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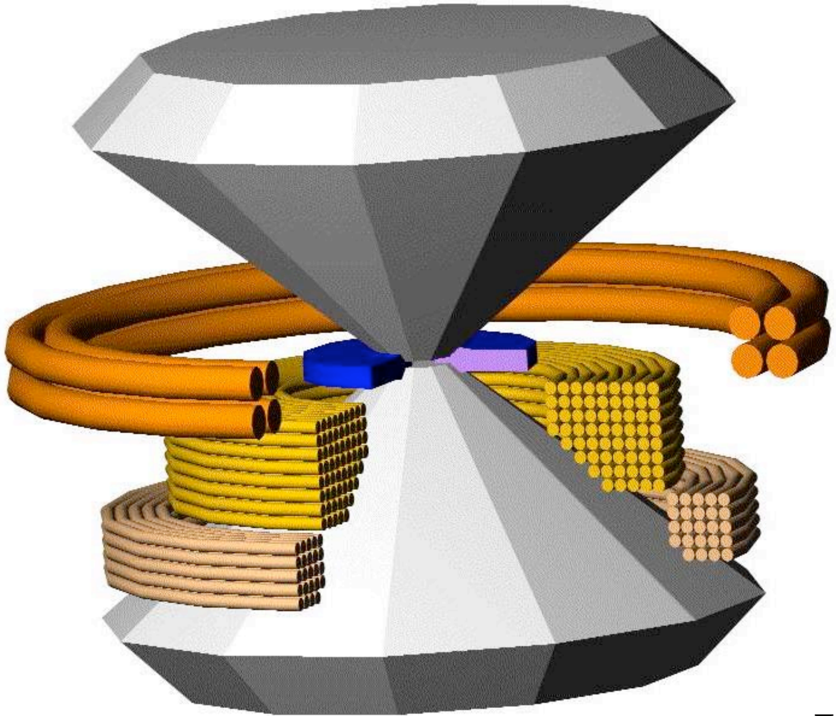
GEOPHYSICS
DEPARTMENT OF EARTH AND ENVIRONMENTAL SCIENCES



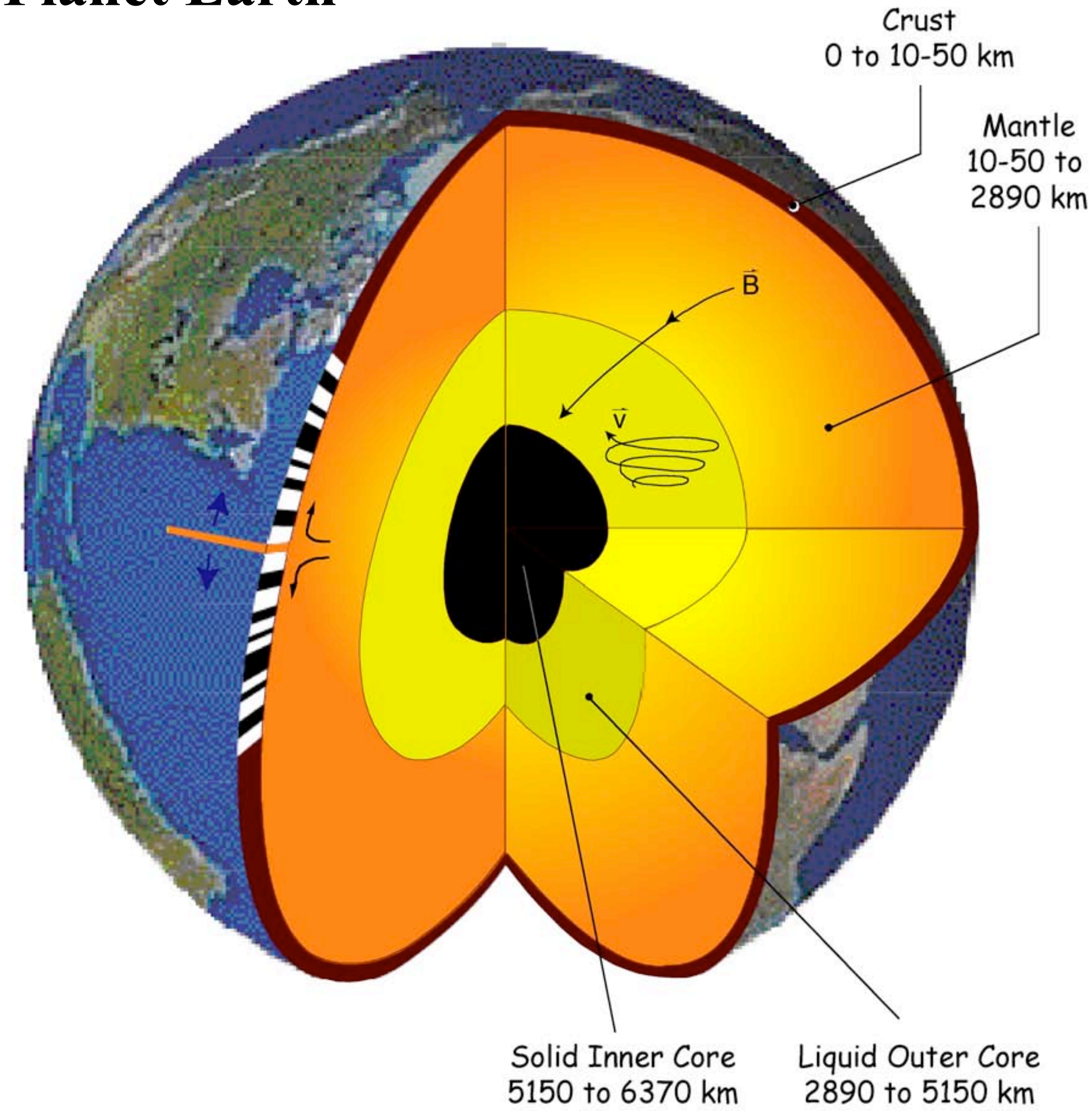
Magnetic properties under high pressure: Insights to planetary magnetic fields, structure and evolution

