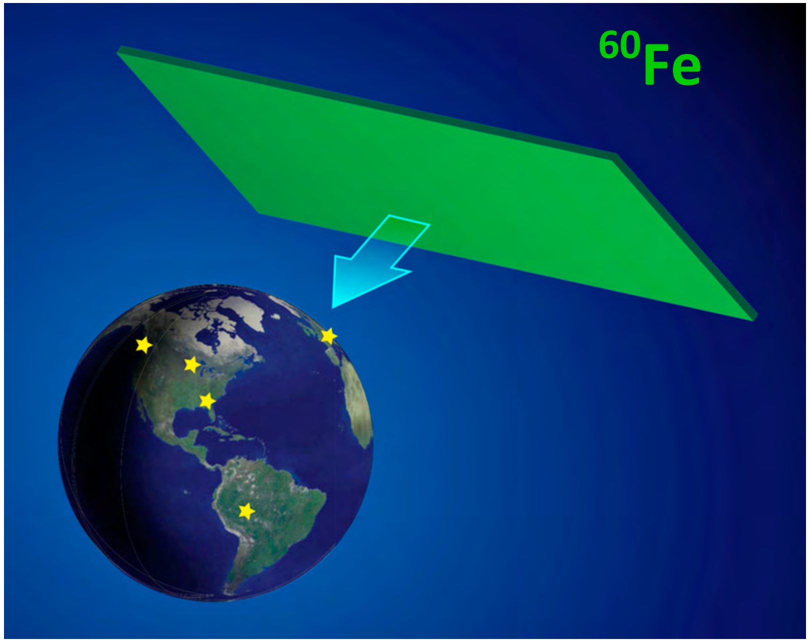
From supernova to terrestrial dirt: a journey between astrophysics, biology, and geophysics

Ramon Egli
Central Institute of Meteorology and Geodynamics of Austria

Peter Ludwig and Shawn Bishop
Technical University Munich

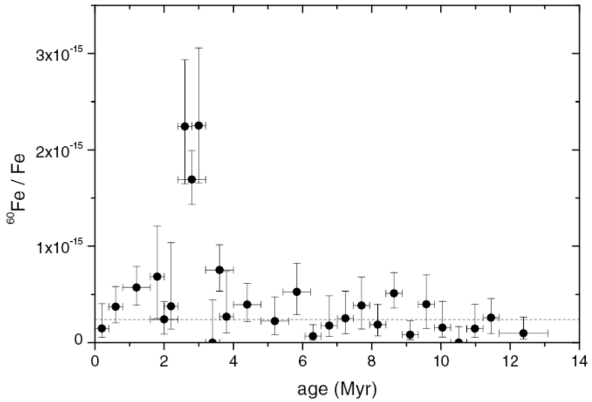
Introduction



VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

^{60}Fe Anomaly in a Deep-Sea Manganese Crust and Implications for a Nearby Supernova Source

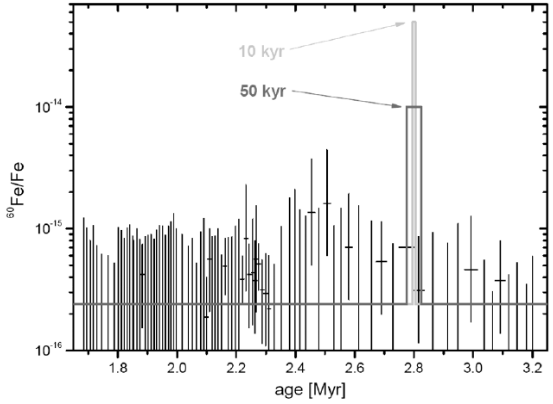
K. Knie,[1] G. Korschinek,[1,*] T. Faestermann,[1] E. A. Dorfi,[2] G. Rugel,[1,3] and A. Wallner[1,3]
[1]*Technische Universität München, Fakultät für Physik, James-Franck-Straße 1, 85747 Garching, Germany*
[2]*Universität Wien, Institut für Astronomie, Türkenschanzstraße 17, 1180 Wien, Austria*
[3]*Ludwig Maximilians Universität München, Strahlenbiologisches Institut, Schillerstraße 42, 80336 München, Germany*
(Received 18 February 2004; published 22 October 2004)



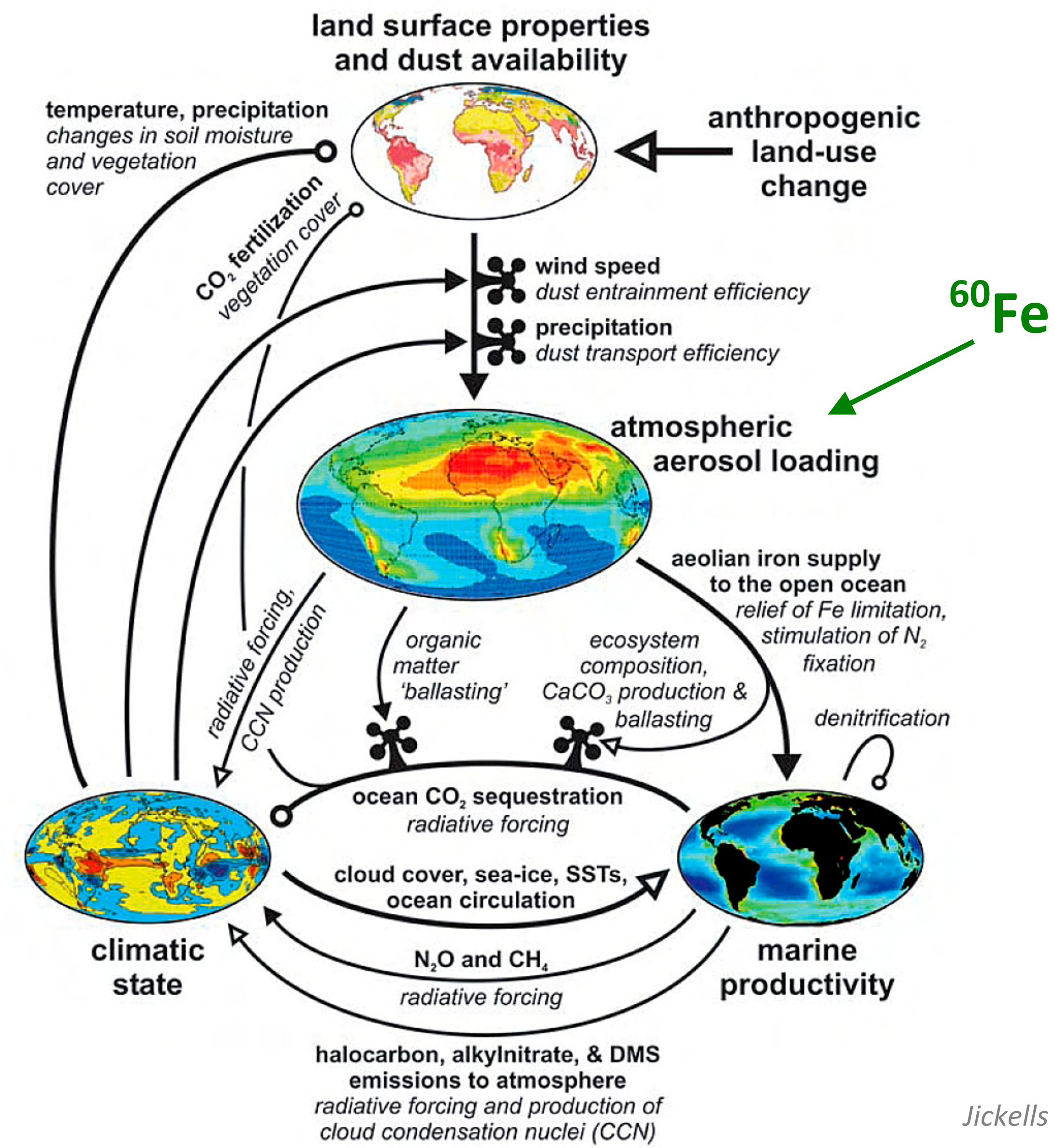
PRL 101, 121101 (2008) PHYSICAL REVIEW LETTERS week ending 19 SEPTEMBER 2008

Search for Supernova-Produced ^{60}Fe in a Marine Sediment

C. Fitoussi,[1] G. M. Raisbeck,[1] K. Knie,[2,5] G. Korschinek,[2] T. Faestermann,[2] S. Goriely,[3] D. Lunney,[1] M. Poutivtsev,[2] G. Rugel,[2] C. Waelbroeck,[4] and A. Wallner[5]
[1]*Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse (CSNSM) IN2P3/CNRS, Université Paris Sud, Bâtiment 108, 91405 Orsay, France*
[2]*Fakultät für Physik, Technische Universität München, James-Franck-Straße 1, 85747 Garching, Germany*
[3]*Institut d'Astronomie et d'Astrophysique, C.P. 226, Université Libre de Bruxelles, Boulevard Du Triomphe, B-1050 Brussels, Belgium*
[4]*Laboratoire des Sciences du Climat et de l'Environnement, Domaine du CNRS, 91198 Gif-sur-Yvette, France*
[5]*VERA Laboratory, Fakultät für Physik, Universität Wien, Währinger Straße 17, A-1090 Vienna, Austria*
(Received 10 August 2007; revised manuscript received 5 February 2008; published 19 September 2008)



The global iron cycle



Jickells et al., 2005

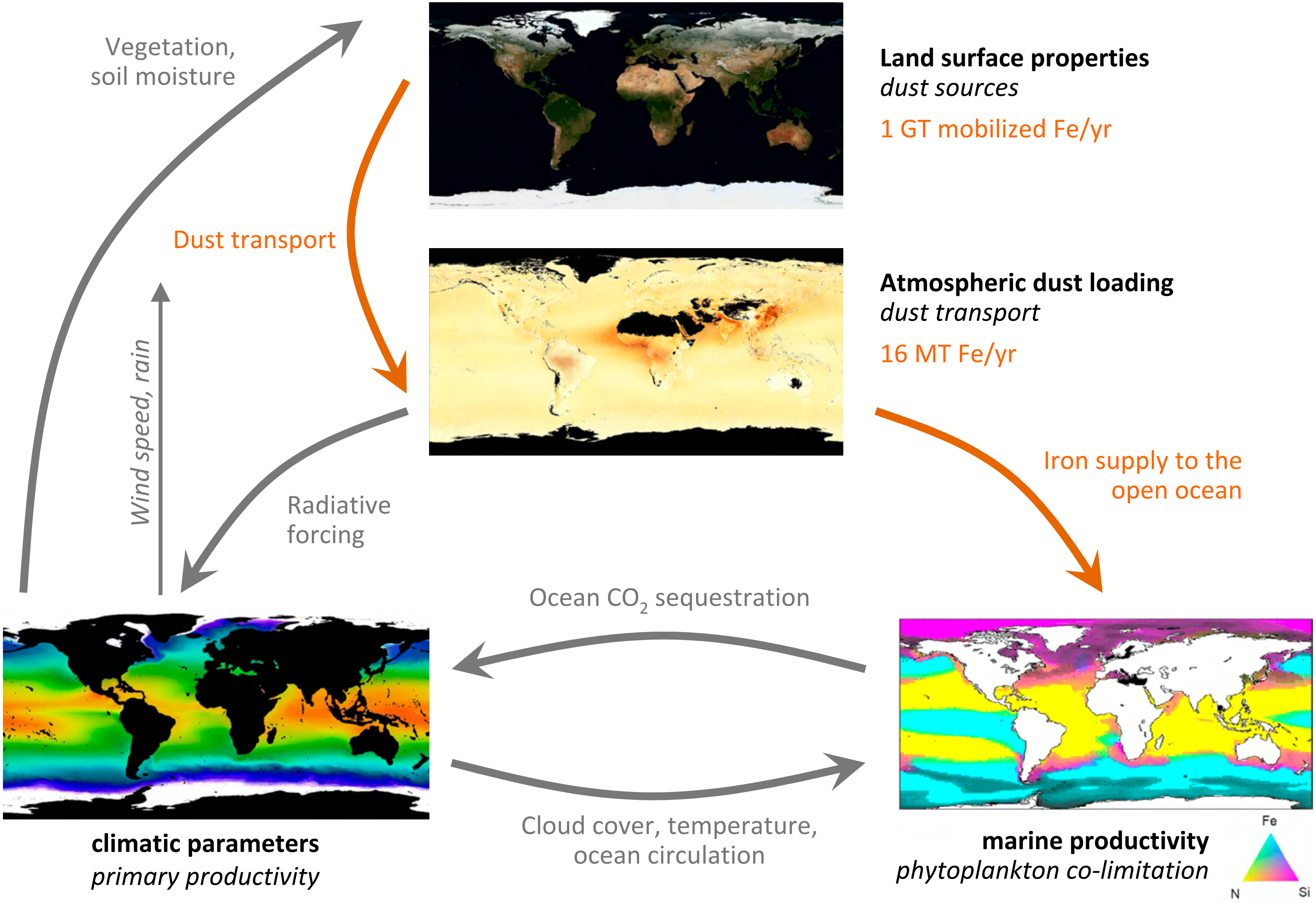
Table 1. Global iron fluxes to the ocean (in Tg of Fe $year^{-1}$).

Source	Flux
Fluvial particulate total iron	625 to 962
Fluvial dissolved iron	1.5
Glacial sediments	34 to 211
Atmospheric	16
Coastal erosion	8
Hydrothermal	14
Authigenic	5

Fe in cosmic dust	$\sim 10^{-3}$
^{60}Fe	$\sim 10^{-13}$

Bishop and Egli, 2011

The role of dust in the global iron cycle



Land surface properties
dust sources
1 GT mobilized Fe/yr

Atmospheric dust loading
dust transport
16 MT Fe/yr

marine productivity
phytoplankton co-limitation

climatic parameters
primary productivity

Vegetation, soil moisture

Dust transport

Wind speed, rain

Radiative forcing

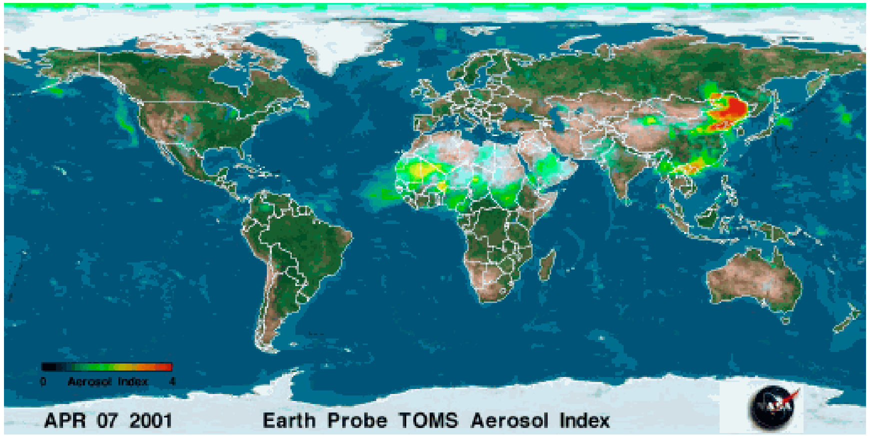
Iron supply to the open ocean

Ocean CO_2 sequestration

Cloud cover, temperature, ocean circulation

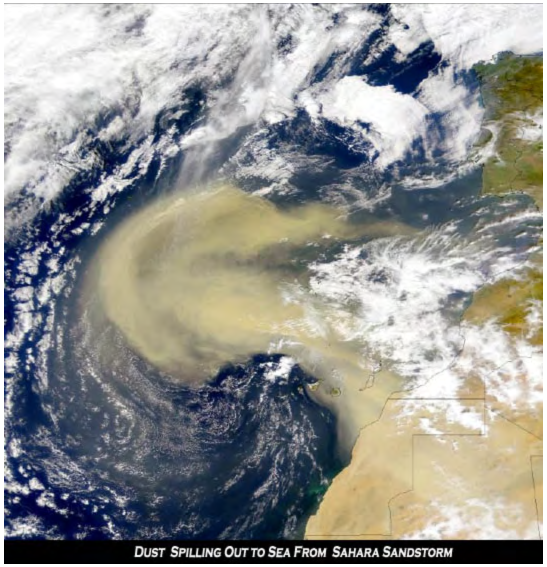
Dust transport in real life

Dust plume from the Chinese Loess Plateau, 2001



Dust storm, Texas, 1935.

