuma Sound during Ocean Drilling Program Leg 101 (Austin et al., 1986). The similarity of these curves provides confirmation of highstand sediment shedding.

CONCLUSIONS

The results establish that a legible magnetostratigraphy that is based presumably on a biogenic magnetite signal can occur in shallow-water carbonates. It is especially significant that the original remanent magnetism is preserved even in recrystallized and dolomitized carbonates. If this first indication of a magnetostratigraphic record in pure shallow-water carbonates can be replicated elsewhere and extended to older strata, a valuable new technique for stratigraphic correlation, dating events, rates of accumulation, and subsidence would be available.

REFERENCES CITED

Austin, J.A., Jr., Schlager, W., Palmer A.A., et al., 1986, Proceedings of the Ocean Drilling Program: College Station, Texas, Ocean Drilling Program, Initial Reports, v. 101, Part A, p. 387–437.

Beach, D.K., 1982, Depositional and diagenetic history of Pliocene-Pleistocene carbonates of northwestern Great Bahama Bank; evolution of a carbonate platform [Ph.D. thesis]: Miami, Florida, University of Miami, 600 p.

Beach, D.K., and Ginsburg, R.N., 1980, Facies succession, Plio-Pleistocene carbonates, northwestern Great Bahama Bank: American Association of Petroleum Geologists Bulletin, v. 64, p. 1634–1642.

Blakemore, R.P., 1975, Magnetotactic bacteria: Science, v. 190, p. 377–379.

Butler, R.F., and Banerjee, S.K., 1975, Theoretical single-domain grain size range in magnetite and titanomagnetite: Journal of Geophysical Research, v. 80, p. 4049–4058.

Chang, S.R., Stolz, J.F., and Kirschvink, J.L., 1987, Biogenic magnetite as primary remanence carrier in limestone deposits: Physics of Earth and Planetary Interiors.

Dawans, J.M., and Swart, P.K., 1987, Textural and geochemical cyclicity in Bahamian Pliocene dolomites: Sedimentology.

Elmore, R.D., Engel, M.H., Crawford, L., Nick, K., Imbus, S., and Sofer, Z., 1987, Evidence for a relationship between hydrocarbons and authigenic magnetite: Nature, v. 325, p. 428–430.

Fuller, M., Goree, W.S., and Goodman, W.L., 1985, An introduction to the use of SQUID magnetometers in biomagnetism, *in* Kirschvink, J.L., et al., eds., Magnetite biomineralization and magnetoreception in organisms: New York, Plenum Press, p. 104–151.

Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G., and Walters, R., 1982, A geologic time scale: Cambridge, England, Cambridge University Press, 131 p.

Hurley, N.F., and Van der Voo, R., 1987, Paleomagnetism of Upper Devonian reefal limestones, Canning basin, Western Australia: Geological Society of America Bulletin, v. 98, p. 138–146.

Jowett, E.C., and Pearce, G.W., 1977, Detrital remanent magnetization of modern lime muds from the Florida Keys [abs]: EOS (American Geophysical Union Transactions), v. 58, p. 728.

Kent, D.V., 1979, Paleomagnetism of the Devonian Onondaga Limestone revisited: Journal of Geophysical Research, v. 84, p. 3576–3588.

Kirschvink, J.L., 1980a, South-seeking magnetic bacteria: Journal of Experimental Biology, v. 86, p. 345–347.

—— 1980b, The least-squares line and plane and the analysis of palaeomagnetic data: Royal Astronomical Society Geophysical Journal, v. 62, p. 699–718.

Kirschvink, J.L., and Chang, S-B.R., 1984, Ultrafine-grained magnetite in deep-sea sediments: Possible bacterial magnetofossils: Geology, v. 12, p. 559–562.

Kono, M., 1980, Statistics of paleomagnetic inclination data: Journal of Geophysical Research, v. 85, p. 3878–3882.

Lins de Barros, H.G.P., and Esquivel, M.S., 1985, Magnetic microorganisms found in muds from Rio de Janeiro, *in* Kirschvink, J.L., et al., eds., Magnetite biomineralization and magnetoreception in organisms: New York, Plenum Press, p. 289–309.

McCabe, C., Sassen, R., and Saffer, B., 1987, Occurrence of secondary magnetite within biodegraded oil: Geology, v. 15, p. 7–10.

Petersen, N., and von Dobeneck, T., 1986, Fossil bacterial magnetite in deep-sea sediments from the South Atlantic Ocean: Nature, v. 320, p. 611–615.

Shackleton, Nicholas J., 1985, Oceanic carbon isotope constraints on oxygen and carbon dioxide in the Cenozoic atmosphere, *in* Sundquist, Eric T., et al., eds., The carbon cycle and atmospheric CO_2; natural variations Archean to present: American Geophysical Union Monograph 32, p. 412–417.