Stuart A. Gilder

Ludwig Maximilians Universität - Munich

2011 MagIC Science & Database Workshop - Scripps Institution of Oceanography

Role of Pressure and Temperature on Magnetization: Planet Earth



- *How does pressure influence magnetic anomalies?*
  titanomagnetite
- *What can we learn about the mantle from magnetism?*
  pyrrhotite-bearing diamonds
- *Influence of the inner core on the geometry and stability of the magnetic field?*
  iron

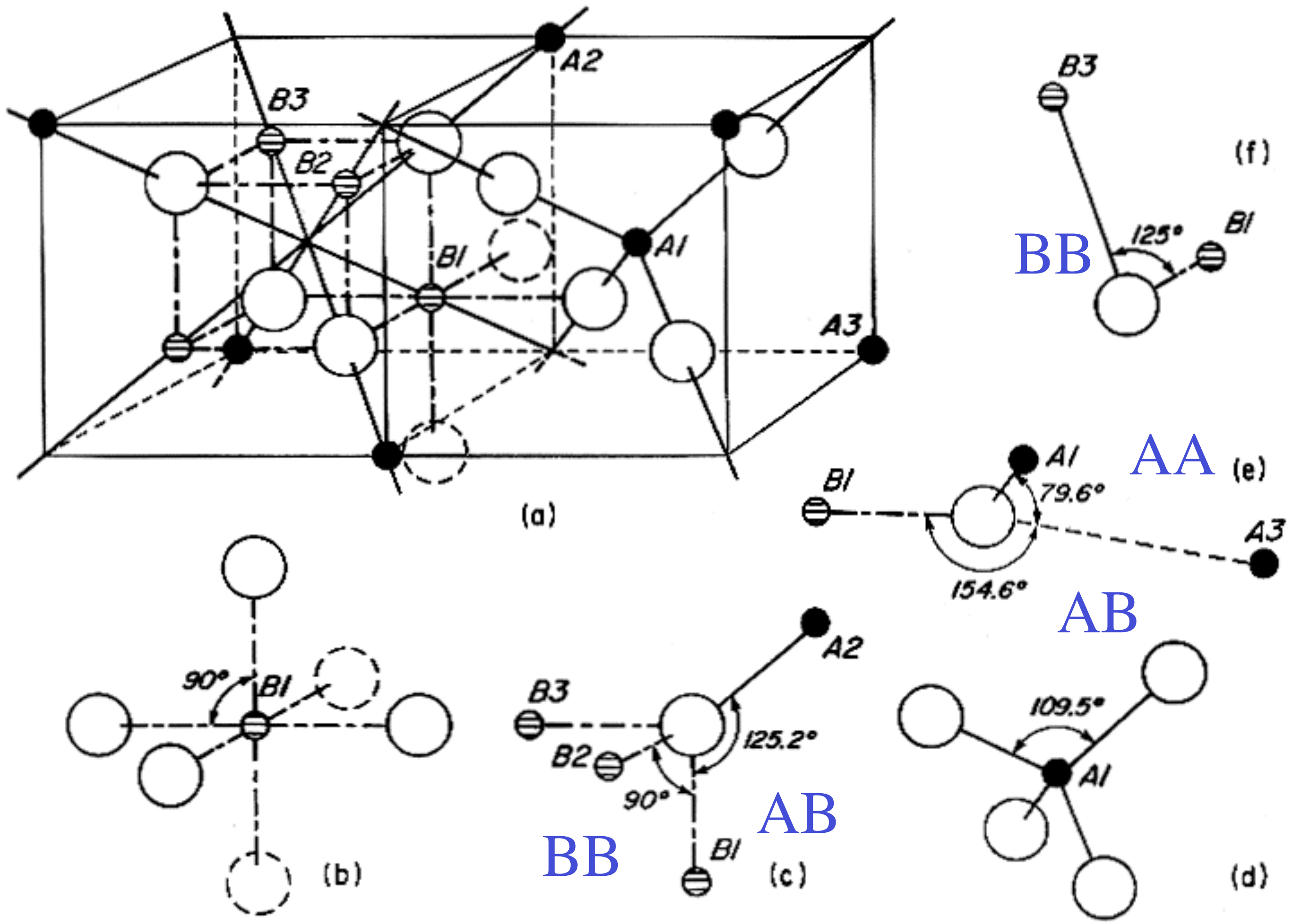


Figure 3.4 (a) Sketch of $\frac{1}{4}$ of a unit cell of magnetite. The lattice parameter is *a*. Solid and hatched circles represent cations in tetrahedral (A-site) and octahedral (B-site) coordination, respectively, with O^{2-} ions (large open circles). (b)–(f) Bond angles for specific cation pairs in (a). Bond angles near 90° are unfavourable for superexchange coupling. [After Gorter (1954), with the permission of the publisher, Philips Research, Eindhoven, The Netherlands.]

