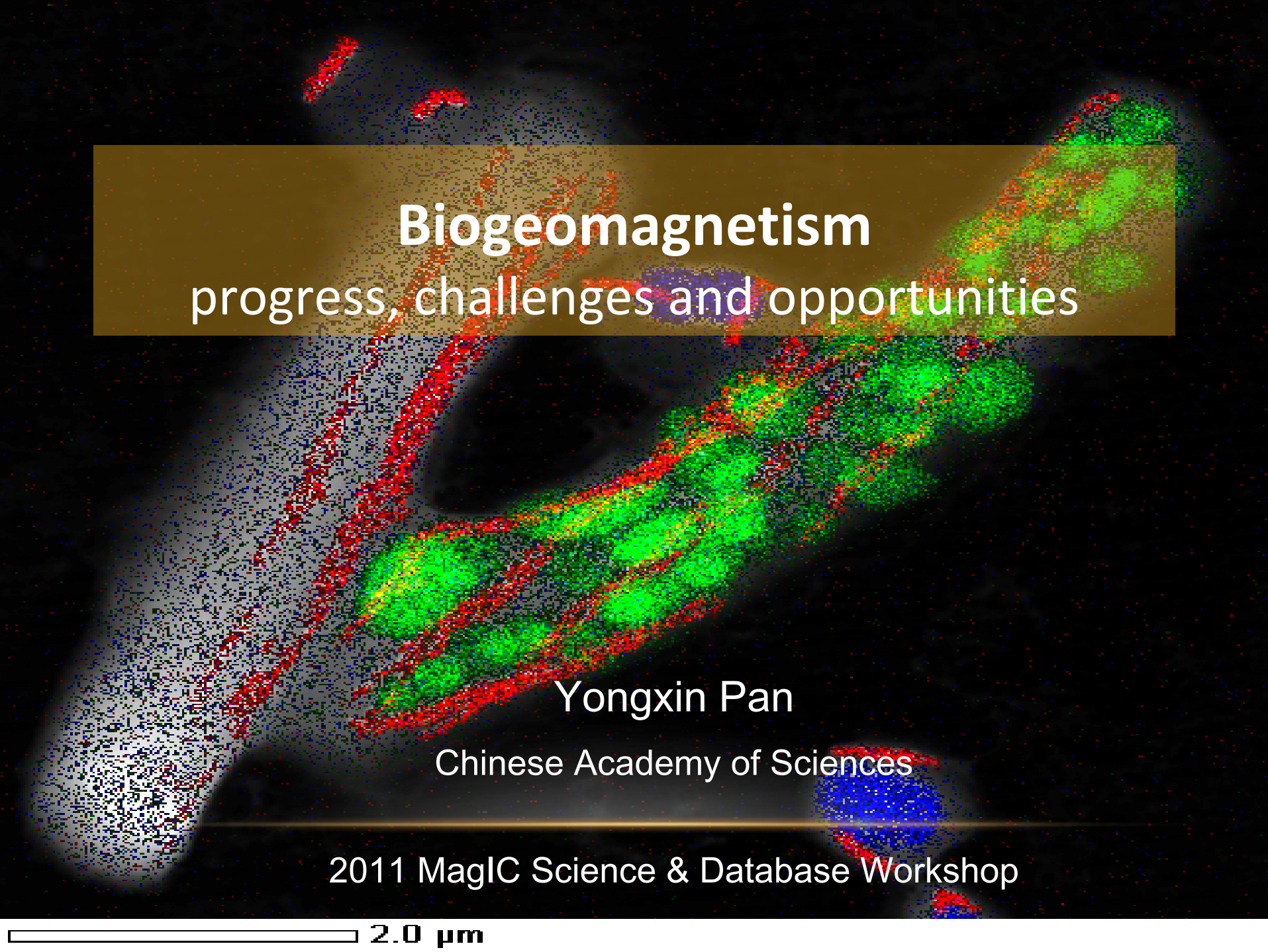

Biogeomagnetism

progress, challenges and opportunities

Yongxin Pan

Chinese Academy of Sciences

2011 MagIC Science & Database Workshop

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L Wu (CNRS, France), N Menguy (Paris VI, France)

B Li, J Li, G Paterson, W Lin, Y Wang

X Ji, C Cao, L Tian, Y Pan, W Wu, Y Cai

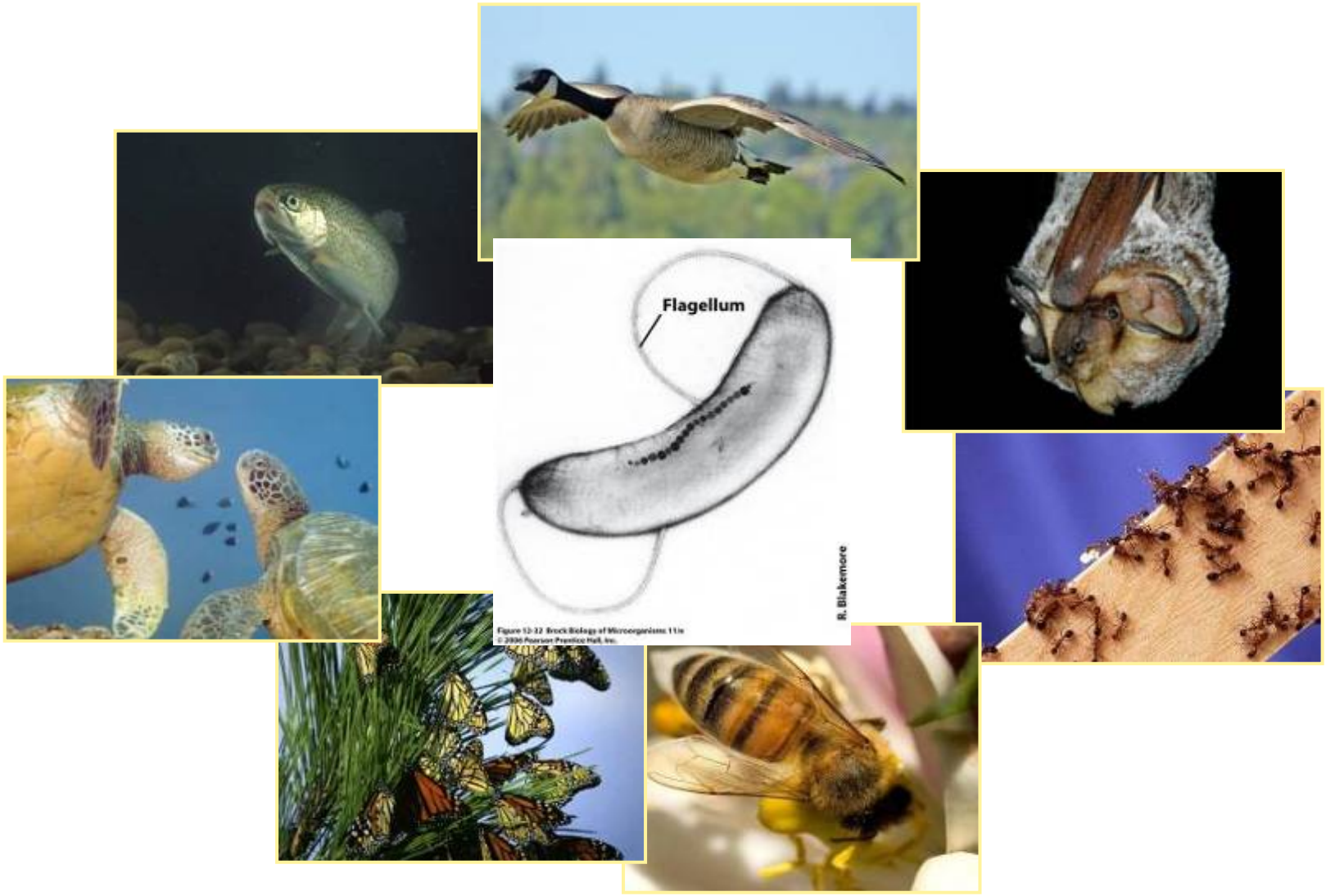
Outline

I. Geomagnetic Orientation and Navigation in Animals

II. Microorganism - Magnetotactic Bacteria

Diversity, mineralization, magnetism & magnetofossils

III. Some Future Objectives of Biogeomagnetism

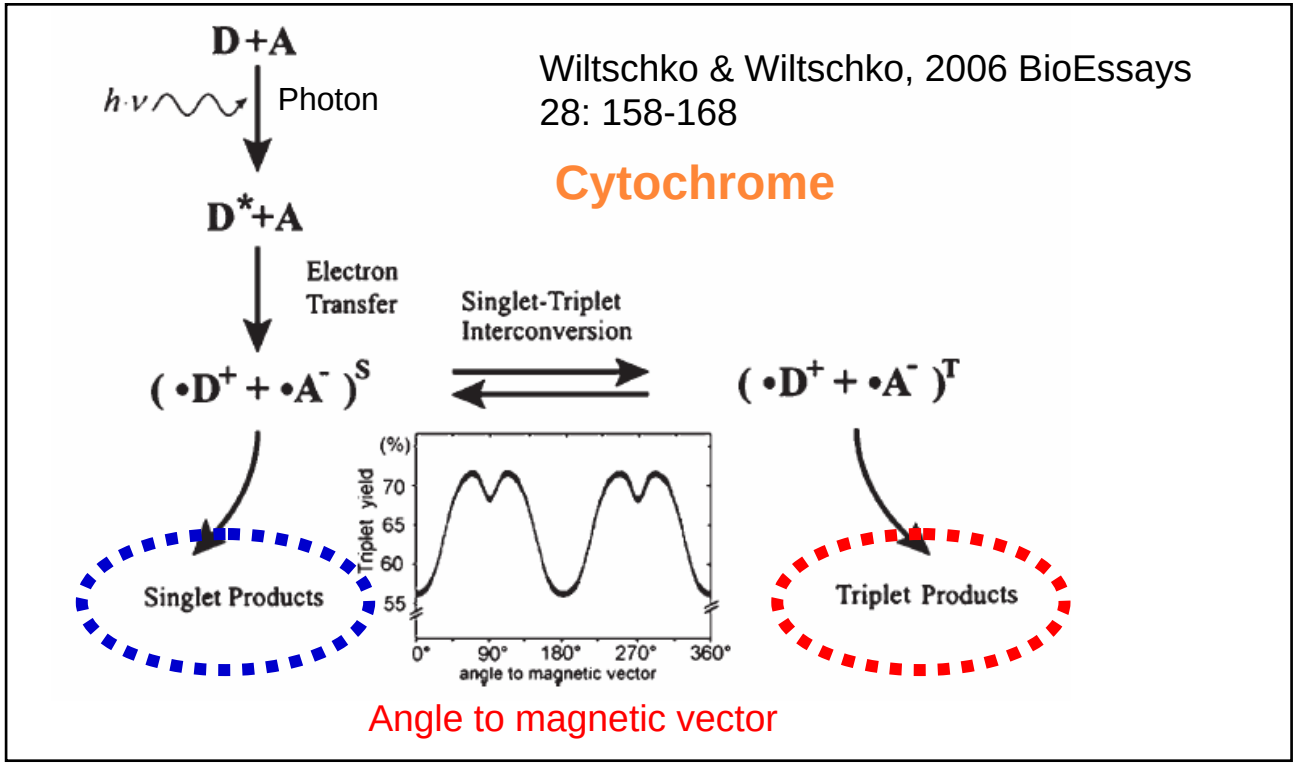


Magnetic sensing in organisms

J Kirschvink et al., Magnetite bimineralization and magnetoreception in organisms, 1985
Wiltschko &Wiltschko, Magnetic orientation in animals, 1995
J Roy Soc Interface, Special Issue, 2010

Two mechanisms:

1. Chemical magnetoreception (radical pair mechanism)



e.g., Schulten & Swenberg, Z Phys Chem NF, 1978

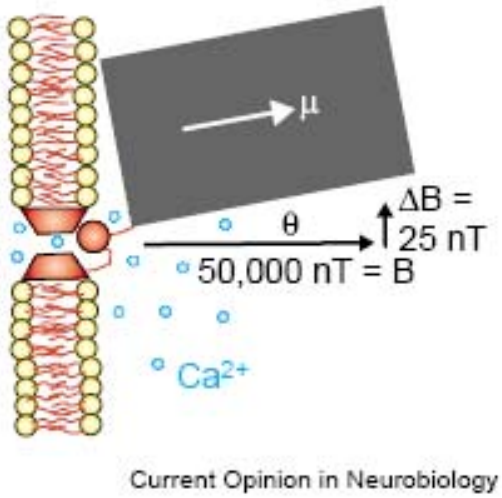
Ritz & Schulten, Nature, 2000, 2004: photoreceptor-based

Wiltschko & Wiltschko, J Exp Biol, 2001

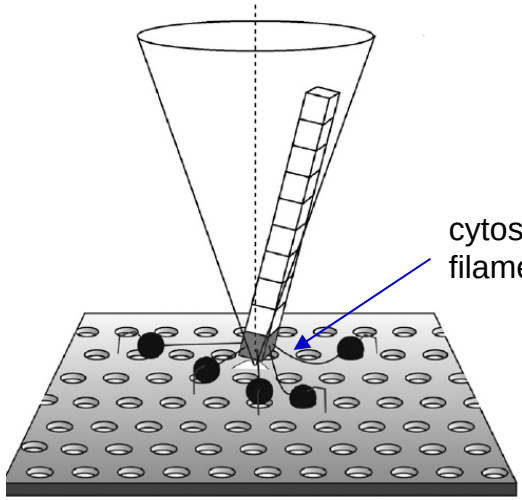
Maeda et al., Nature, 2008

Rodgers & Hore, PNAS, 2011; plus

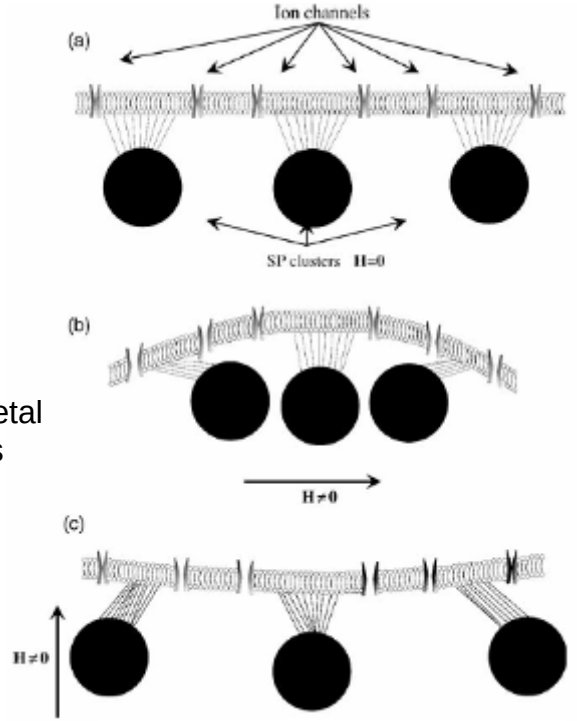
2. Magnetite-based magnetoreception



Kirschvink et al. 2000



Walker, 2008 J Theo Biol



Davila et al. 2003 PCE

e.g., Kirschvink & Gould, Biosystems, 1981: Honeybee dance

Kirschvink et al., Curr Opin Neurobiol, 2000; J Roy Soc Inter 2010

Diebel et al., Nature 2000: vertebrate sense

Davila et al., Phys Chem Earth, 2003

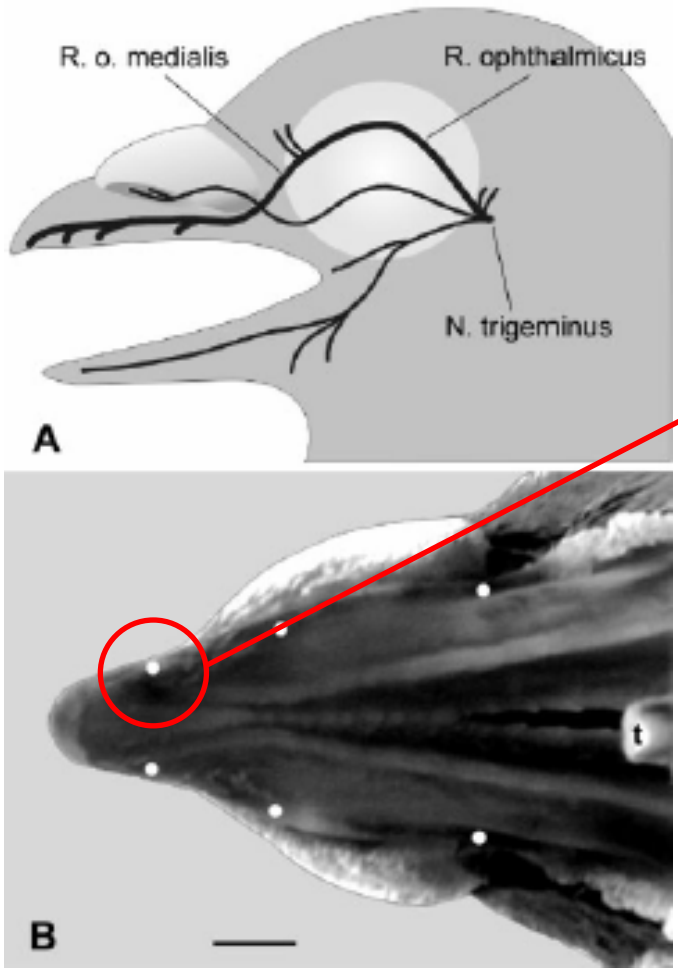
Walker et al., 1997; 2002, 2008, 2010

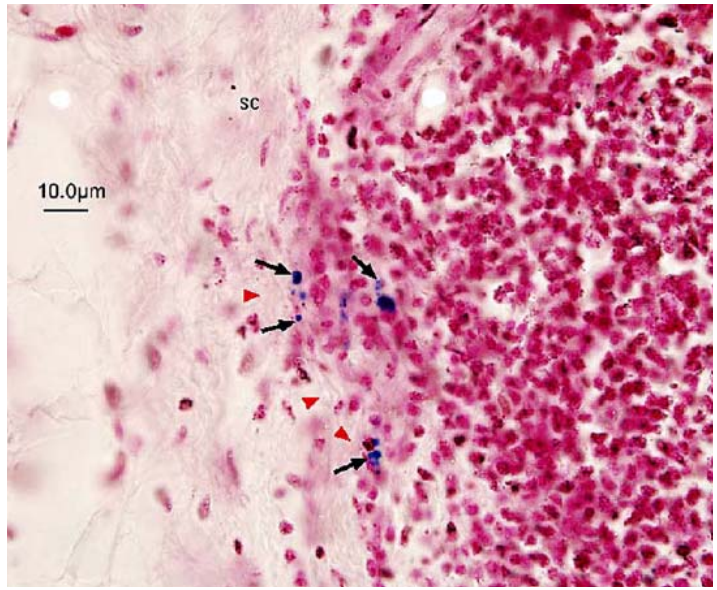
Winklhofer & Kirschvink, J Roy Soc Interface 2010;

