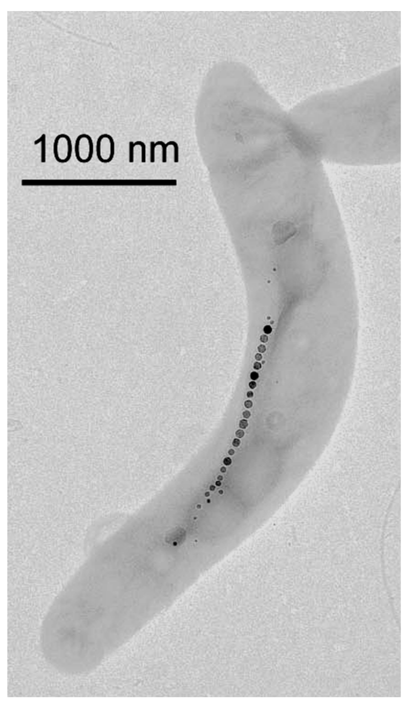

Variations in the morphologies and magnetic properties of magnetite crystals in bacteria

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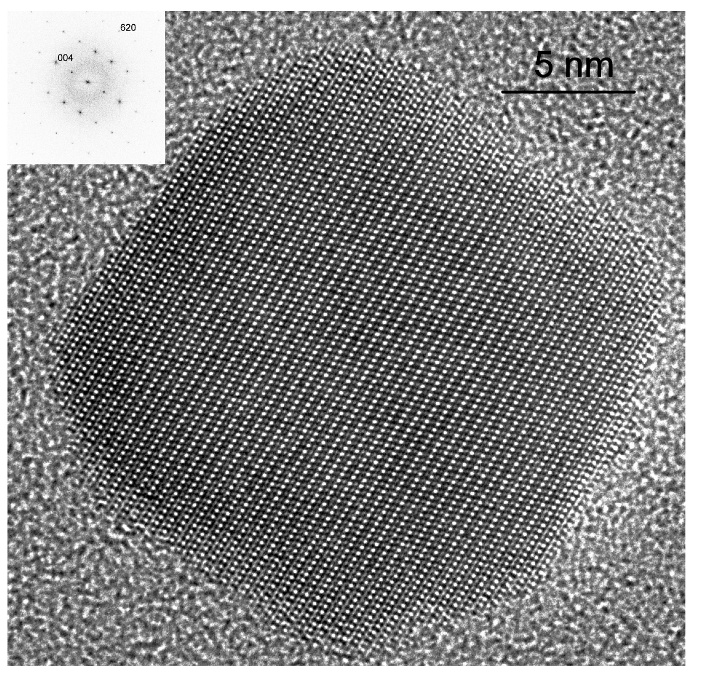
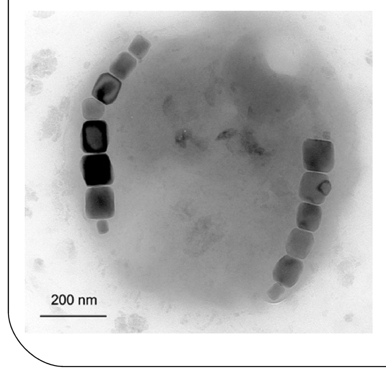


Magnetotactic bacteria



Cells contain ferrimagnetic nanocrystals of magnetite (Fe_3O_4) or greigite (Fe_3S_4), usually in chain configuration

Cells perform magnetotaxis: they are oriented by Earth's magnetic field and actively swim along the geomagnetic field lines