Satellite image of a dust plume from Sahara



Dust deposited on car, Beijing 2008.

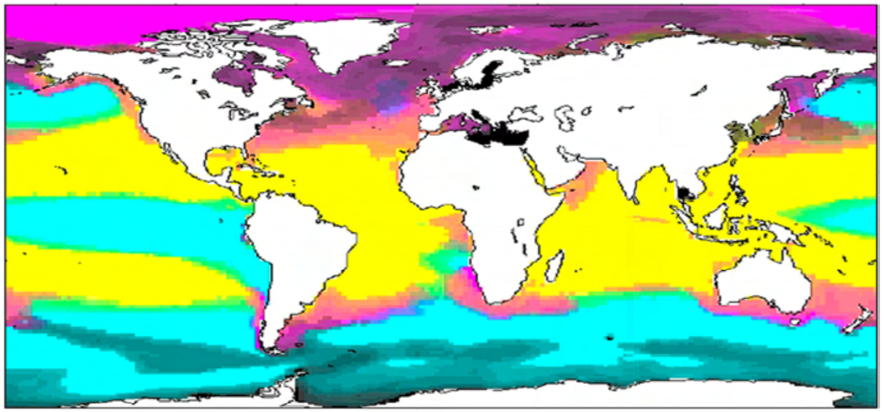
The “time integral” of dust transport over the Earth’s history

Western Chinese Loess Plateau
(Geology cover image, Sept. 2008)

Pampean Loess,
Argentina

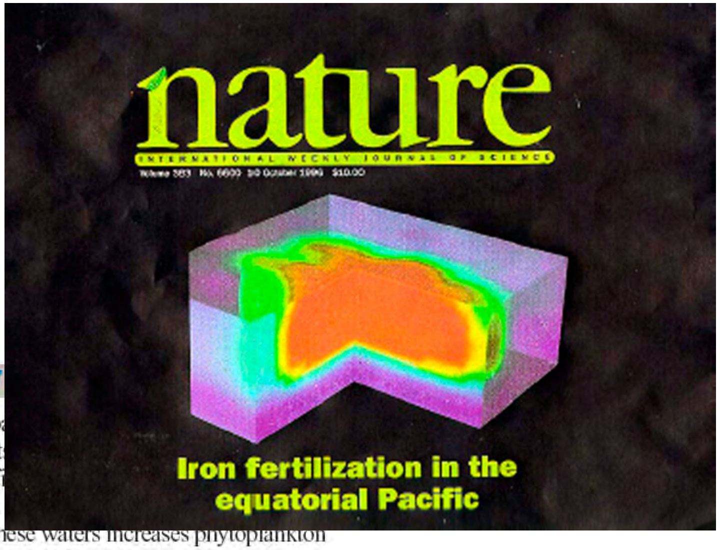
Black earth soil on
loess, Germany

Iron as a limiting factor for marine productivity



marine productivity
phytoplankton co-limitation

Mesoscale iron fertilization experiments (SOIREE, SEEDS…):



SCIENCE'S COMPASS • POLICY

POLICY FORUM: OCEANS

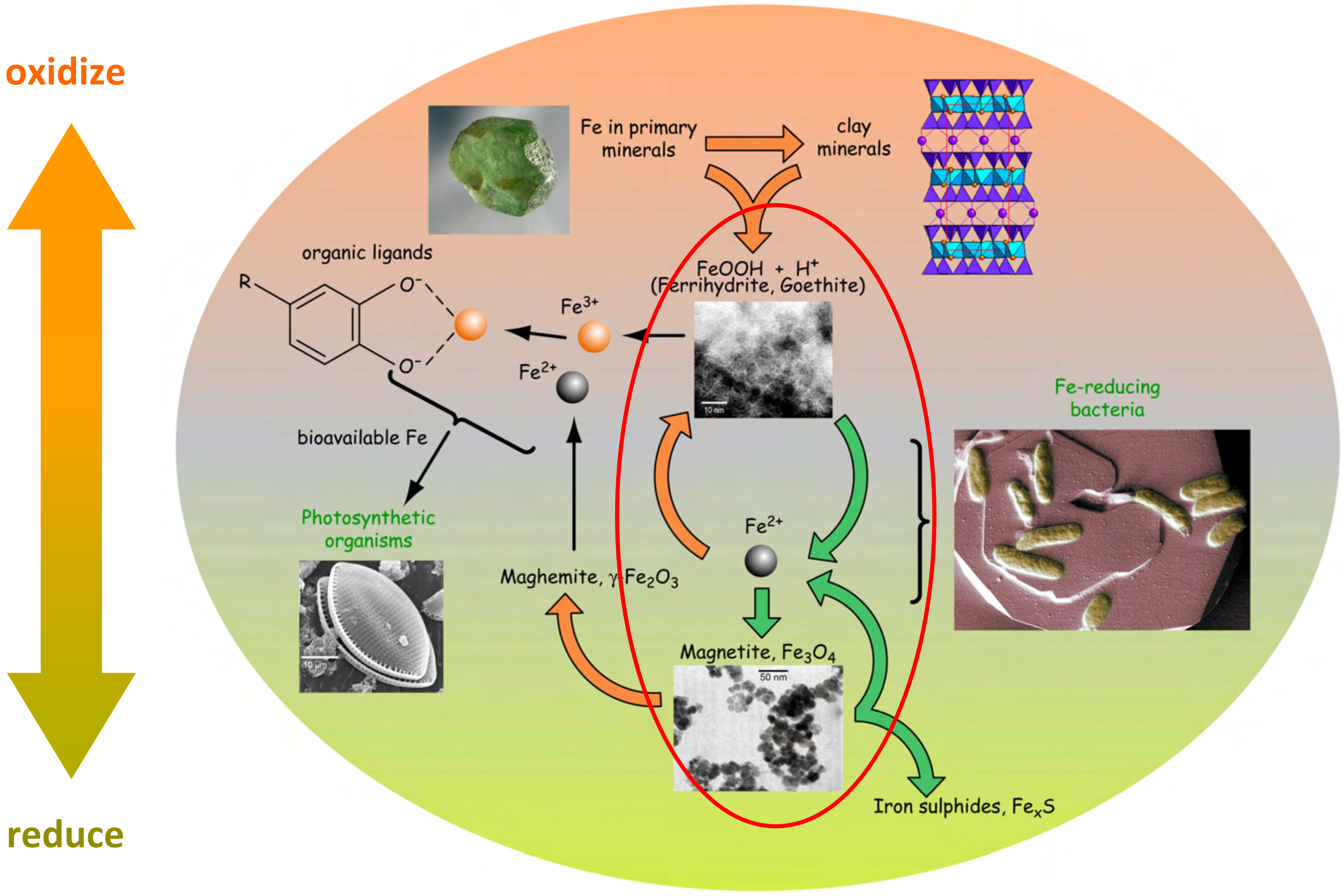
Dis-Crediting Ocean Fertilization

Sallie W. Chisholm,* Paul G. Falkowski, John J. Cullen

The oceans play a key role in the global carbon cycle and climate regulation. Central to this function are phytoplankton, single-celled photosynthetic never exhausted in surface waters, and phytoplankton biomass is less than expected. Martin (6, 7) suggested that it is the scarcity of biologically available iron in these high-nutrient, Over the p experiment torial Pacifi They have of iron to these waters increases phytoplankton productivity and biomass over periods of a few days to weeks. In one experiment, phytoplankton biomass increased 20- to 30-fold (11).

These scientific experiments, which were conducted on very small scales, did not document a net transfer of CO_2 from the atmosphere to the deep sea. Press coverage, how-

How Fe is made available for transport: the “iron mill”



oxidize

reduce

Fe in primary minerals

clay minerals

$FeOOH + H^+$ (Ferrihydrite, Goethite)

organic ligands

Fe^{3+}

Fe^{2+}

bioavailable Fe

Photosynthetic organisms

Maghemite, γ-Fe_2O_3

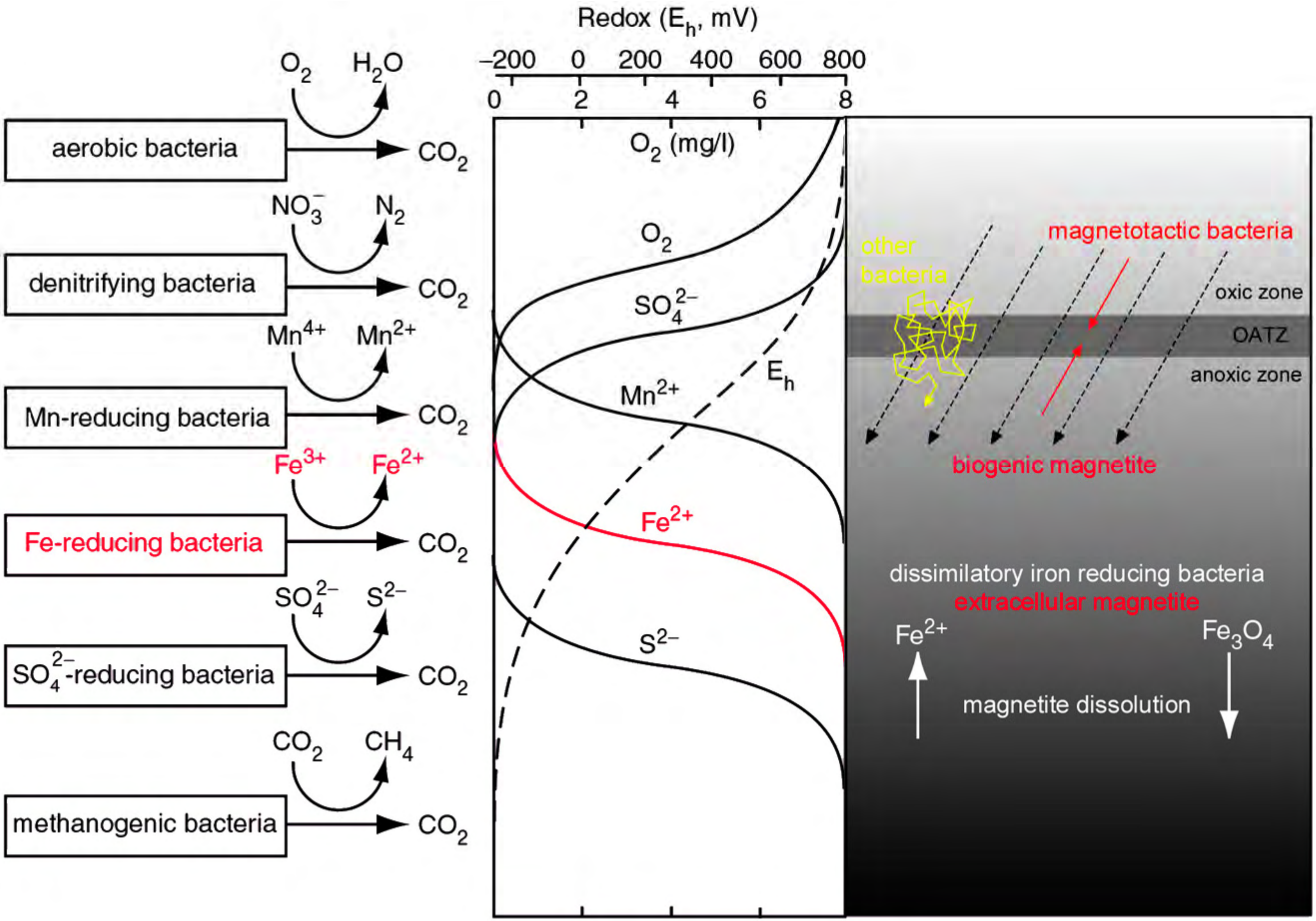
Fe^{2+}

Magnetite, Fe_3O_4

Fe-reducing bacteria

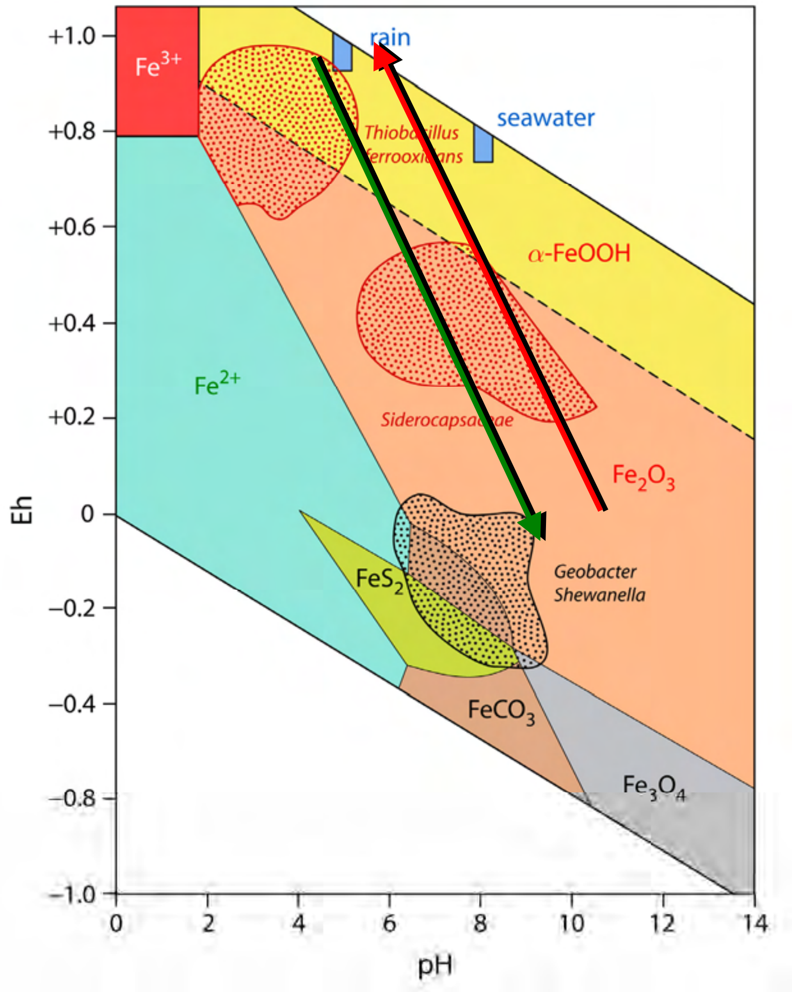
Iron sulphides, Fe_xS

The role of living organisms in Fe redox cycling

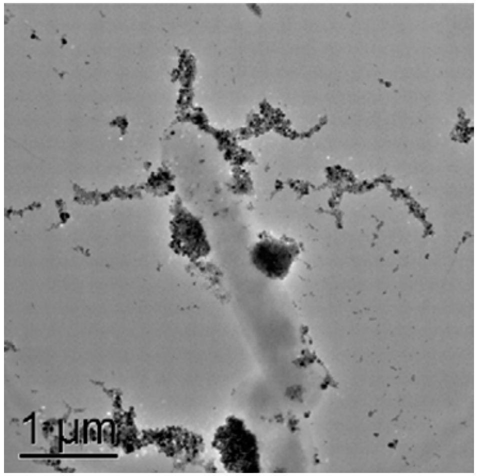


The role of living organisms in Fe redox cycling

☞ **Reduction** and **oxidation** paths are iron cycle “motor”.



[Adapted from *Zavarzina.*, 2001]



Magnetite precipitated around electron-conducting *Shewanella Oneidensis* Pili.

