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Investigation of magnetotaxis of magnetotactic bacteria in water and sediment

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Magnetotactic bacteria contain chains of magnetic particles which allow them to align and move along the magnetic field to search for optimal habitats in chemically stratified environments. This phenomenon is known as magnetotaxis. The alignment is passive, and driven by the torque $\mathbf{m}\times\mathbf{B}$ between the magnetic dipole $\mathbf{m}$ of the chain and the external magnetic field $\mathbf{B}$. The alignment is counteracted by the randomizing effect of Brownian motion, and the average alignment of free bacteria in water, expressed by $\cos(\theta)$, where θ is the angle between $\mathbf{m}$ and $\mathbf{B}$, is expected to follow the Langevin law $\cos(\theta) = L(mB/kT)$ where k is the Boltzmann constant and T the absolute temperature [*Frankel*, 1980]. This law implies that a minimum strength for the Earth's field is required for a bacterium with given magnetic moment to have a certain alignment with the field. The resulting motion is a biased random walk whose "efficiency" for a displacement along $\mathbf{B}$ is equal to the average aligmnent. Calculated values for $\cos(\theta)$ in the present Earth's field give good alignments >0.9. Direct experimental observations of the Langevin law on living bacteria in various field intensity are limited to one study by [*Kalmijn*, 1981]. Here we report systematic observations for two types of wild-type bacteria: magnetic cocci containing two to five chains of $\sim$100 magnetosomes, and *magnetobacterium Bavaricum* , a rod-shaped bacterium containing several hundreds magnetosomes [*Hanzlik et al.*, 1996]. We also investigated the aligment of those bacteria in natural sediment, where physical constraints imposed by the pore volume are expected to have a great influence on their capability of to align with an external field. Our results show that the alignment of free swimming magnetotactic bacteria in water obeys Langevin's law, with >0.8 alignments in external fields of 3μT for *Bavaricum* and 30μT for big cocci (the present earth's field is at avrage 50μT). This result shows that magnetotactic bacteria, and in particular Bavaricum, synthesize more than 10 times magnetosomes than they need for magnetotaxis in present field. This fact could leat to the suggestion that magnetosomes could have other unknown functions besides navigation in a magnetic field. On the other hand, typical sedimentary environments pose drastically different conditions for magnetotaxis. This is shown by our measurements of bacteria's alignment in acquaria containing natural lake sediments. Because direct observation of bacteria in sediment is not possible, we applied strong pulsed magnetic field to reverse the magnetic moment of bacteria whose magnetic moment forms a $>90^\circ$ angle to the pulse field. These bacteria become South-seeking and can be counted. By applying pulses along different directions with respect to the external field it is possible to calculate their alignment from the ratio between North- and South seeking.

Our results indicate that the bacteria's alignment in sediment is $<3\%$ and becomes closer to typical alignments for DRM magnetizations. This means that a larger torque is necessary to overcome mechanical constraints in sediments, which could explain the large number of magnetosomes in a large bacterium such the *Bavaricum*. These results also suggest that the so-called "magnetotactic advantage" has to be reconsidered when dealing with bacteria in sediment.