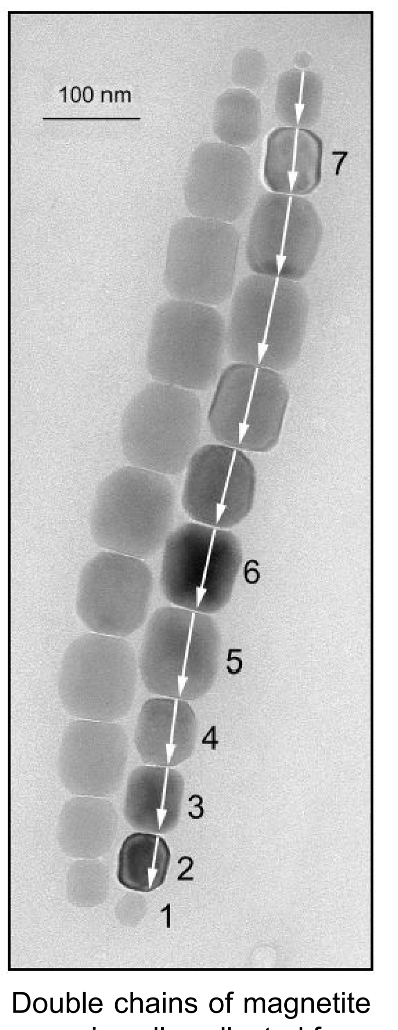
Crystals inside magnetotactic bacteria: research topics, problems

Magnetotactic bacteria provide a model system for studying the fundamental effects that influence the magnetic properties of nanoscale magnets → electron holography

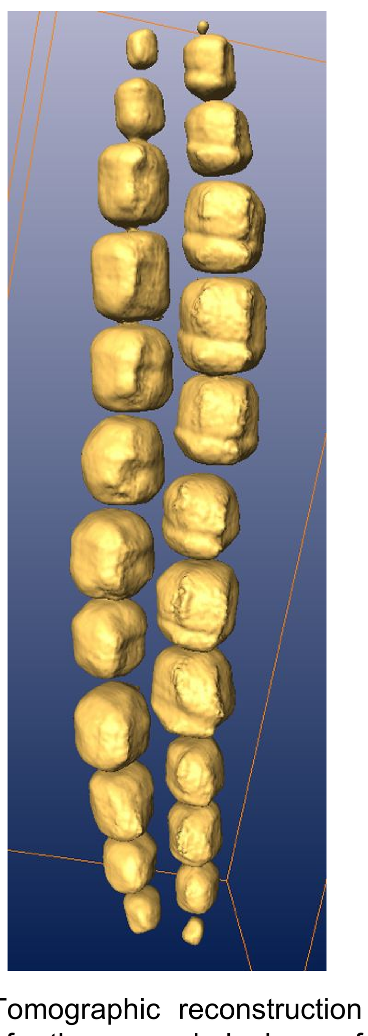
How does the bacterium control the formation of nanocrystals having strain-specific sizes, morphologies, orientations and spatial arrangements? → HRTEM, SAED, EELS, electron tomography

Magnetic properties of nanocrystals: competing effects
example: magnetic cells from Séd stream

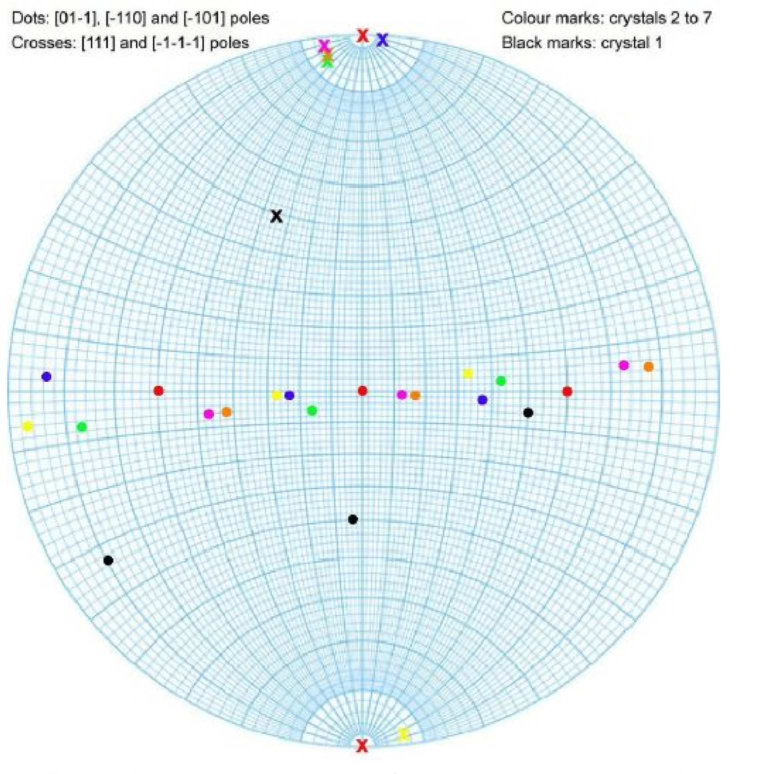
• crystal size	magnetite: ~30 to 120 nm magnetic single domain
• magnetocrystalline anisotropy	magnetite: [111] easy axis of magnetisation
• shape anisotropy	bacterial magnetite (Séd): elongated, prismatic habit
• interactions among crystals	bacterial magnetite (Séd): double, linear chains
• external factors: temperature	magnetite: @ 119 K cubic → monoclinic transformation (Verwey-transition), instead of [111] the easy axis of magnetisation is [100]



