Magnetic Particles in the Lateral Line of the Atlantic Salmon (Salmo salar L.)

A. Moore, S. M. Freake and I. M. Thomas

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Magnetic particles in the lateral line of the Atlantic salmon (*Salmo salar* L.)

A. MOORE[1], S. M. FREAKE[2] AND I. M. THOMAS[2]

[1] *Directorate of Fisheries Research, Fisheries Laboratory, Ministry of Agriculture Fisheries and Food, Lowestoft NR33 0HT, Suffolk, U.K.*
[2] *Physics Department, Open University, Milton Keynes MK7 6AA, U.K.*

SUMMARY

Magnetization measurements with a superconducting quantum inference device magnetometer of various tissues of the Atlantic salmon (*Salmo salar* L.) have shown the presence of magnetic material associated with the lateral line. The data suggest that the material is magnetite and of a size suitable for magnetoreception. Magnetic particles were isolated from the lateral line and nerve tissue, which have characteristics suggesting that the material is magnetite and of biogenic origin. The magnetic particles and their association with the lateral line are discussed in relation to their possible role in allowing the salmon to orientate with respect to the geomagnetic field during the high-seas phase of their migration.

1. INTRODUCTION

A variety of organisms such as bacteria (Blakemore 1975), honey bees (Lindauer & Martin 1968), birds (Walcott & Green 1974; Beason & Nichols 1984) and sea turtles (Perry *et al.* 1985) are sensitive to the geomagnetic field and may use it as a navigational aid. The tissues of many of these species contain biologically deposited particles of magnetite, suitable for use in magnetoreception. In teleosts, magnetite has been detected predominantly in the region of the ethmoid tissue (Walker *et al.* 1984; Kirschvink *et al.* 1985; Walker *et al.* 1988; Mann *et al.* 1988). However, ultrastructural studies have not shown that the magnetite is innervated or associated with an existing receptor system. This paper describes the presence of magnetic material, probably magnetite, concentrated in the lateral line of the migratory Atlantic salmon (*Salmo salar* L.). The size and number of the magnetic particles are sufficient to allow the salmon to detect the geomagnetic field. It is suggested that the particles may have a navigational role during the high-seas migration of the salmon.

2. MATERIALS AND METHODS

(*a*) *Magnetic measurements*

Seventeen salmon (11 smolts and 6 adults) were examined for the presence of magnetic material. To exclude magnetic contamination, tissue samples were dissected from each fish by using glass microtome knives in a clean laboratory (Walker *et al.* 1985). Each sample was weighed, washed in glass distilled water and packed into plastic cylindrical pots (14 mm diameter, 9 mm high). After freezing in liquid nitrogen, plugs of tissue of consistent size were extracted. Tissue samples examined included the eye, skin, ethmoid tissue, brain, muscle and an area containing the lateral line and nerve. Magnetization measurements were made with a superconducting magnetometer (SHE Model BMP with rf superconducting quantum interference device (SQUID)). Initially, the natural remanent magnetization of all the samples was measured. Subsequently the saturation isothermal remanent magnetization (SIRM) was measured immediately after exposing each tissue sample to a unidirectional magnetic field of 0.7 T. Coercivity spectra were then obtained for the lateral line and nerve tissue of an adult salmon by subjecting the samples to progressive isothermal remanent magnetization (IRM) acquisition and alternating field (Af) demagnetization in fields ranging from 2–700 mT.

(*b*) *Extraction of magnetic material and electron microscopy*

Magnetic material was extracted from the lateral line and nerve tissue of several adult salmon by using a technique similar to that of Walker *et al.* (1985). Tissue was ground with glass-distilled water in a glass tissue grinder. Released oil and fat droplets were removed by adding anhydrous ether and decanting. The residue was centrifuged and digested with 5% Millipore-filtered hypochlorite solution. After digestion, the residue was repeatedly washed and centrifuged, and then resuspended ultrasonically. The magnetic material was concentrated at the side of the test tube by using a high magnetic field produced by a rare earth (iron–neodymium boride) magnet wrapped in heatshrink plastic. The final extracts of the particles were prepared for observation under the transmission electron microscope (TEM) by pipetting the material, in suspension, onto carbon-coated copper grids and allowing the sample to evaporate to dryness.