Plus

Test of magnetite in upper-beak skin of homing pigeons

Hanzlik et al., 2000 BioMetals; Winklhofer et al., 2000 Eur J Mineral; Fleissner et al., 2003 J Comp Neurol; Davila et al. 2003 PCE; Tian et al., 2007 BioMetals





Aggregates of SP magnetite nanocrystals

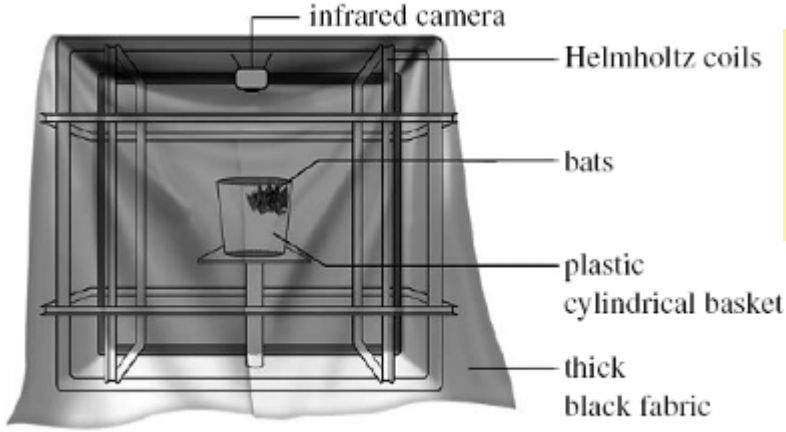
Tian et al., 2007 BioMetals

NAVIGATION

Bat orientation using Earth's magnetic field

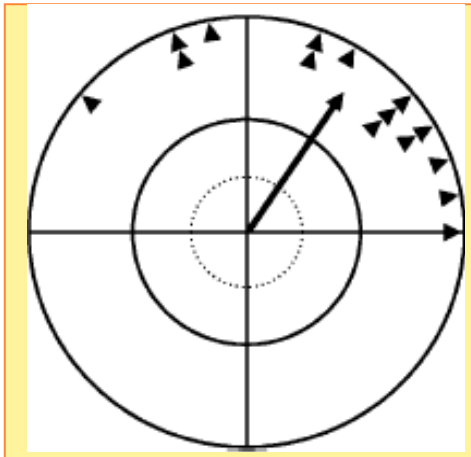
Holland et al., 2006 Nature; 2008 PLOS One; Wang et al., 2007 Proc R Soc B

Nyctalus plancyi

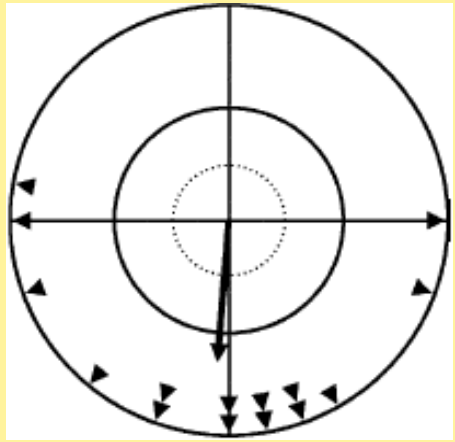


Bats respond to polarity of a magnetic field

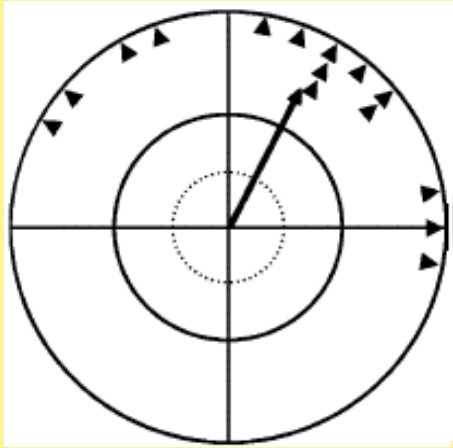
Wang et al. 2007
Proc R Soc B



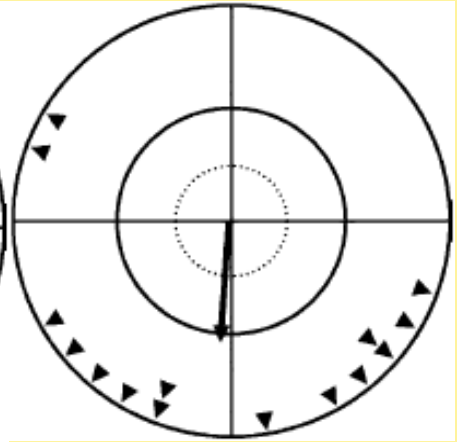
D=1º
I = 61º
M = 99 μT
α=34±40º



D=182º
I = --61º
M = 99 μT
α=185±52º



D=358º
I = -65º
M = 115 μT
α=26±48º



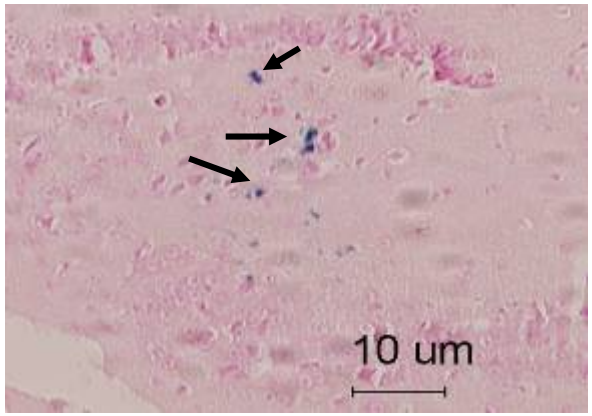
D=181º
I = 61º
M = 100 μT
α=183±63º

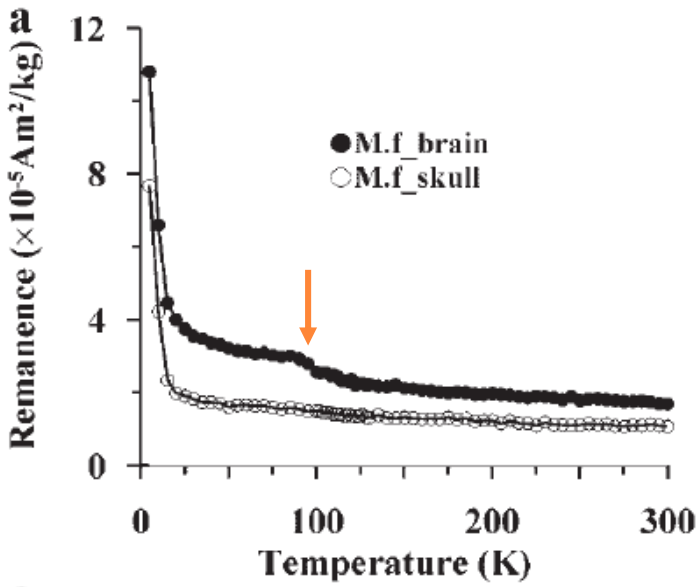
Bats Use Magnetite to Detect the Earth's Magnetic Field

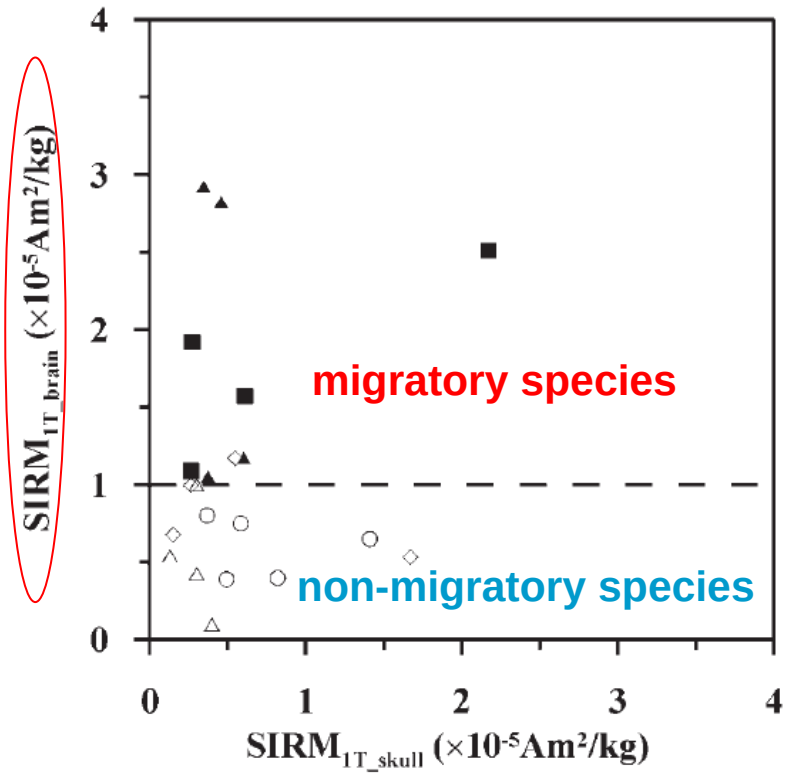
Dr. LX Tian

brain tissues

Tian et al., 2010 *Bioelectromagnetics*







Recap

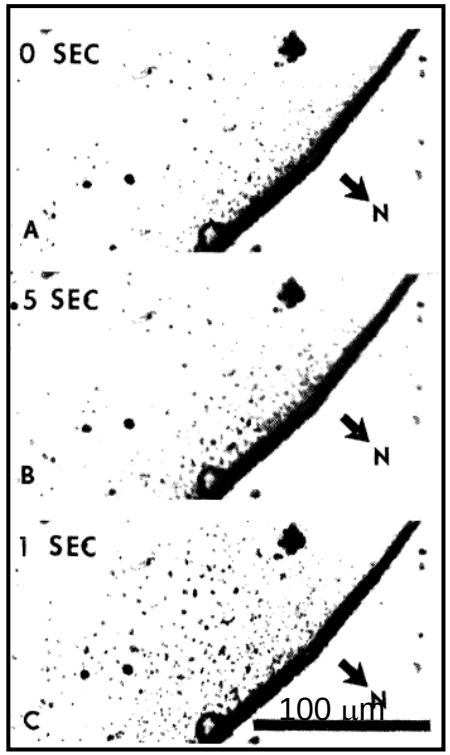
- Migratory bats use polarity compass for orientation and navigation.
- Migratory bats' brains contain more magnetite that those of non-migratory species. It suggests that those migratory bats use magneite-based magnetoreceptor system.
- Although the mechanism and receptor mechanism have been explored for decades, they are still quite challenging for researchers due to their complexity. More comprehensive investigations, e.g., *neuro-, electro-physiology & magnetism,* are needed to decipher them and evaluate their effectiveness.

II. Microorganism - Magnetotactic Bacteria

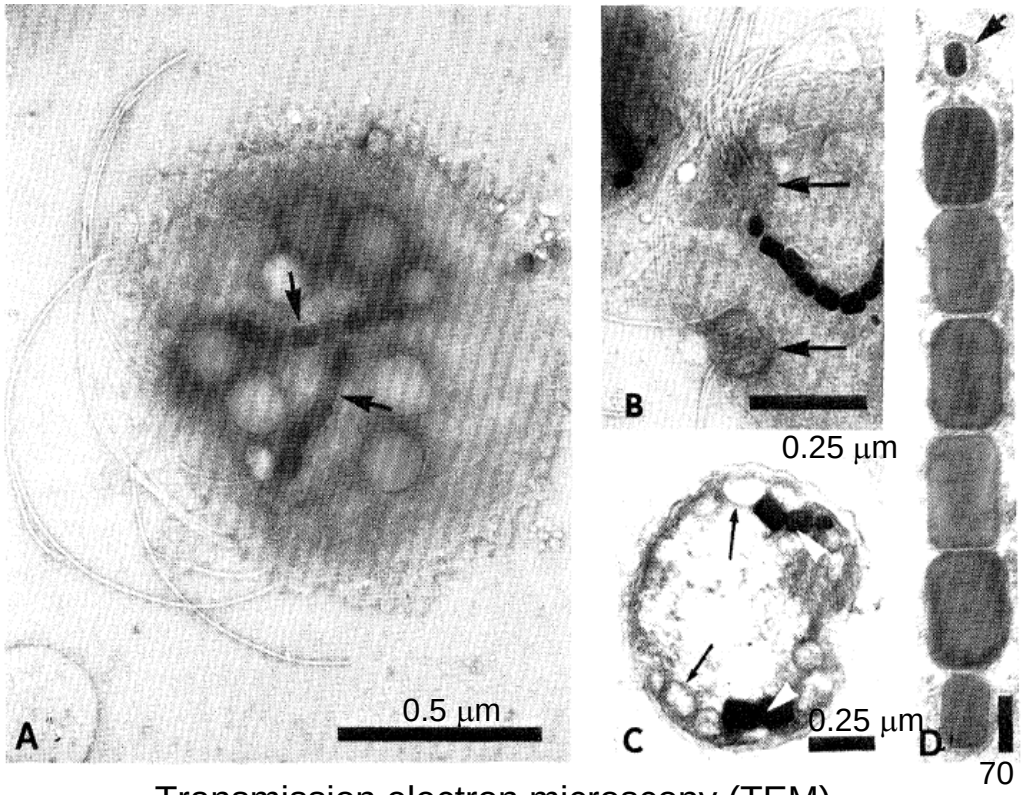
Magnetotactic bacteria produce magnetic crystals—magnetosome: which are intracellular, membrane-bound, high chemical purity (magnetite or greigite), tailored-shape & chain(s) arrangement, that cause the bacteria to swim along geomagnetic field lines.

A model microorganism for biogeomagnetism study

Richard Blakemore, 1975. Science, 190: 377-379



Light microscopy



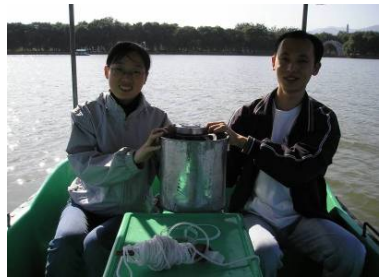
Transmission electron microscopy (TEM)

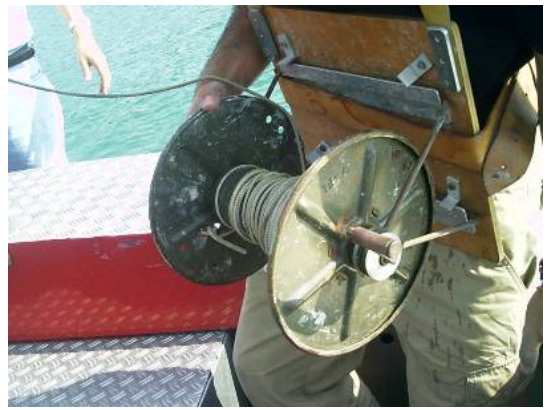
1. Bio-diversity & biogeography of magnetotactic bacteria

Are they common, diverse, and environmental dependent?