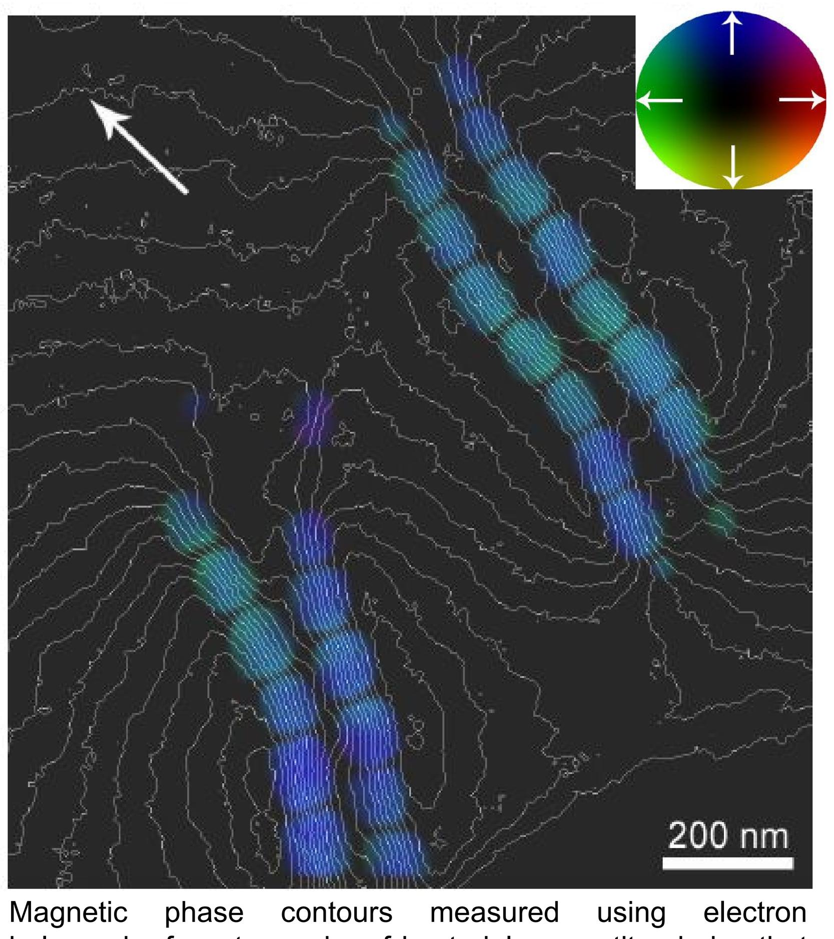
Double chains of magnetite occur in cells collected from a stream (Séd) in Hungary.



Tomographic reconstruction of the morphologies of nanocrystals in the same double chain of magnetite.