The magnetic extracts were then viewed with a Jeol 300 CX electron microscope at magnifications of

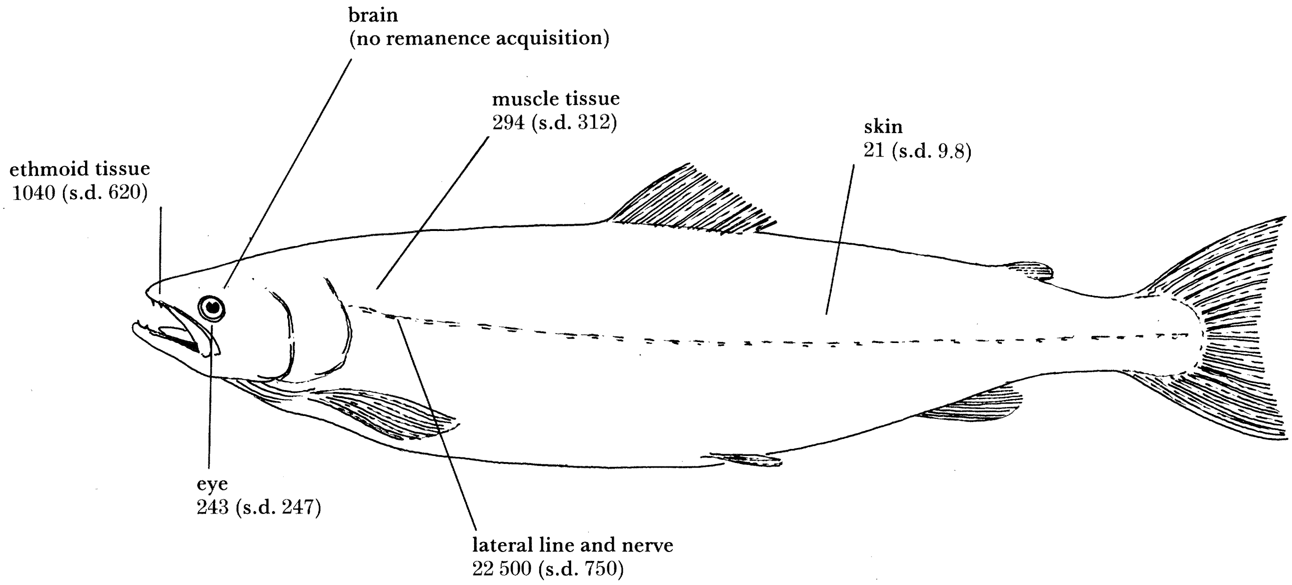

Figure 1. Schematic diagram of Atlantic salmon showing the SIRM values obtained for each of the various tissue types. Values are measured in pA m^2 g^{-1}.

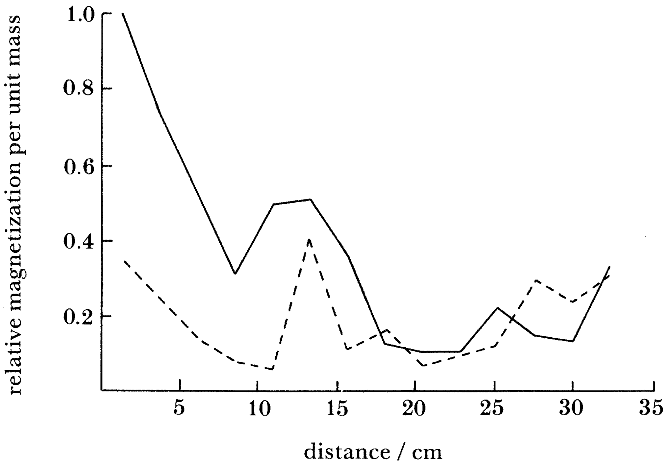

Figure 2. SIRM of the lateral line and nerve (solid line) and muscle tissue (dashed line) as a function of distance posterior to the operculum in an adult salmon (total length of fish 84 cm). Samples of the lateral line and nerve (2 cm long) were dissected with the surrounding tissue and an adjacent muscle sample used as a control.