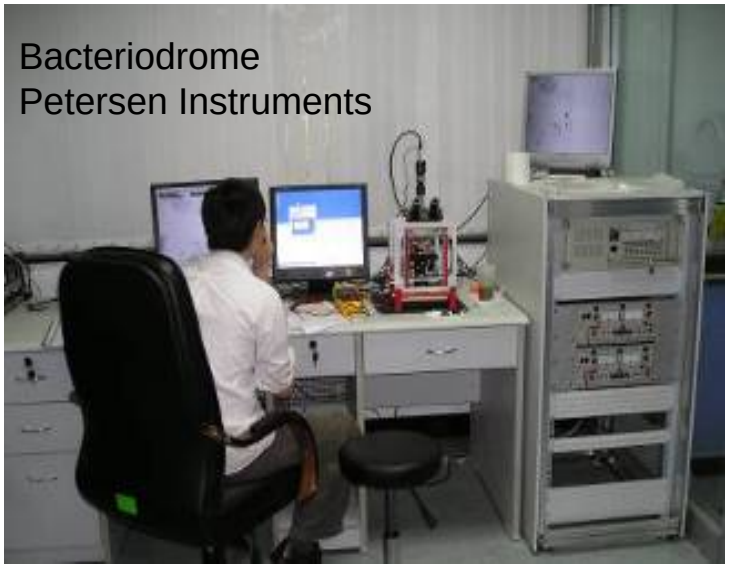


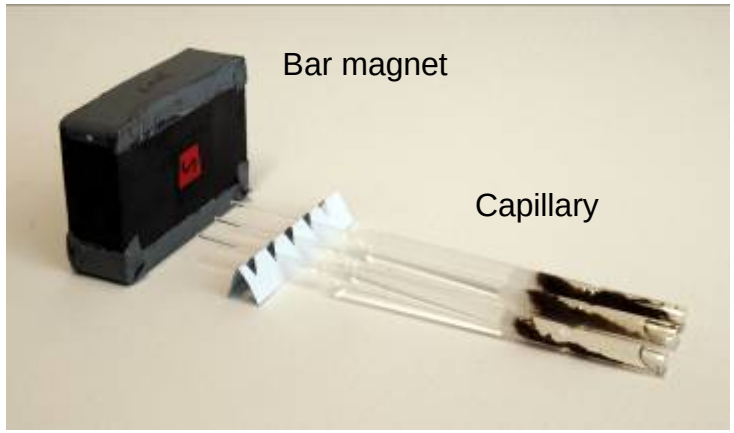


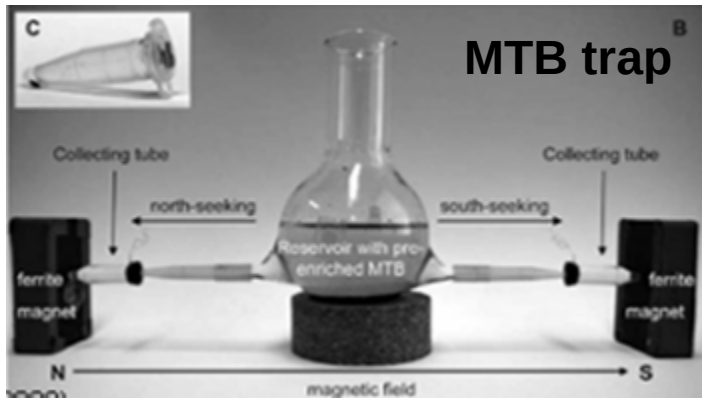


Magnetic enrichments







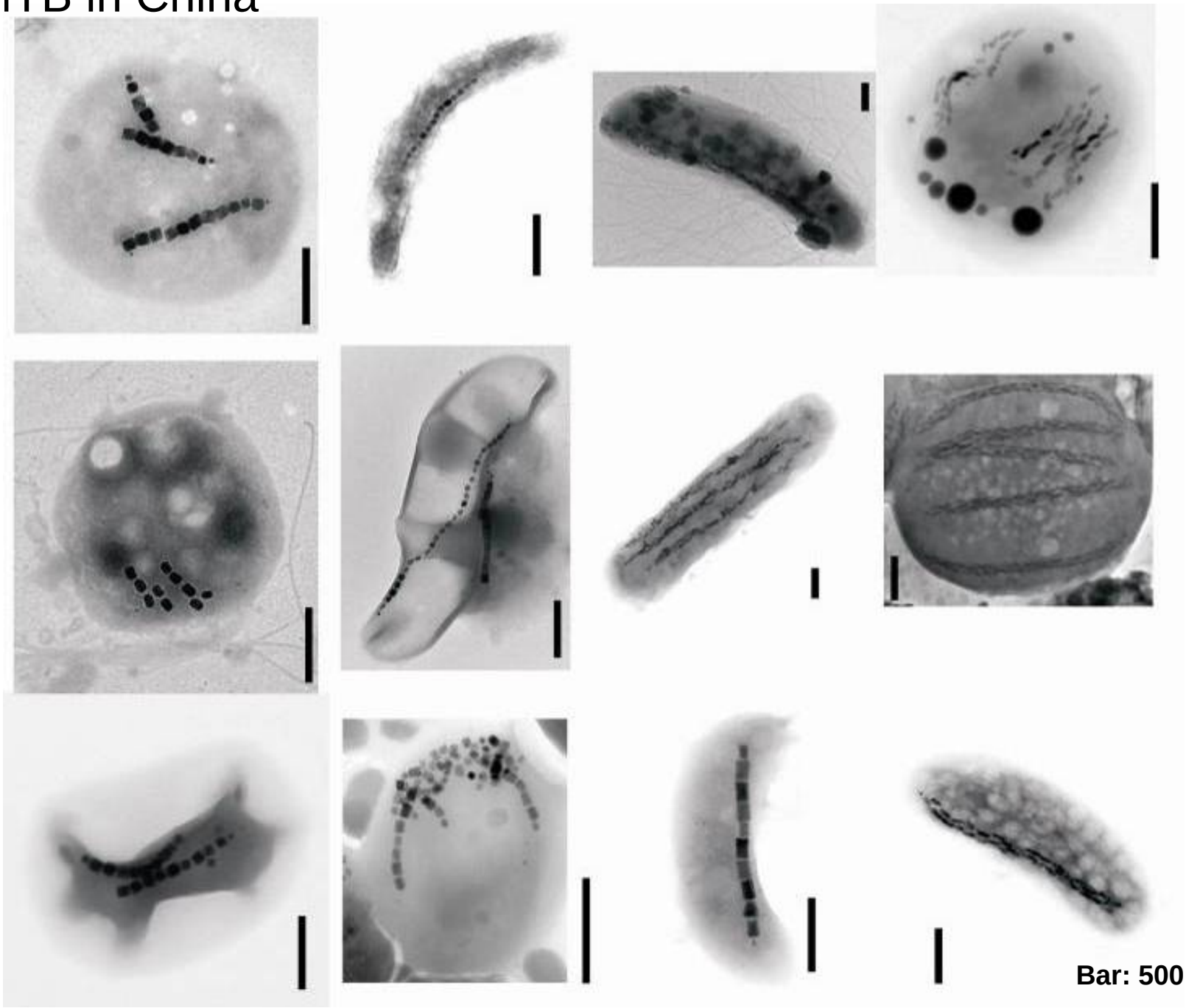
Analyses

→ TEM (cell morphology, magnetosomes)

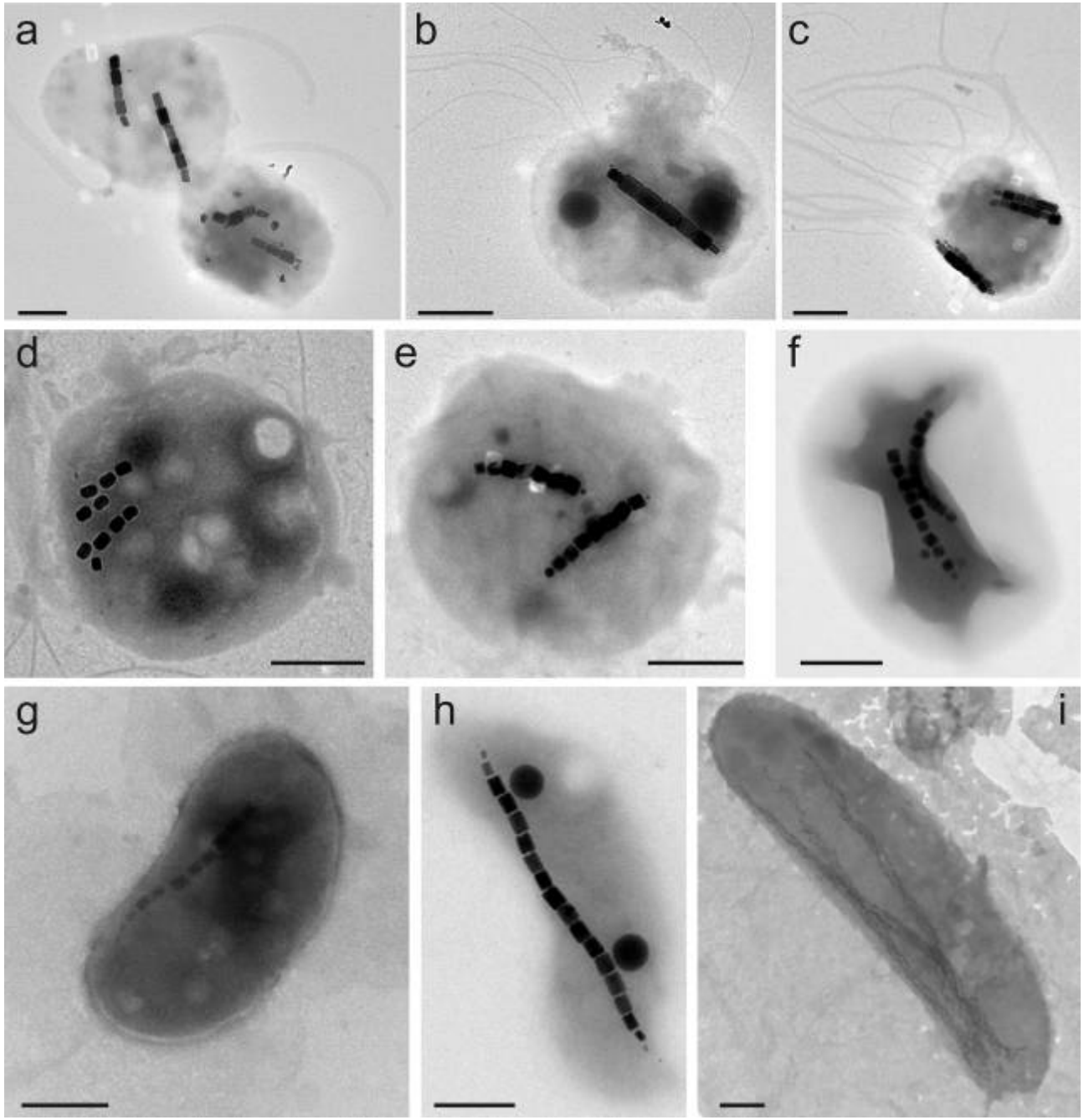
→ Rock magnetic (domain, composition, concentration)

→ Biological analysis (16s rRNA gene, FISH)

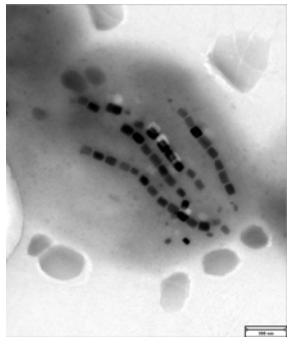
MTB in China



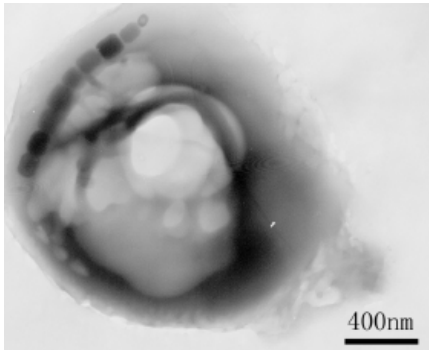
Bar: 500 nm



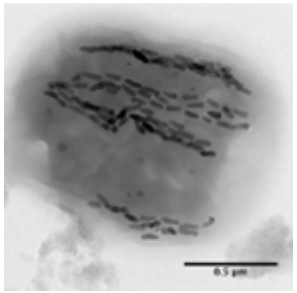
Lin et al., 2011 ***The ISME J*** doi:10.1038/ismej.2011.112