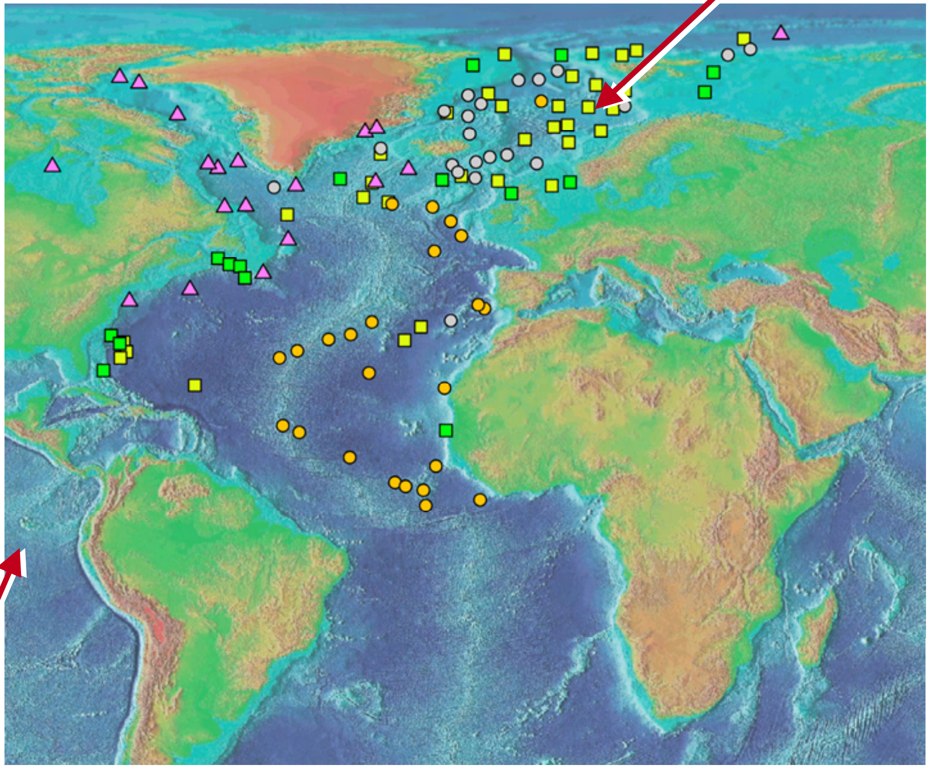
[*Gorby et al.* 2006]

Shewanella Oneidensis thriving on a hematite crystal.

[Oak Ridge National Laboratory]

Where to search for 60-Fe in sediment ?

***Fitoussi et al.* 2008**
ODP leg 162, core 985 (Norwegian Sea)


[Adapted from: *Watkins and Maher*, 2003]

Ludwig *et al.* 2013
ODP leg 138, cores 848 and 851 (Equatorial Pacific)

Desert dusts (N. Africa)

Ice rafting

Volcanic input (coarse, Island)

Detrital input

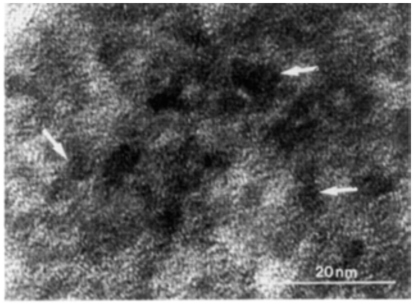
Bacterial magnetite

↓

^{60}Fe

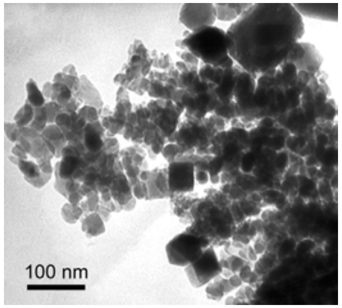
Fe redox cycling by bacteria

Dissimilatory metal reducing bacteria



Ferrihydrite

Shewanella O.
on hematite

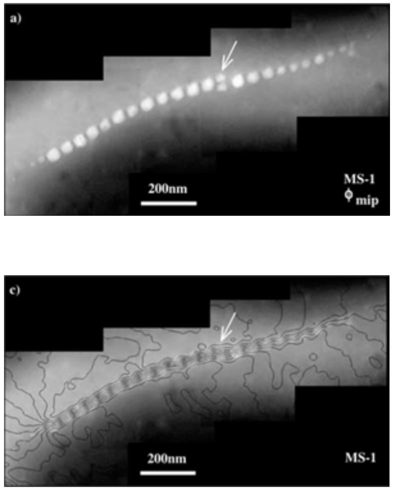


Magnetite
nanoparticles

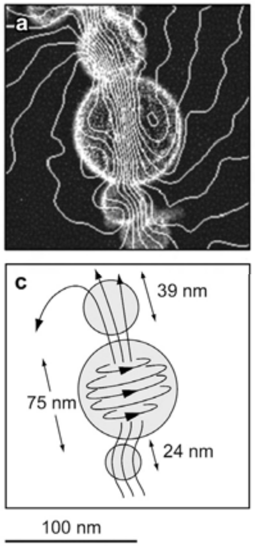
Magnetotactic bacteria

Magnetospirillum
magnetotacticum

Electron holography of
magnetite chains



Magnetic vortices
in FeNi particles



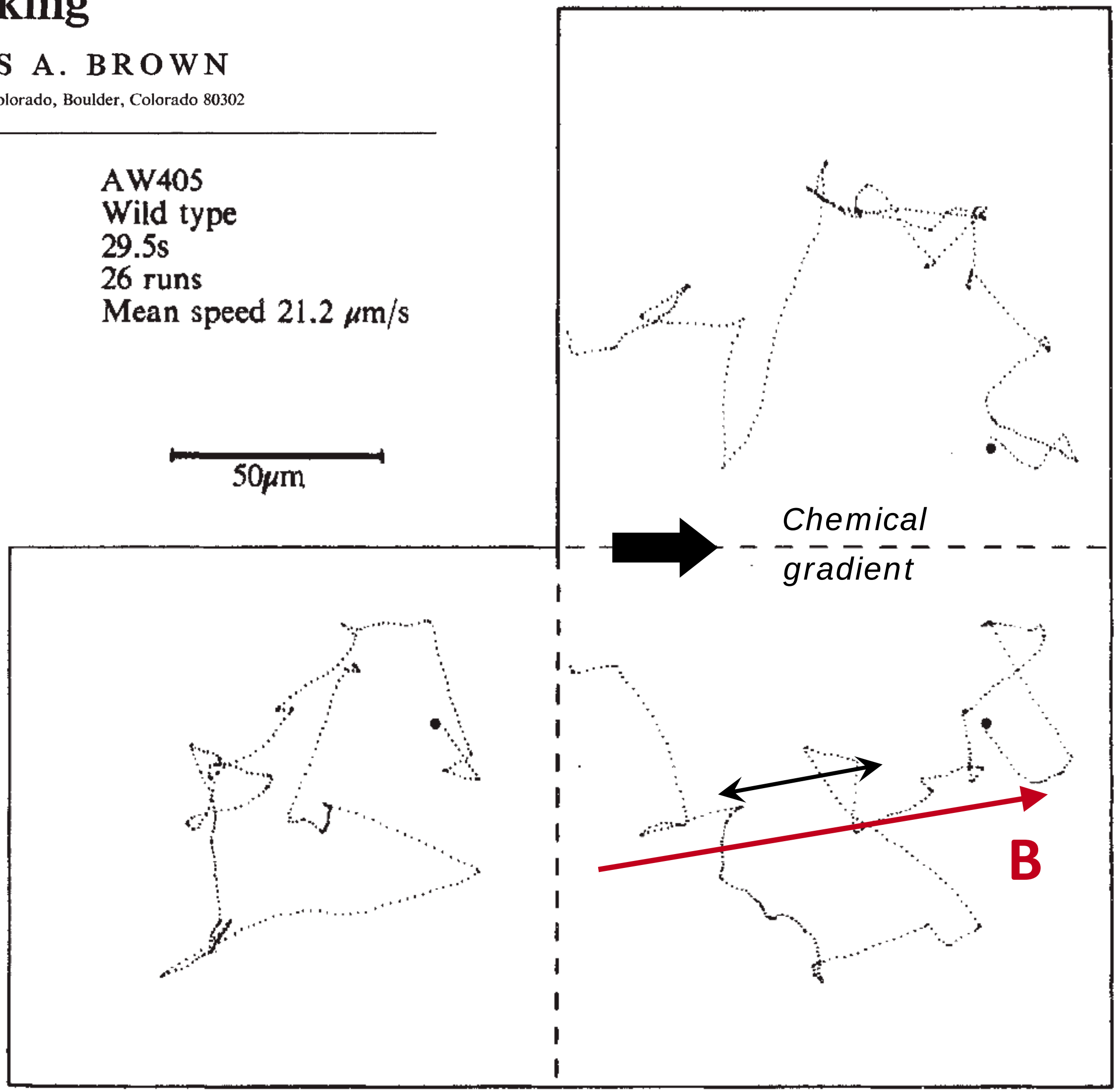
How do bugs move around blindfolded

Chemotaxis in *Escherichia coli* analysed by Three-dimensional Tracking

HOWARD C. BERG & DOUGLAS A. BROWN

Department of Molecular, Cellular and Developmental Biology, University of Colorado, Boulder, Colorado 80302

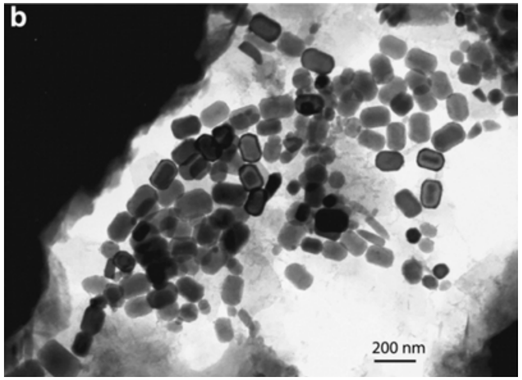
AW405
Wild type
29.5s
26 runs
Mean speed 21.2 μm/s

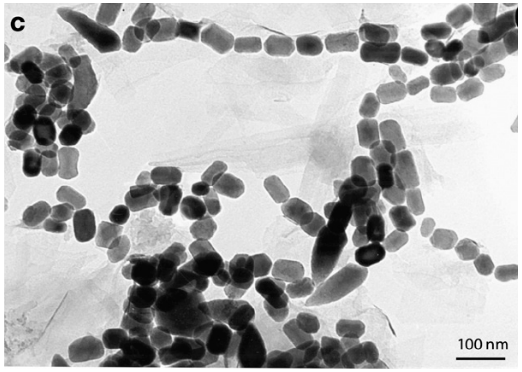


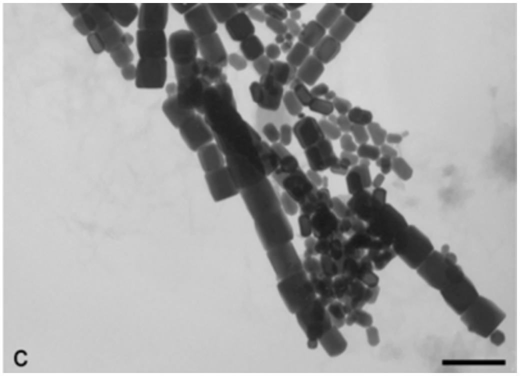
Chemotaxis:
Biased 3-D random walk

Magneto-chemotaxis:
Biased 1-D random walk

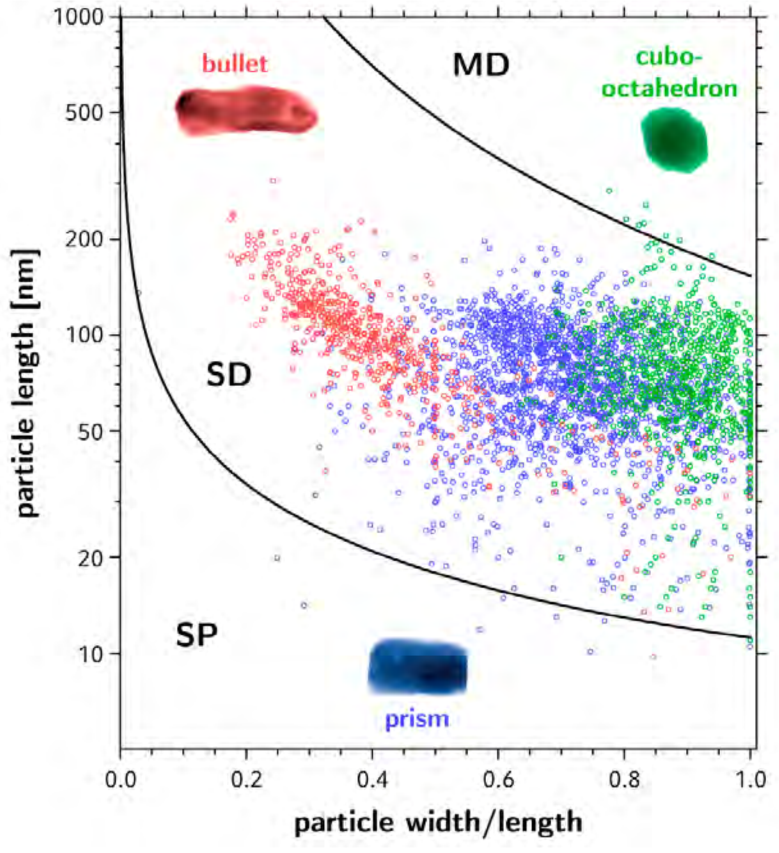
Fossil remains of magnetotactic bacteria: magnetofossils



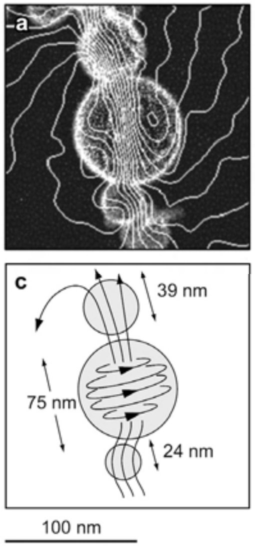


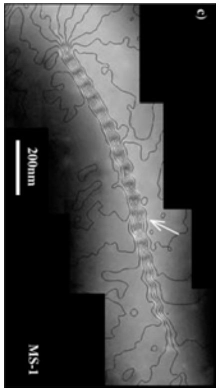


Summary of ~4000 TEM observations of fossil magnetosomes:

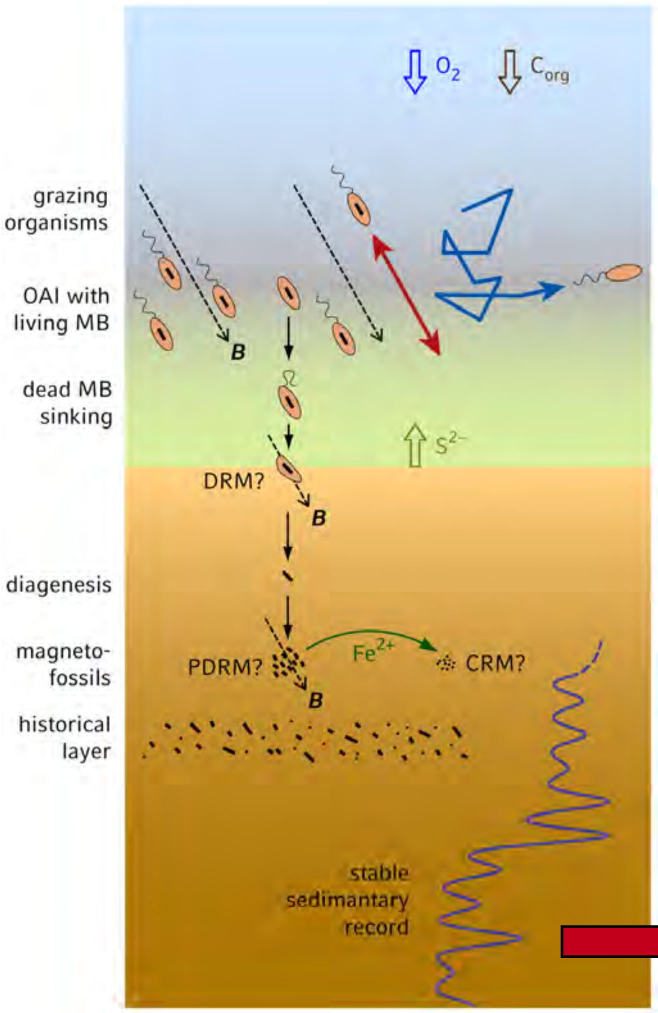


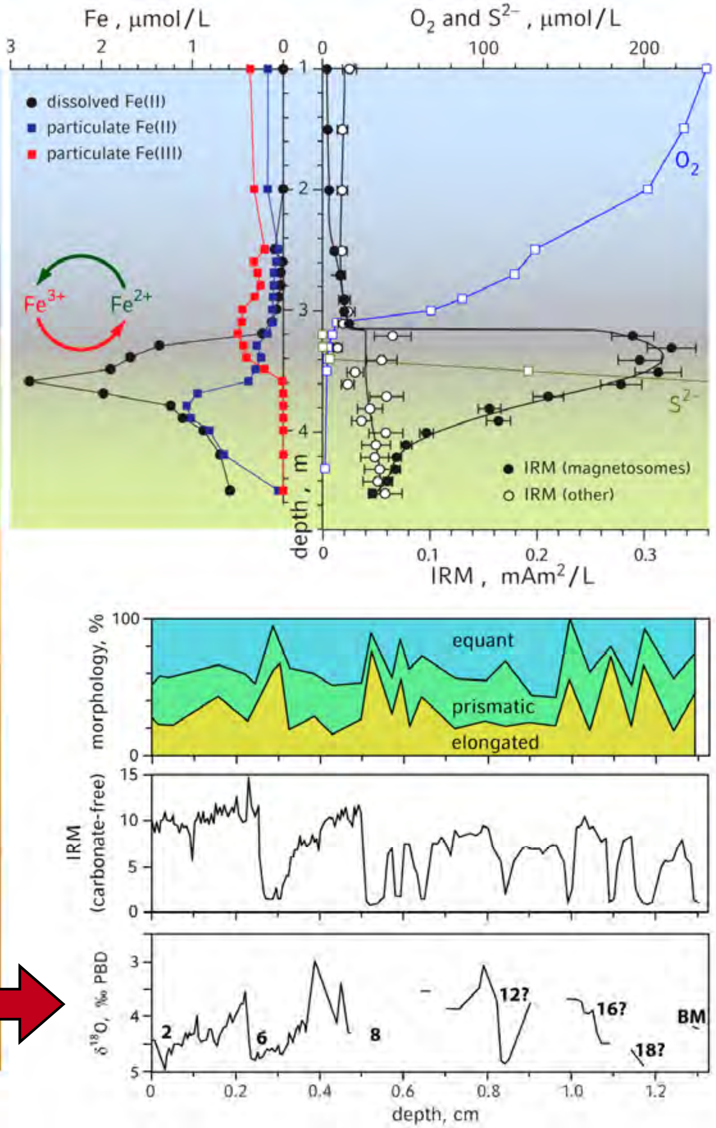
Egli et al., in prep.