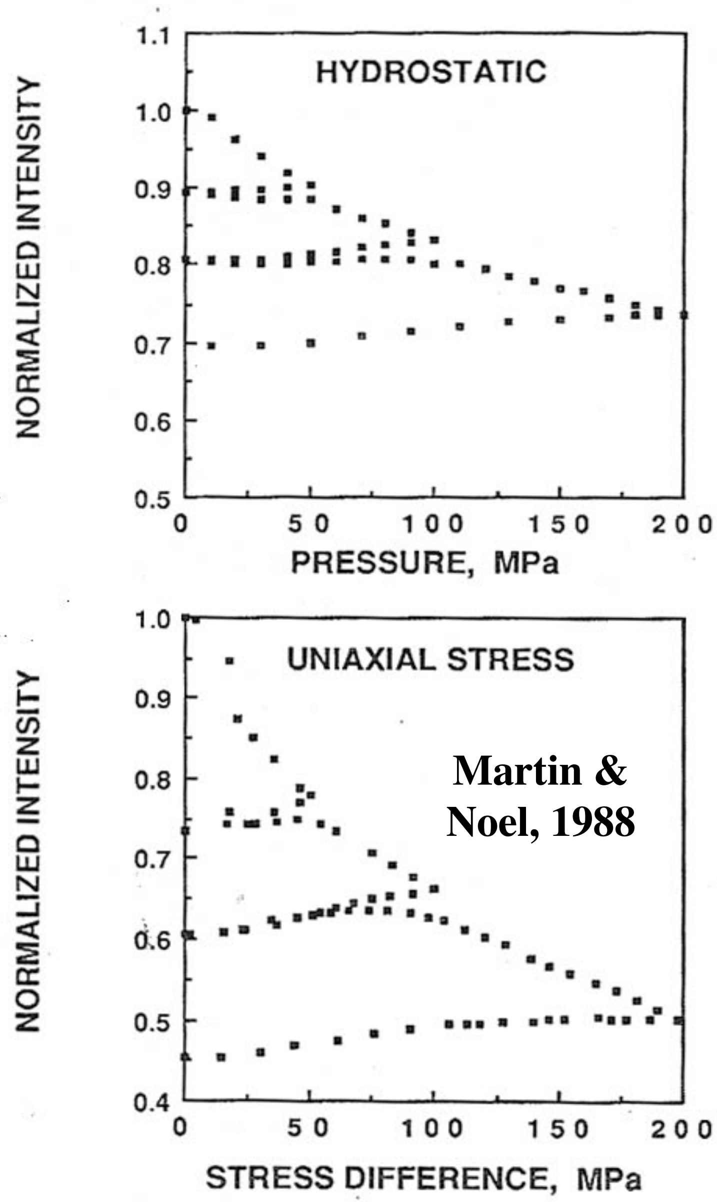
Dunlop and Özdemir (1997)

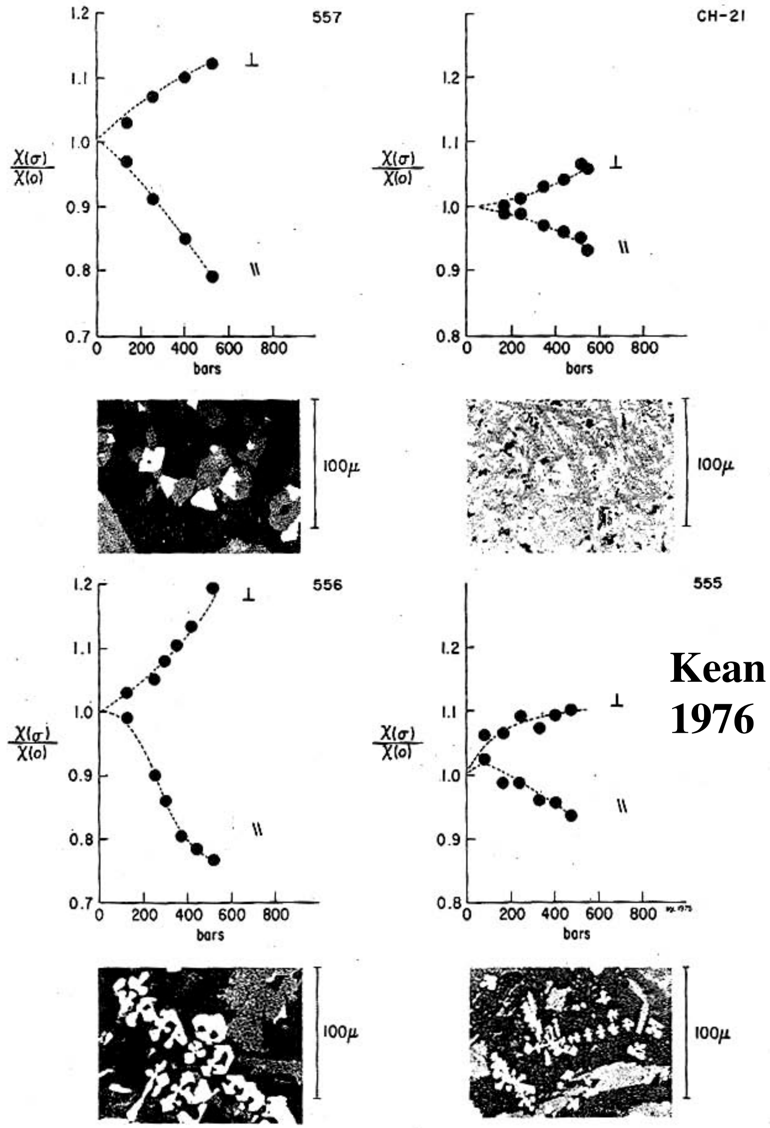
The interactions of electrons between Fe-Fe give magnetite its remanence.