Shackleton, N.J., and 16 others, 1984, Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region: Nature, v. 307, p. 620–623.

Smith, D.L., MacFadden, B.J., and Bauer, T.R., 1980, Preliminary investigation of the paleomagnetism of Florida Cenozoic carbonates: Southeastern Geology, v. 21, p. 197–208.

Stanley, S.M., 1986, Anatomy of a regional mass extinction: Plio-Pleistocene decimation of the Western Atlantic bivalve fauna: Palaios, v. 1, p. 17–36.

Stolz, J.F., Chang, S-B.R., and Kirschvink, J.L., 1986, Magnetotactic bacteria and single-domain magnetite in hemipelagic sediments: Nature, v. 321, p. 849–851.

—— 1987, The effect of magnetotactic bacteria on the magnetic properties of marine sediments, *in* Crick, R.E., ed., Proceedings, International Symposium on Biomineralization, 5th: Dordrecht, Netherlands, Reidel.

Supko, P.R., 1977, Subsurface dolomites, San Salvador, Bahamas: Journal of Sedimentary Petrology, v. 47, p. 1063–1077.

Torres de Araujo, F.F., Pires, M.A., Frankel, R.B., and Bicudo, C.E.M., 1986, Magnetite and magnetotaxis in algae: Biophysical Journal, v. 50, p. 375–378.

Towe, K.M., and Moench, T.T., 1981, Electron-optical characterization of bacterial magnetite: Earth and Planetary Science Letters, v. 52, p. 213–220.

Williams, S.C., 1985, Stratigraphy, facies evolution, and diagenesis of late Cenozoic limestones and dolomites, Little Bahama Bank, Bahamas [Ph.D. thesis]: Miami, Florida, University of Miami, 215 p.

Zijderveld, J.D.A., 1967, A.C. demagnetization of rocks: Analysis of results, *in* Collinson, D.W., et al., eds., Methods in paleomagnetism: New York, Elsevier, p. 254–286.

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Reviewer's comment

This paper is quite important; first, because it provides the first evidence for the timing of Ice Age extinction in the Bahamas; second, because it demonstrates the value of undertaking magnetostratigraphic studies in limestone borings; and third, because it raises the possibility that bacteria may have produced the magnetic material.

Steven Stanley

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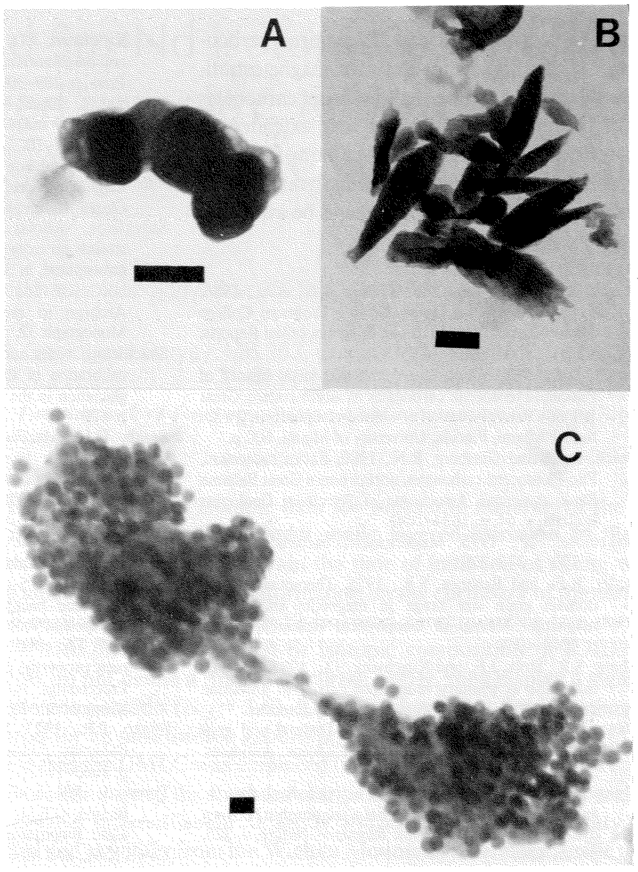
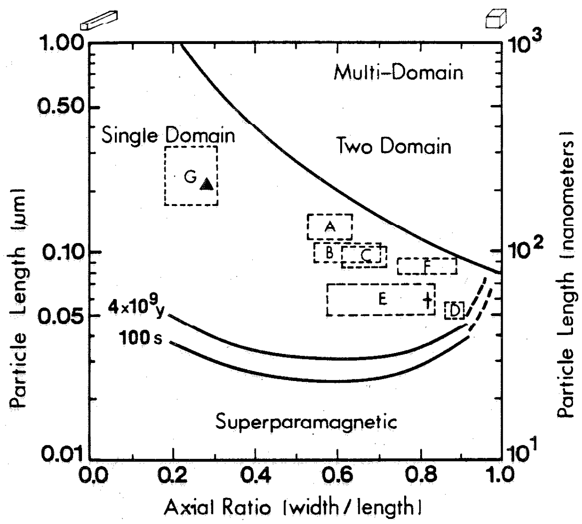