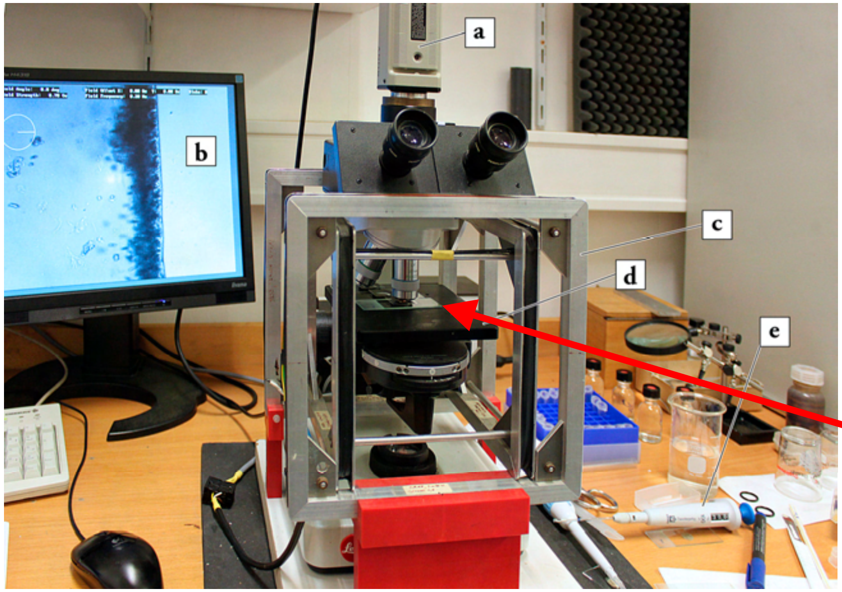


How magneto-chemotaxis works

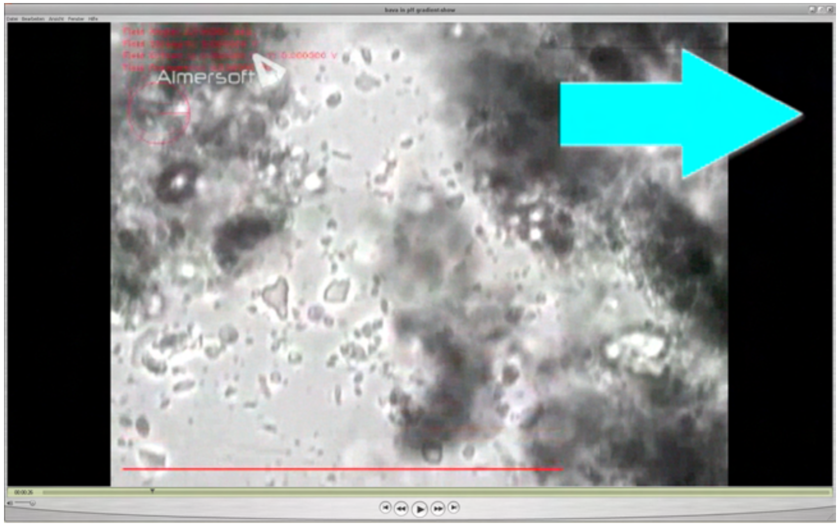




The first direct observation of magneto-chemotaxis



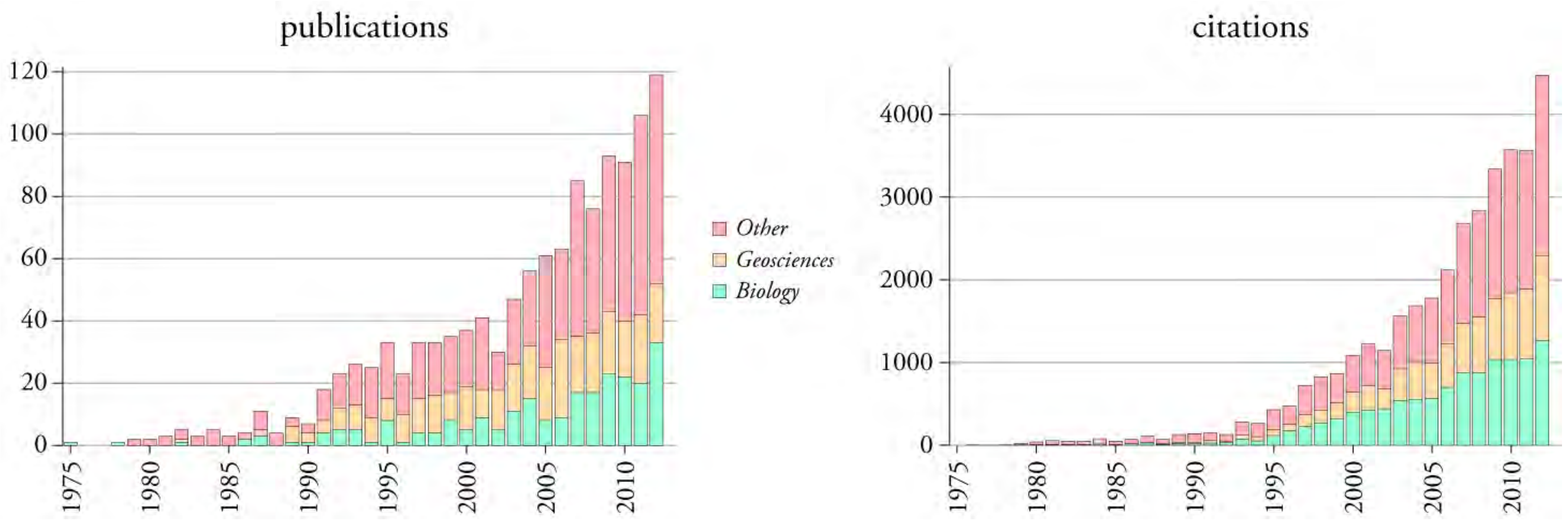
[*Mao and Egli*, 2013]



The growing interdisciplinary interest around MB

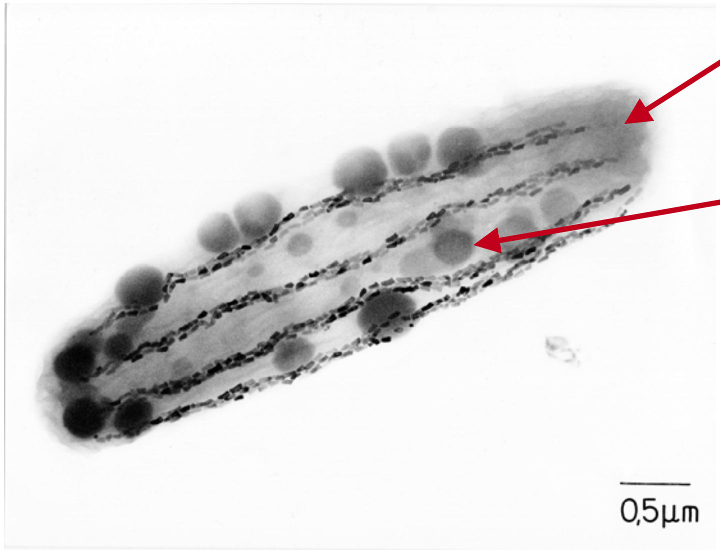
ISI publication and citation numbers related to the keywords:

Magnetotactic bacteria,
Magnetosomes,
Magnetofossils
Biogenic magnetite



The outsider: *Magnetobacterium bavaricum*

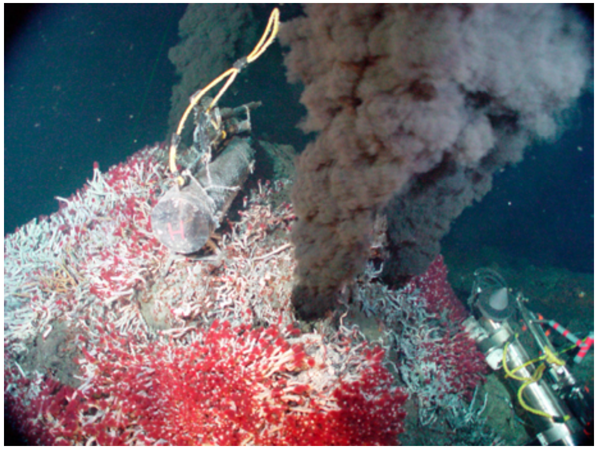
Magnetobacterium bavaricum



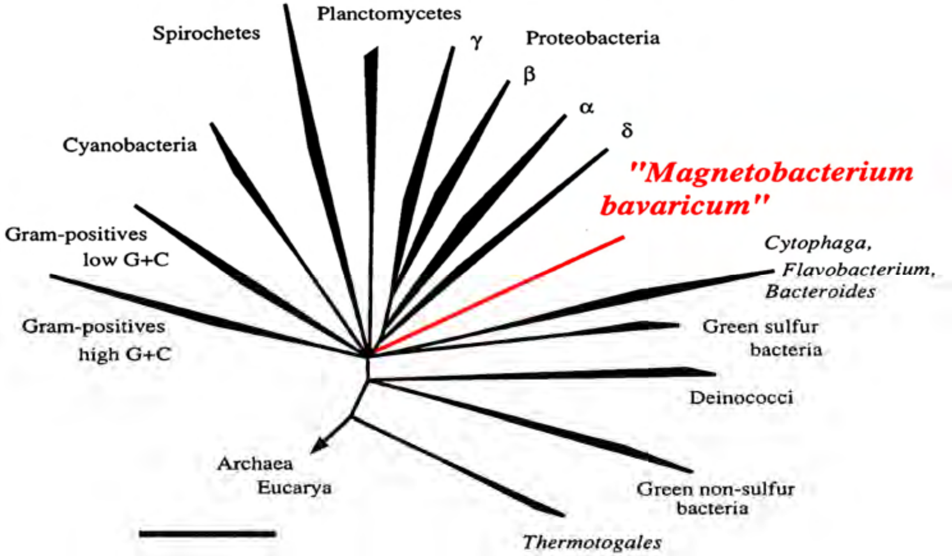
Chain bundles of tooth-shaped magnetosomes
~100 times more than required for magnetotaxis

Elementar sulfur inclusions
~1000 times more Fe and S than in any known organism

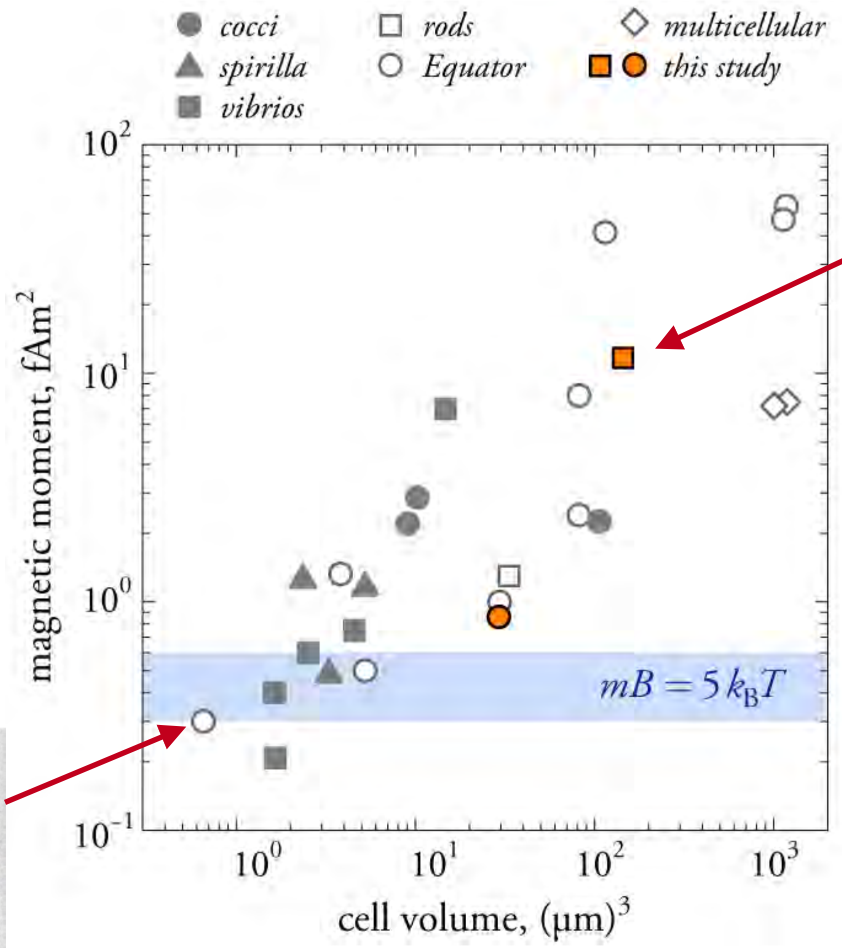
Origin from Hydrothermal vents ?

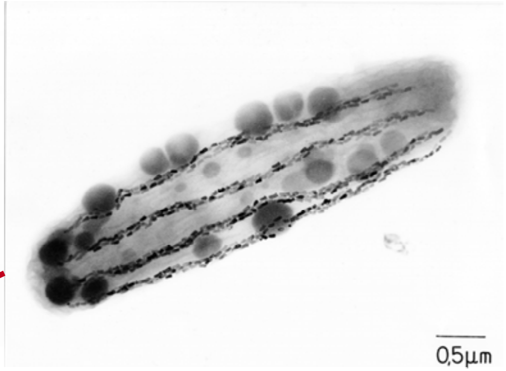


Very ancient organism
Branched from common ancestor ~3 Gyr BP.



