MAGNETITE AND MAGNETOTAXIS IN ALGAE

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ABSTRACT Magnetotactic algae of the genus *Anisonema* (Euglenophyceae) have been isolated from a coastal mangrove swamp in northeastern Brazil. The magnetotactic response is based on a permanent magnetic dipole moment per cell $\sim 7\ 10^{-10}$ emu. Each cell contains many magnetite (Fe_3O_4) particles organized in chains.

INTRODUCTION

Magnetite (Fe_3O_4) has been reported as a biomineralization product in bacteria (1, 2) and in many multicellular organisms (3). In magnetotactic bacteria, magnetite particles are deposited intracellularly in membrane vesicles (magnetosomes) (4) and have dimensions ranging from 400 to 1,200 Å and morphologies that are species specific (5). The particles are often arranged in a chain that imparts a magnetic dipole moment to the cell that is responsible for the magnetotactic response (6). In chitons, magnetite particles of irregular shape are deposited extracellularly in an organic matrix on the tooth denticles of the radula (7). In the other eucaryotic organisms, magnetite particles have only been identified magnetically in whole organisms and after extraction (8). Thus their in vivo arrangement is unknown, although they are thought to be responsible for magnetic effects on behavior (1, 3, 9). Here

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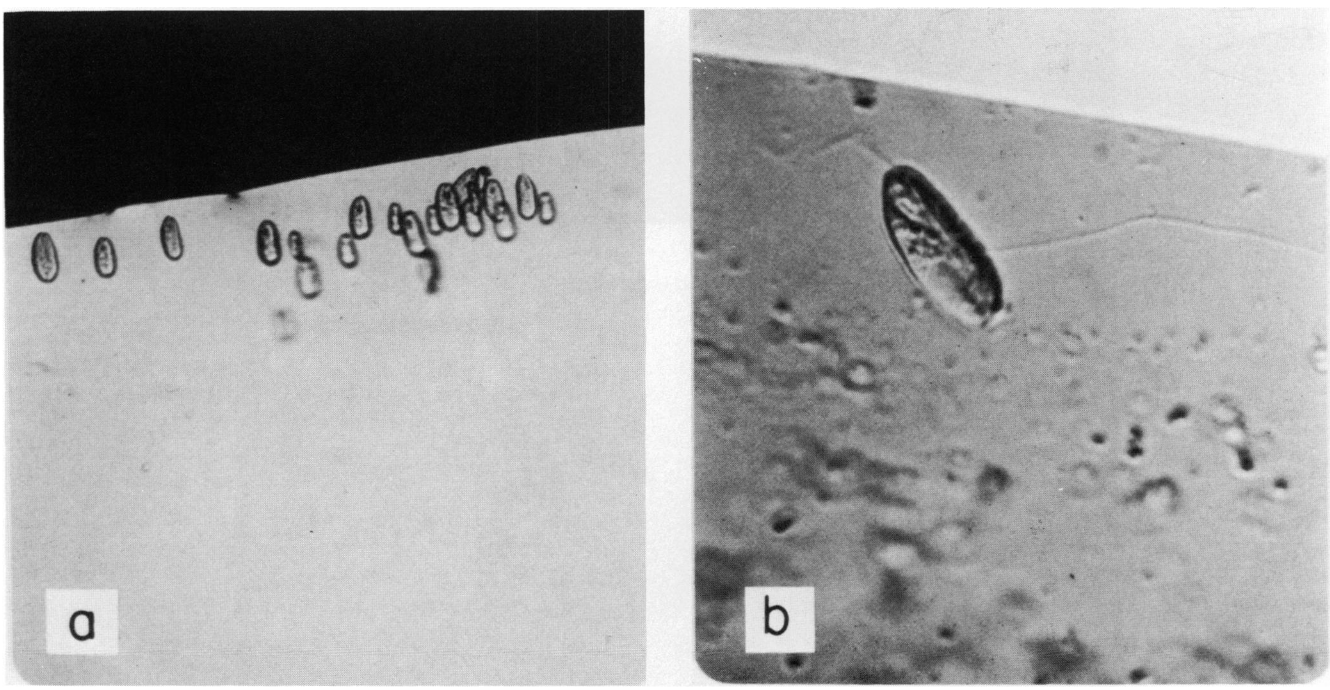

FIGURE 1 (*a*) Light micrograph of magnetotactic algae oriented in a magnetic field at the edge of a water drop. Cells are ~20 μm long, 12 μm wide and 4 μm thick. (*b*) Light micrograph of an individual alga.