However, this interaction is indirect, passing through oxygen atoms.

Magnetite possesses three magnetic lattices which govern its magnetic characteristics.

Magnetism is sensitive to the type and direction of applied stress

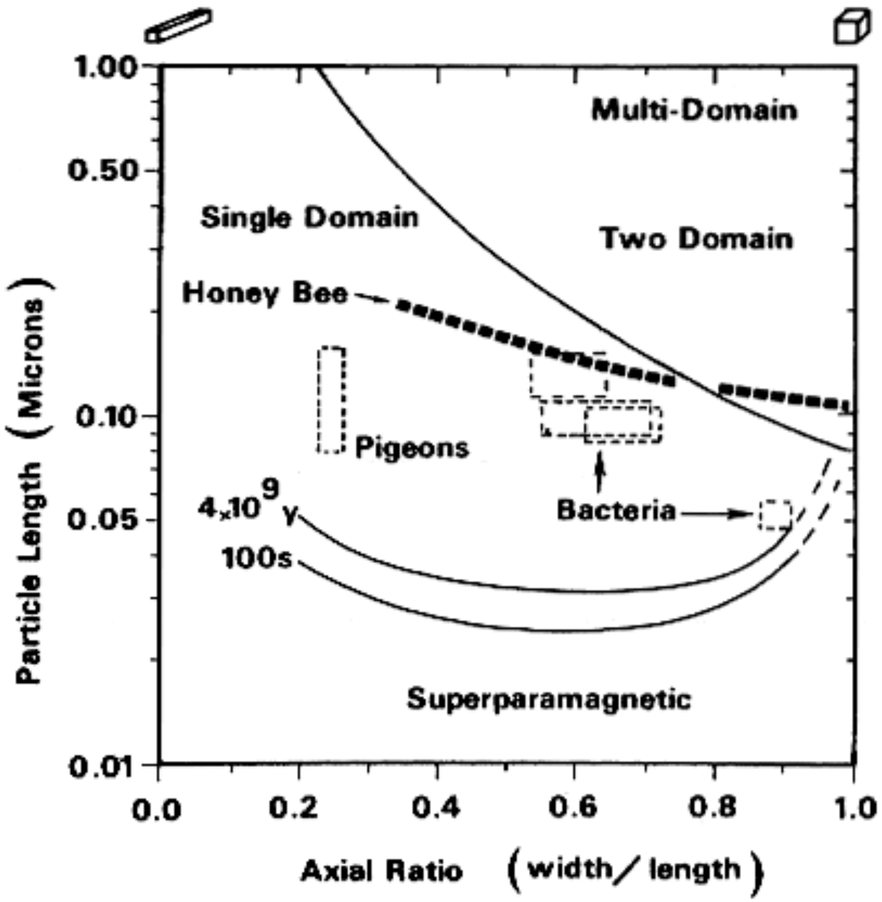