× 10000 to × 130000. Elemental spectra of the particles were obtained with a Philips EM 400 electron microscope and a Link Systems energy dispersive X-ray analyser with an accelerating voltage of 100 kV.

3. RESULTS

(*a*) *Magnetic measurements*

The magnetization values for each of the tissue types are shown in figure 1. All tissue except the brain was capable of remanence acquisition to varying degrees. Highest consistent SIRM values were obtained from the lateral line and nerve tissue. The lateral line and nerve were dissected *in situ* with a portion of the surrounding muscle tissue. The value for the lateral line and nerve tissue alone was then calculated to give a value of 22500 (s.d. 750) pA m^2 g^{-1}. SIRM values for the lateral line tissue in the smolts were an order of magnitude smaller than in the adult salmon, suggesting that the concentration of magnetic material increases as the fish becomes older (Walker *et al.* 1988). Remanence acquisition was found for both the left and the right lateral lines and sectioning showed that significantly more magnetic material was located in the anterior 30% of each lateral line (figure 2). Samples where the lateral line was removed gave values similar to those of muscle.

The coercivity spectra for the lateral line show that the tissue samples acquired virtually all their remanence in fields of less than 200 mT, and demagnetization was nearly complete in fields of less than 100 mT (figure 3). This is consistent with the presence of a ferromagnetic material, such as magnetite, of single-domain size (Evans *et al.* 1968; Walker *et al.* 1984; Kirschvink *et al.* 1985; Walker *et al.* 1985). The coercivity value, taken as the value of the magnetizing field at the intersection of the IRM acquisition and demagnetization curves, is 37 mT, which is within the range reported for single-domain magnetite particles (Cisowski 1981; Kirschvink 1983). The Wohlfarth's *R* value, (Cisowski 1981) is 0.21, suggesting that there is significant interaction between the magnetic particles

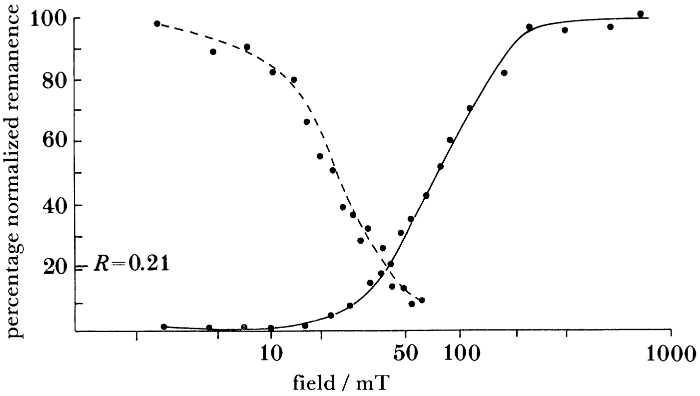

Figure 3. Acquisition of IRM (solid line) and Af demagnetization of SIRM (broken line) for the lateral line and nerve tissue from an adult fish. Coercivity (at intersection point) = 37 mT and Wohlfarth's $R = 0.21$. The IRMs were acquired in incremental steps up to a peak magnetic field of 0.7 T.