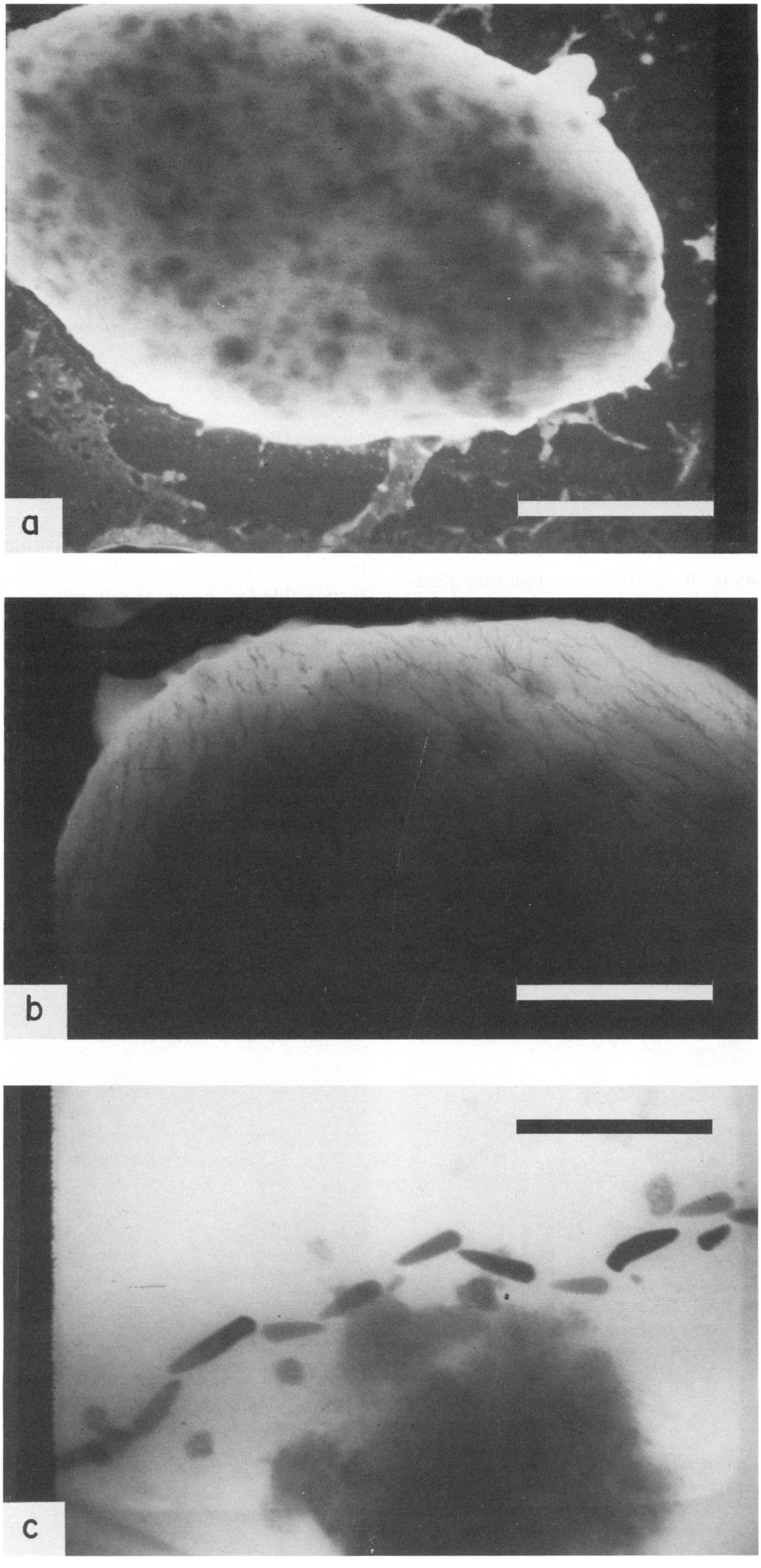

FIGURE 2 (*a*) Electron micrograph of *A. platysomum* (bar length: 5 μm). (*b*) Electron micrograph of periphery of cell showing chains of particles (bar length: 2.5 μm). (*c*) Electron micrograph of particle chain (bar length: 0.5 μm).

