TERRA RESEARCH

Atoll magnetostratigraphy: calibration of their eustatic records

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ABSTRACT

Results of palaeomagnetic measurements of a core from Mururoa atoll, French Polynesia, led us to document for the first time the atoll's magnetostratigraphy. Periods of slow aggradation, correlated with sea-level low-stands, show that atolls are accurate recorders of sea level fluctuations. The timing and amplitude of sea level fluctuations may be reconstructed on the basis of precise dating of atolls and shallow-water platforms. Magnetostratigraphy is therefore a first step towards a quantitative calibration of the eustatic records of coral atolls.

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Recent pilot studies demonstrated the ability of shallow-water carbonates deposited in reefs to preserve a stable Natural Remanent Magnetization (NRM) through various levels of diagenesis (Kirschvink and Lowenstam, 1979; Chang and Kirschvink, 1989; McNeill *et al.*, 1988; Aïssaoui *et al.*, 1990a). Based on magnetostratigraphic dating of a 206 m core from Mururoa Atoll, French Polynesia (Pacific 21°50 S 138°50 W), we report here the timing of the atoll growth and related eustasy for the last 6.5 Myr. Because the main carriers of NRM in the atoll sediments are abundant bacterial magnetofossils (Aïssaoui *et al.*, 1990a), Cenozoic and older carbonates deposited in shallow-water, reefal environments must have initial, stable remanent magnetization amenable to palaeomagnetic dating.

Mururoa Atoll includes a 450 m thick sequence of limestone and dolomite formed by coral reef growth over a basaltic volcano (Buigues, 1985) developed on an oceanic crust of about 52 Myr age (Talandier and Okal, 1987; Schlanger *et al.*, 1987). The substratum is overlain by conglomerates which progressively grade up into a multiple sequence of thick boundstone units, composed of massive and branched corals, alternating with coarse biodetritus. Peripheral reefs are gradually replaced by coeval skeletal sand and mud towards the central lagoon. Formation of the atoll was interrupted by several periods of sub-aerial exposure, leading to depositional hiatuses (Buigues, 1985; Aïssaoui *et al.*, 1986). Prior to palaeomagnetic studies, information on the stratigraphy of Mururoa atoll was limited to radiometric dating with low resolution, which indicated that the age of the basaltic substrate is about 11±1 Myr (Buigues *et al.*, 1987), and that the limestones at 39 m depth are of Late Pleistocene age (Labeyrie *et al.*, 1969; Aïssaoui *et al.*, 1990a).

Our study is based on a continuous core recovered from the NE rim of the atoll by the French Commissariat à l'Energie Atomique. Of the 384 paleomagnetic specimens sampled at intervals averaging 0.5 m along the 206 m long core, 249 were coherently magnetized and were therefore used to reconstruct the magnetostratigraphic sequence (Fig. 1). 171 samples composed of mixed aragonite and calcite and 78 samples of pure dolomite were processed at Caltech palaeomagnetics laboratory using a two-axis ScT cryogenic SQUID magnetometer, enclosed within a Mu-metal shielded room. Samples are stable to progressive, incremental demagnetization and exhibit magnetic components of both normal and reversed polarity. Specimens were demagnetized progressively by the application of increasing alternating fields (up to 10 mT) followed by stepwise, thermal demagnetization (up to 520°C) under zero field conditions. The NRM of the Mururoa core is weak, with 63% of the samples having a magnetic intensity of 10^{-9} Am^{2} kg^{-1}, and 34% an intensity of 10^{-8} Am^{2} kg^{-1}. The overall mean intensity is 1.15 10^{-8} Am^{2} kg^{-1} (arithmetic value). The measured intensities are slightly weaker for the dolomites than the limestones. Using the method of Kono (1980), the mean inclination value is estimated as 43.4° ($\alpha_{95} = 3.2$, $k = 8$), which is close to the 38.7° inclination value expected for the axial geocentric dipole field for the Tuamotu archipelago.