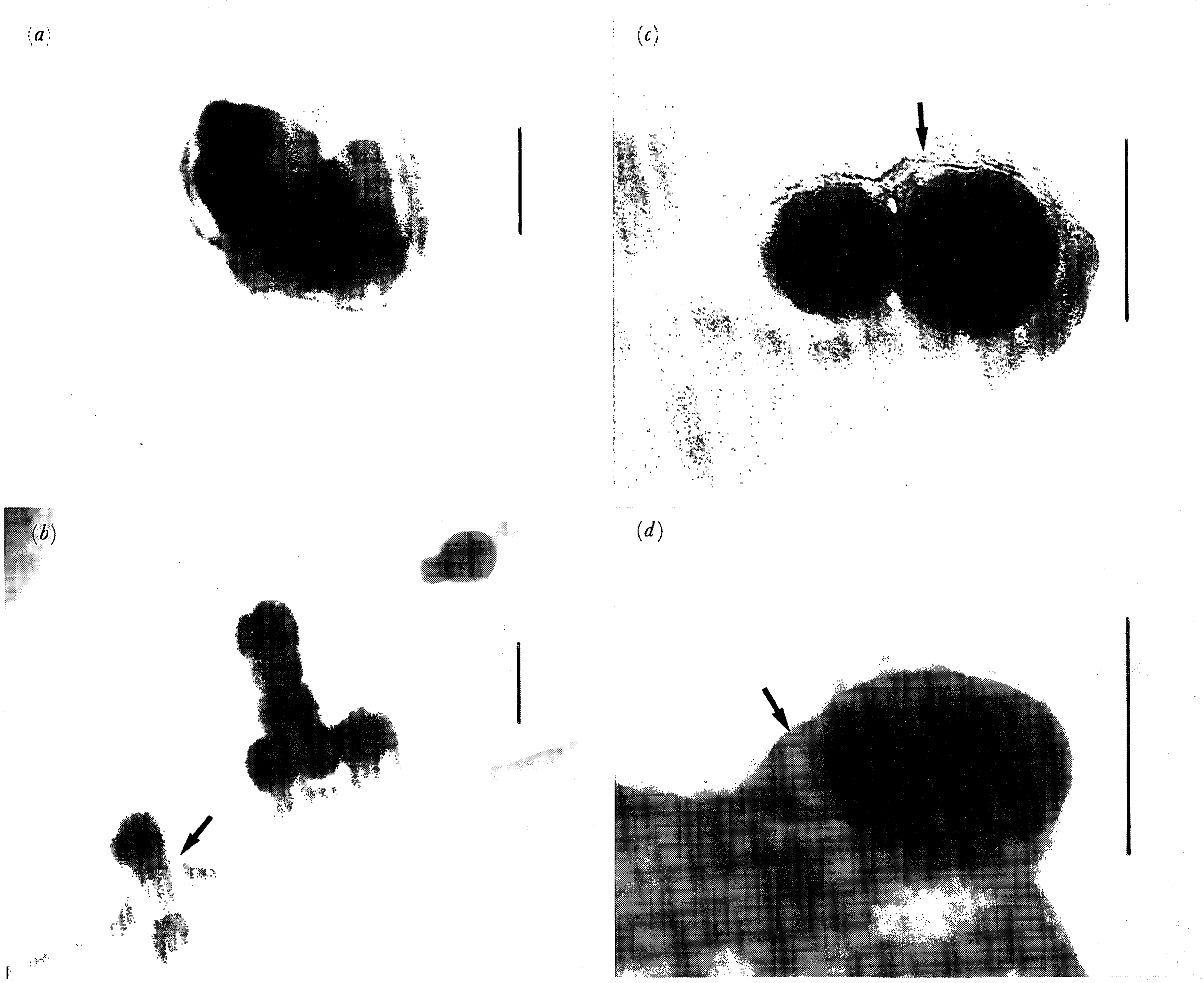

Figure 4. (*a*–*d*). TEM images of the particles magnetically extracted from the lateral line and nerve tissue, the organic matrices are indicated by arrows (scale bars in (*a*) and (*c*) indicate 0.1 μm and in (*b*) and (*d*) they represent 0.3 μm).

(Kirschvink *et al.* 1985; Walker *et al.* 1988). Coercivity spectra obtained for the ethmoid tissue were similar to those for the lateral line tissue, again suggesting the presence of magnetite.