Figure 5. Transmission electron microscope photomicrographs of magnetic mineral separates from 20.1 m depth in San Salvador core. A: Cubic to spherical magnetite particles in short chain; grains are similar in size to bacterial magnetite. B: Oblate spherical magnetite crystals in elongate sheaths of unknown origin, but resembling blunt, elongate crystals from recently discovered magnetotactic eukaryotic algae (Torres de Araujo et al., 1986). C: Abundant magnetite crystals within unknown matrix material, similar to particle aggregates found in colonial magnetotactic organisms (Lins de Barros and Esquivel, 1985). Scale bar in all three micrographs = 0.1 μm.



A. Fresh-water sediments of New Zealand (Blakemore et al., 1980)

B. Complex simulated natural environment (Towe and Moench, 1981)

C. Fyshwick sewage pond, Australia (Kirschvink, 1980a)

D. Salt marshes of Cape Cod, Massachusetts (Blakemore, 1975)

E. Santa Barbara basin (Stolz et al., 1986)

F. Laguna Figueroa, Baja California, and Sugarloaf Key, Florida (Stolz et al., 1987)

G. Magnetotactic algae (Torres de Araujo et al., 1986) and teardrop-shaped magnetite in magnetotactic bacteria from New Zealand (Blakemore et al., 1980)

Figure 6. Grain-size/stability field diagram of Butler and Banerjee (1975) showing position of magnetite crystals from magnetotactic organisms of different environments. Mean length and axial ratios from Figures 5B (triangle) and 5C (cross) are within single-domain field, similar to known magnetotactic algal and bacterial crystals, respectively.

where most of our samples become unmeasurable, these TEM observations of the magnetic particles are consistent with the alternating-field and thermal-demagnetization results from the core samples. Two observations support this conclusion. First, extremely small crystals that plot near the bottom margin of the single-domain stability field shown in Figure 6 will become superparamagnetic at temperatures well below the Curie point, and many of the magnetic particles extracted from the samples fall within this size range. Second, many of the ultrafine-grained magnetites extracted from deep-sea carbonates have been partially oxidized to maghemite, as deduced by the partial dissolution of their surface features during treatment with Na-dithionite (Kirschvink and Chang, 1984). Maghemite is known to invert to hematite at temperatures between 300 and 600 °C, and for any magnetofossil with a magnetite core and maghemite rim, this conversion would similarly yield a superparamagnetic particle. Note, however, that both maghemite and magnetite share the same electronic crystal lattice superstructure, and therefore the solid-state oxidation of single-domain magnetite to maghemite does not alter the direction of the primary remanent magnetization.

In summary, the presence of an internally consistent magnetic polarity stratigraphy, the discovery of bacterial magnetofossils, and the lack of obvious diagenetic magnetites all indicate that we are dealing with a primary or early diagenetic magnetic remanence.

DISCUSSION

Remanent Magnetism Unaffected by Variations in Depositional and Diagenetic Textures

There are significant variations in depositional and diagenetic textures in the core, but these do not appear to have any detectable effect on the preservation of the remanent magnetism established during deposition. The upper 37 m of the core is limestone that is a mix of packstones and wackestones composed of ooids and peloids; the lower 54 m, now all dolomite, was originally skeletal debris of varying grain sizes and composition. These differences in composition and grain size do not correlate with changes in magnetic polarity. Similarly, the variations in mineralogy have no major discernible effect on the preserved magnetism. From the top of the core to a depth of 10.7 m, the prevailing (>50%) mineralogy is aragonite. From 10.7 to 33.5 m, the core is all calcite. From 33.5 to 91.4 m, the core is almost entirely dolomite. The upper section shows the least postdepositional modification, judging from the presence of original aragonite and the sparse cementation (Supko, 1977). In the middle calcitic section, there is much evidence of dissolution and cementation that probably occurred in meteoric environments (Supko, 1977; Beach, 1982; Williams, 1985). The lower section of almost pure dolomite has significant variations in texture, from microsucrosic to coarse-crystalline varieties that preserve original fabric elements. These variations in diagenesis and especially the dolomitized interval have no detectable effects on magnetic polarities; long normal and reversed intervals traverse changes in dolomite texture. However, the microsucrosic dolomites consistently exhibit a slightly weaker NRM intensity (Fig. 3). This weaker signal may be indicative of sediments that were inverted to calcite prior to dolomitization (Dawans and Swart, 1987). The slightly weaker signal in these zones is still well