Candidatus Magnetococcus yuand

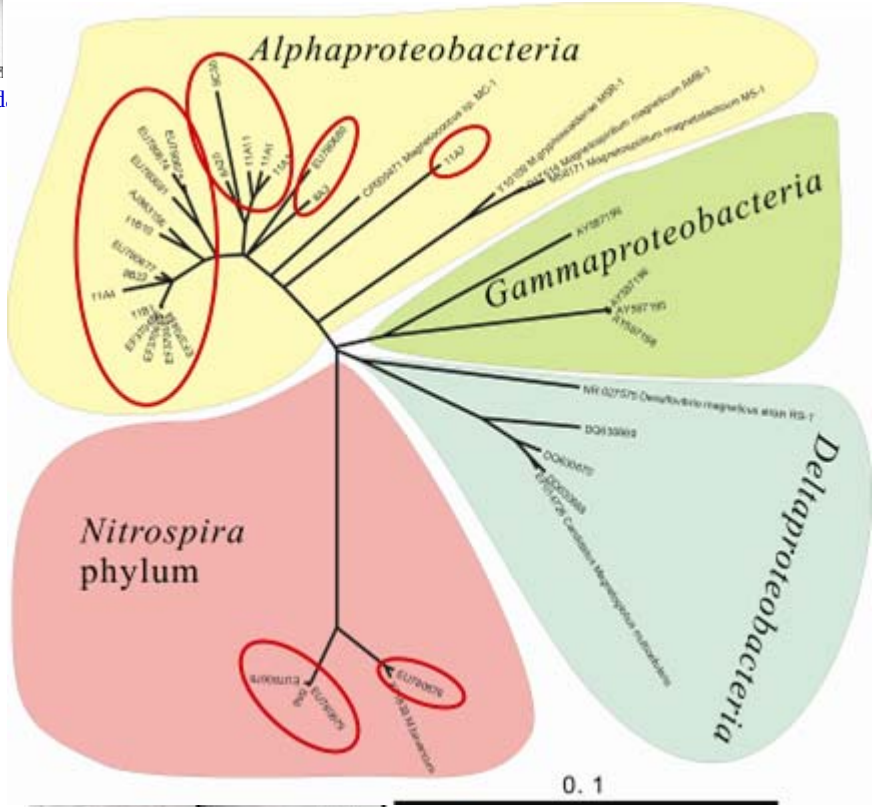


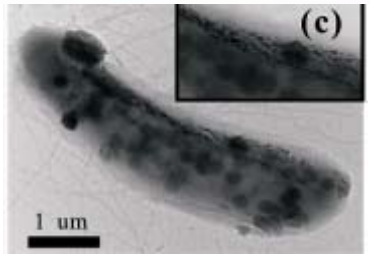
MYC-1



Watermelon-shaped

Phylogenic Tree of MTB near Beijing





Barvaricum-like

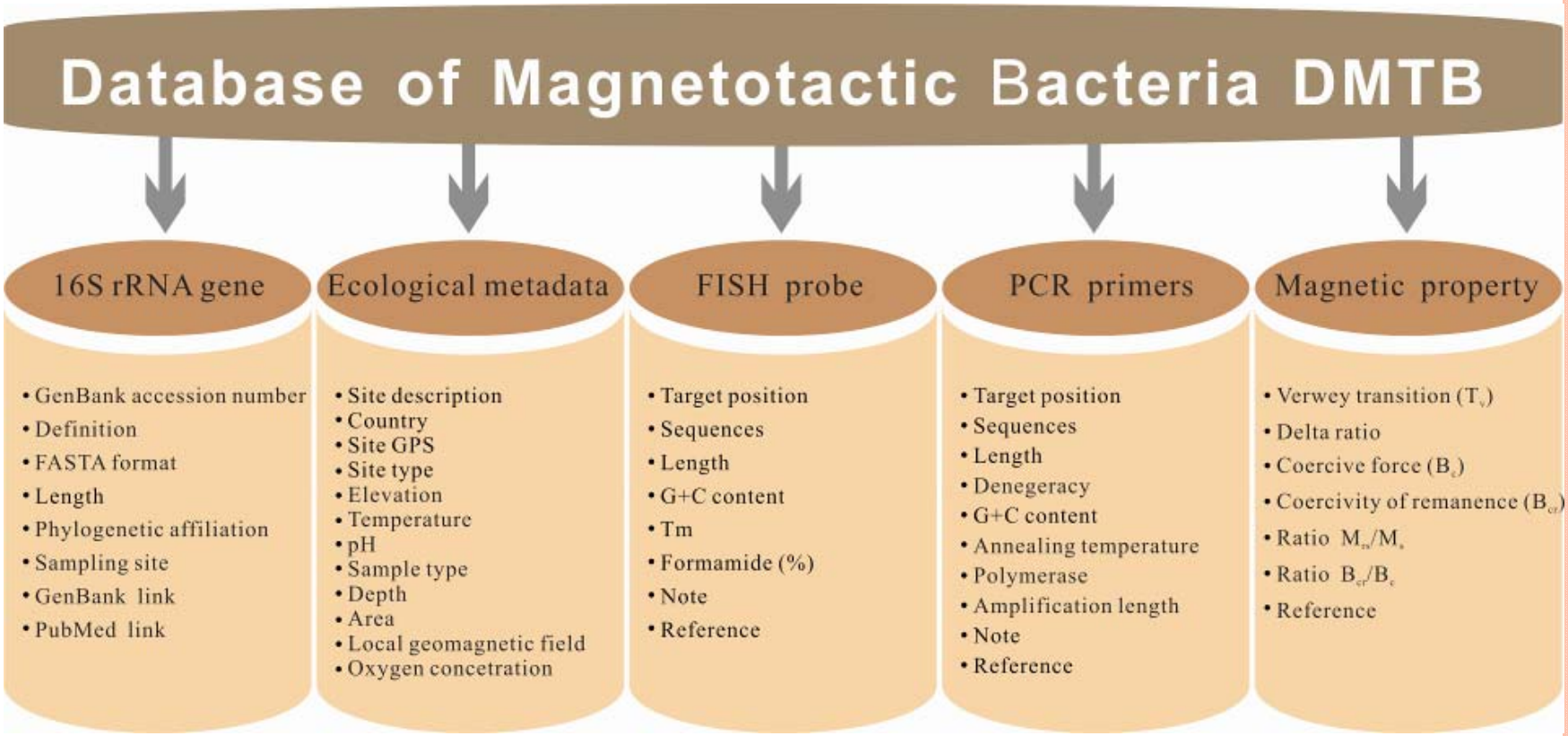
DMTB

Database of Magnetotactic Bacteria

Dr. Wei Lin

Database of Magnetotactic Bacteria

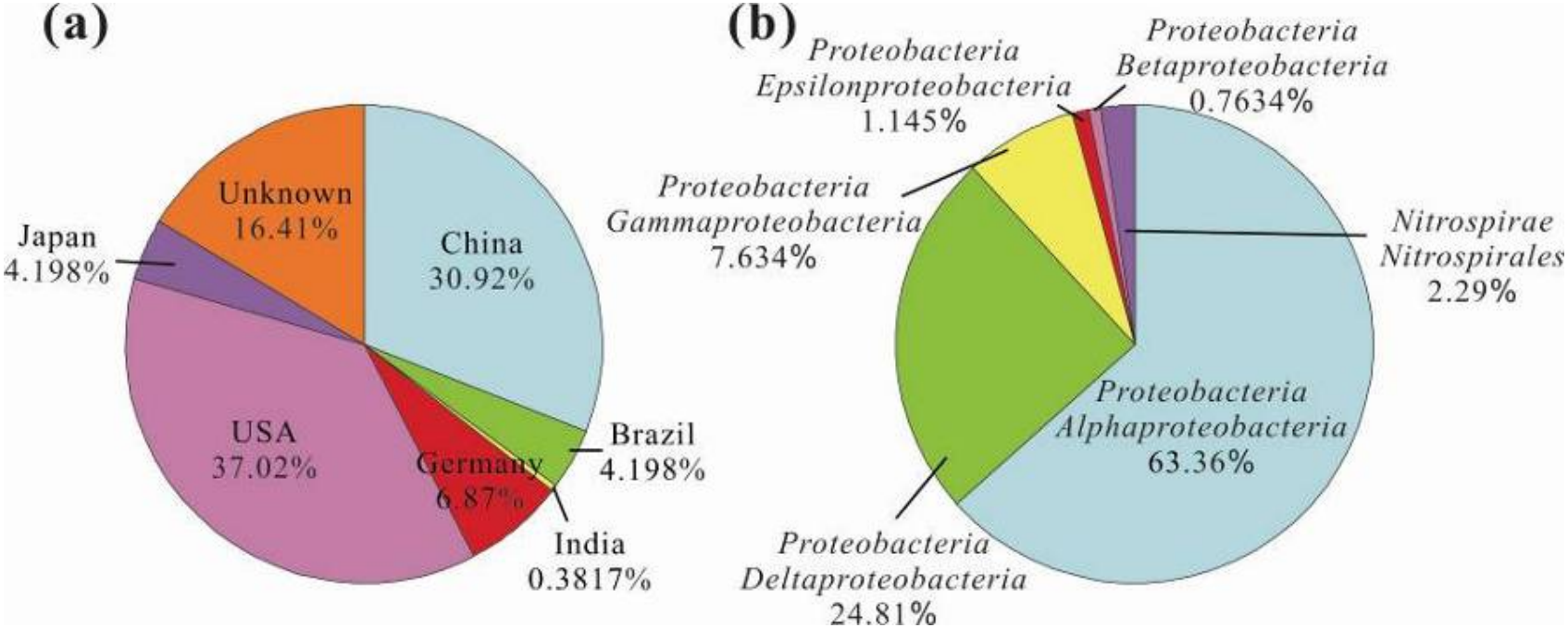
http://database.biomnsl.com



Lin, Li & Pan, 2010 *Chin Sci Bull 56: 476-478*

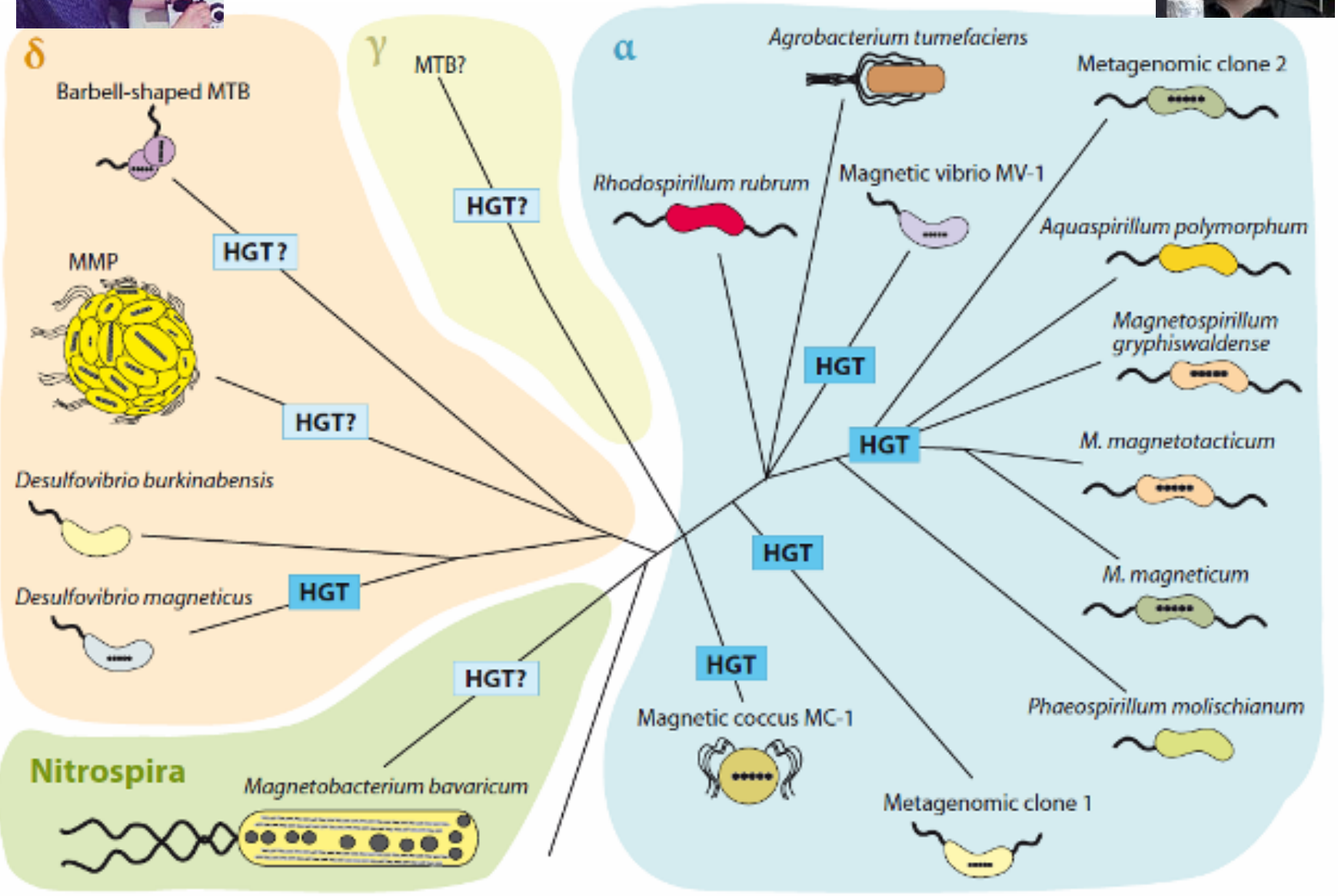
Published MTB 16s rRNA gene sequences

Sites (a) and Phylogenic positions (b)



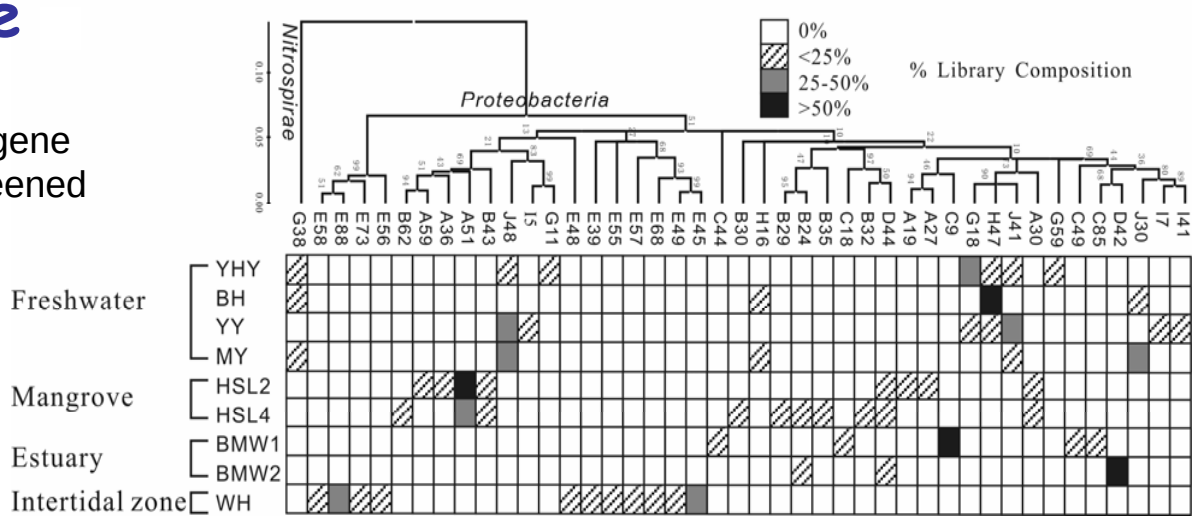
Diversity of magnetotactic bacteria

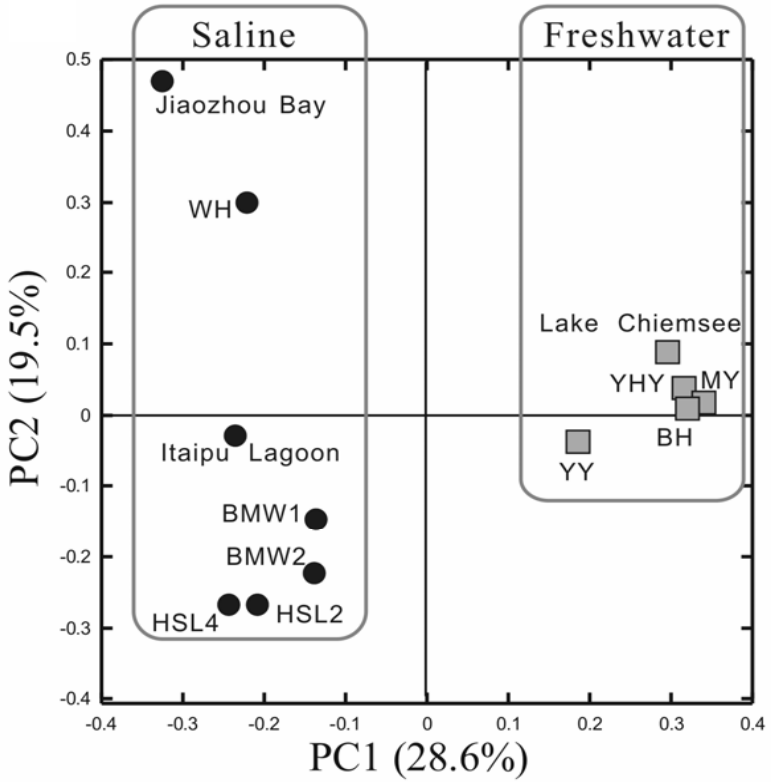
Jogler & Schuler, 2009 Annu Rev Microbiol

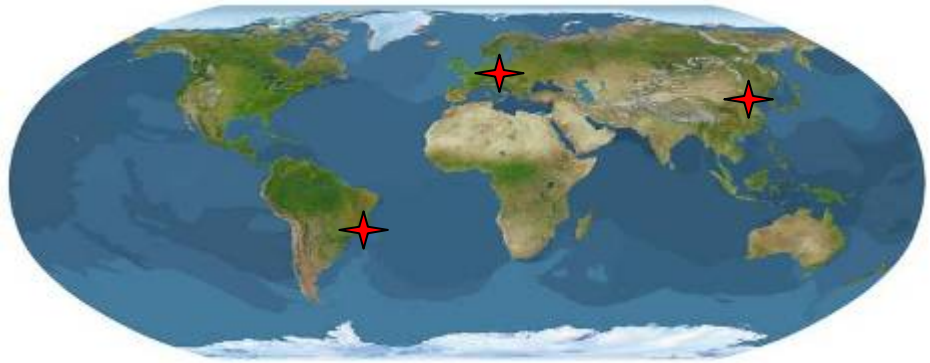


Salinity Influence

334 16s rRNA gene sequences screened







The composition of MTB communities across globally heterogeneous environments is influenced by salinity.

Nitraspirae is found only in freshwater.

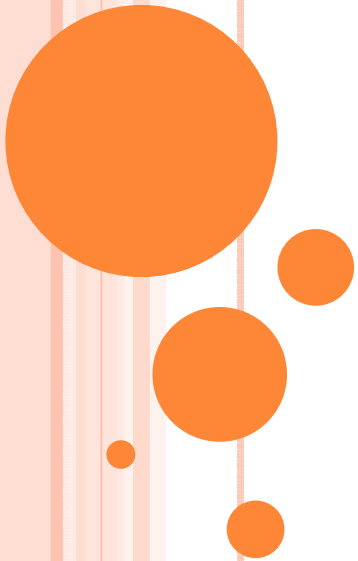
Lin et al., 2011 ***The ISME J*** doi:10.1038/ismej.2011.112

Recap

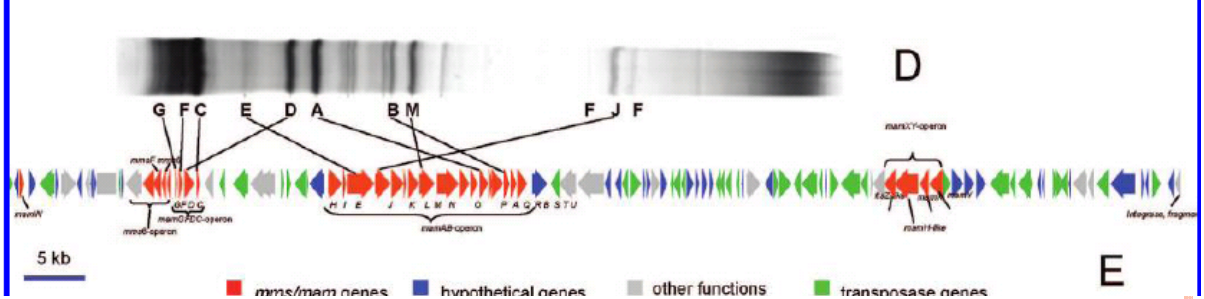
- ✓ Magnetotactic bacteria are ubiquitous and highly diverse, from freshwater to brackish water, more than previously expected.
- ✓ Database of Magnetotactic Bacteria, DMTB, has been developed. It is open access at http://database.biomnsl.com
- ✓ Magnetotactic bacteria usually live near the oxic-anaerobic transition zone (OATZ).
- ✓ The community and distribution of magnetotactic bacteria are environmentally dependent, e.g., salinity, temperature, suggesting it as useful potential environmental proxies.
- ✓ Magnetotactic bacteria may play important roles in element biogeochemical cycling, e.g., Fe, C, S, in natural environments.

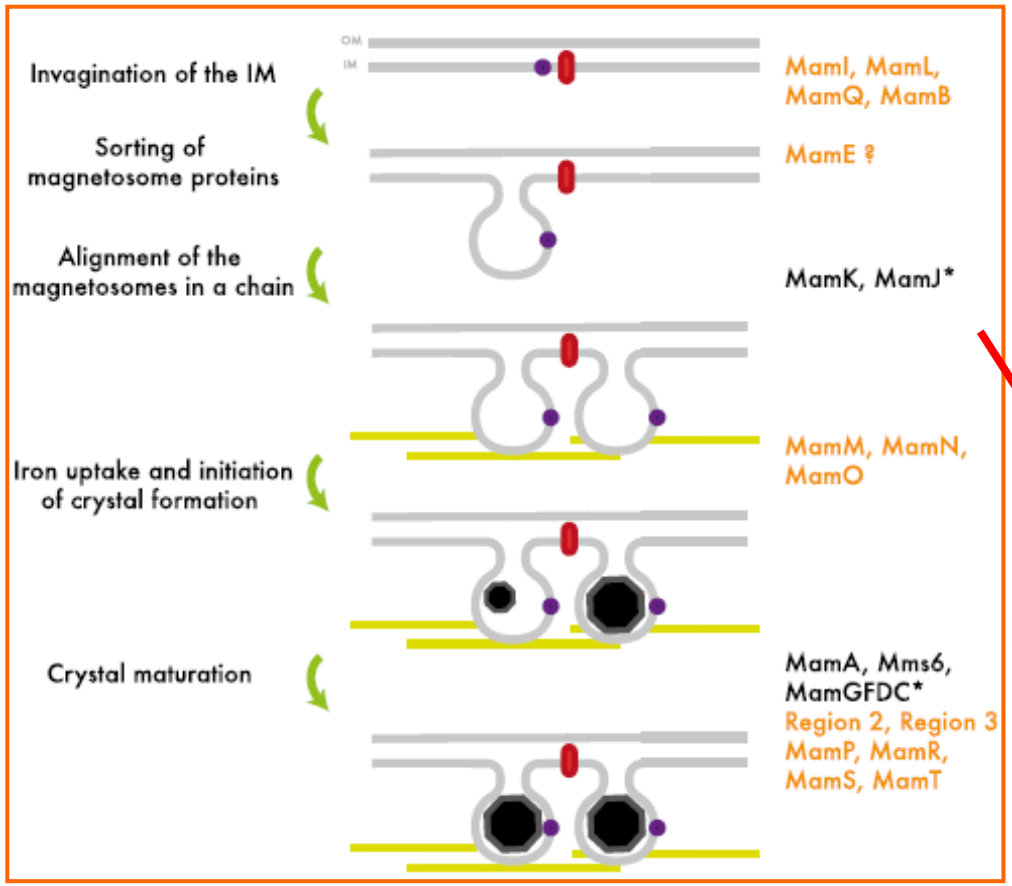
2. Mineralization of magnetosomes

unusual crystal growth and composition



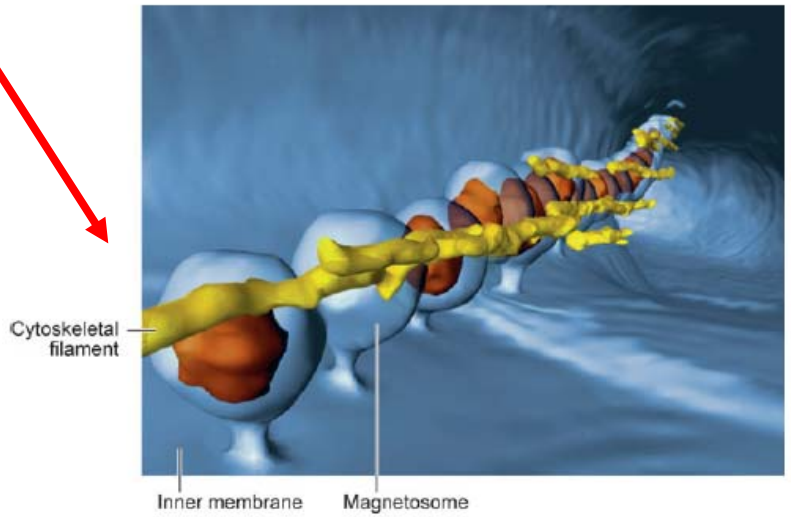
Genetically Controlled Biomineralization





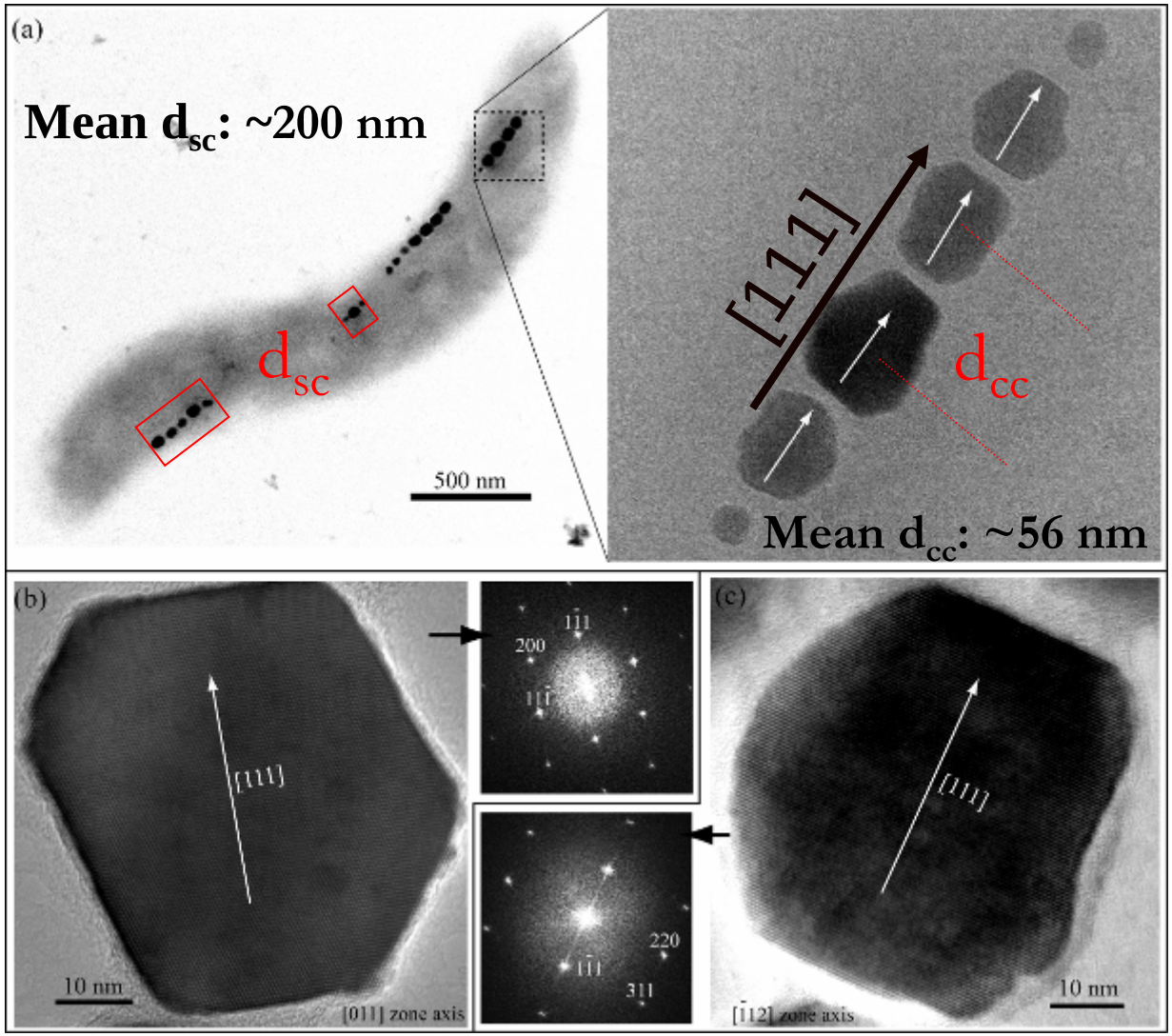
Model for step-wise assembly of magnetosomes in AMB-1. *Murat et al. 2010 PNAS*