(*b*) *Extraction of magnetic material and electron microscopy*

The magnetic particles, when aggregated at the side of the test tube and viewed under the light microscope, were black, suggesting the presence of magnetite (Kirschvink 1983). No such material could be magnetically extracted from control samples of muscle. When viewed under the transmission electron micro-

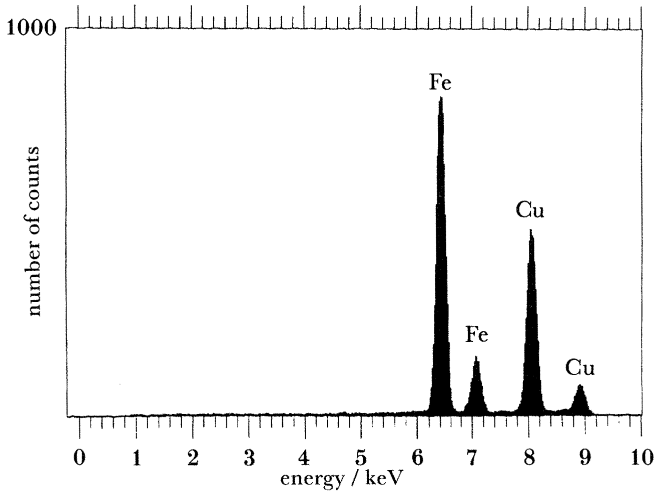

Figure 5. Energy dispersive X-ray analysis of the magnetically extracted particles in a Philips EM 400 with Link Systems analyser (copper peaks are from the support grids).

scope, spherical, electron opaque particles were observed. These were of two sizes and varied continuously within the ranges 0.06–0.10 μm and 0.34–0.38 μm in diameter. They showed no volatilization under the electron beam and appeared to be closely associated with an organic matrix (figure 4, plate 1). Iron was the only detectable element present in the particles (figure 5). Chains of single-domain magnetite crystals reported in other species of salmon were not observed (Kirschvink *et al.* 1985; Mann *et al.* 1988; Walker *et al.* 1988).

DISCUSSION

We conclude from the results of this study that the lateral line of the Atlantic salmon contains magnetic material, probably magnetite, which is of biogenic origin. The absence of measurable quantities of other metals such as titanium, nickel and chromium suggests that the particles are not geological contaminants (Perry *et al.* 1985). The close association of the particles with an organic matrix, the greater concentration in older salmon and the spherical shape also suggest a biogenic origin (Lowenstam 1981; Walker *et al.* 1988) for the particles. Although the black coloration of the particles suggests that they consist of magnetite, independent identification by electron diffraction, Curie point analysis or Mossbauer spectroscopy would be desirable. The larger particles appear to be an order of magnitude larger than the single-domain magnetite crystals reported in other fish (Walker *et al.* 1984; Kirschvink *et al.* 1985; Walker *et al.* 1988), but they may be surrounded by an organic coat (Perry *et al.* 1985). The morphology of the particles is similar to the magnetite spheres shown in the green turtle (Perry *et al.* 1985).

The sensory cues controlling navigation during the high-seas migration of the Atlantic salmon are a matter of conjecture. The results of this study suggest that the number of magnetic particles present, the significant degree of interaction, the anatomical distribution and the possible association with the lateral line canal would be sufficient to provide the salmon with a magneto-sensory system capable of responding to magnetic field direction (Yorke 1979; Kirschvink & Gould 1981). The association of the magnetic material with the lateral line supports the theory that the magnetic field detector in salmon may have evolved by the modification of an existing system with a conventional function rather than the development of a system exclusively for magnetoreception (Quinn *et al.* 1981). The putative magnetoreceptor may be several modified lateral line mechanoreceptors. A previous study has shown that the supraophthalmic trunk nerve that carries branches of the anterior lateral line nerve ramifies in the ethmoid region of the skull (Walker *et al.* 1984). We suggest that the single-domain magnetite particles located in the ethmoid region of other salmon species and the magnetic particles located in the lateral line may be part of the same system.

This appears to be the first report of magnetic material associated with an existing receptor system in a migratory teleost fish. Further studies on the identification of the material and also an anatomical investigation of the relation of the particles with a receptor associated with the lateral line are being done. The lateral line receptors and nerve may also provide a suitable preparation for an electrophysiological study of the salmon's ability to detect changes in magnetic field direction.