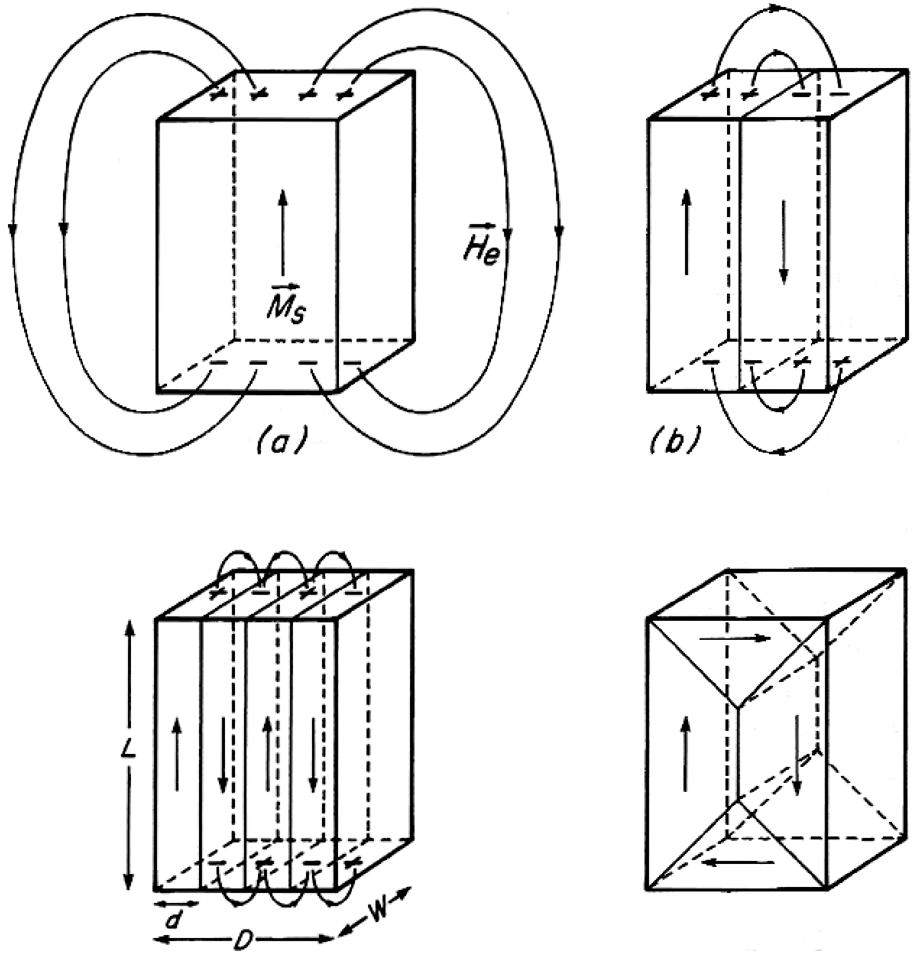


Kean et al., 1976

Fig. 3. Changes in susceptibility with stress for samples

MAGNETITE





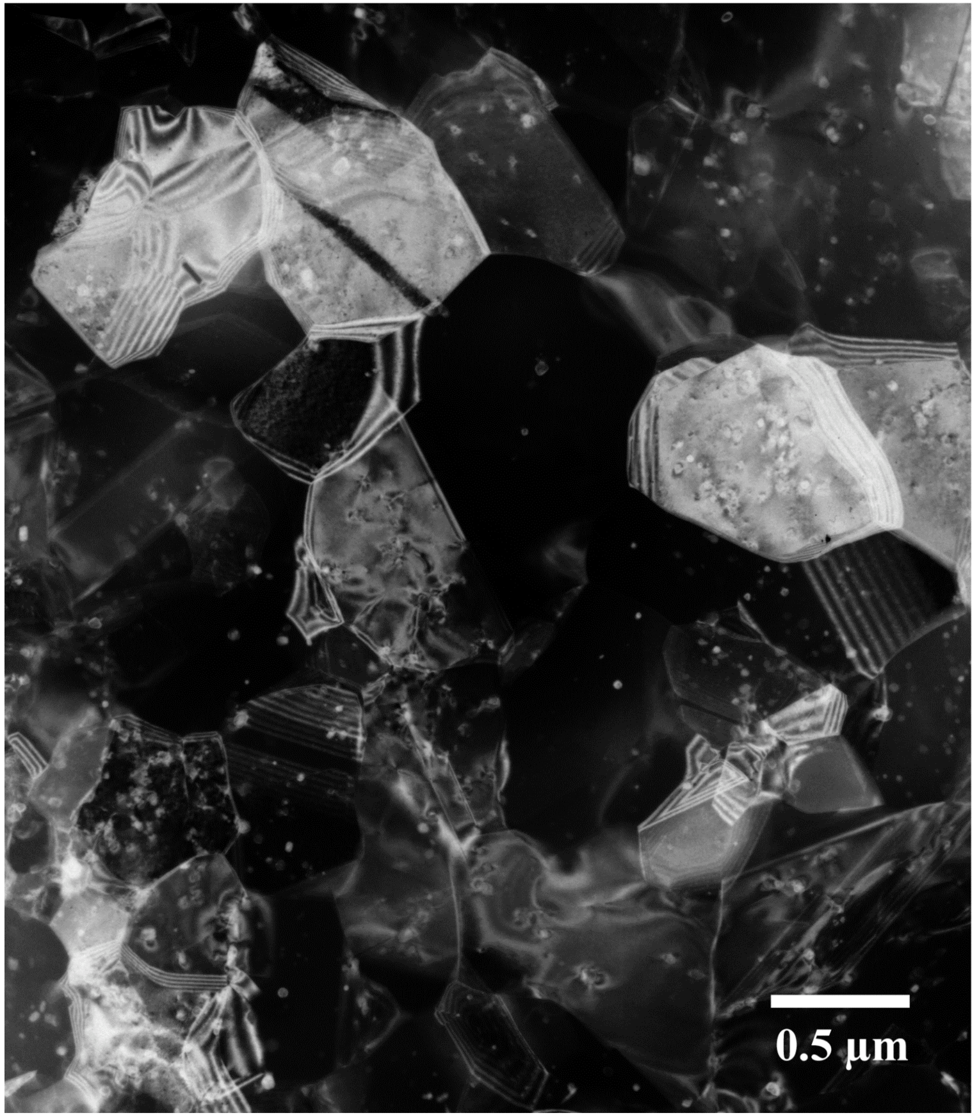
Magnetic properties are size and shape dependent