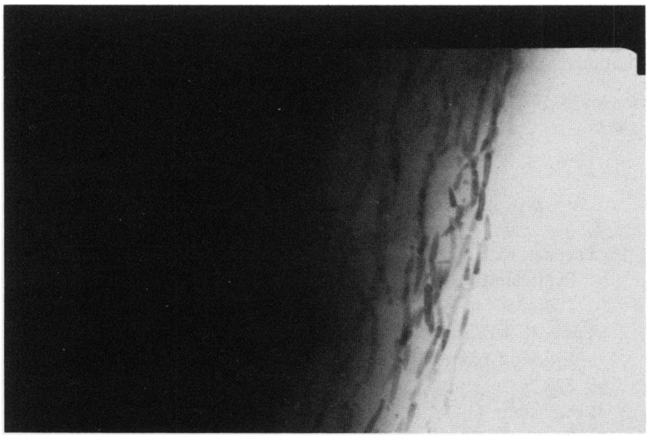

FIGURE 3 Electron micrograph showing relative orientations of particles and chains at edge of cell.

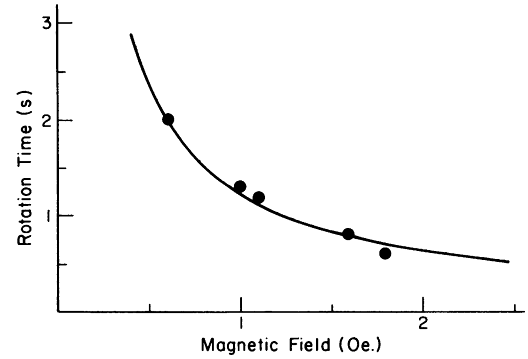

FIGURE 4 Values of the 180° rotation time for a killed alga suspended in water after reversal of the magnetic field plotted as a function of magnetic field strength. The line is a theoretical fit of Eq. 1 to the data with $M = 5\ 10^{-10}$ emu and $R = 8\ \mu m$.

we report that eucaryotic cells, euglenoid, motile, magnetotactic algae of the genus *Anisonema*, contain many Fe_3O_4 particles organized in chains.

METHODS

The algae were collected in brackish water sediments from a coastal mangrove swamp near Fortaleza, Brazil. Their magnetotactic response was observed microscopically in drops of water and sediment with small bar magnets or Helmholtz coils placed on or near the microscope stage as previously described for magnetotactic bacteria (10). Cells eventually migrated along magnetic field lines either parallel or antiparallel to the field direction, that is, they were either North-seeking or South-seeking, respectively. Killed cells rotated and oriented along magnetic field lines. Cells were flat and ovate (Fig. 1) with length and width of ~20 and ~12 μm, respectively. There were two flagella per cell, one trailing. On the basis of light microscopic examination the organism was identified as *Anisonema platysomum* Skuja (11).

Algae were isolated from the sediments by using their magnetotactic response to collect them at the edge of a drop of water and sediment on a microscope slide, where they were picked up with a micropipette and deposited on a carbon-coated electron microscope grid. They were then fixed in situ by incubation in 1% glutaraldehyde in K_2HPO_4 buffer for several minutes. The grids were examined in a 100 keV VG HB5 STEM electron microscope (VG microscopes, East Grinstead, U.K.) equipped with energy dispersive x-ray analysis (EDX) and electron diffraction capabilities (Figs. 2 and 3). The size of the algae prevented penetration of the electron beam at the centers of the cells (Fig. 2 *a*). However, numerous electron-opaque particles arranged in chains oriented more or less parallel to the long axis of the cell could be seen at the electron-transparent periphery of each cell (Figs. 2 *b* and 3). Individual particles were roughly arrowhead or tooth shaped (Fig. 2 *c*) with lengths of 800–1,800 Å (1,400 Å average) and widths of 400–500 Å (480-Å average).