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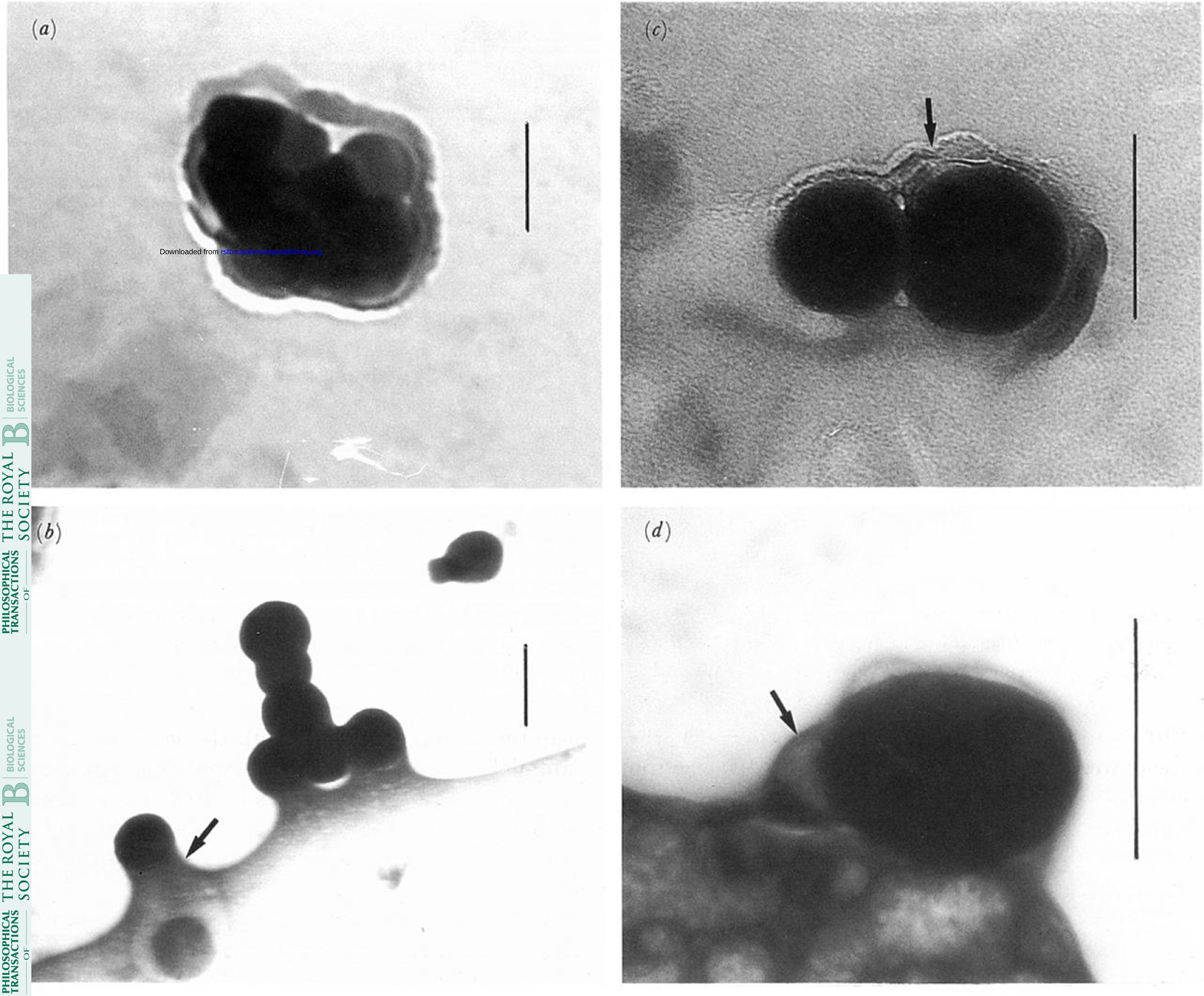

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