The genomic magnetosome island (MAI) *M. gryphiswaldense*. *Faivre & Schüler. 2008*



Organization of magnetosome chain. *Komeili et al. 2006 Science; Scheffel et al. 2006 Nature*

We examine the crystal growth and compisition of magnetosomes by HRTEM



Magnetite magnetosome chain in AMB-1

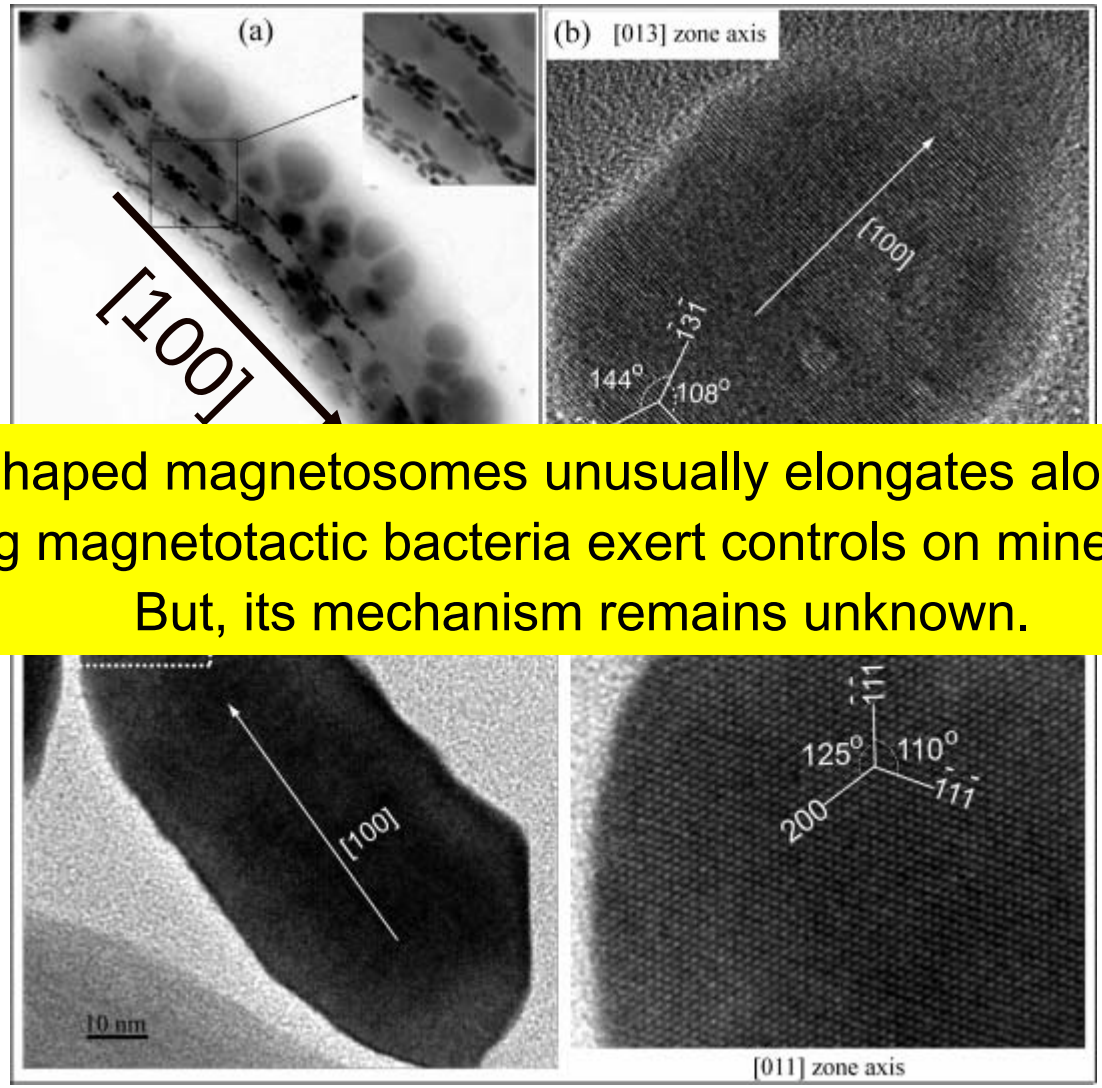
Li et al., 2009, GJI; 2010, CSB

Dr. Jinhua Li

Most MTB's magnetosome magnetite 'grow' or elongate along <111> direction

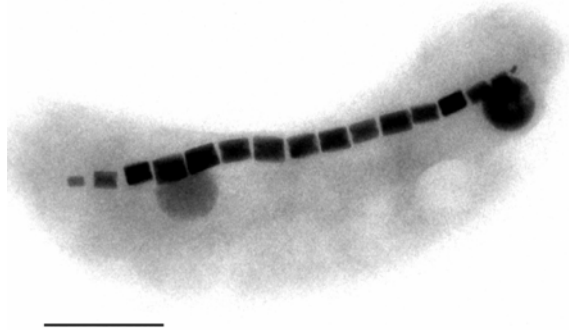
Not all the case is along <111> direction elongation

bullet-shaped magnetite crystals



Bullet-shaped magnetosomes unusually elongates along <100>, showing magnetotactic bacteria exert controls on mineralization. But, its mechanism remains unknown.

Li et al., 2010, *Earth Planet Sci Lett* 293: 368-376

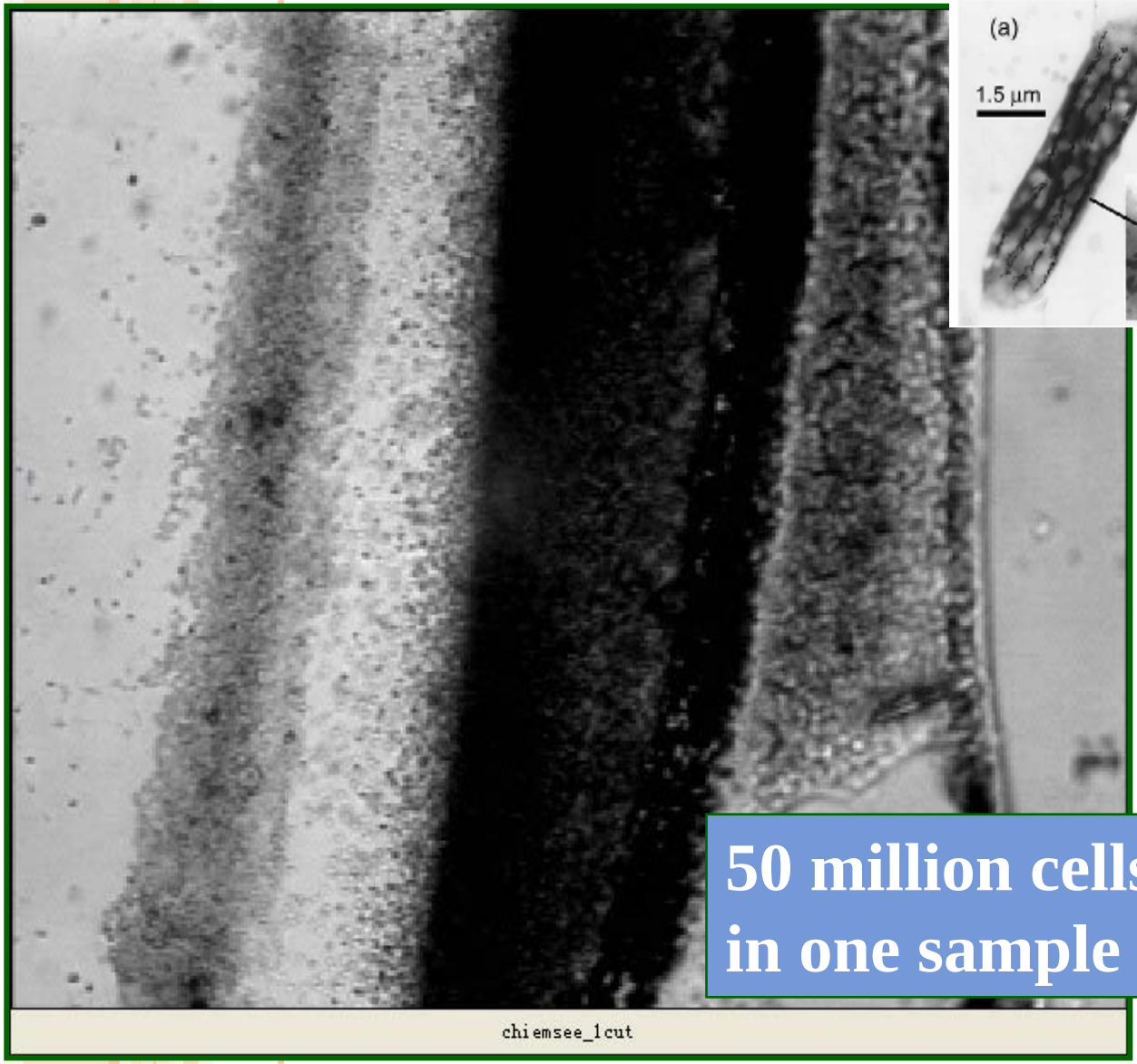


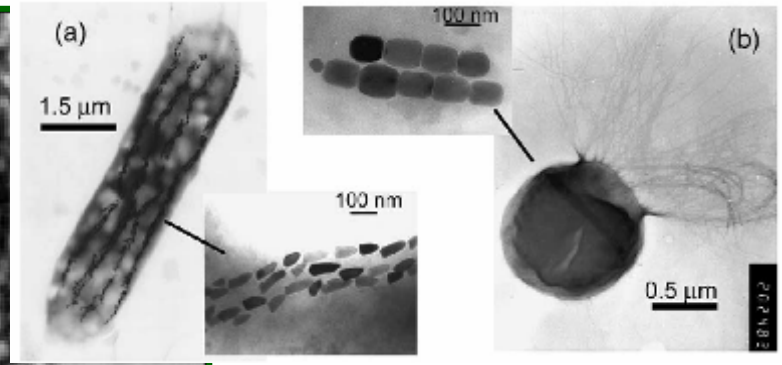
3. Magnetism of MTB

unusual magnetic properties

MTBs' rock magnetism

Pan et al. 2005. *EPSL, 237:311-325. Rock magnetic properties of uncultured magnetotactic bacteria*

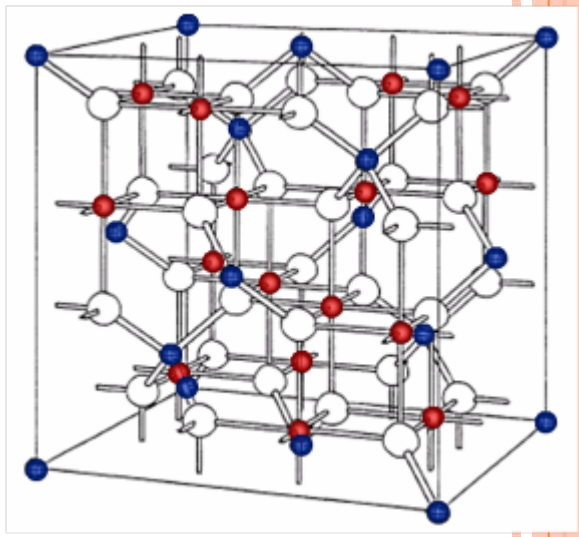




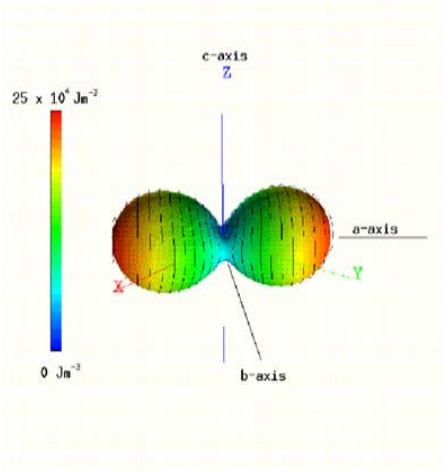
50 million cells in one sample

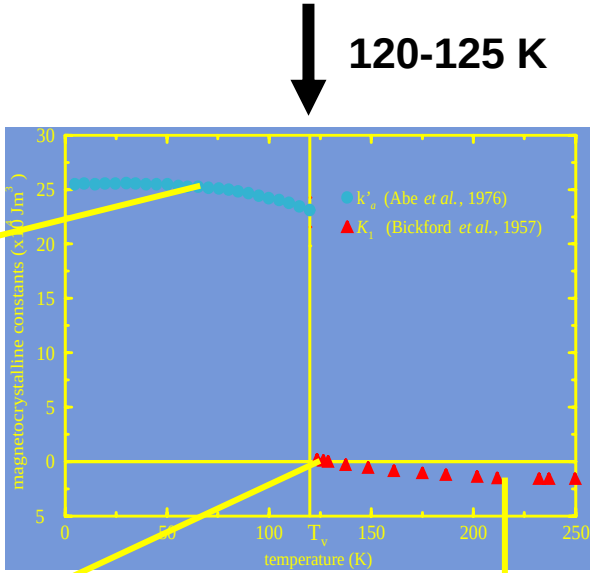
Mrs/Ms 0.47-0.64
Hcr/Hc 1.36-1.51

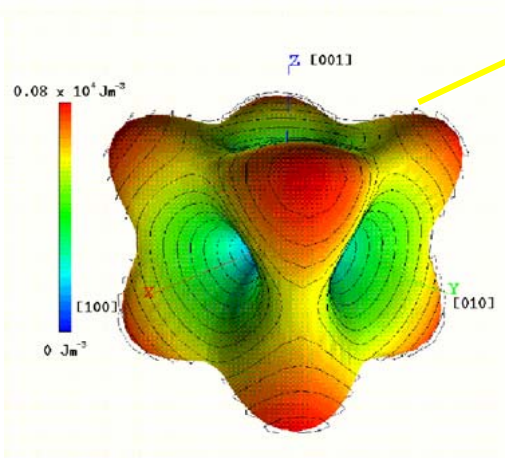
Lower Verwey transition temperature: A puzzle

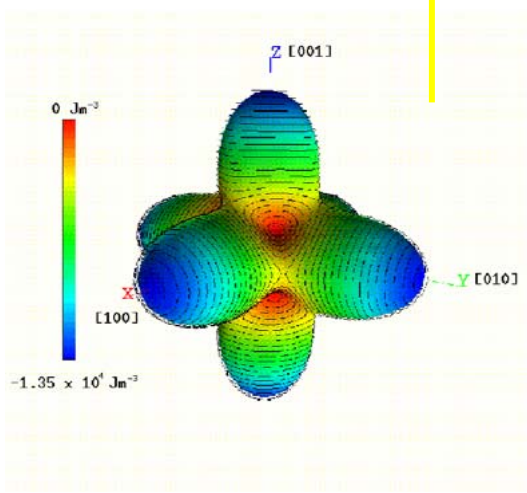


Crystal structure of magnetite. Blue atoms are tetrahedrally coordinated Fe^{2+}; red atoms are octahedrally coordinated, 50/50 Fe^{2+}/Fe^{3+}; white atoms are oxygen









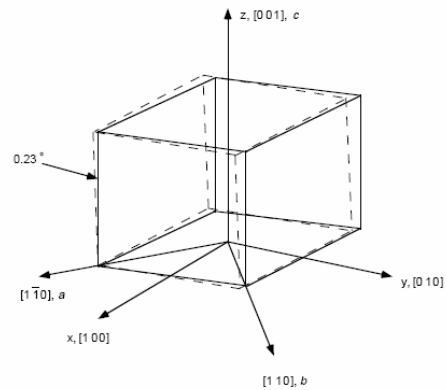
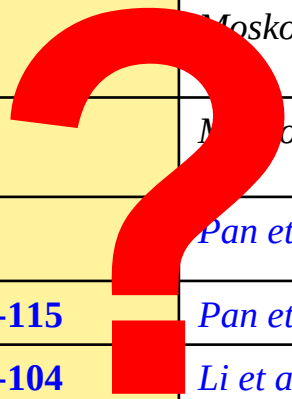


Figure 1. Relationship between the low-temperature monoclinic axes (*a*, *b* and *c*), the rhombohedrally distorted cell (solid line), and the high-temperature cubic unit cell (dashed line). Each monoclinic unit cell consists of four rhombohedrally distorted cells.

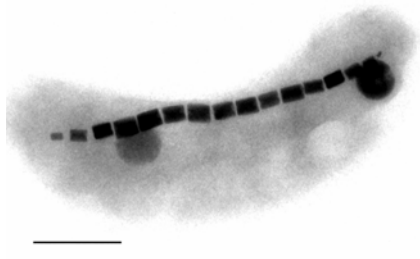
Lower Verwey transition temperature of magnetite

MTB	T_v (K)	*Reference*
MV-1	**110 or 117**	*Moskowitz et al., 1993;R. Prozorov et al., 2007*
MS-1	**101**	*Moskowitz et al., 1993*
MV-2	**110**	*Moskowitz et al., 1993*
Chiemsee (uncultured)	**100**	*Pan et al., 2005*
Miyun (uncultured)	**104-115**	*Pan et al., 2009*
MSR-1	**100-104**	*Li et al., unpublished data*
AMB-1	**100-108**	*Weiss et al., 2004; Prozorov et al., 2007; Li et al. 2009*
MMS-1	**101**	*R. Prozorov et al., 2007*
MC-1	**102**	*R. Prozorov et al., 2007*
QH-2	**108-110**	*Li et al. 2010*
Uncultured MTB	**95-105**	*Moskowitz et al., 2008*



4. Magnetofossils

novel source of SD magnetite in sediments



After MTB died, they may be preserved in sediments. As single-domian magnetite, magnetofossils are important remanence carriers.