Current magetotaxis models clash with natural selection



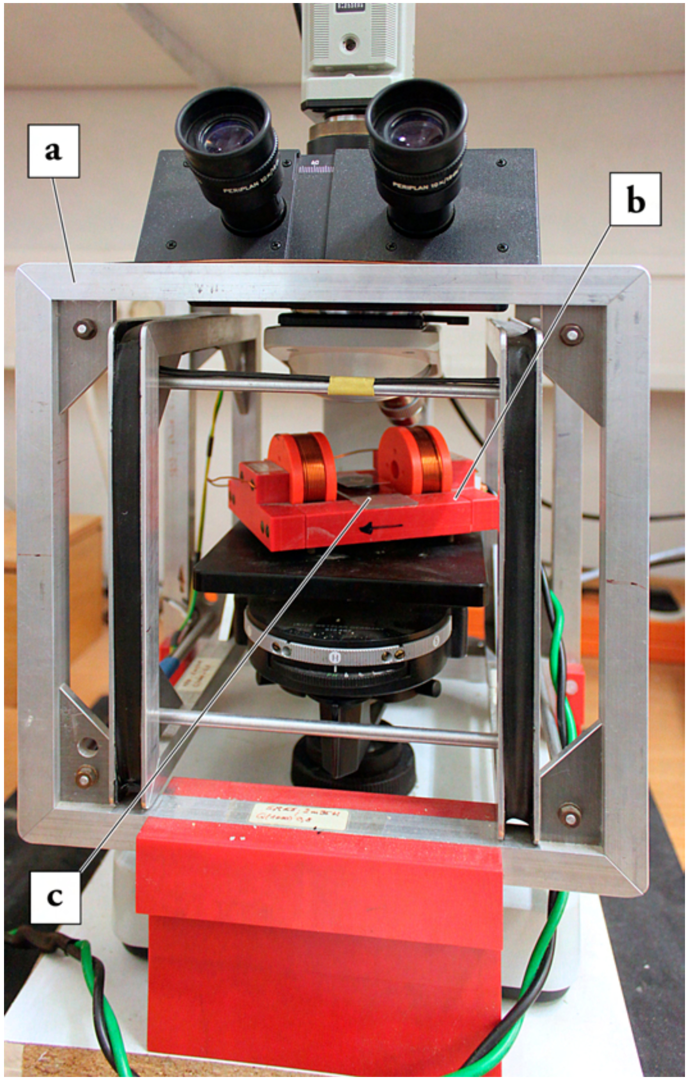


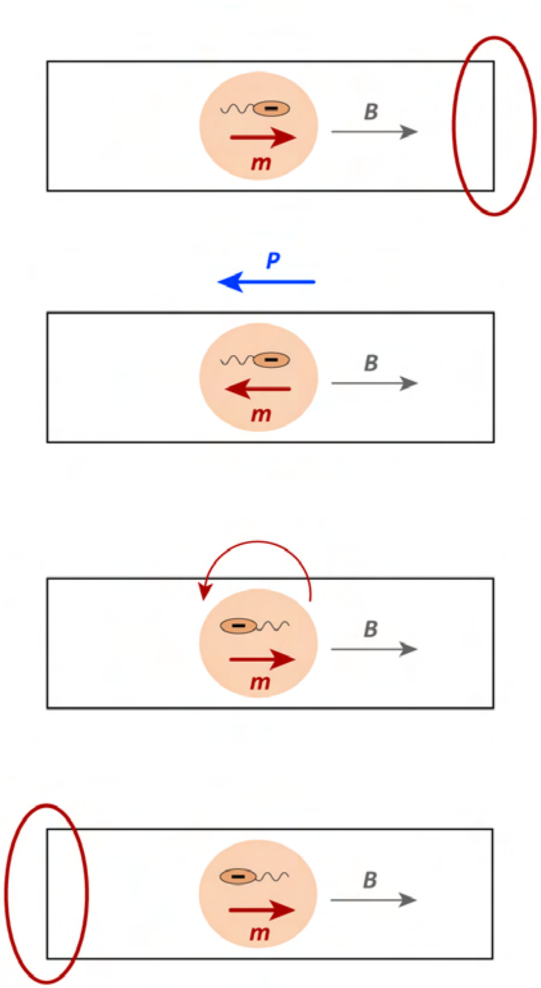
M. bavaricum

Spirilla

[*Mao and Egli*, 2013]

How is magnetotactic life inside sediment ?





100% „normal“
North-seeking cells

A strong pulse is
given against
existing field

Magnetically
switched cells rotate
180°

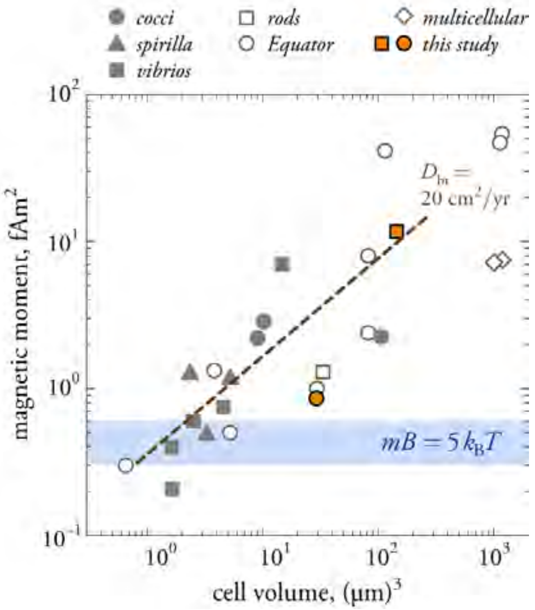
100% switched
South-seeking cells

~48% South-seeking cells
⇒ 1% alignment in the Earth magnetic field.

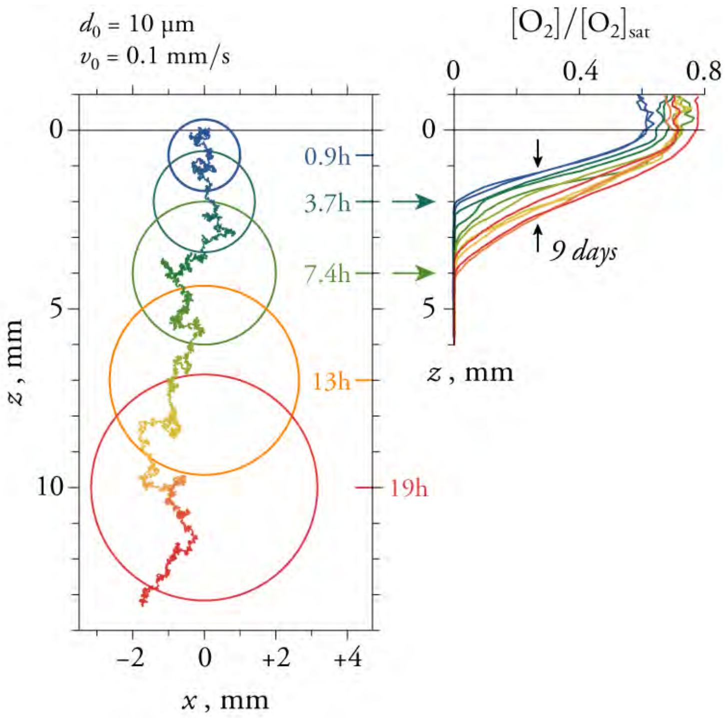
[*Mao and Egli*, 2013]

A revised magnetotaxis model

- *Large cells require large magnetic moments to overcome sediment interaction.*



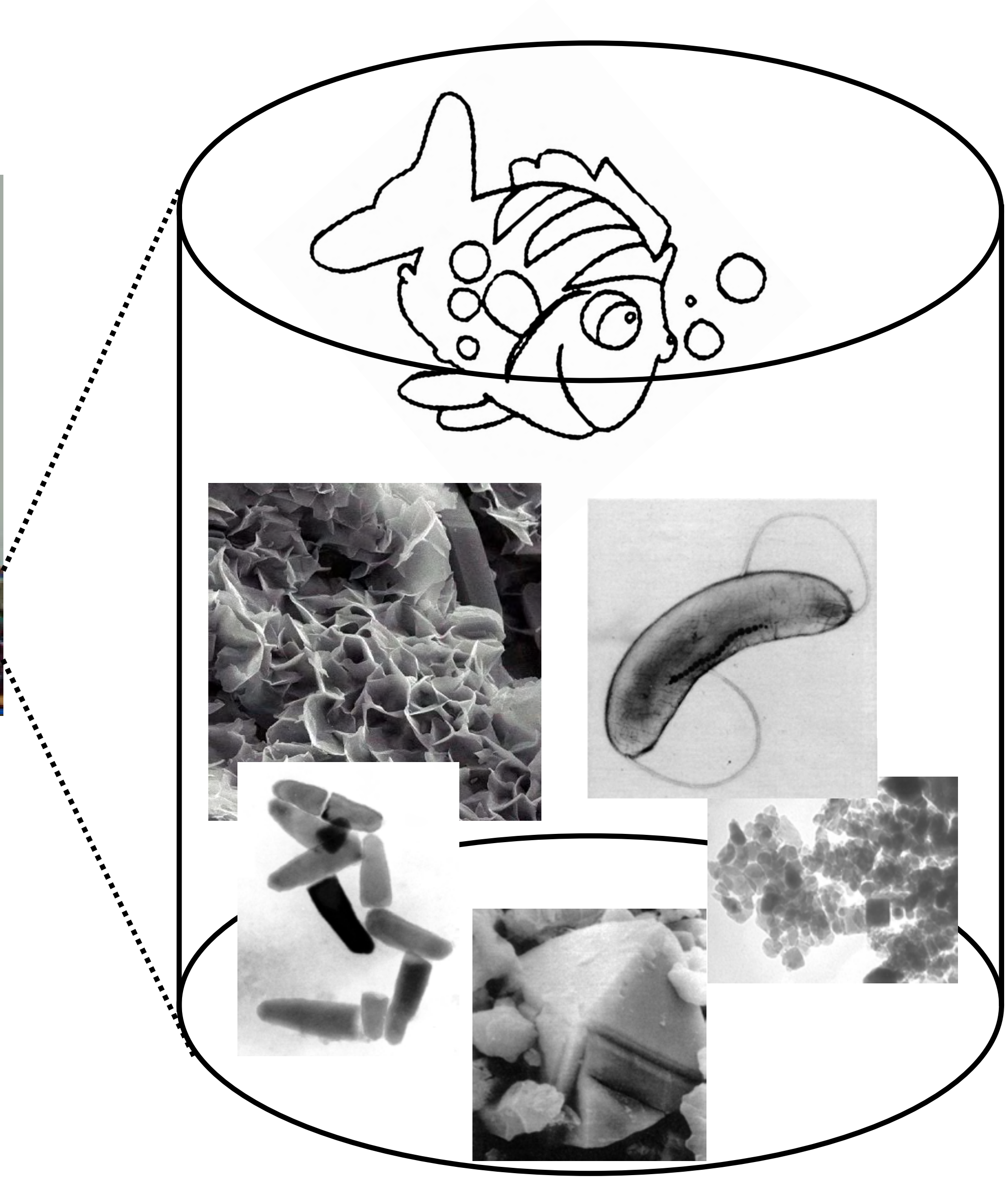
- *Magnetotaxis provides a biological advantage only for macroscopic displacements.*



⇒ New magnetotaxis model with active vertical shuttling for alternating redox conditions

[*Mao and Egli*, 2013]

Back to sediment selection



- detrital magnetite
- magnetosomes
- pedogenic magnetite
- goethite
- …

Hysteresis properties in a nutshell

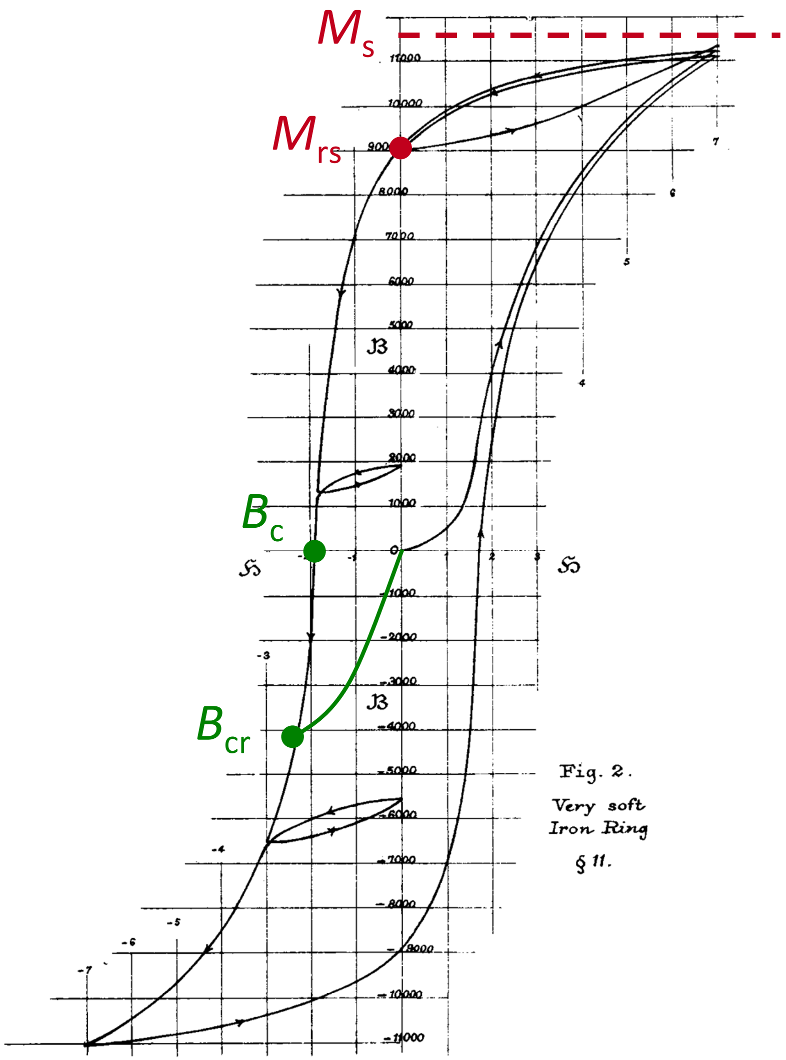
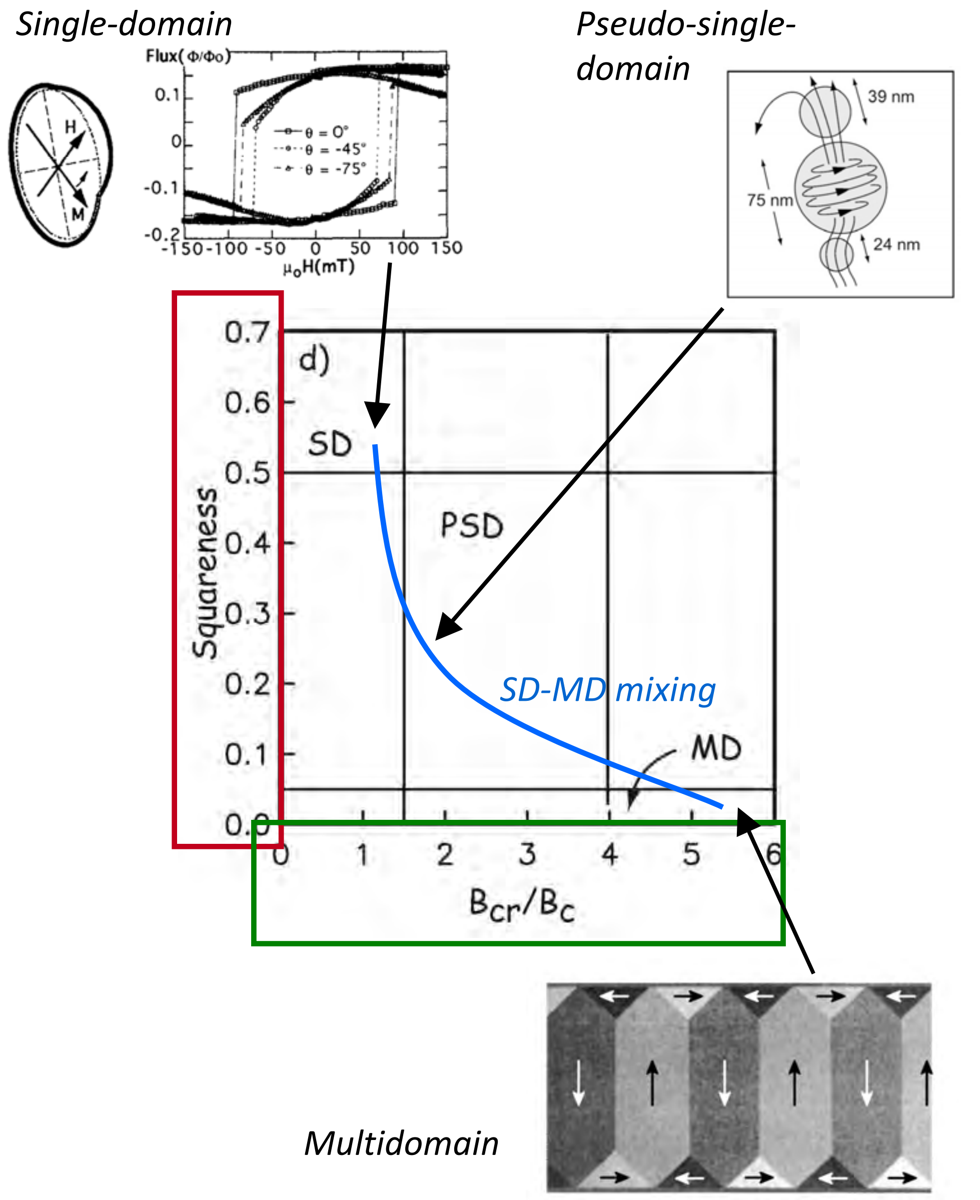


Fig. 2.
Very soft
Iron Ring
§ 11.