TABLE I
LATTICE SPACINGS FROM ELECTRON DIFFRACTION IN ALGAL PARTICLES

Algal particles d-spacings	Fe_3O_4 d-spacings	Lattice planes hkℓ
Å	Å*	
4.8 ± 0.5	4.8	111
4.2		
2.9	2.967	220
2.6	2.532	311
2.1	2.099	400
1.8	1.715	422
1.6	1.616	511
1.5	1.485	440
1.2	1.281	533

*ASTM Card 19-629.

RESULTS

EDX spectra were recorded with the electron beam focused on and off the particles. Comparison of the spectra showed that the particles were highly enriched in iron compared to the cell wall and cytoplasm. No Fe x rays were observed beyond the apparent cell boundary, indicating that the particles were intracellular. Electron diffraction patterns were recorded for forty individual particles. The patterns indicated that each particle was a single crystal with orientation that varied from particle to particle along the chain. Analysis of the diffraction patterns gave interplanar spacings that are consistent with the known interplanar spacings of Fe_3O_4 (Table I).

Magnetotactic bacteria, cocci and spirilla, were also found in the same sediments with the algae. These organisms, typically 1–3 μm, contained single or double chains of cuboidal-shaped magnetite particles with linear dimensions 400–600 Å similar to those reported previously (1, 2). Arrow-head shaped particles similar to those in the algae have previously been found in bacteria from sediments in New Zealand (12) and New England (13).

Thus magnetotactic algae of the genus *Anisonema* contain numerous chains of Fe_3O_4 particles that appear to be located in or near the cell wall. The individual particles are within the single-magnetic-domain size range for Fe_3O_4. Hence, each chain is a permanent, magnetic dipole (14). If the moments of all the chains are oriented parallel to each other, a cell would have a magnetic dipole moment equal to the sum of the moments of all its particles. An estimate of the magnetic dipole moment of whole algae was obtained from measurements of the 180° rotation time of killed cells suspended in water, after reversal of the direction of the magnetic field produced by a pair of Helmholtz coils. Using the coefficient of viscous drag for a flat disk, the rotation time τ is related to the magnetic moment M by the equation (15)

$$\tau = \frac{32R^3\eta}{3MH} \ln\left(\frac{2MH}{kT}\right), \qquad (1)$$

where R is the radius of the cell, η is the viscosity of water, H is the magnetic field, and kT is Boltzmann's constant multiplied by temperature. Experimental sets of values of τ vs. H for eleven algal cells were each fit (Fig. 4) with Eq. 1, yielding an average permanent, magnetic moment per cell $M = 6.7\ 10^{-10}$ emu. This is ~1,000 times the magnetic moment of a typical magnetotactic bacterium. The saturation magnetization in magnetite is 480 emu cm^{-3}. Therefore the magnetic moment of an average-sized particle (1,400 × 480 × 480 Å) is $1.5\ 10^{-13}$ emu. Hence, each algal cell must contain on the order of $3\ 10^3$ magnetite particles, with the particles occupying ~0.2% of the cell volume.

Although the motility of the algae in a magnetic field is more complex than magnetotactic bacteria, the magnetotactic response mechanism of the algae appears to be similar to that in magnetotactic bacteria, i.e., passive orientation of the cell by the torque exerted by the magnetic field on its permanent, magnetic dipole (14). The fact that the algal magnetic moment is three orders of magnitude larger than typical bacterial moments means that algae and bacteria have similar ratios of magnetic torque to viscous drag, that is, they have similar recovery times after deorientation events (16).

The biological significance of magnetotaxis in these organisms is unknown at present, but since Fortaleza is within 4° of the magnetic equator, both North-seeking and South-seeking algal cells will be directed horizontally. The genus *Anisonema* is typically heterotrophic and the sediments are a rich source of nutrients. Thus magnetotaxis in these cells might serve to keep them in the sediments and away from high oxygen tension, high light intensity, and high temperatures at the water surface.

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