The community of magnetotactic bacteria are environmental dependent, oxygen isotopes of magnetofossils can be also used as paleotemperature indicators.

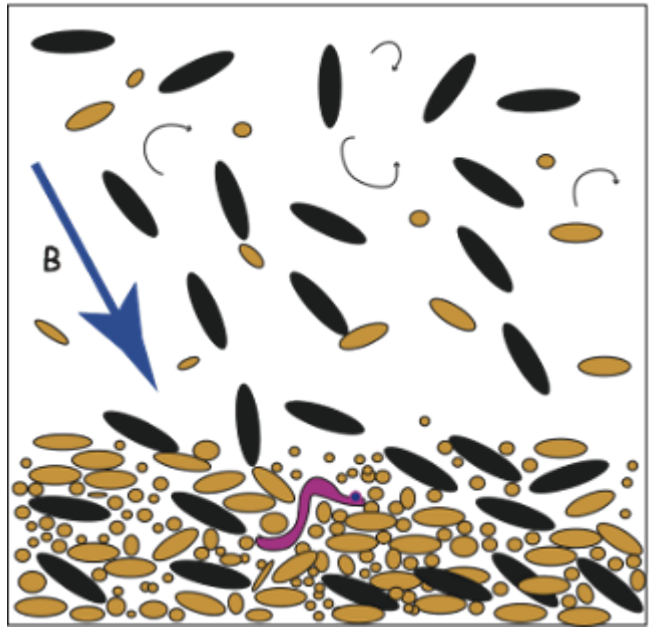
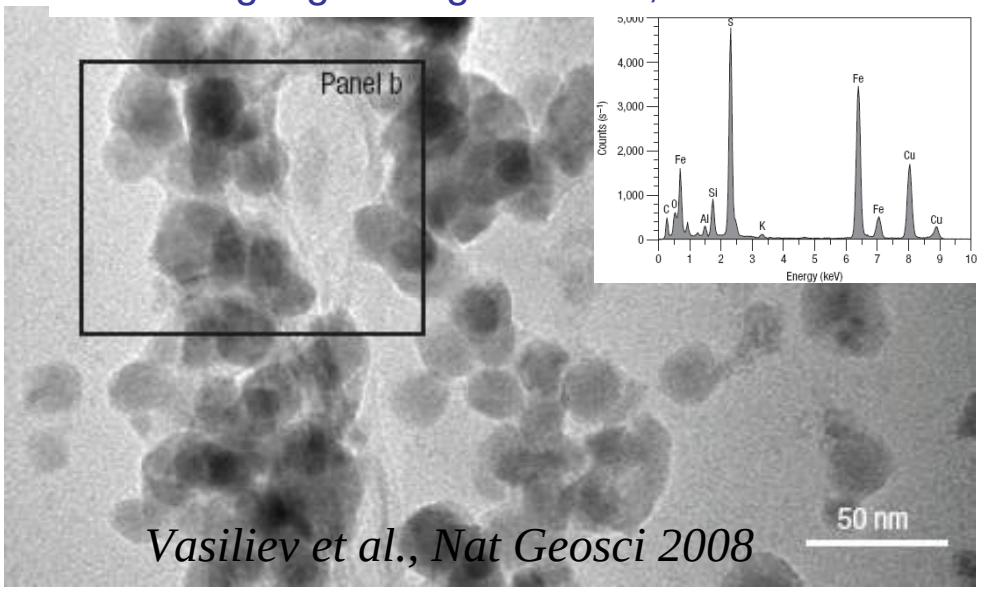
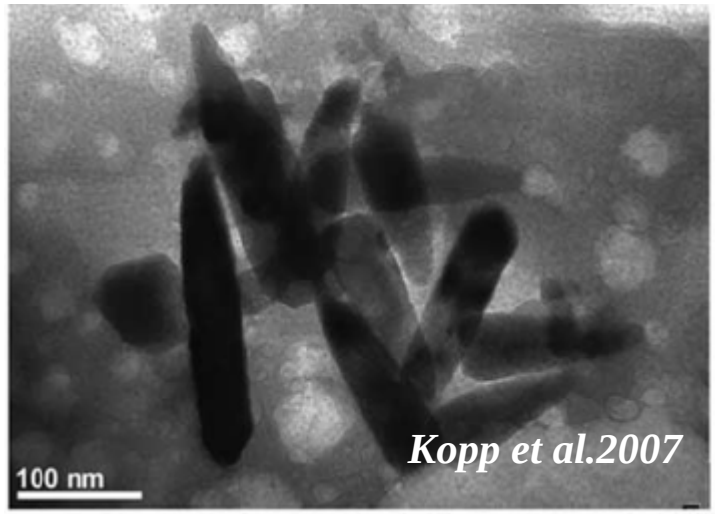


Image from L Tauxe

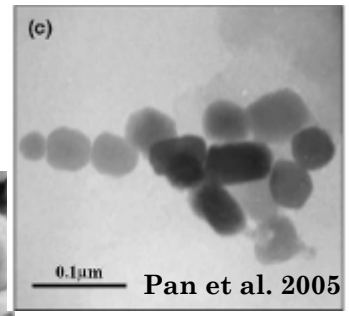
Putative greigite magentfossils, Pliocene

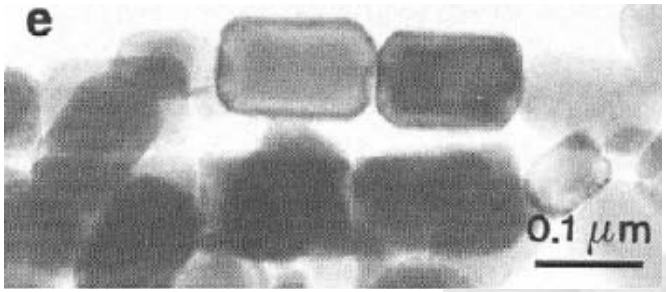


PETM magnetofossils, 55.8 Ma



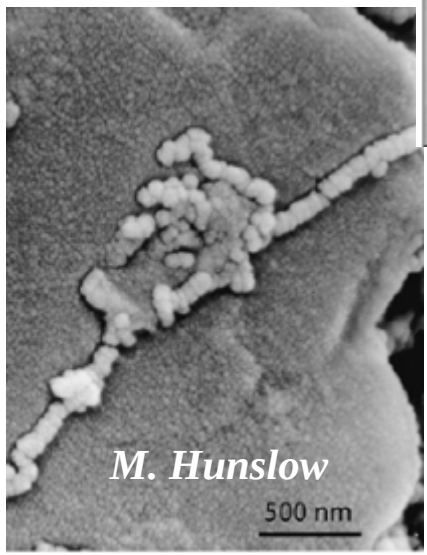
Cretaceous magnetofossils





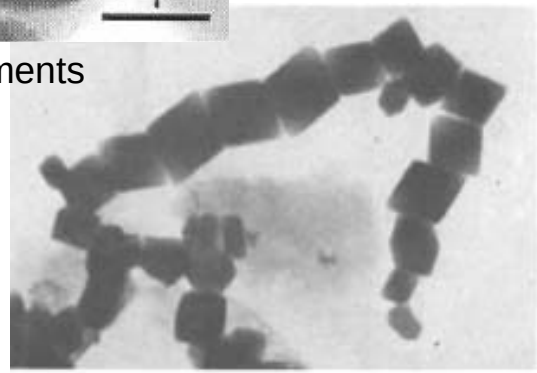
Vali et al., 1987 EPSL

Antarctic resent sea sediments



Magnetofossils in lake sediments

Magnetofossils in marine sediments



Petersen et al, 1986 Nature

Some useful references:

Kirschvink & Chang, 1984, *Geology;*

Peck et al, 1996, *EPSL;*

Yamazaki et al. 1998, *Geology;*

Mandernack et al., 1999, *Science;*

Weiss et al. 2004, *PNAS;*

Pan et al. 2005, *EPSL;*

Kopp et al. 2007; 2009 *Paleoceanography*

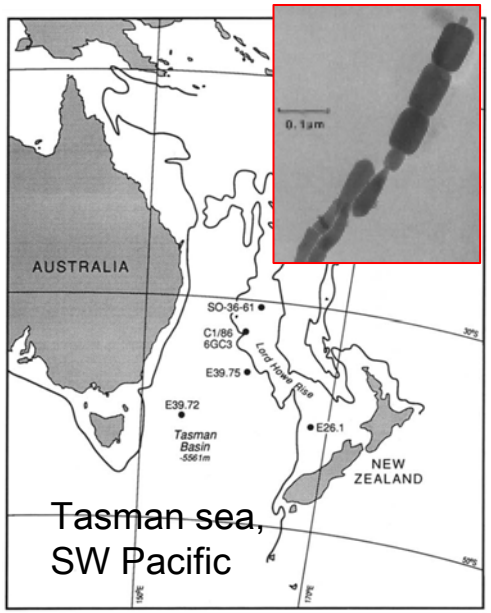
Kopp & Kirschvink, 2008 *Earth-Sci Rev*; robustness criteria

Abrajevitch et al. 2011, *EPSL*

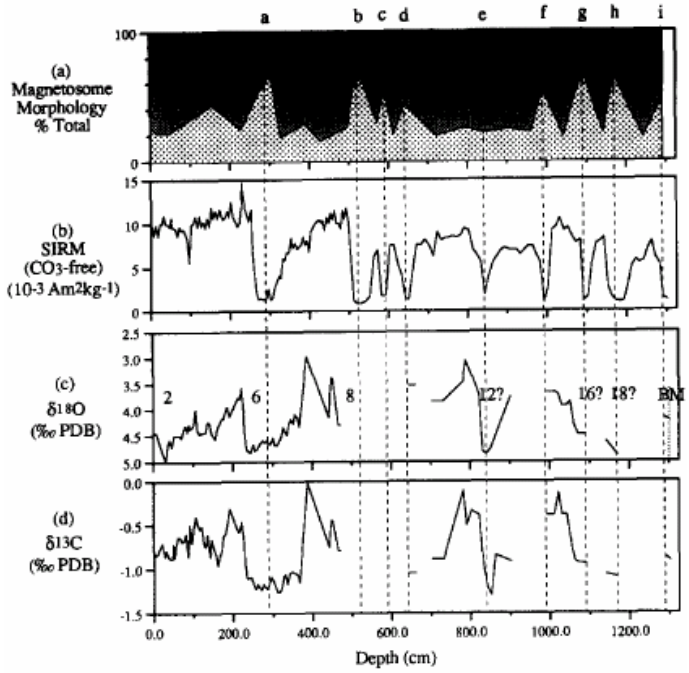
plus

Major approaches to identify magnetofossils:

- Extraction plus TEM observation (e.g., Thomas-Keprta 2000 GCA)
- Rock magnetic analysis (e.g., Moskowitz et al. 1993 EPSL; Egli 2004 PCE)
- Ferromagnetic resonance (Weiss et al., 2004 EPSL)
- Iron isotope fractionation (Pan et al)



Hess *Marine Geology* 1994



We need to study the preservations conditions, detection methods, and recording reliabilities of magnetofossils.

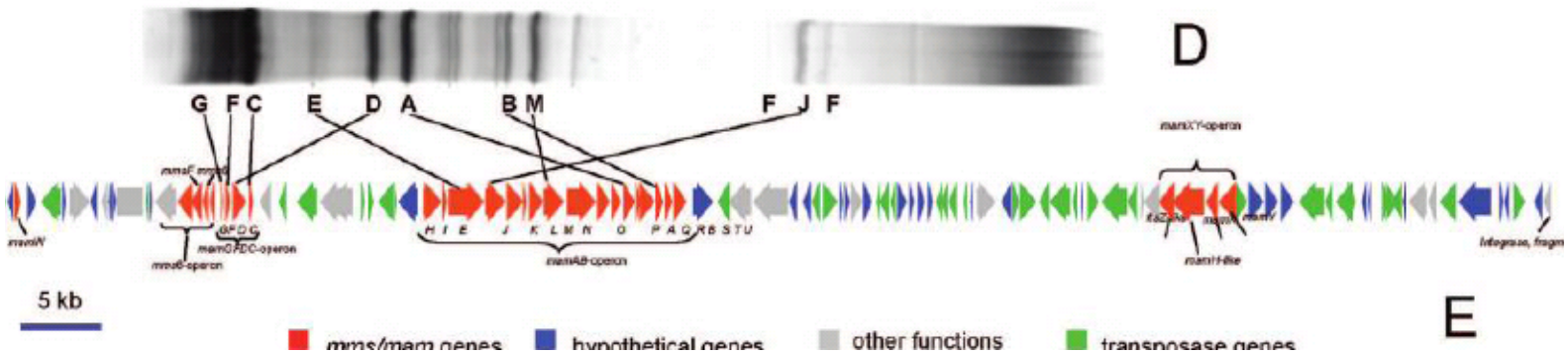
We need to make greater efforts to retrieve the magnetic, environmental, and signals from preserved magnetofossils.

III. Some future Objectives of Biogeomagnetism

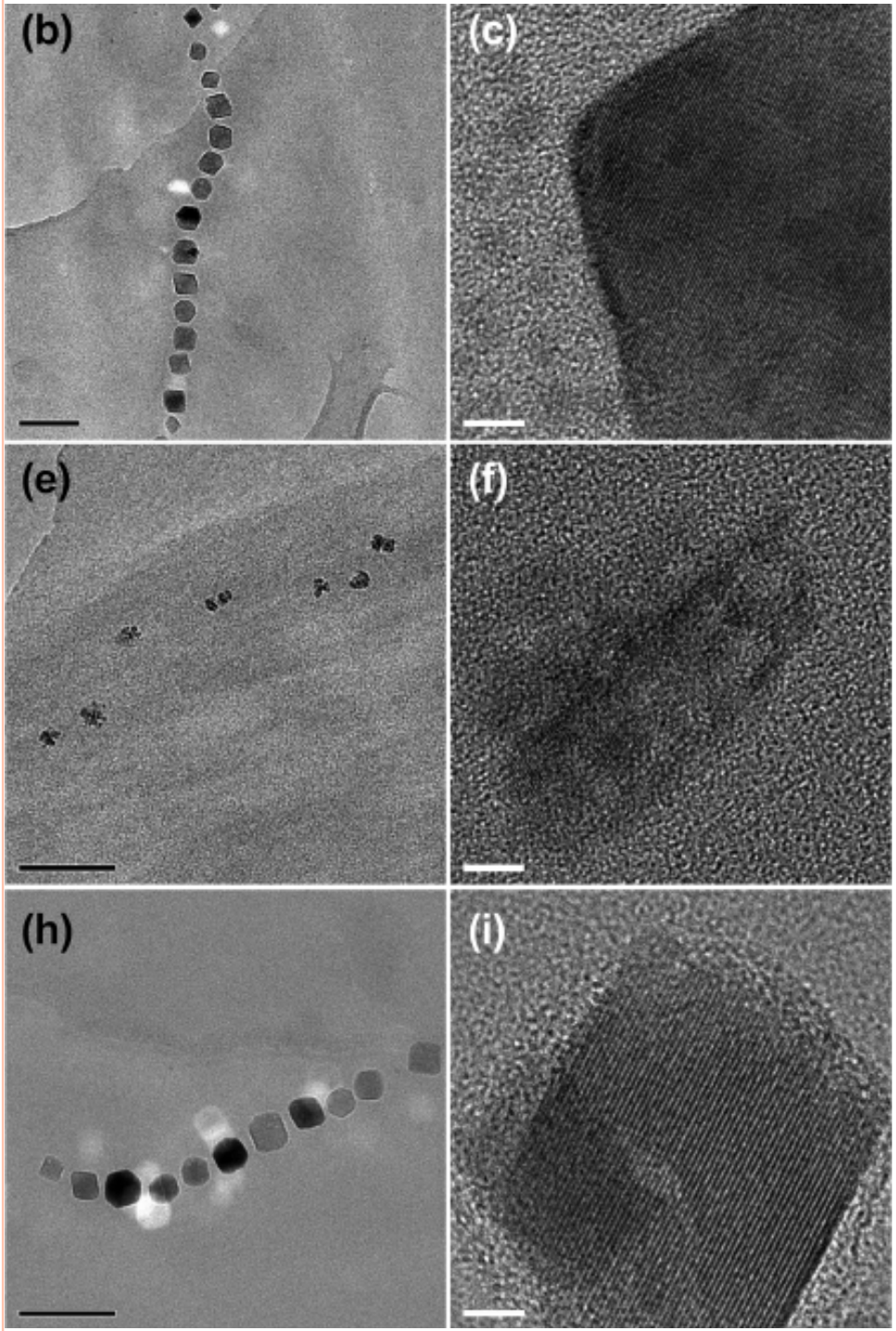
1. Biogenic magnetic nano-particles

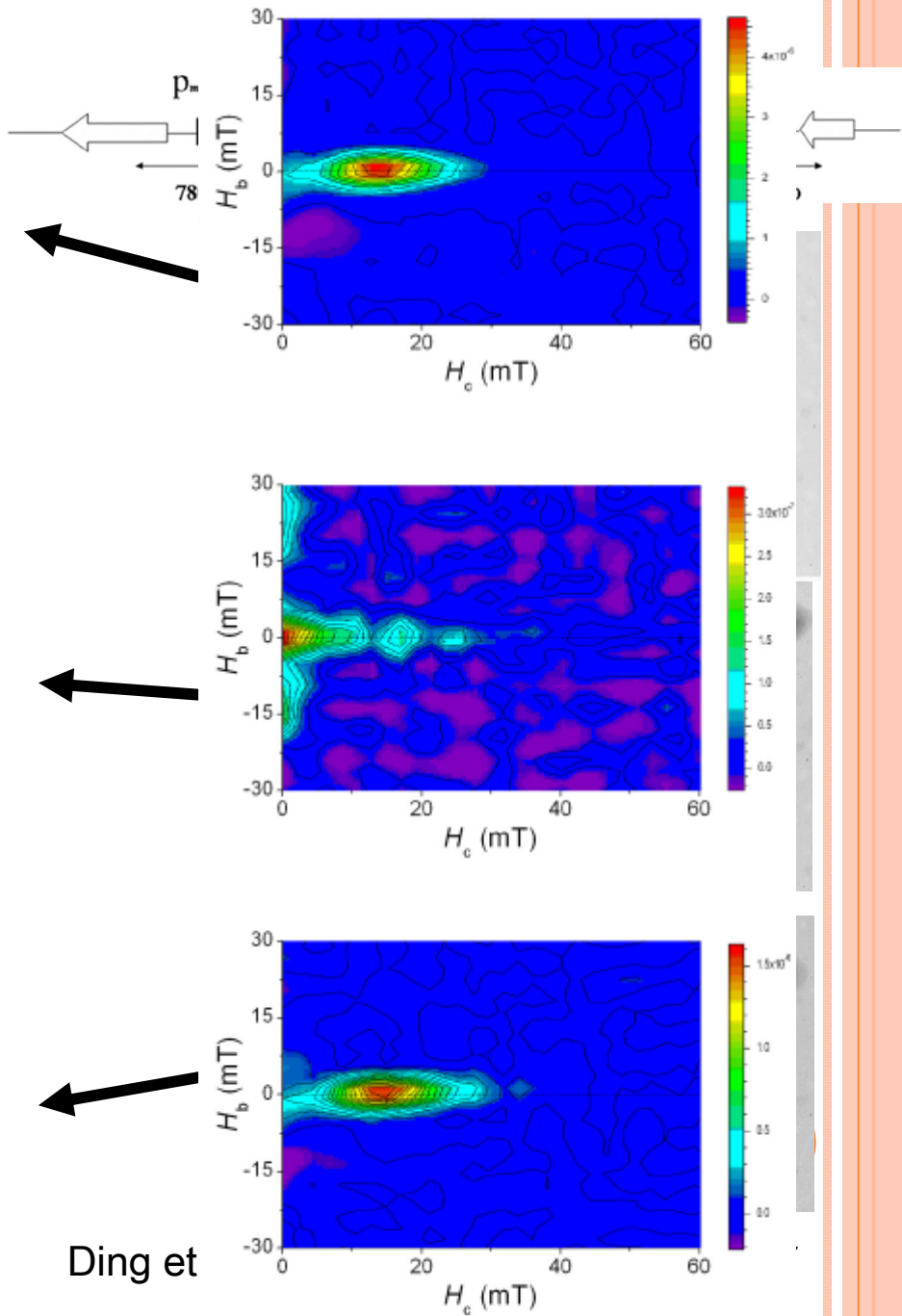
Fundamental magnetism & Applied research

Can we genetically manipulate the synthesis of MNPs through magnetotactic bacteria?