The dominant carrier of remanent magnetization in these rocks was characterized by means of rock magnetic experiments (Fig. 2). Paired IRM acquisition and Af demagnetization analyses of selected samples indicate that a very fine-grained iron-oxide is the principal carrier of the magnetic remanence by comparison with previous studies (Chang *et al.*, 1987; Vali and Kirschvink, 1989; McNeill, 1989). Related ARM acquisition implies that the magnetic minerals in our samples are probably non-interacting, single domain (SD) particles as supported by comparison with biogenic magnetite (Fig. 2). Magnetic minerals were extracted from Mururoa samples and their examination under the TEM revealed a mixture of crystals whose size and shape fall into the theoretical stability

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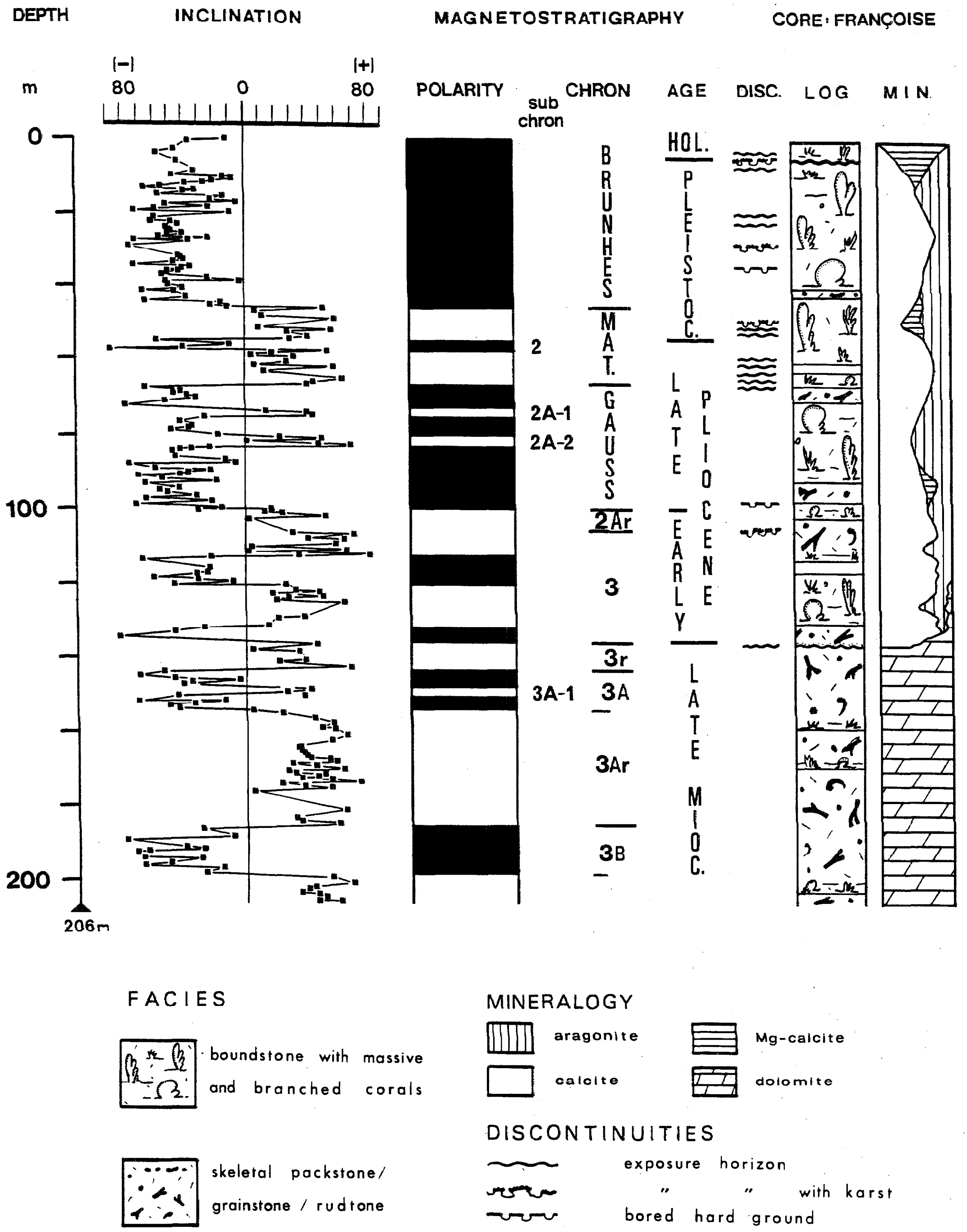