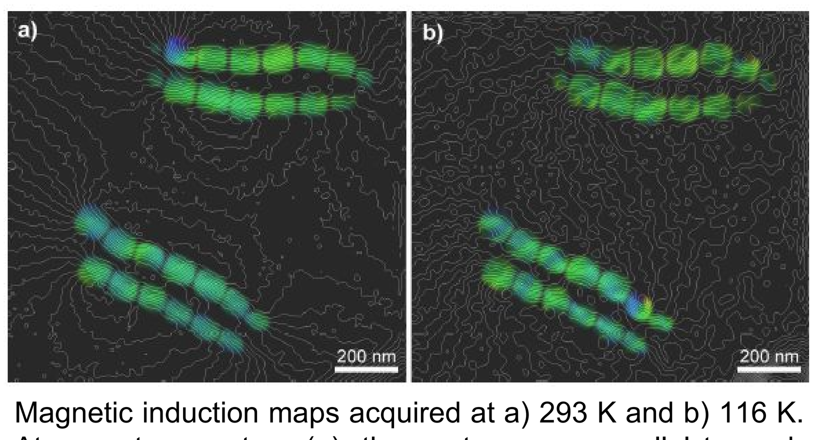
The relative orientations of the numbered crystals on the left were determined from SAED patterns and high-resolution TEM images. In the stereographic plot each colour represents a crystal; dots correspond to [110] and crosses to [111] poles. With the exception of the small crystal at the end of the chain (1, black colour above) all crystals are analogous to beads on a string, with their [111] directions strictly constrained along the chain axis, but allowed to freely rotate about [111].



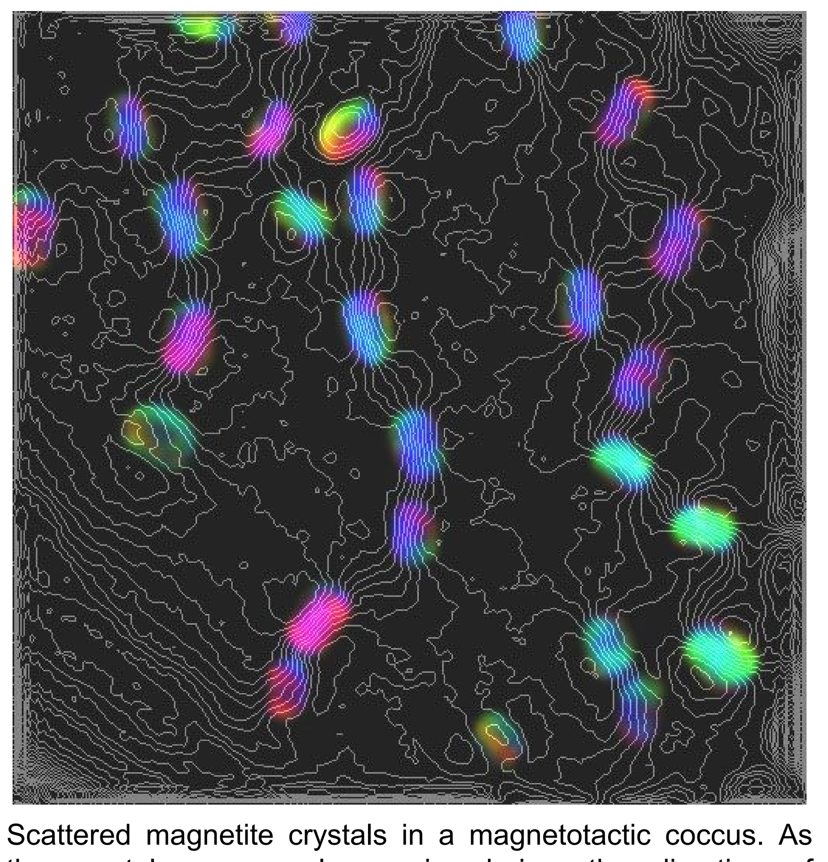
Magnetic phase contours measured using electron holography from two pairs of bacterial magnetite chains that were magnetized parallel and antiparallel to the arrow. The contour spacing is 0.25 radians. The directions of the contours and the uniform colour indicates that all crystals are magnetic single domains and are magnetized along the same direction.

Electron Holography

Electron holography is a transmission electron microscopy (TEM) technique that allows the phase shift of an electron wave to be recorded. The phase shift can be used to obtain information about magnetic fields at the nanometre scale.
The magnetic induction maps shown on this poster contain contours, which represent magnetic field lines, and colours, which show the direction of the field according to the colour wheel shown on the left.