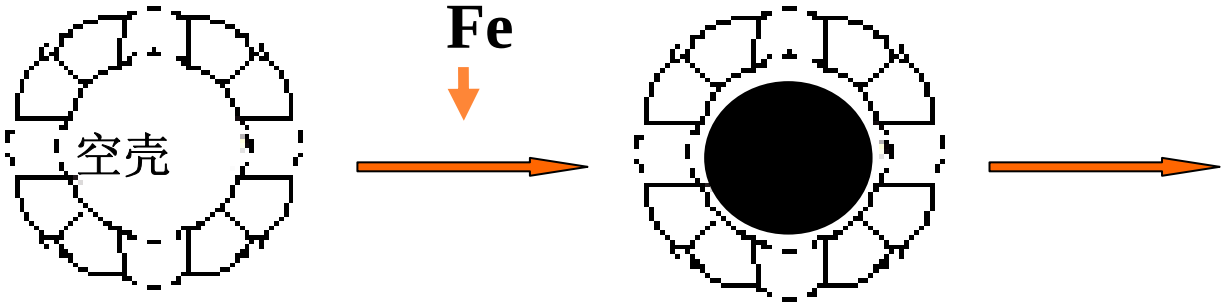
Faivre & Schüler. 2008

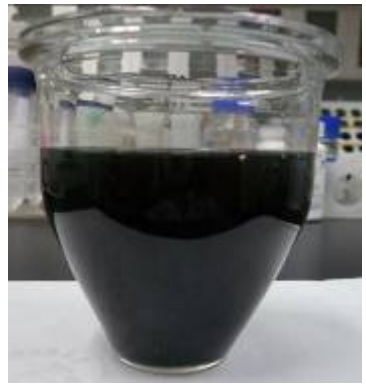


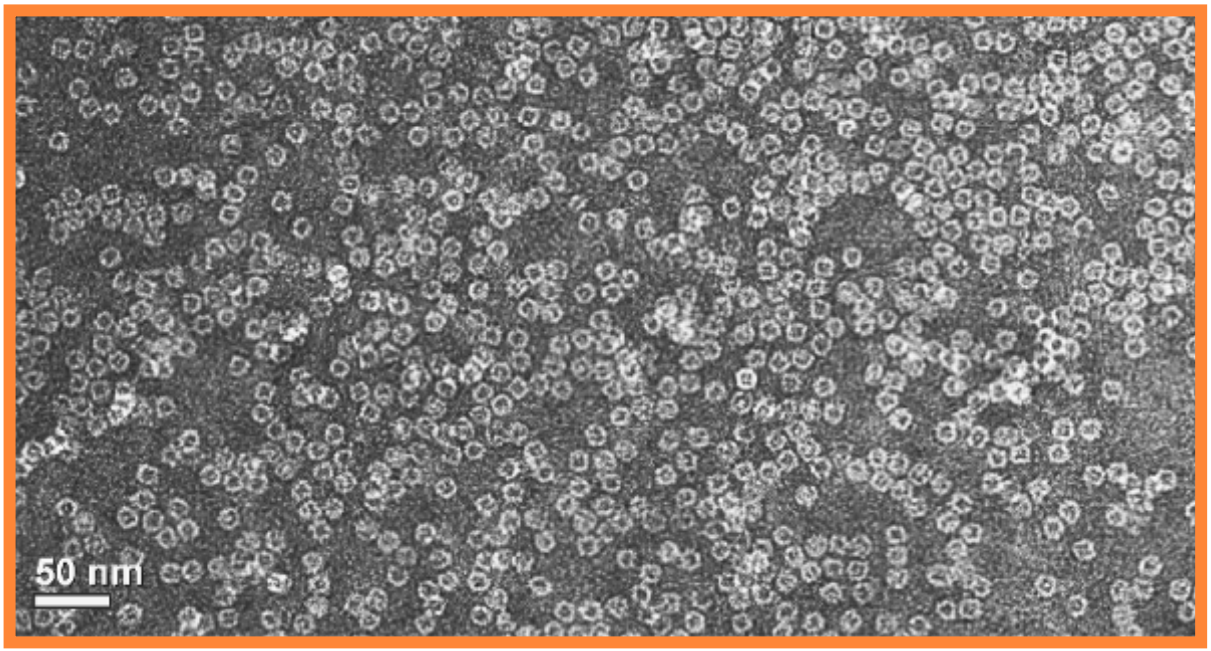


Ding et

Can we biomimetic synthesis of MNPs at protein level, and study their superparamagnetism ?

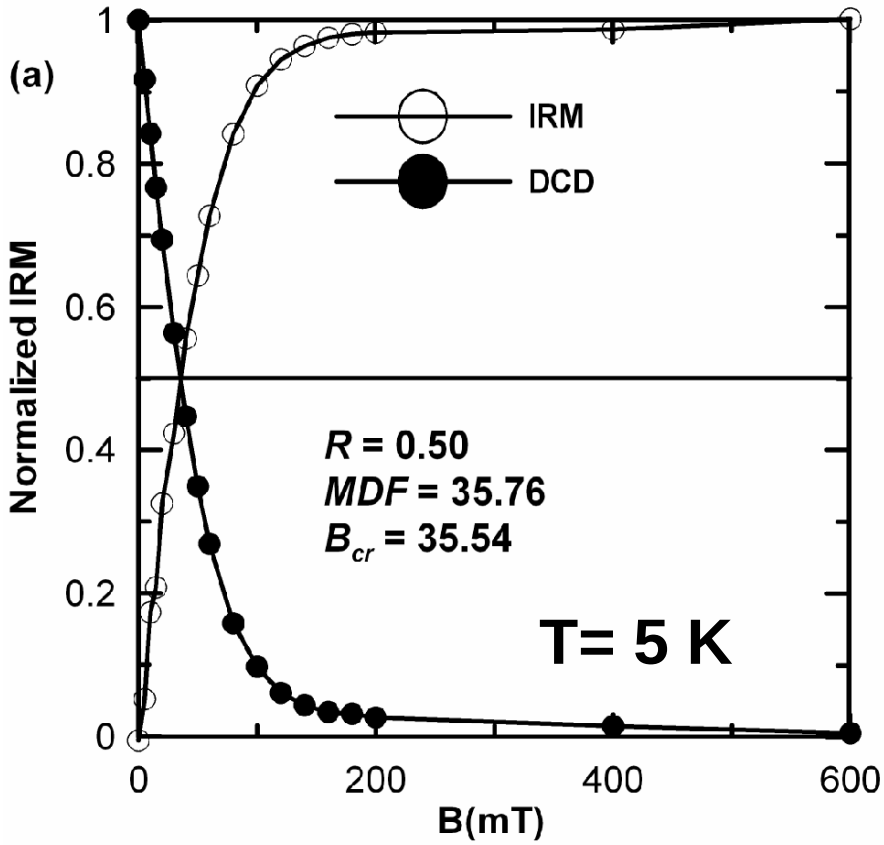




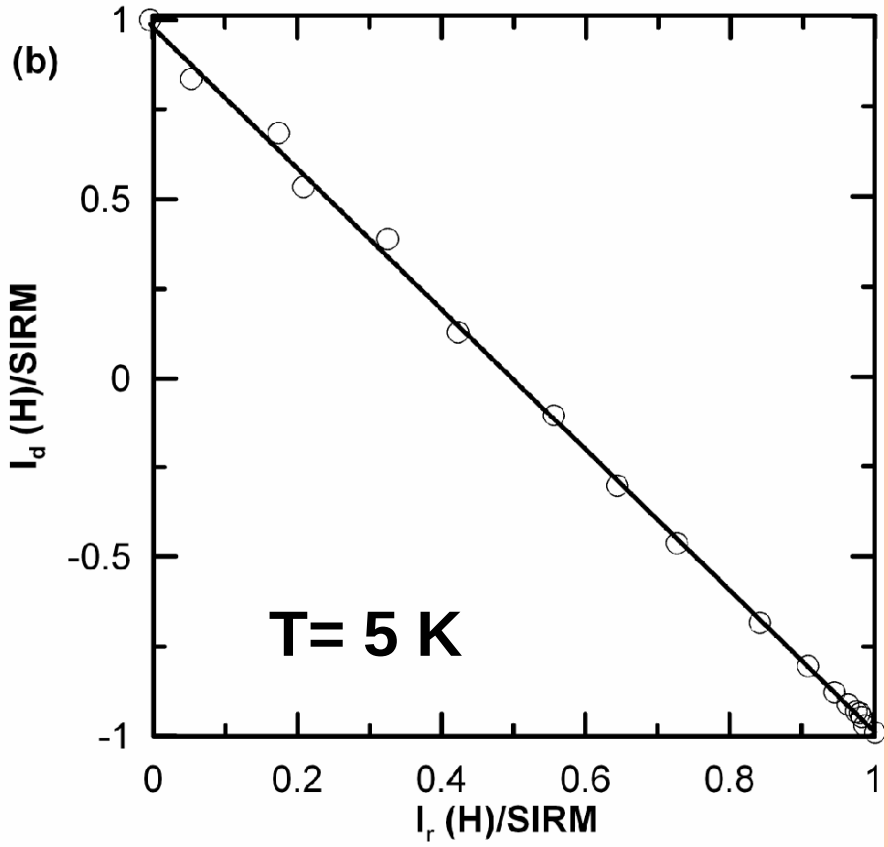


Remanences and magnetostatic interactions

The Wohlfarth-Cisowski test



The Henkel plot

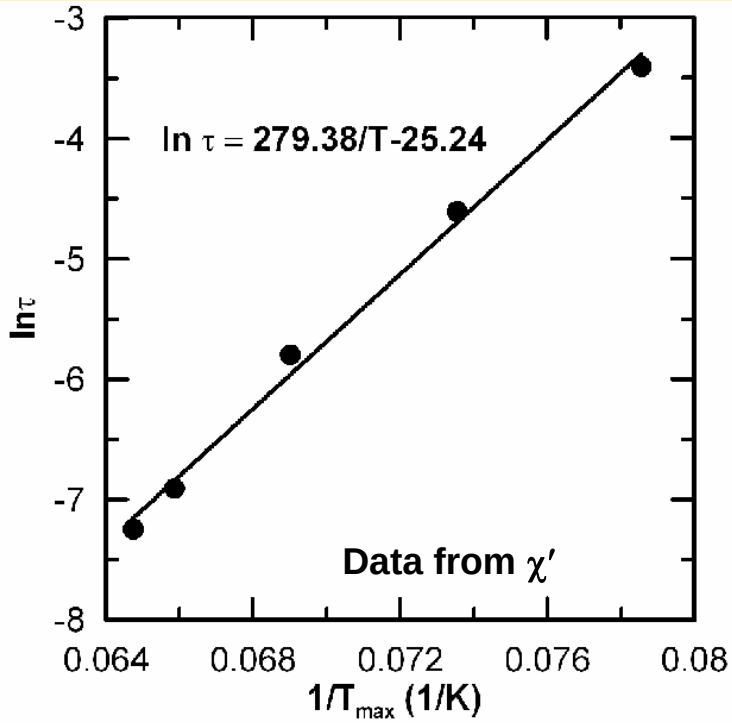


Cao et al., 2010. JGR doi:10.1029/2009jb006855

Néel-Arrhenius equation:

$$\tau = 1/f_0 \exp(E_a/kT)$$

Physical meaning value of f_0 are hardly obtained because of interaction



We get :

The pre-exponential frequency factor

$f_0 = 9.18 \times 10^{10}$ Hz >> 10^9 Hz (*Moskowita et al., 1997*)

The average effective energy barrier

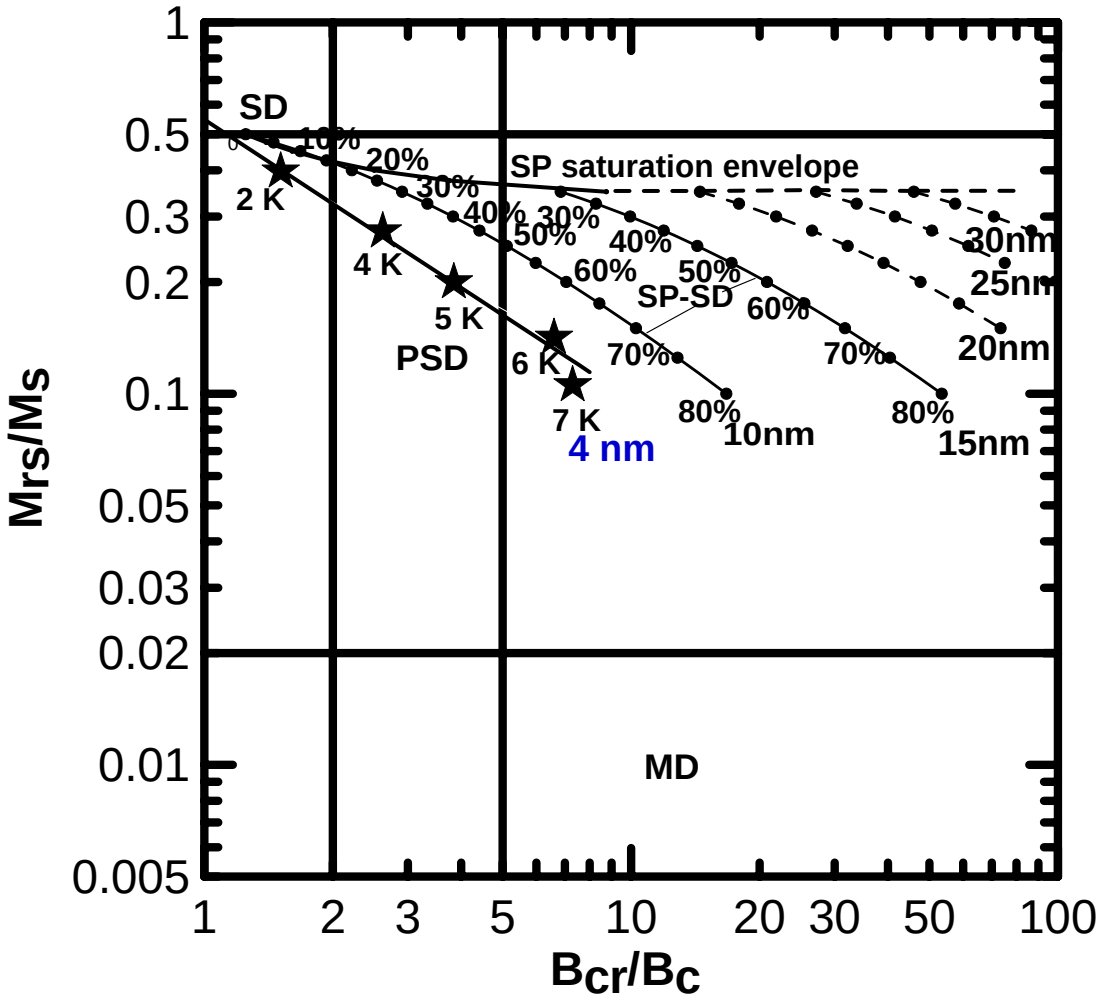
$E_a = 3.86 \times 10^{-21}$ J eq. $E_a = - K_{eff} V$