Fig. 1. *Magnetostratigraphy of the Mururoa core.*

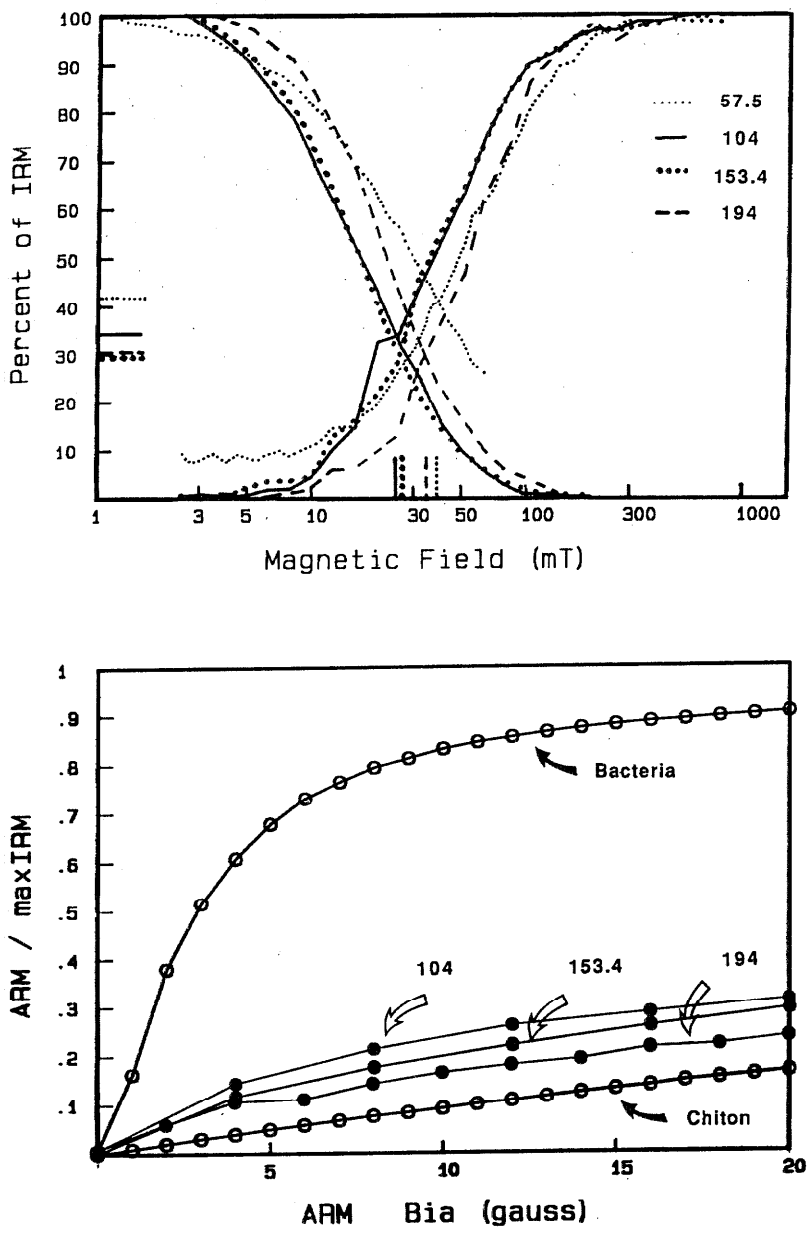

Fig. 2. *Top: Isothermal Remanent Magnetization (IRM) plotted versus alternating field demagnetization (Af) for four representative samples. All samples have low remanent coercive fields (H_{Rc}) between 25 and 36 mT. This suggest that magnetite or maghemite are the dominant magnetite carriers despite the presence in the sub-samples of a small amount of magnetically hard component such as hematite or goethite as indicated by the unsaturated remanence in fields above 300 mT. The 'soft' demagnetization path exhibited by all samples is characteristic of a single domain ferrimagnetic mineral, probably magnetite or maghemite. Values for R (crossover point), i.e. the ratio of IRM at H_{Rc} to the saturation IRM, range from 30 to 43 %, indicating a moderate to low particle interaction. Bottom: Anhysteretic Remanent magnetization (ARM) versus the ratio of ARM/IRM for three representative samples, compared with intact, freeze-dried cells of* Aquaspirillium magnetotacticum *(Bacteria) and* Polyplacophora sp. *(Chiton teeth). Samples fall clearly above the region of strongly interacting magnetite of Chiton teeth, but below the region of non-interacting bacterial magnetosomes curve, confirming the moderate interaction between the single domain magnetic carriers.*