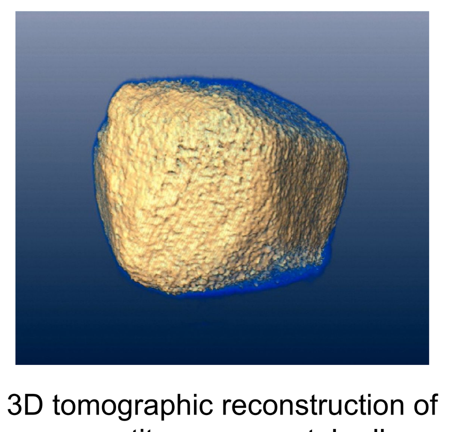
Magnetic induction maps acquired at a) 293 K and b) 116 K. At room temperature (a), the contours are parallel to each other within the crystals. At 116 K, the field lines undulate to a greater degree within the crystals, as well as at kinks in the chains, reflecting the change in the direction of the magnetic easy axis.



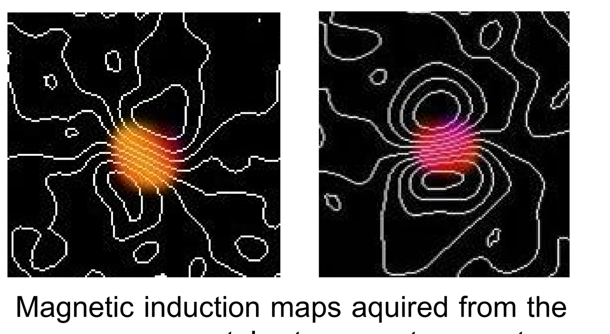
Scattered magnetite crystals in a magnetotactic coccus. As the crystals are no longer in chains, the direction of magnetisation varies and is generally determined by shape anisotropy.

Electron tomography

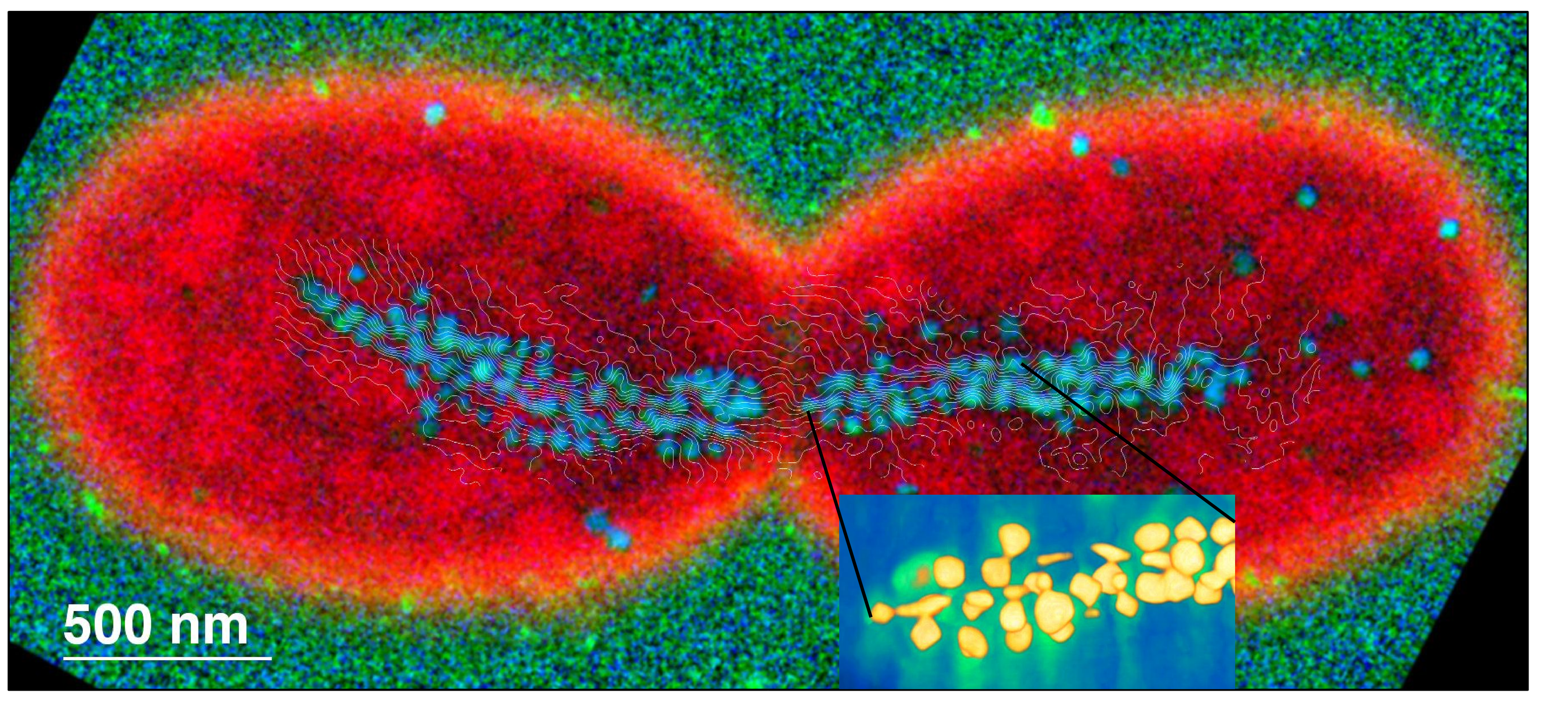
Electron tomography allows the shapes of materials to be measured. We obtain 3D reconstructions of magnetite nanocrystals from series of high-angle annular dark field images acquired over a large range of sample tilt angles.