Superparamagnetic vs. Single domain vs. Multidomain

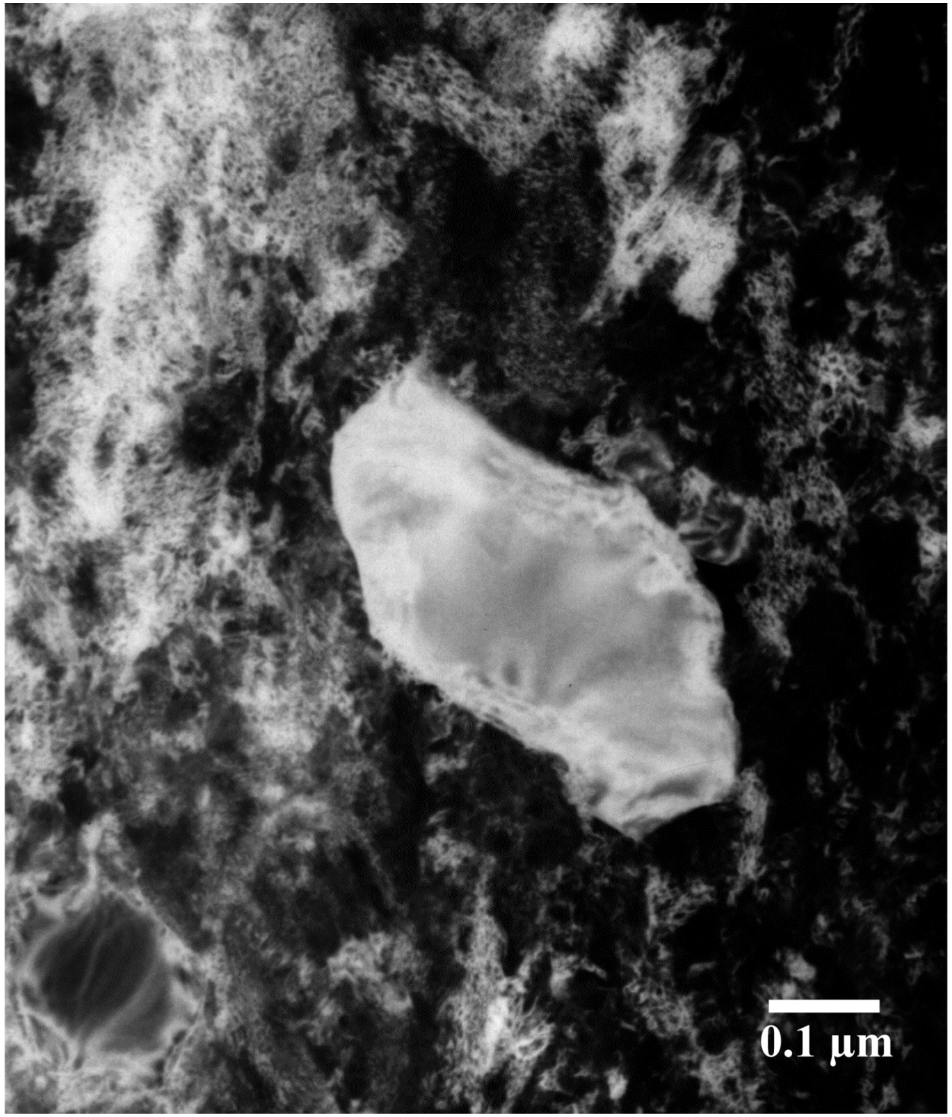
TEM images of iron foil

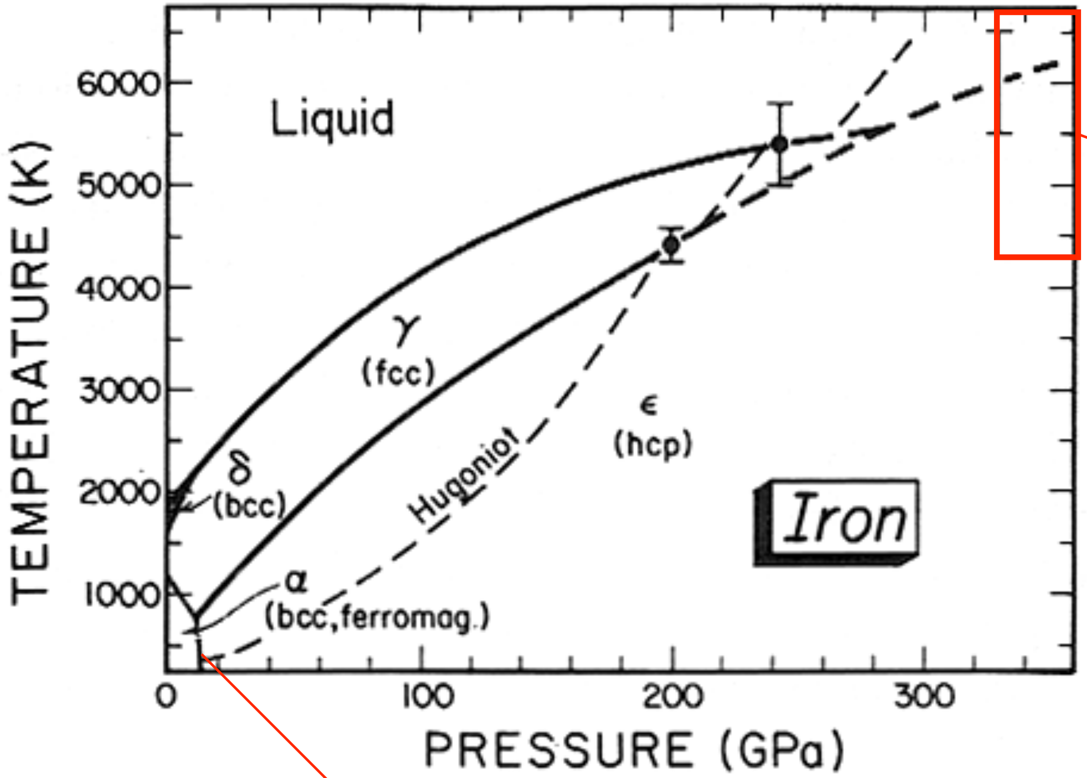
bcc to hcp: a Martensitic phase transition

Non-compressed



Decompressed from 30 GPa





The inner core probably consists of Fe in a hexagonal closed packed (hcp) phase.