range of SD (0.05–0.08 μm) and two-domain (0.1–0.3 μm) magnetite particles (Butler and Barnejee, 1975). We therefore conclude that the main carrier of remanent magnetization in the Mururoa limestones and dolomites is the SD magnetite (see Fig. 9 of Aïssaoui *et al.*, 1990a), or possibly maghemite, with crystal morphologies similar to those of bacterial magnetofossils (Blakemore, 1975; Kirschvink and Chang, 1982; Chang *et al.*, 1987). This is consistent with observations that larger grains are rare, and that the occurrence of SD magnetofossils in Cenozoic carbonates is widespread (Chang *et al.*, 1987; Vali and Kirschvink, 1989; Chang and Kirschvink, 1989; McNeill *et al.*, 1988; Aïssaoui *et al.*, 1990a).

The following three lines of evidence indicate that the dominant magnetic component of the Mururoa carbonates is either of primary or early secondary origin: (1) the consistent magnetic polarity zones within the 206 m Mururoa core; (2) the presence of probable biogenic magnetites, together with the lack of obvious inorganic magnetite; and (3) the nature of the Af and thermal demagnetization behaviour exhibited by the subsamples measured, which is similar to that of other modern and ancient carbonates (McNeill *et al.*, 1988; Aïssaoui and Kirschivink, unpubl.). Correlation between the Mururoa magnetic reversal sequence and the geomagnetic time-scale of Harland *et al.* (1982) provides several well-established chronological control-points in the core (Table 1). We have used three tie-points: (1) the occurrence of the Late Pleistocene coccolith *Geophyrocapsa oceanica* at depths of about 40 m (Aïssaoui *et al.*, 1990a); (2) the presence of an assemblage of benthic foraminifera typical of the Late Miocene, at depths of 255 m (Blondeau and Matsumaru, 1986); and (3) the characteristic pattern of chrons 3A and 3Ar in the Mururoa sequence (Fig. 1).

The accumulation rate of Muroroa Atoll is highly variable, ranging between 12.3 and 90.7 m/Myr (Fig. 3). The curve shown in Fig. 3 is not corrected for isostatic subsidence, and the duration of exposure periods is unknown. However, lithological compaction is negligible, and no major tectonic activity has been recorded in this area (Bardinzeff *et al.*, 1985; Keating *et al.*, 1987). Reefs and atolls are very sensitive to bathymetric changes because coral growth depends both on light and on hydrodynamic controls on the nutrient supply. The observed pattern of accumulation is therefore a good approximation to sea-level fluctuations and tectonic subsidence. Two periods of slow growth rate are apparent at Mururoa (Fig. 3). The first occurred during the late Pliocene and early Pleistocene (between 0.73 and 2.48 Ma), resulting in condensed sequence representing the Matuyama Chron, which coincides with the presence of several hiatuses (exposure horizons and bored surfaces). The second period occurred close to the Mio–Pliocene transition (between 4.59 and 6.07 Ma). Similar decreases in the rate of shallow-water carbonate sedimentation have been reported from the Bahamas (McNeill,

Table 1. Dated horizons deduced from the magnetostratigraphy of the Mururoa core.