West Newman & Co. lith.

[*Ewing*, 1885]



Single-domain

Pseudo-single-domain

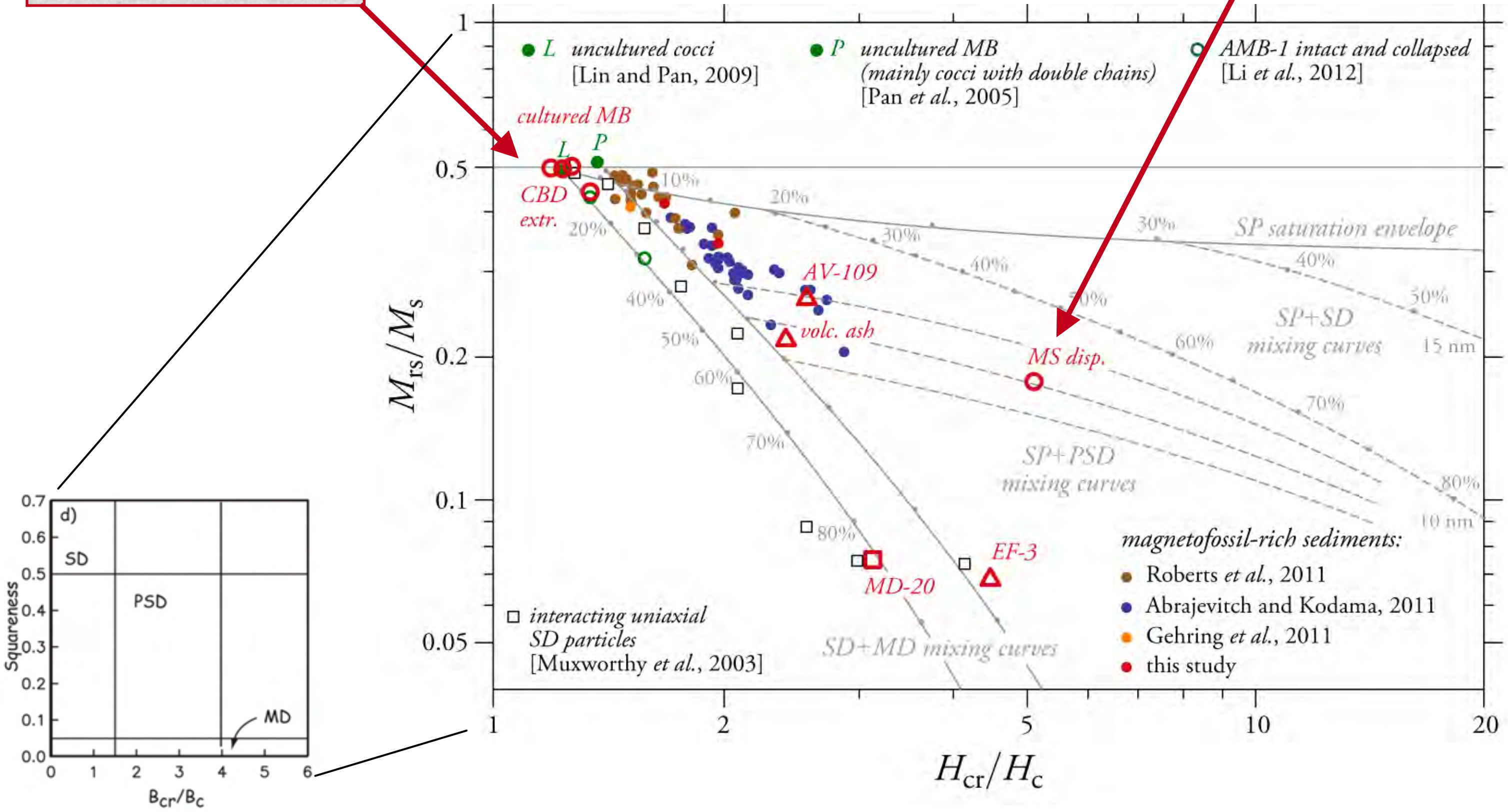
SD-MD mixing

Multidomain

Simple magnetic parameters don‘t work with mud

Cultured magnetotactic bacteria

Dispersed magnetotactic bacteria chains



The “multiproxy approach”: opening the Pandora box

Magnetic parameters:

- χ_{ARM}/χ

  „King plot“: grain size

- M_{rs}/M_s

  „Remanence ratio“: grain size

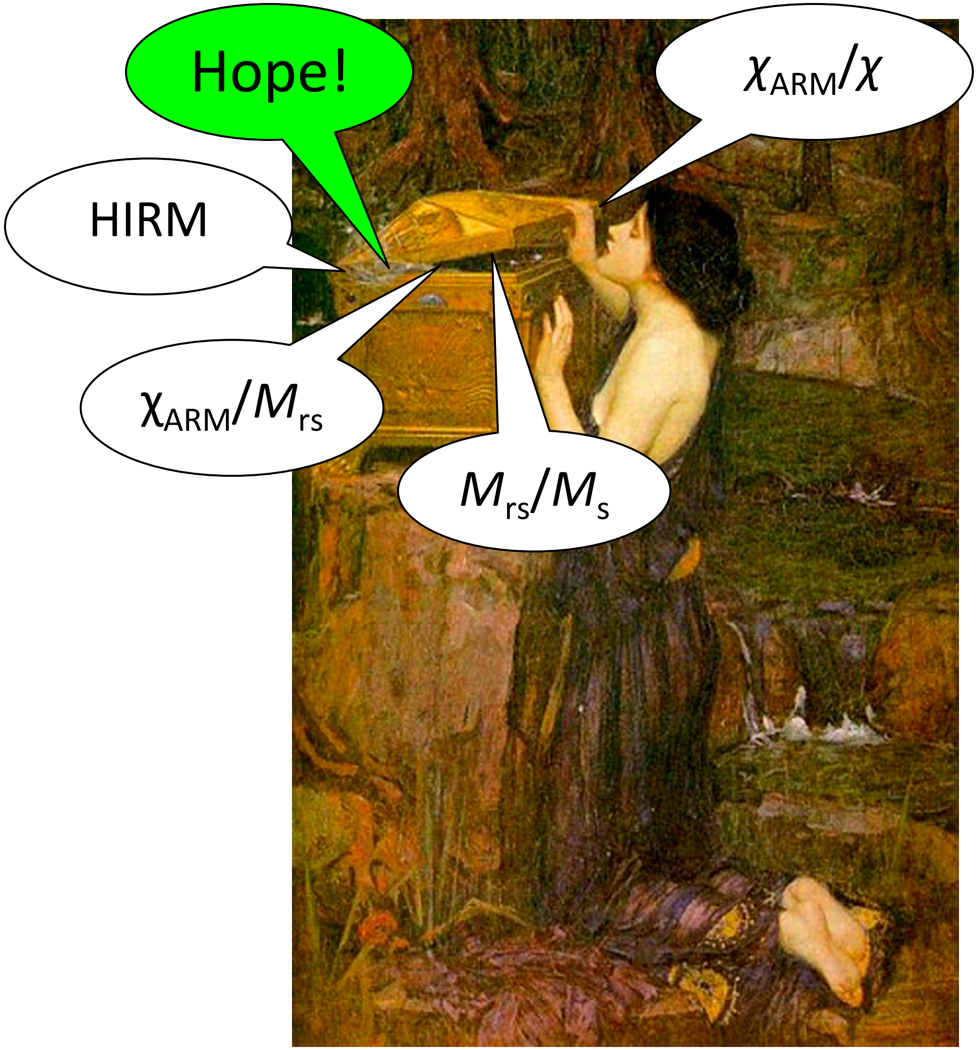
- χ_{ARM}/M_{rs}

  „ARM ratio“, SD grains

- HIRM

  „Hard IRM“, high-coercivity minerals

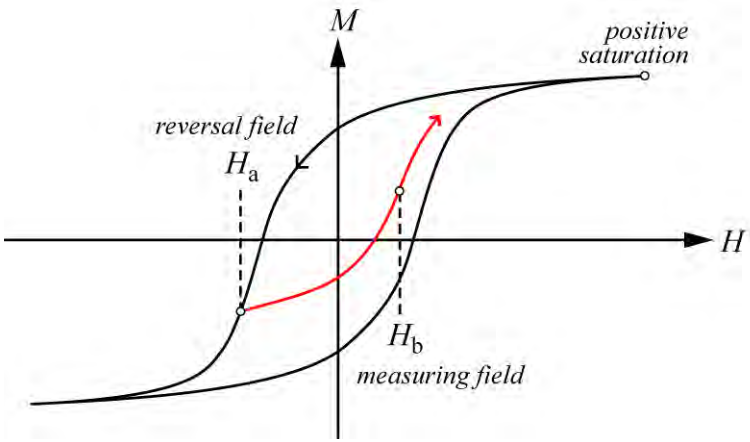
…

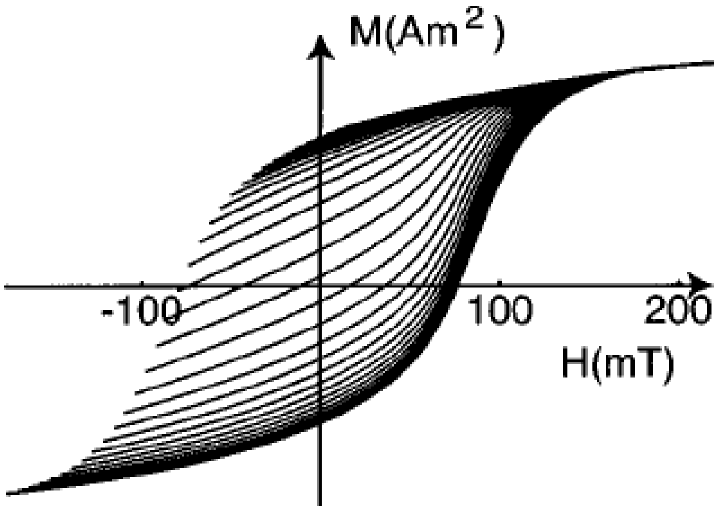


John William Waterhouse: Pandora (1896)

Recent solution: FORC diagrams

Hysteresis measurements:



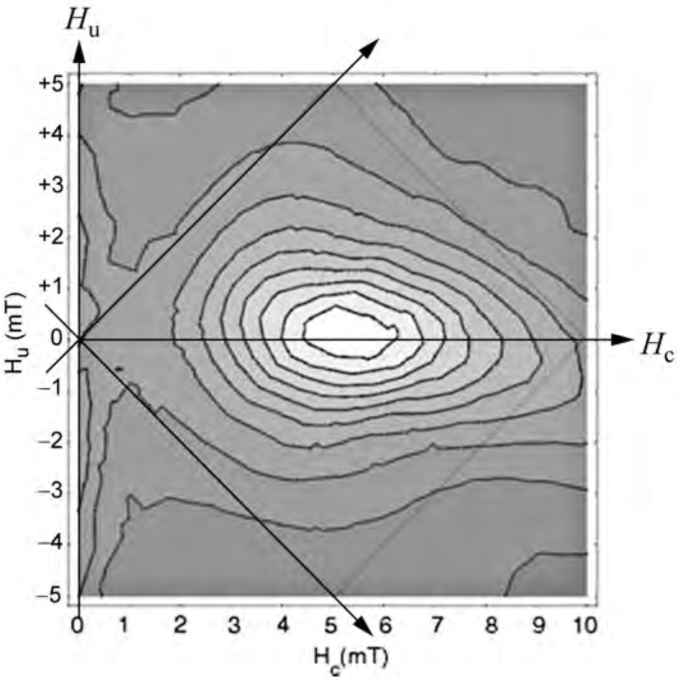


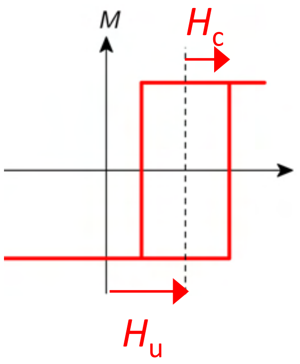
Mapping the „FORC space“:

FORC function: $$\rho(H_a, H_b) = -\frac{\partial^2 M}{\partial H_a \partial H_b}$$

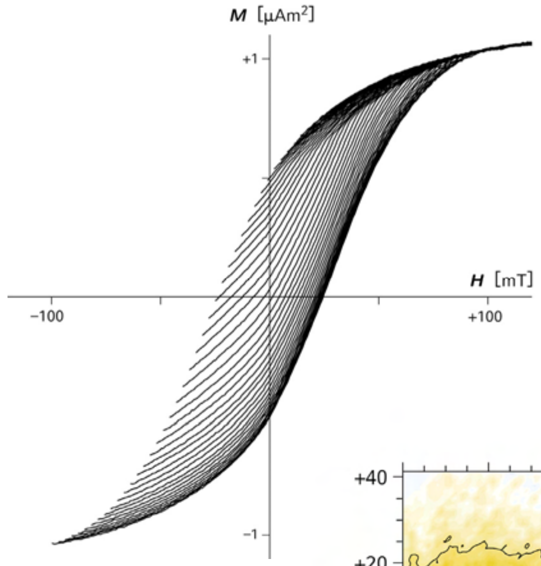
FORC space: $$H_c = \tfrac{1}{2}(H_b - H_a)$$
$$H_u = \tfrac{1}{2}(H_b + H_a)$$

FORC diagram:





Identifying magnetite nanoparticles in sediment



Central ridge

A signature of non-interacting SD particles and linear magnetosome chains.