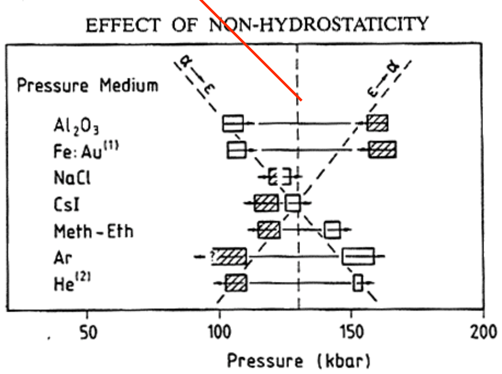
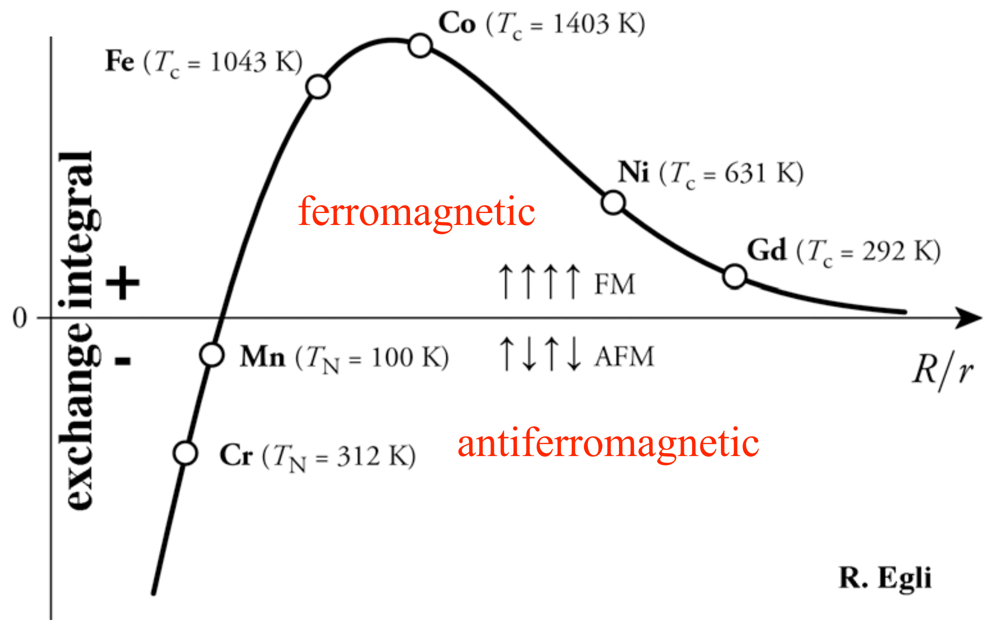
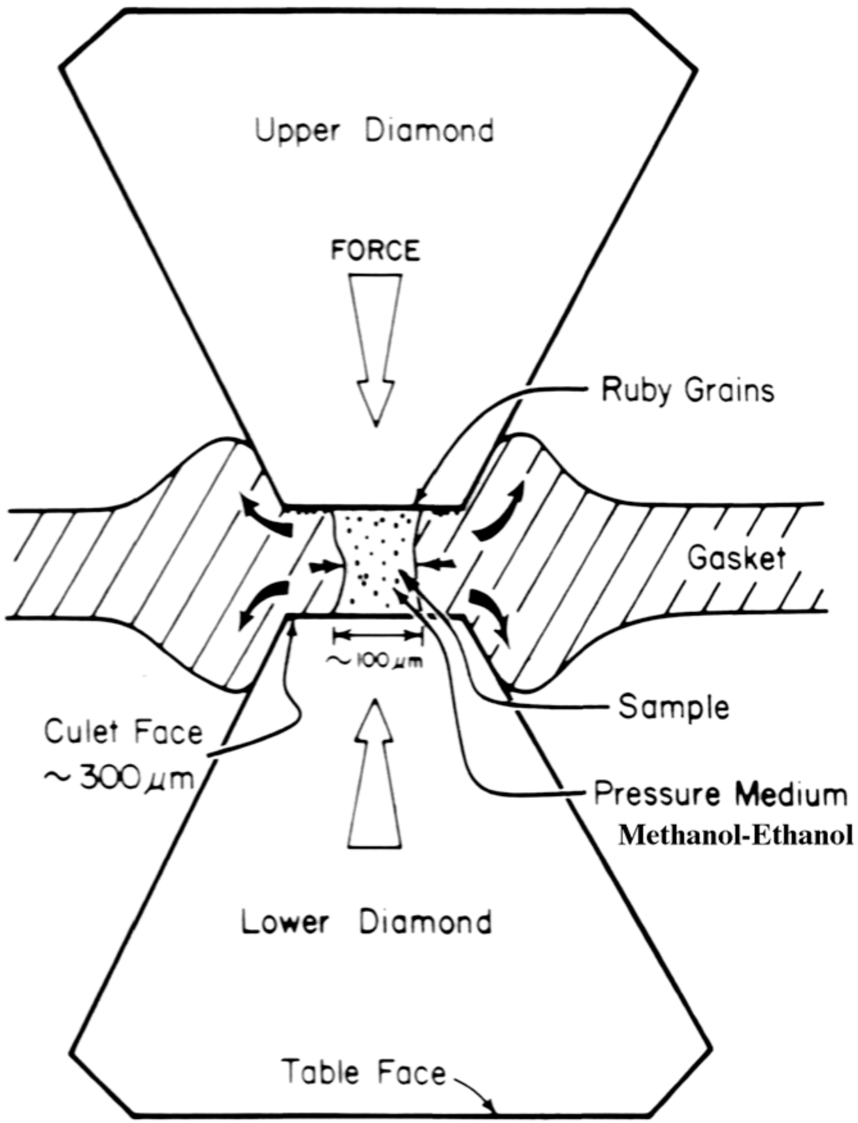


Figure 4 Pressures of the onset of the $\alpha \to \varepsilon$ (open bars) and $\varepsilon \to \alpha$ transitions (filled bars) in different pressure media. The bars represents the uncertainty in pressure. (1) Huang *et al.*[10], (2) Zou *et al.*[11]