3D tomographic reconstruction of a magnetite nanocrystal allows the shape and orientation of the crystal to be correlated with its magnetic properties.



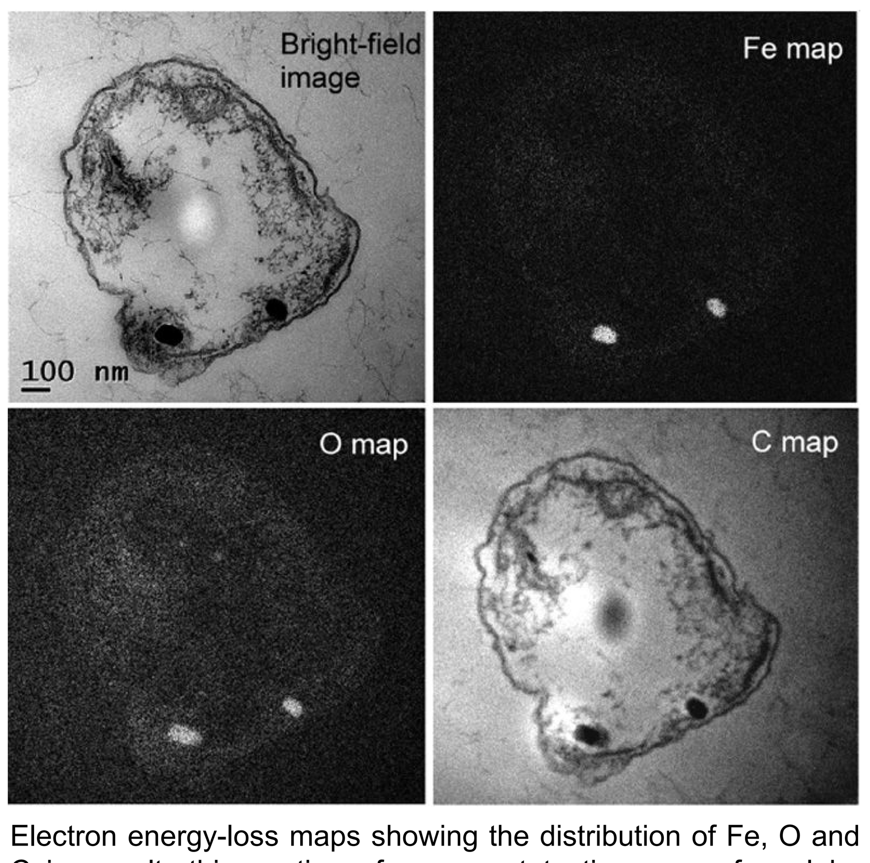
Magnetic induction maps aquired from the same nanocrystal at room temperature (left) and at ~90K (right). Below 119K magnetite undergoes a phase transition that changes the crystallographic direction of the easy axis of magnetisation. The direction of magnetisation changes by ~30° between the two images.