Geochemistry
Geophysics
Geosystems
G^3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 11, Number 1
27 January 2010
Q01Z11, doi:10.1029/2009GC002916
ISSN: 1525-2027

Click Here for Full Article

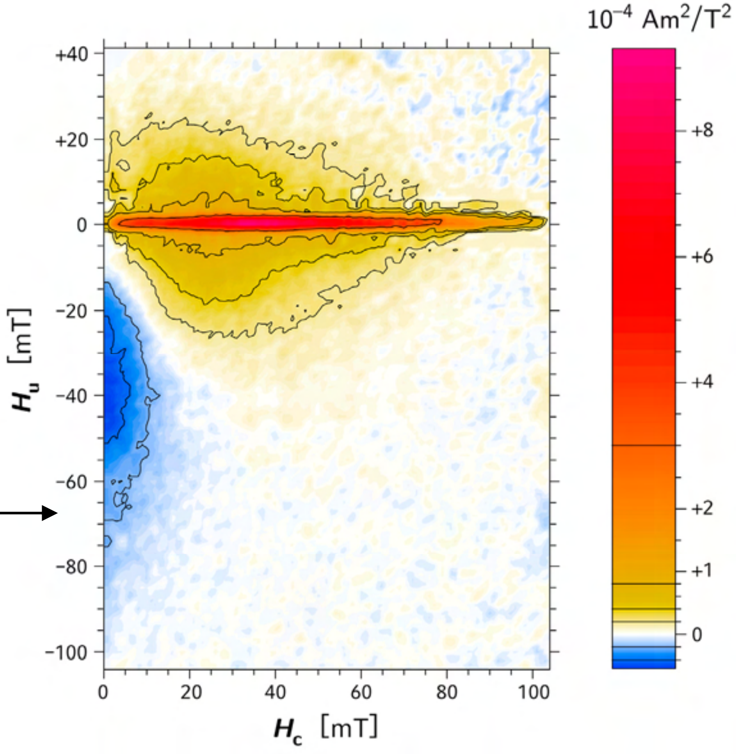
Detection of noninteracting single domain particles using first-order reversal curve diagrams

Ramon Egli, Amy P. Chen, and Michael Winklhofer
Department of Earth and Environmental Sciences, Ludwig-Maximilians University, Theresienstrasse 41, D-80333 Munich, Germany (egli@geophysik.uni-muenchen.de)

Kenneth P. Kodama
Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, Pennsylvania 18015-3188, USA

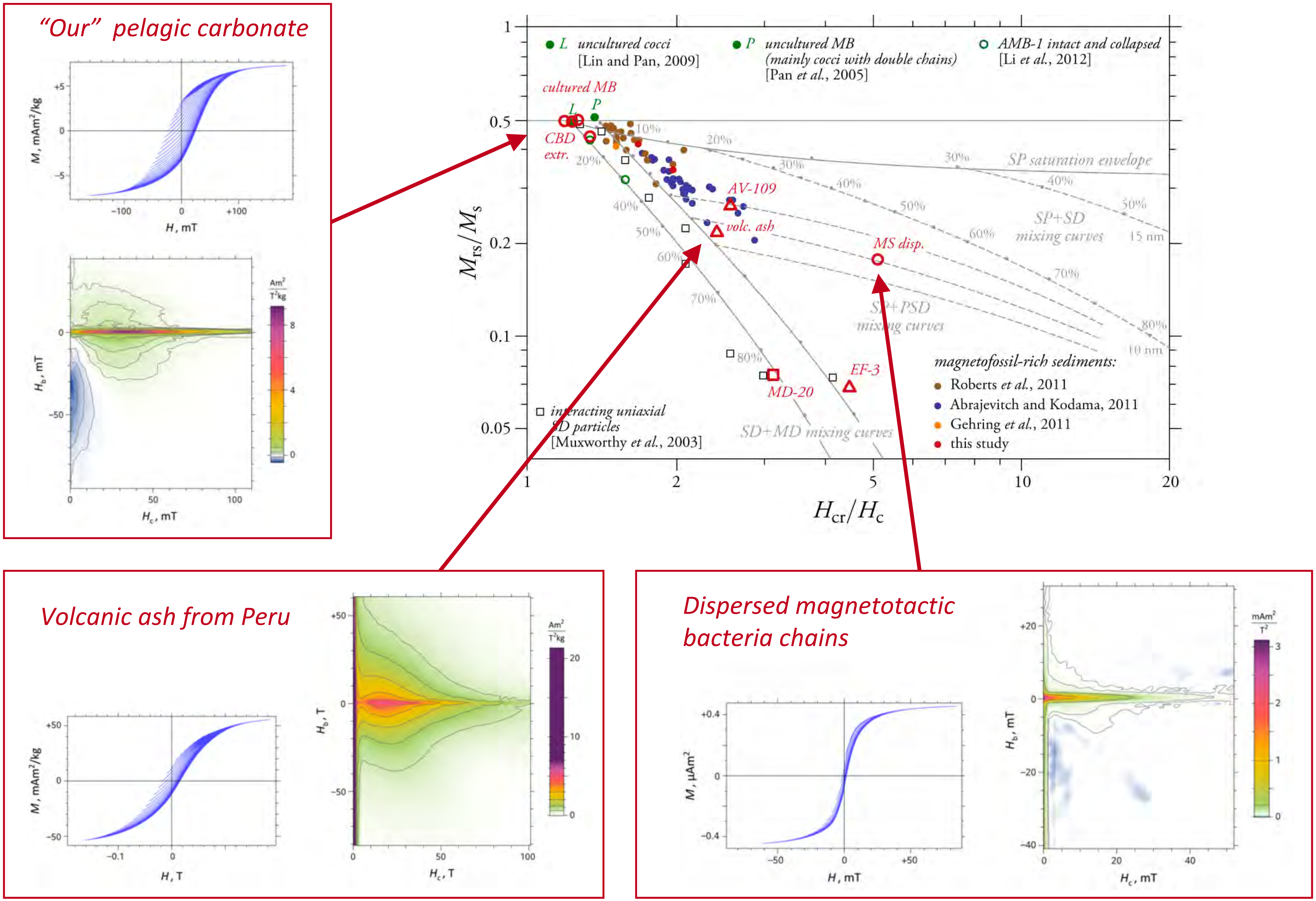
Chorng-Shern Horng
Institute of Earth Sciences, Academia Sinica, PO Box 1-55, Taipei 115, Taiwan

FORC measurement of a magnetofossil-rich lake sediment sample from Lake Ely.



Central ridge +
Rorschach-Test-like background

FORC diagrams work also with complex mixtures



“Our” pelagic carbonate

Volcanic ash from Peru

Dispersed magnetotactic bacteria chains

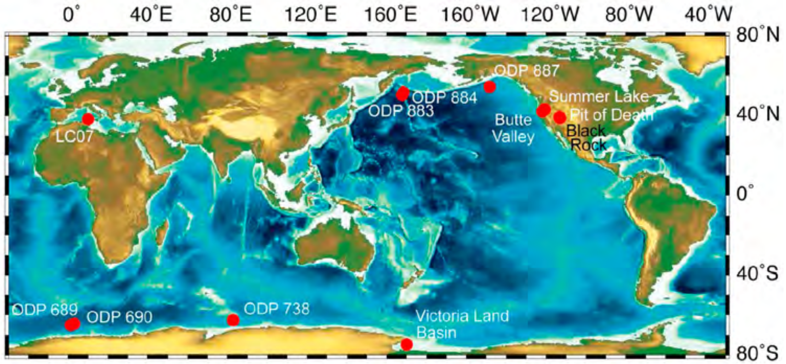
Are magnetofossils ubiquitous in marine sediment?

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, B08104, doi:10.1029/2012JB009412, 2012

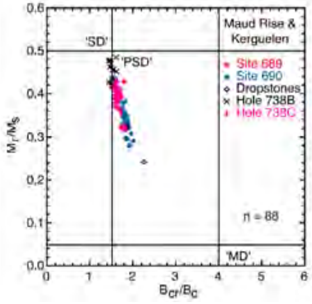
Searching for single domain magnetite in the "pseudo-single-domain" sedimentary haystack: Implications of biogenic magnetite preservation for sediment magnetism and relative paleointensity determinations

Andrew P. Roberts,[1,2] Liao Chang,[1,3] David Heslop,[2] Fabio Florindo,[4] and Juan C. Larrasoaña[2,5]

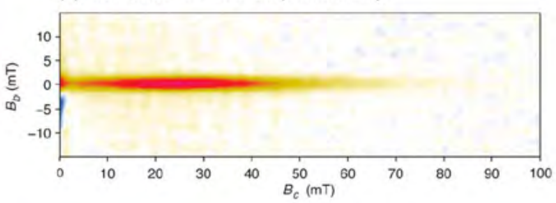
Received 30 April 2012; revised 5 July 2012; accepted 10 July 2012; published 22 August 2012.



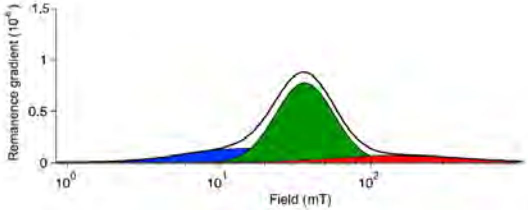
Biogenic marine sediments



(e) ODP 690C–7H–1A–30 (54.90 mbsf)

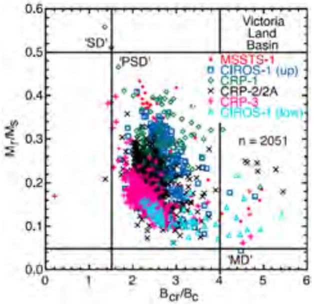


High-resolution FORC with central ridge

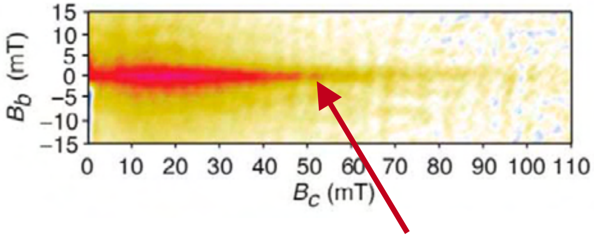


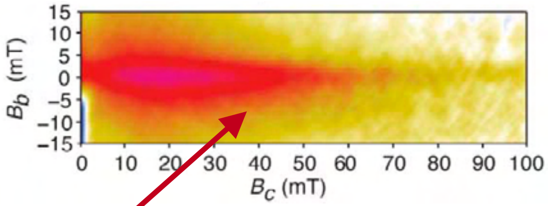
Coercivity analysis with biogenic components

Glaci-marine sediments



CRP–1 145.15 m

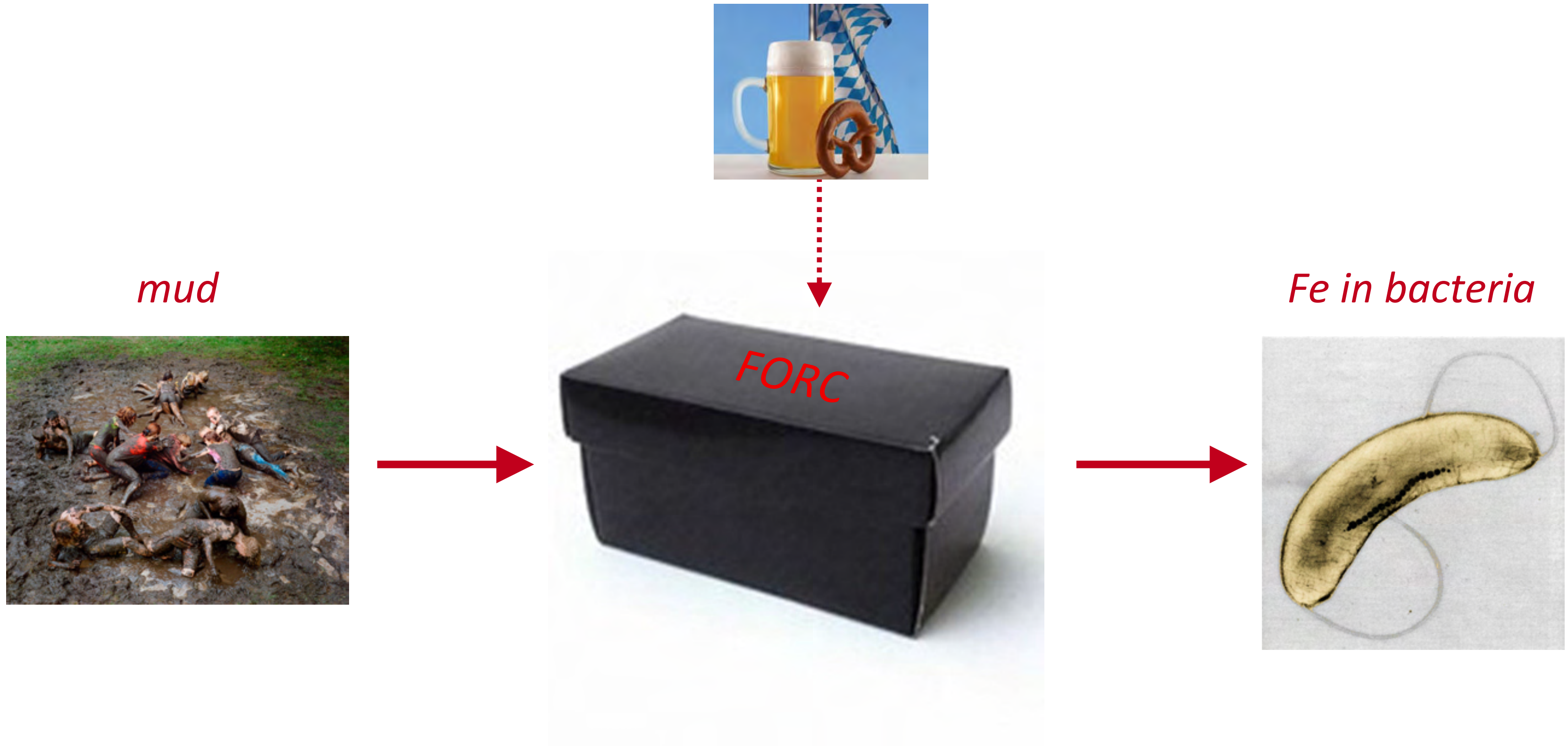




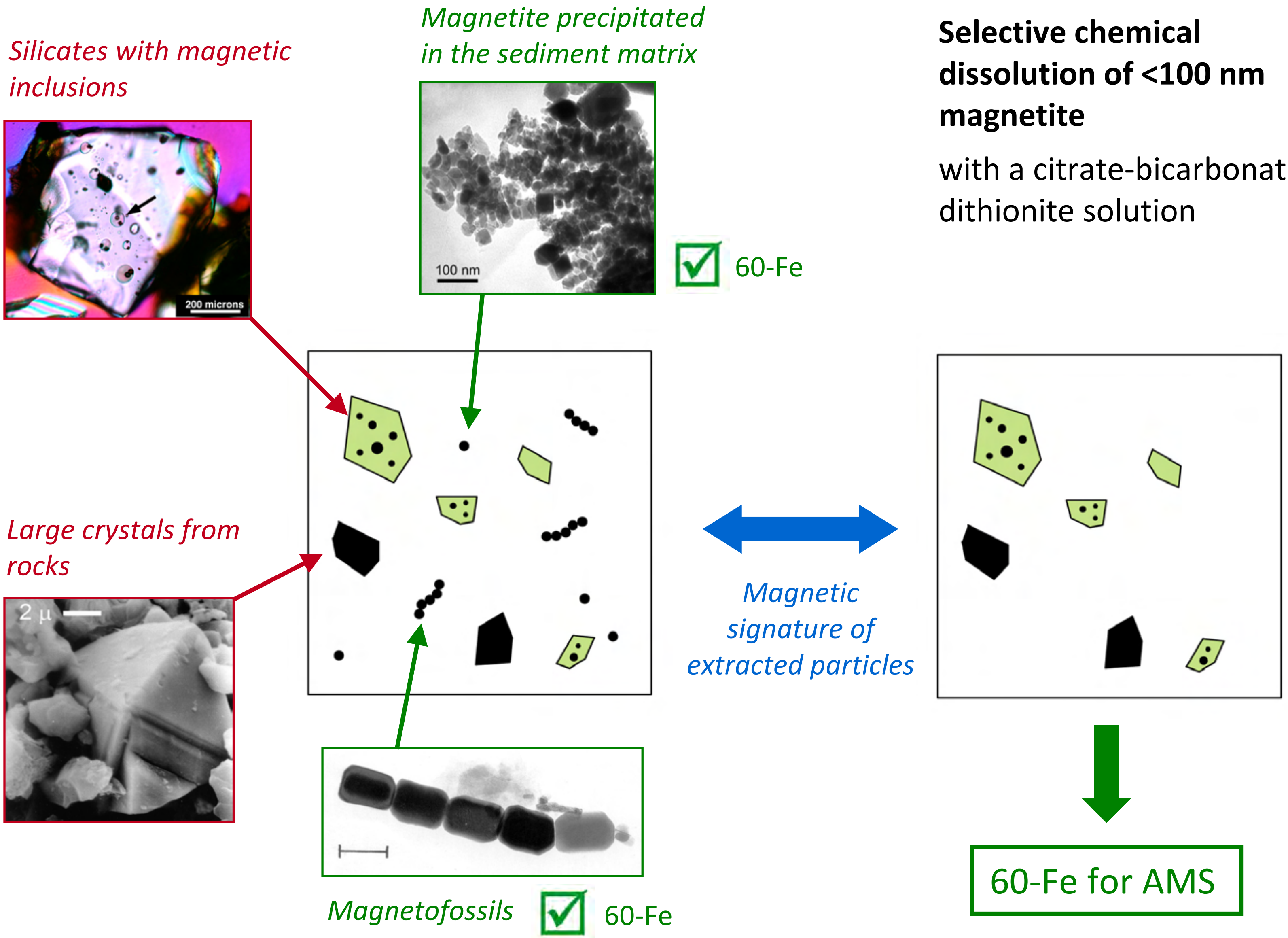
Are these central ridges?

Model verification

Are we sure about our model ?