	Depths (m)	Age (Ma)
Chrons		
Brunhes (start)	45.8	0.73
Gauss	66.6–100.2	2.48–3.4
2Ar	100.2–106.1	3.40–3.86
3	106.1–134.7	3.86–4.79
3r	134.7–143.7	4.79–5.41
3A	143.7–154.7	5.41–6.07
3Ar	154.7–185.5	6.07–6.42
3B	185.5–198.2	6.42–6.55
3Br	198.2	6.55
Periods		
Pleistocene	4.5 to 54.5	0.12 to 1.6
Late Pliocene	54.5 to 100.2	1.6 to 3.4
Early Pliocene	100.2 to 134.5	3.4 to 4.79
Late Miocene	134.5	> 4.79

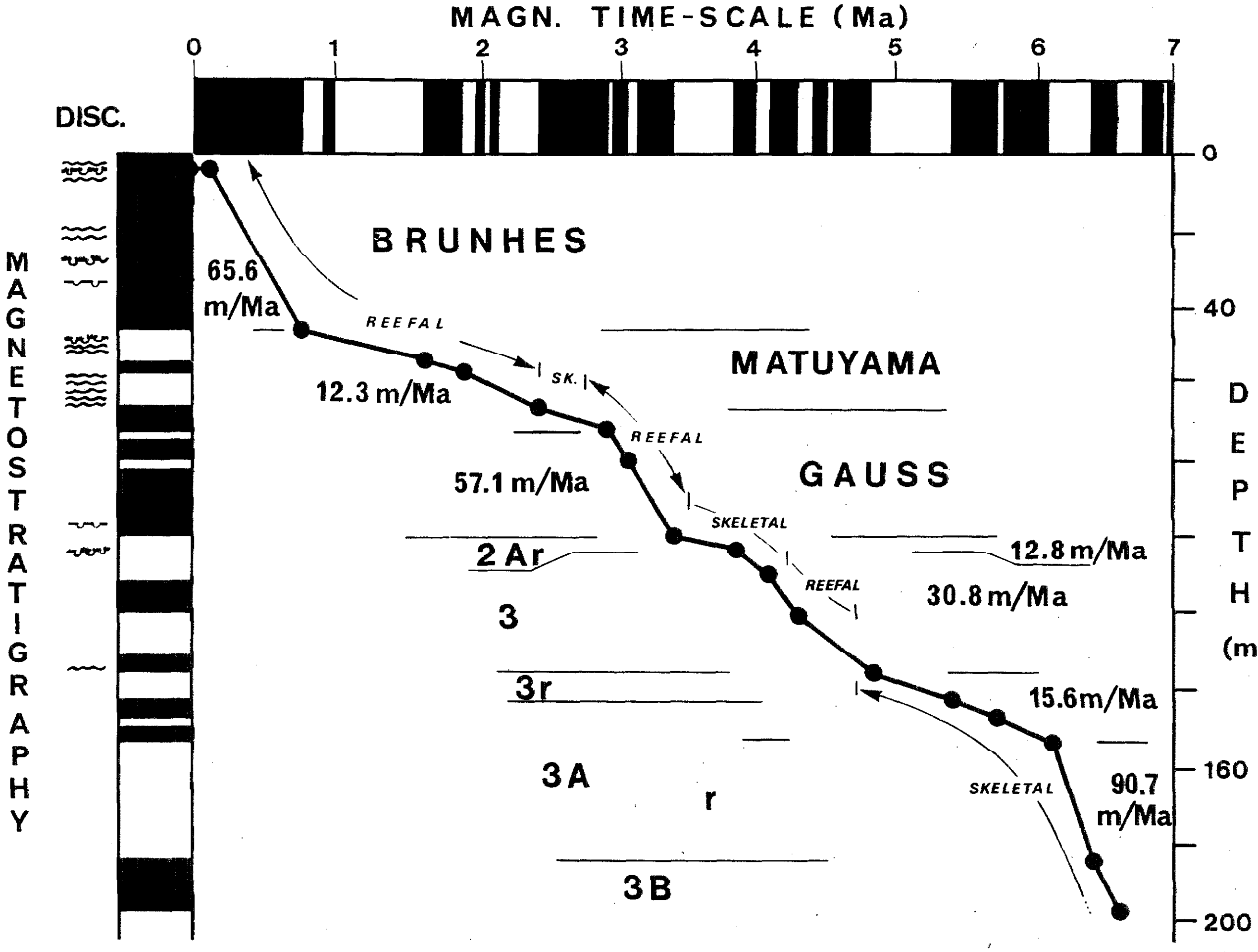

Fig. 3. *Depth/age curve for Mururoa atoll showing variable accumulation rates approximating to the atoll growth rate.*