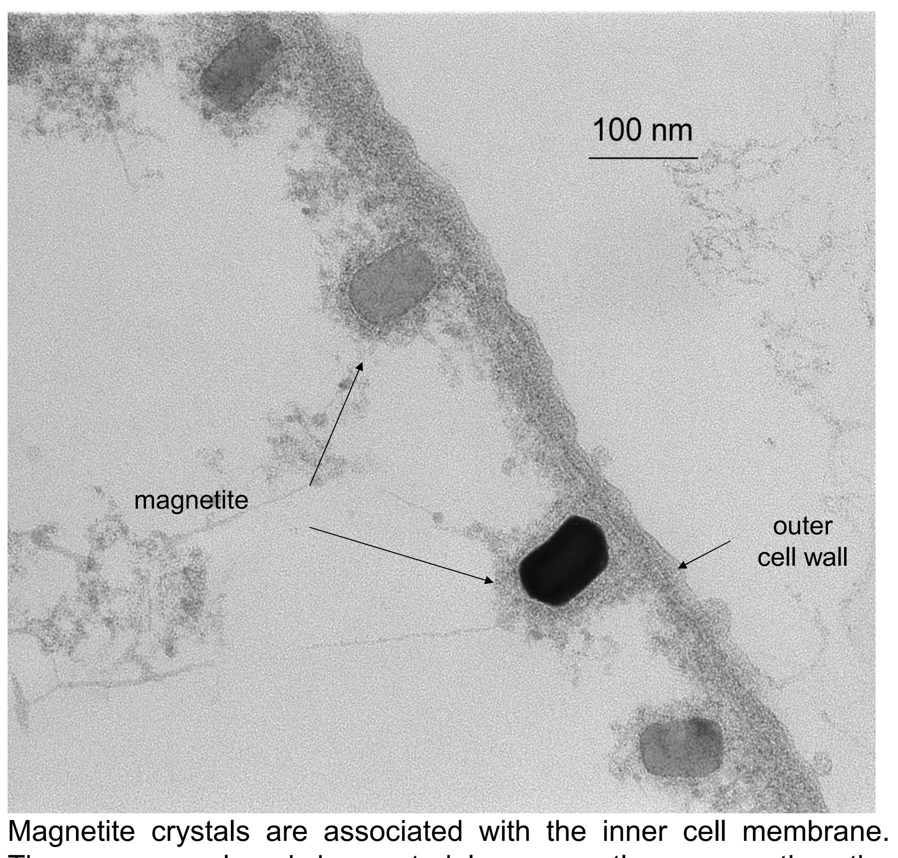
A composite of electron energy-loss and magnetic induction maps obtained from a dividing cell that contains multiple chains of iron sulfide magnetosomes (red: O, green: S, blue: Fe). Some crystals seem less magnetic than others. The insert shows a tomographic reconstruction of part of the multiple chain; the crystals have irregular shapes.

Positions of magnetosomes inside cells
– clues about the biological control over crystal growth

Spatial relationships between magnetosomes and other cell structures can reveal how the magnetic nanocrystals aquire their special orientation, size and shape by nucleating and growing on membranes. In order to observe the positions of magnetosomes, we used electron tomography and studied ultrathin sections of both magnetite and iron sulfide producing bacteria.



Electron energy-loss maps showing the distribution of Fe, O and C in an ultrathin section of a magnetotactic coccus from lake Balaton. There is no detectable iron outside the magnetosomes.



Magnetite crystals are associated with the inner cell membrane. They are enveloped by material, apparently representing the magnetosome membrane, and are aligned with [111] perpendicular to the cell wall.

Conclusions

Magnetic microstructures of chains of bacterial magnetite:
- the nanocrystals are magnetic single domains
- at room temperature shape and magnetocrystalline anisotropy and interparticle interactions are mutually favorable for creating a perfect compass for magnetotactic cells
- changes in magnetocrystalline anisotropy can be detected at the temperature of the Verwey transition

Biogenic control over crystal growth:
- in various types of cells the magnetosomes are anchored to the inner cell membrane → nucleation and growth are controlled by biological membranes

Bacterial iron sulfides:
- random crystal shapes, orientations not as well controlled as for magnetite, crystals in the center of the cell → the control mechanism is different from that in magnetite-bearing cells

Electron holography and tomography are excellent methods for studying magnetic nanocrystals in organisms