The effective magnetic anisotropy energy constant

$K_{eff} = - 1.21 \times 10^5$ J/m^3

Cao et al., 2010. JGR doi:10.1029/2009jb006855

M_r/M_s-T and B_{cr}/B_c-T variations in Day plot

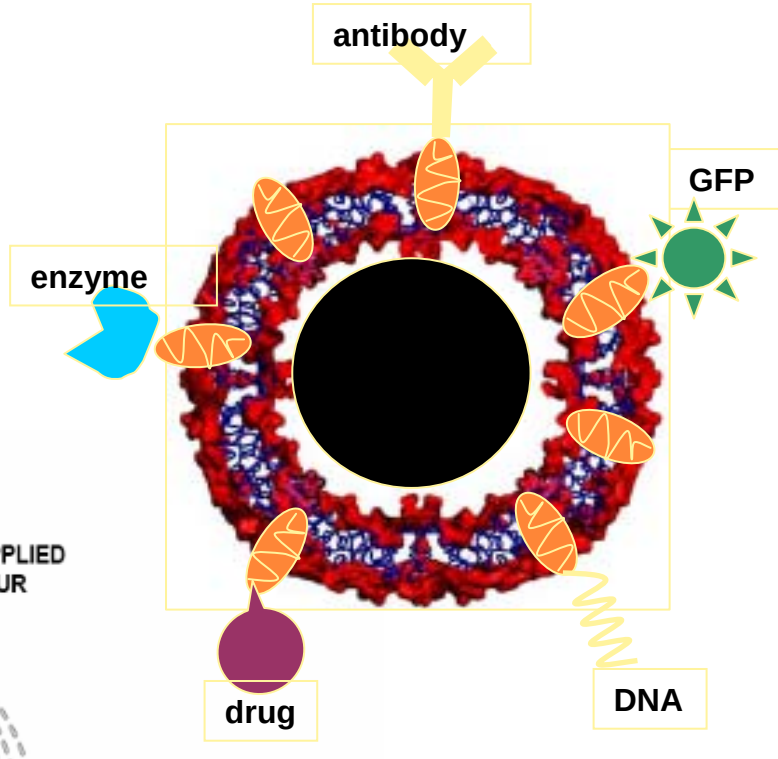


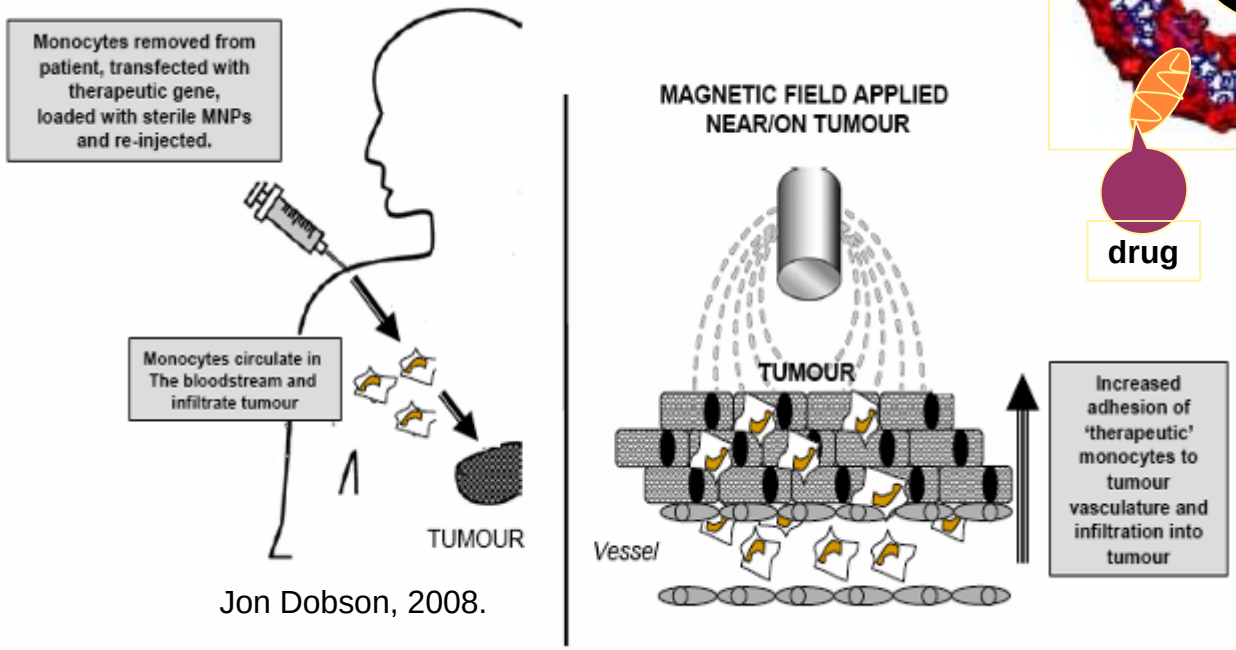
M_{rs}/M_s = 0.51 at 0 K, indicating dominantly uniaxial anisotropy

B_{cr}/B_c = 1.12 @ M_{rs}/M_s = 0.50, slightly larger than theoretical value 1.09

Biogenic magnetic nanoparticles not only provide us unique magnetic nanomaterials for magnetic study, but also do have promising applications in biomedical and material sciences.

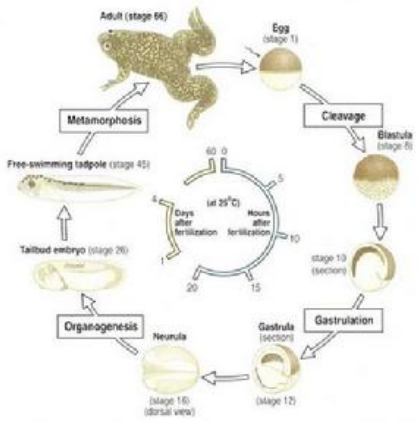
- ✓ novel MRI contrast agent
- ✓ novel drug & gene targeting delivery
- ✓ novel hyperthemia materials





Jon Dobson, 2008.

2. Geomagnetic Field Strength & Life

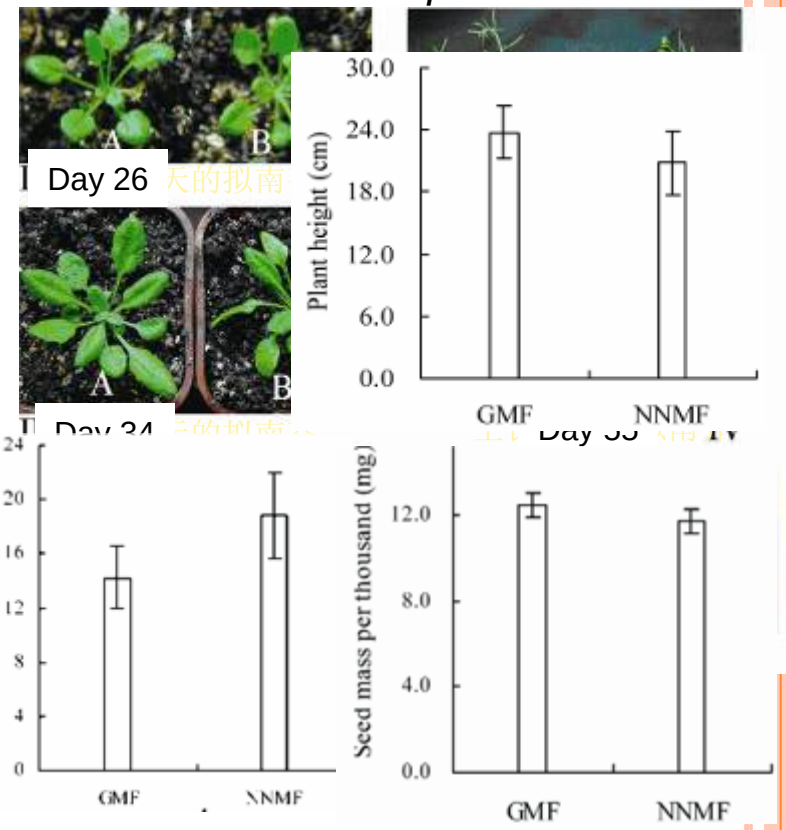


Hypogeomagnetic field

HGMF conditions DC field strength: 66-105 nT

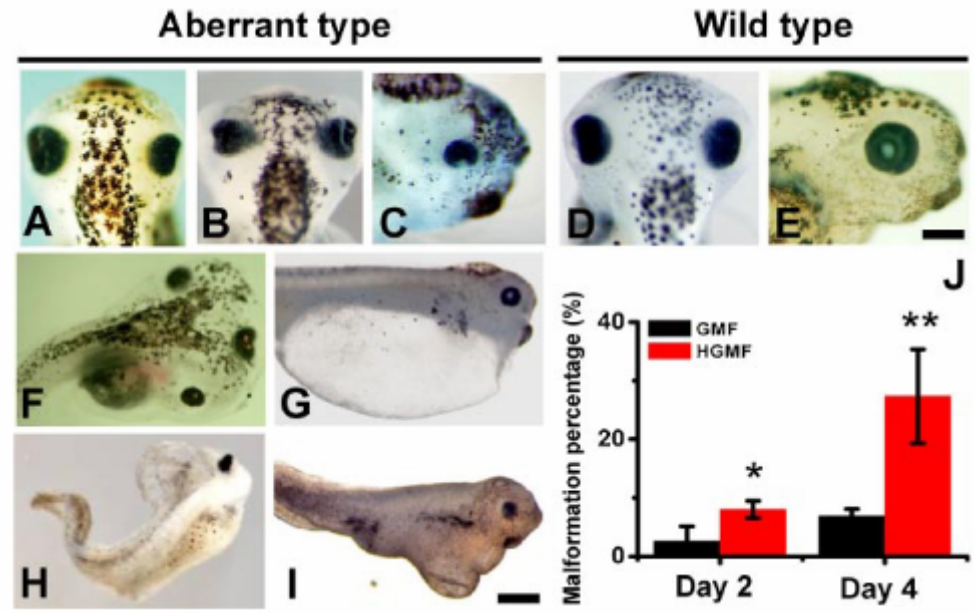
GMF control: ~50 μT

Arabidopsis thaliana



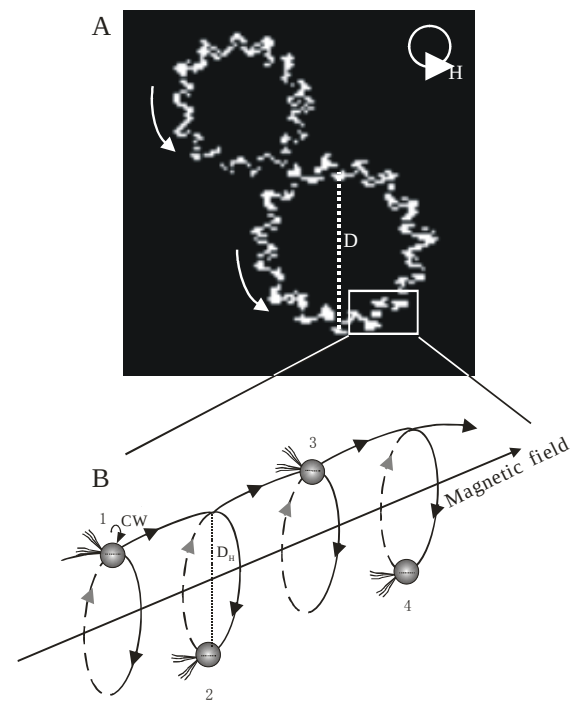
Beijing Biogeomagentism Lab, IGGCAS

Altered Development of *Xenopus* Embryos in a Hypogeomagnetic Field

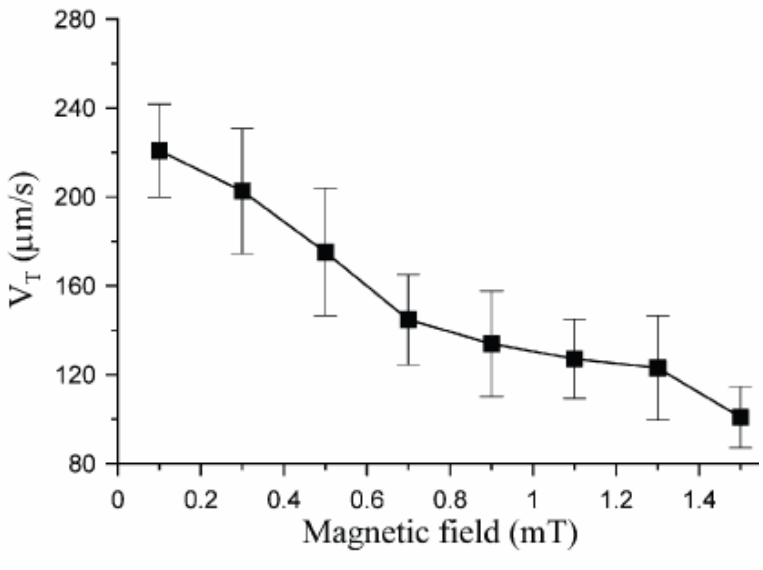


Mo et al., 2011. Bioelectromagnetics

MTB Swimming Speed



Pan et al., 2009 *Biophys J 97: 986-991*

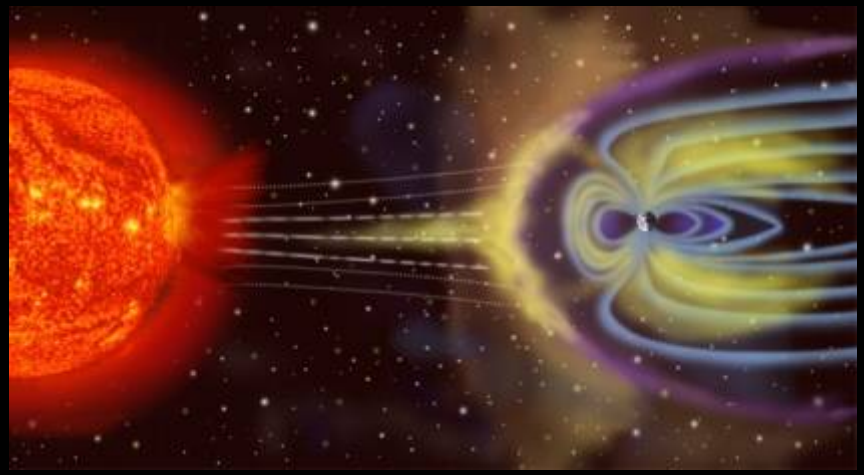


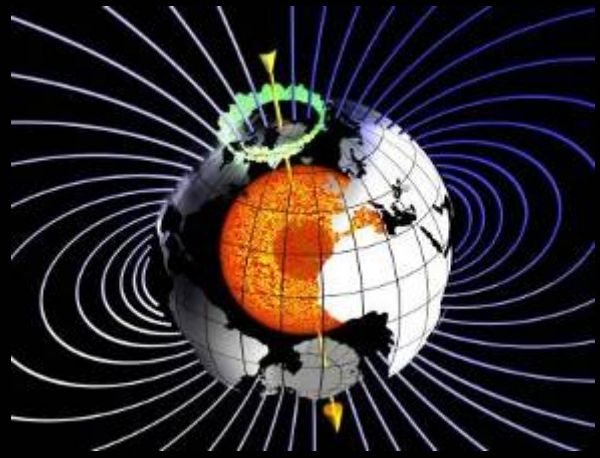
We found that the field-parallel migration velocity decreases with increasing of magnetic field strength.

Indicative of bio-evolution?

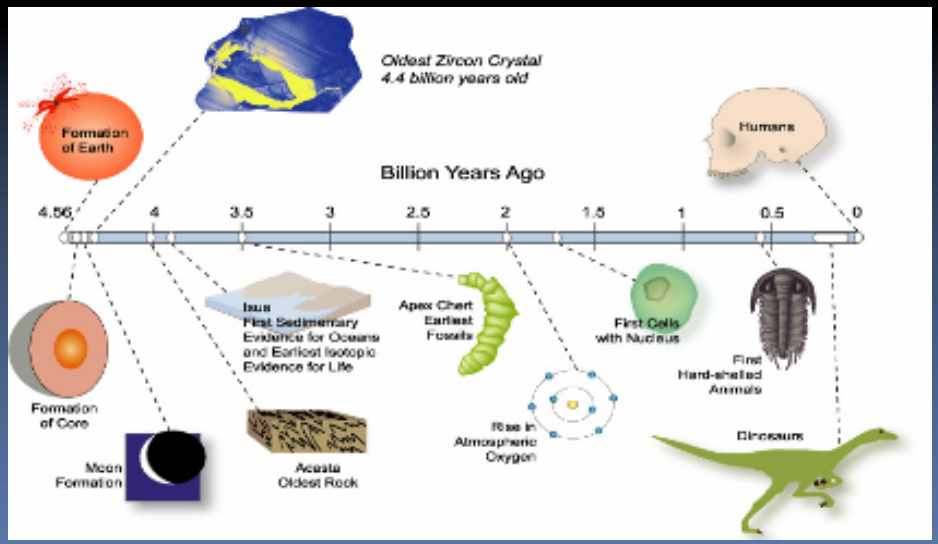
Geomagnetic field & life ?

Fundamental problems and Practice





Polarity reversal 2-4 times / Myr



The goal is to understand its

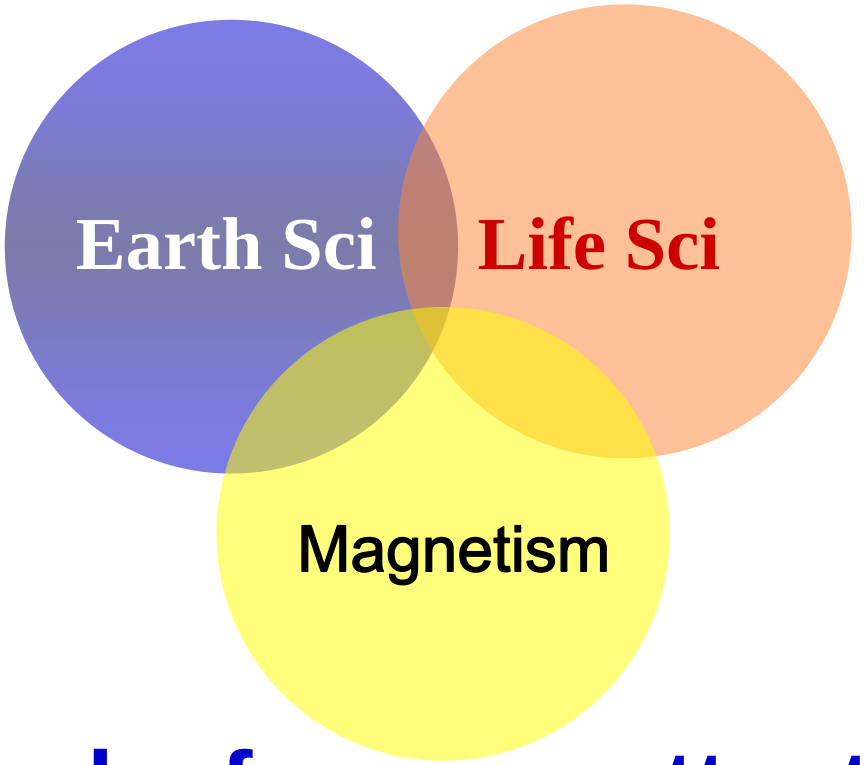
present,

Past &

Future

Open a new avenue……

Biogeomagnetism, an interdisciplinary research field



Thanks for your attention

Every time you peel off another layer of nature and look in a little bit further, it always gives you the most fantastic feeling !

Note: some slides of this talk had been removed due to related un-publication data