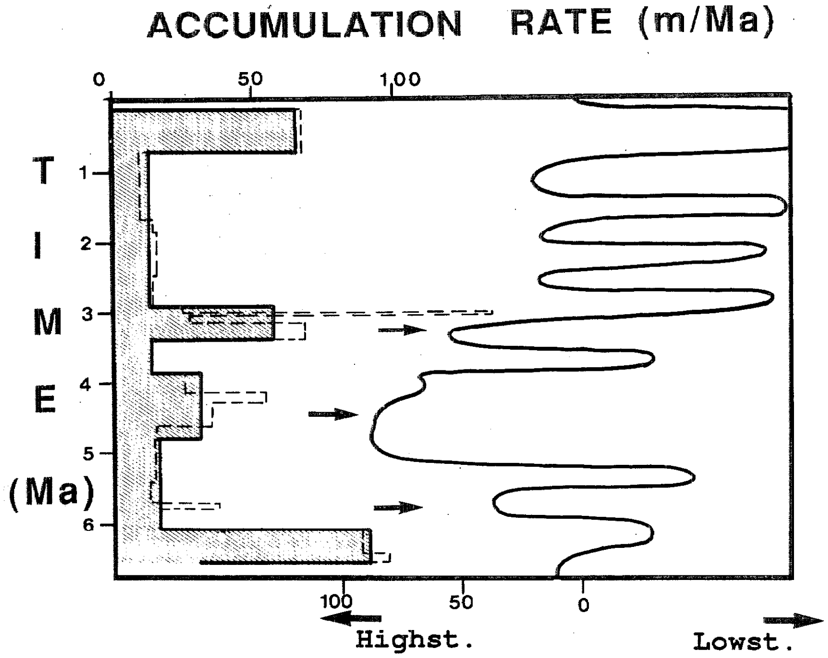

Fig. 4. *Comparison between the atoll growth rate (left) and the Cenozoic Sea Level Curve (Haq* et al., *1987). The solid line represents the accumulation rates given in Figure 3; the dashed line is based on all the normal and reversed intervals identified in the studied core. The arrows point out the correlation between the increase of the atoll-growth and the sea level highstands. The poor correlation for the period between 0.73 and 2.98 Ma may be explained by the low-amplitude of the sea-level rises.*

1989). The Bahamian carbonate accumulation-rate variations may be correlated with Mururoa, and hence have been attributed to global eustastic changes (Aïssaoui *et al.*, 1990a,b). The detailed correlation between the Mururoa accumulation rates and the proposed trend in sea level fluctuations for the Late Cenozoic (Haw *et al.*, 1987) attempts to calibrate the eustatic variation recorded by the atoll (Fig. 4). Most of the sea level highstands correlate with an increase in the accumulation rates of the atoll. This is particularly true when the amplitude of sea-level rise is high (Fig. 4). However, despite the fluctuations of the sea-level between 2.9 and 0.7 Ma, there is no significant increase in the growth-rate, and the atoll exhibited repeated sub-aerial exposures during the same period. The relatively low amplitude of sea-level rise (Fig. 4) may be an explanation for this apparent negative correlation. Finally, the sea-level trend of Haq *et al.* (1987) does not mention the rapid increase in the accumulation rate since 0.73 Ma recorded both in Mururoa atoll and in the Bahamas platform (Aïssaoui *et al.*, 1990a,b).

Our results present two important implications:

(1) For the first time, the chronology of an atoll growth is documented with extremely high resolution. This demonstrates that the carbonate sediments of atolls and guyots are now amenable to quantitative chronostratigraphic investigation, thus facilitating a better understanding of the relative importance of eustatic versus tectonic controls on the depositional history of reefal sediments. Spatial correlation of sea-level high and low stands can now be investigated on a global scale.

(2) The identification of SD magnetite within the Mururoa carbonates provides additional evidence for widespread distribution of geologically stable, remanent magnetization in shallow-water carbonate sediments. Similar deposits have a wide occurrence throughout the geological record, and are often hydrocarbon reservoirs; they may have initial stable remanent magnetism amenable to palaeomagnetic dating. Preliminary tests of the Jurassic samples in the Paris Basin show magnetization patterns and behaviour similar to those of the Cenozoic samples (Aïssaoui and Kirschvink, 1991).

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