The principle of selective chemical extraction



Silicates with magnetic inclusions

Large crystals from rocks

Magnetite precipitated in the sediment matrix

☑ 60-Fe

Magnetofossils ☑ 60-Fe

Magnetic signature of extracted particles

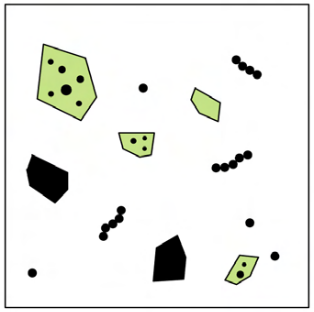
Selective chemical dissolution of <100 nm magnetite

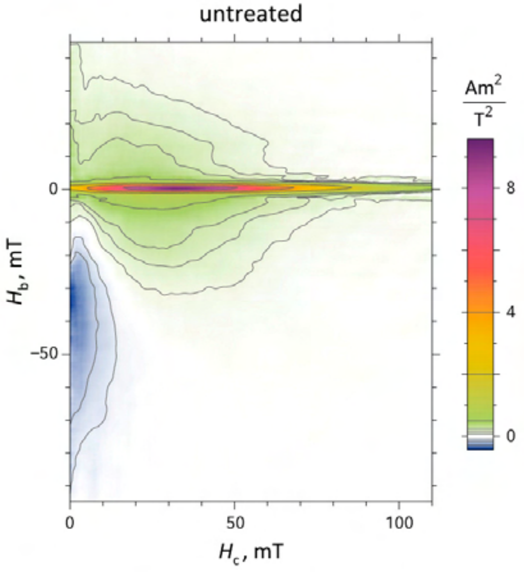
with a citrate-bicarbonate-dithionite solution

60-Fe for AMS

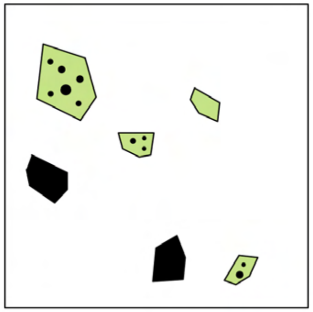
Validation of FORC results

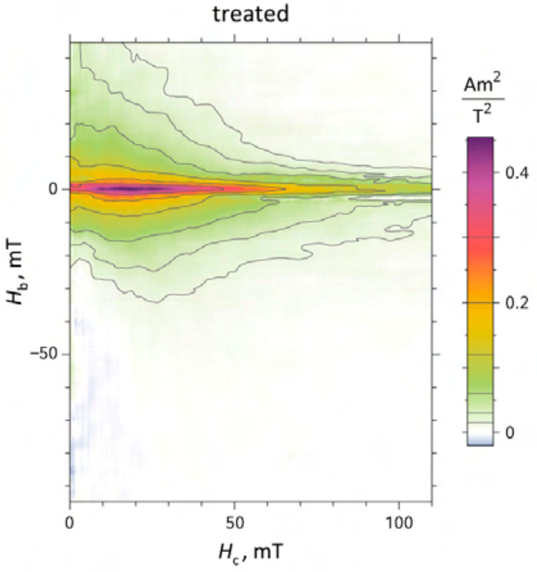
Before dissolution



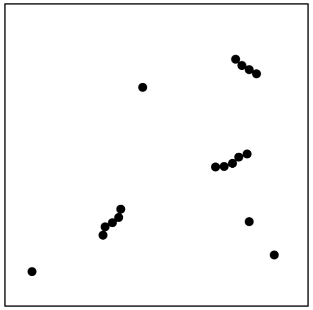


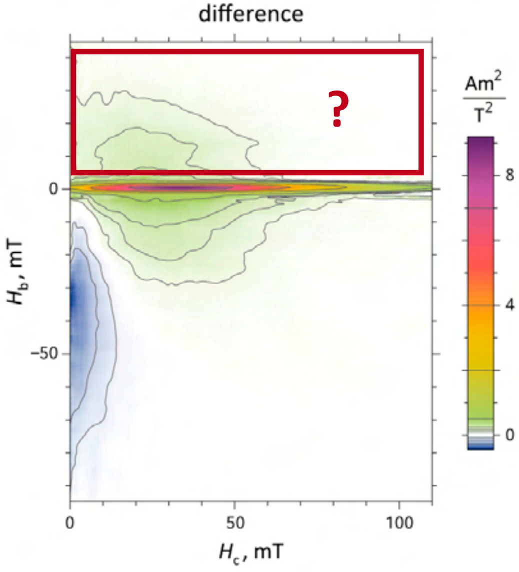
After dissolution





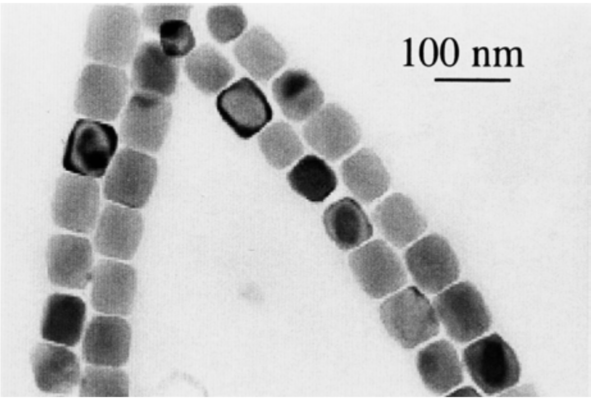
Dissolved minerals

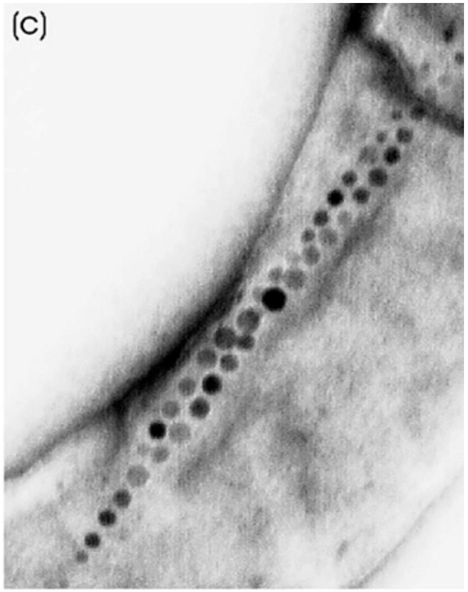




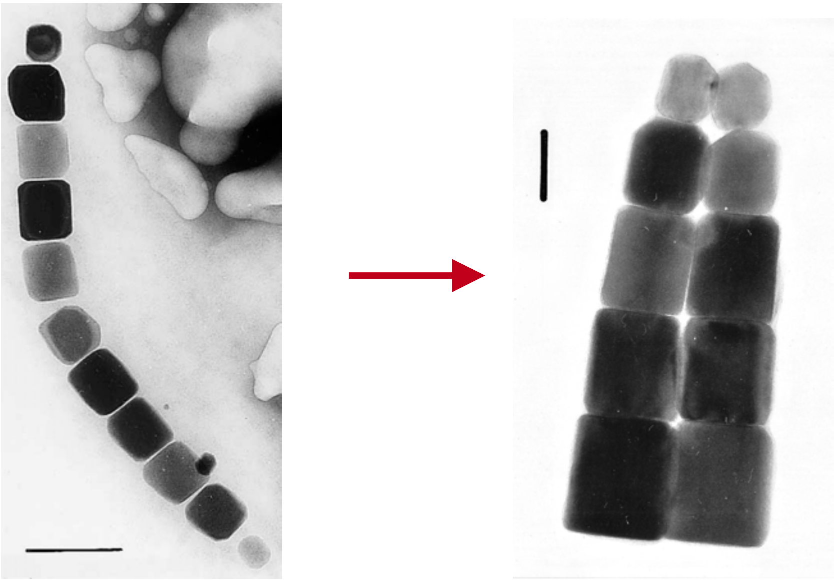
Geometry matters: magnetofossil configurations

Double chains

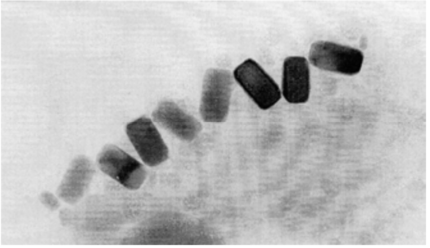


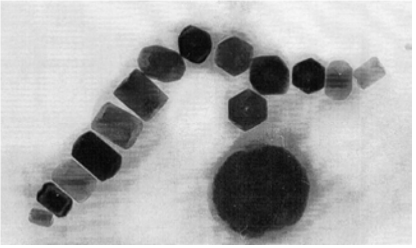


„Jackknife-collapsed“ chains



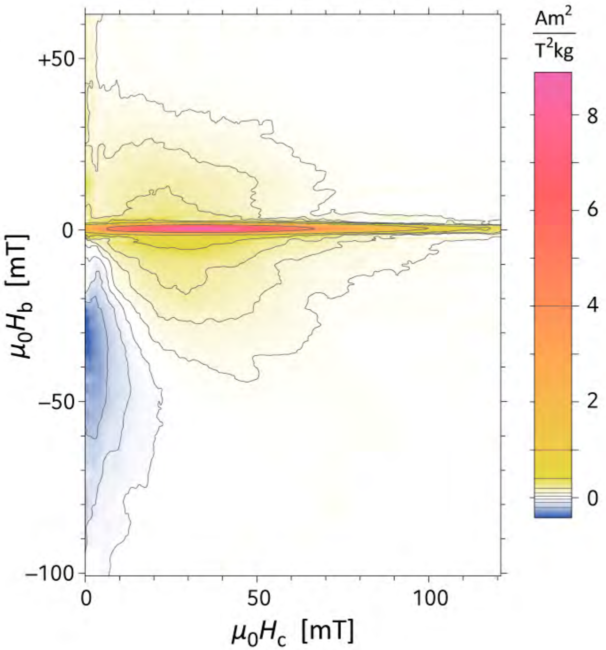
„Zigzag-collapsed“ chains





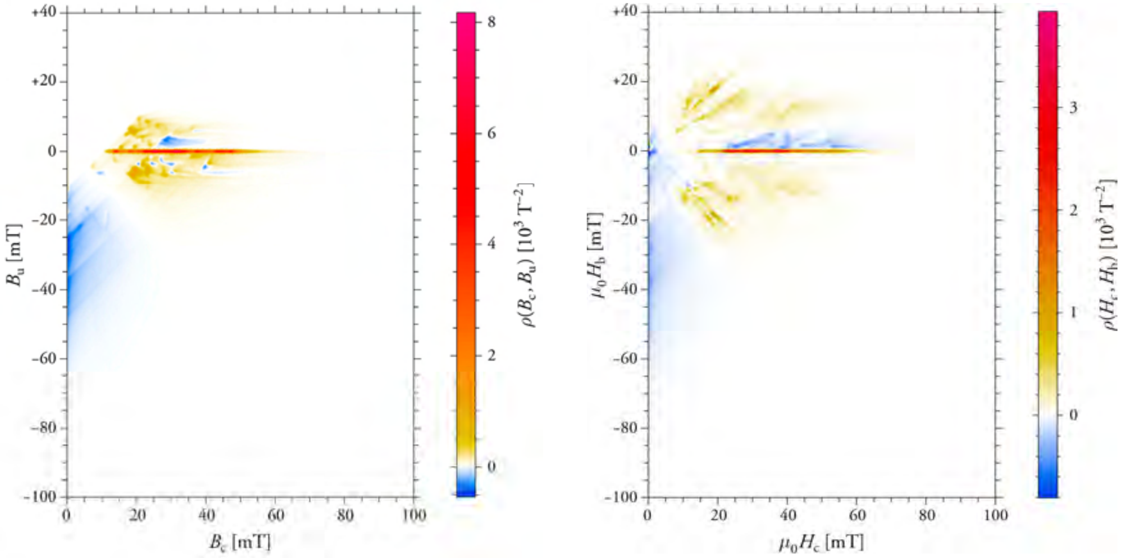
“Rorshach-test-like” FORC signatures are of bacterial origin!

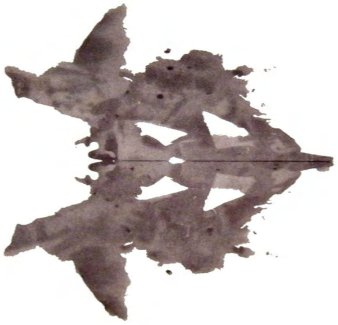
Secondary magnetite
in pelagic carbonate



Ludwig et al., 2013

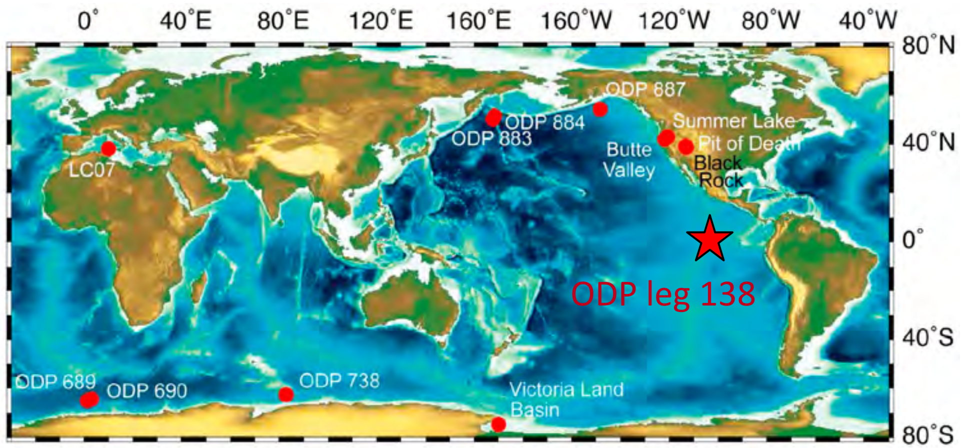
Micromagnetic calculations for double chains and
“jackknife-collapsed” chains





Egli and Winklhofer, in prep.

Our final results

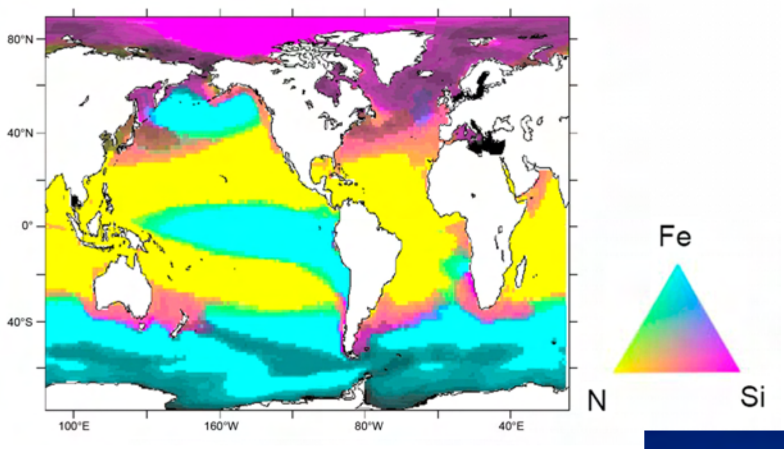


Some facts about our sediment core:

- Fe concentration from magnetite: 6.0×10^{-5} (g Fe)/(g sediment),
- Chemically extractable Fe: 10×10^{-5} (g Fe)/(g sediment),
- ~55% of chemically extractable Fe was contained in ferrimagnetic minerals,
- ~30-50% of chemically extractable Fe was contained in magnetofossils,
- 60-90% of all secondary magnetite was produced by magnetotactic bacteria,
- $(1\text{-}60) \times 10^8$ cells/cm^3 were needed to produce the observed magnetofossil concentration,
- Considering the sedimentation rate, $(2\text{-}100) \times 10^4$ cells/cm^3 grew every year,
- The estimated lifespan of individual cells is 0.4-20 days,
- The total Fe content of the sediment is 1.5-3.5 wt%,
- Leaching all Fe with a total extraction would yield a 100 × ^{60}Fe dilution.

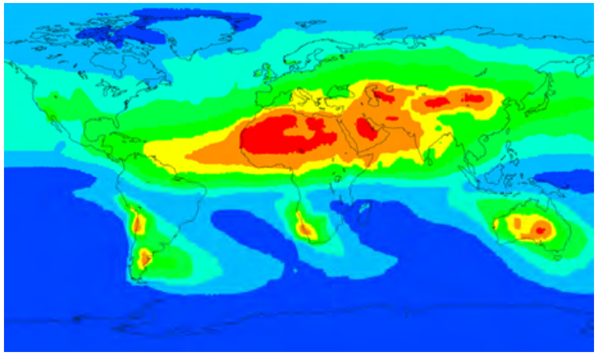
The 60-Fe giant tracer experiments

Limiting elements for phytoplankton:



[PISCES model for diatoms, *Aumont et al.*, 2003]

Iron supply to the ocean:



[*Mahowald et al.*, 2005]