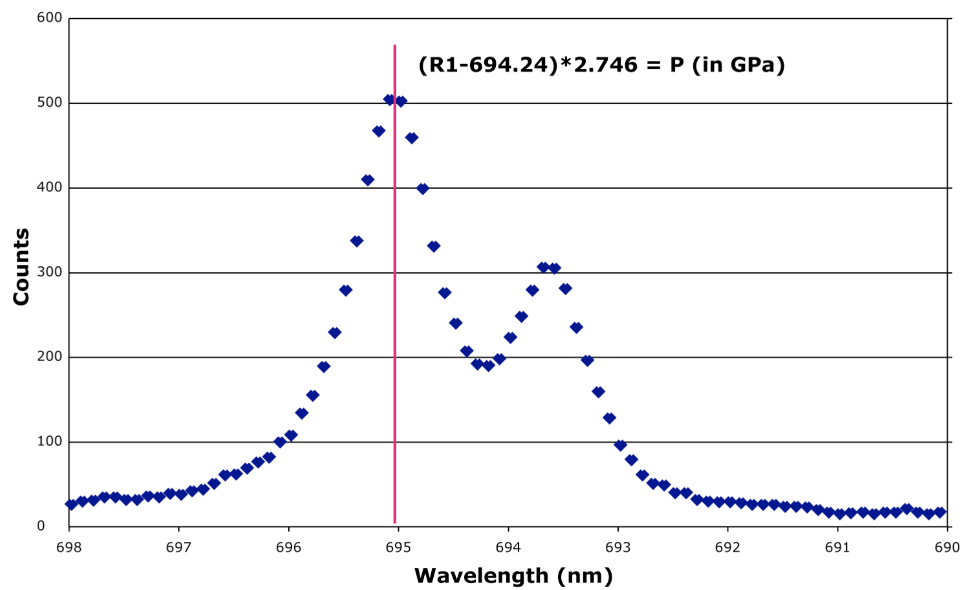
von Bargen and Boehler (1990)

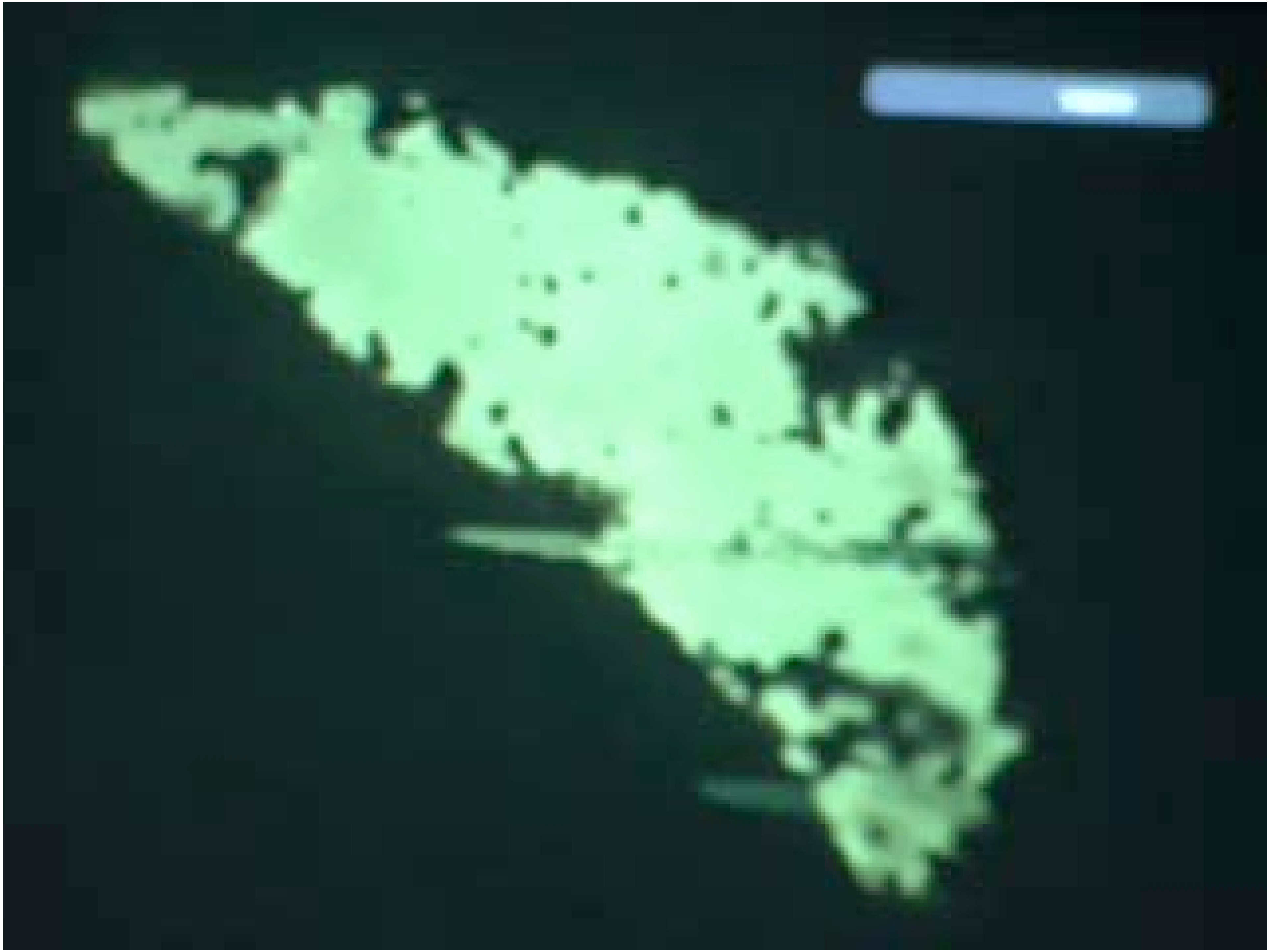


R. Egli

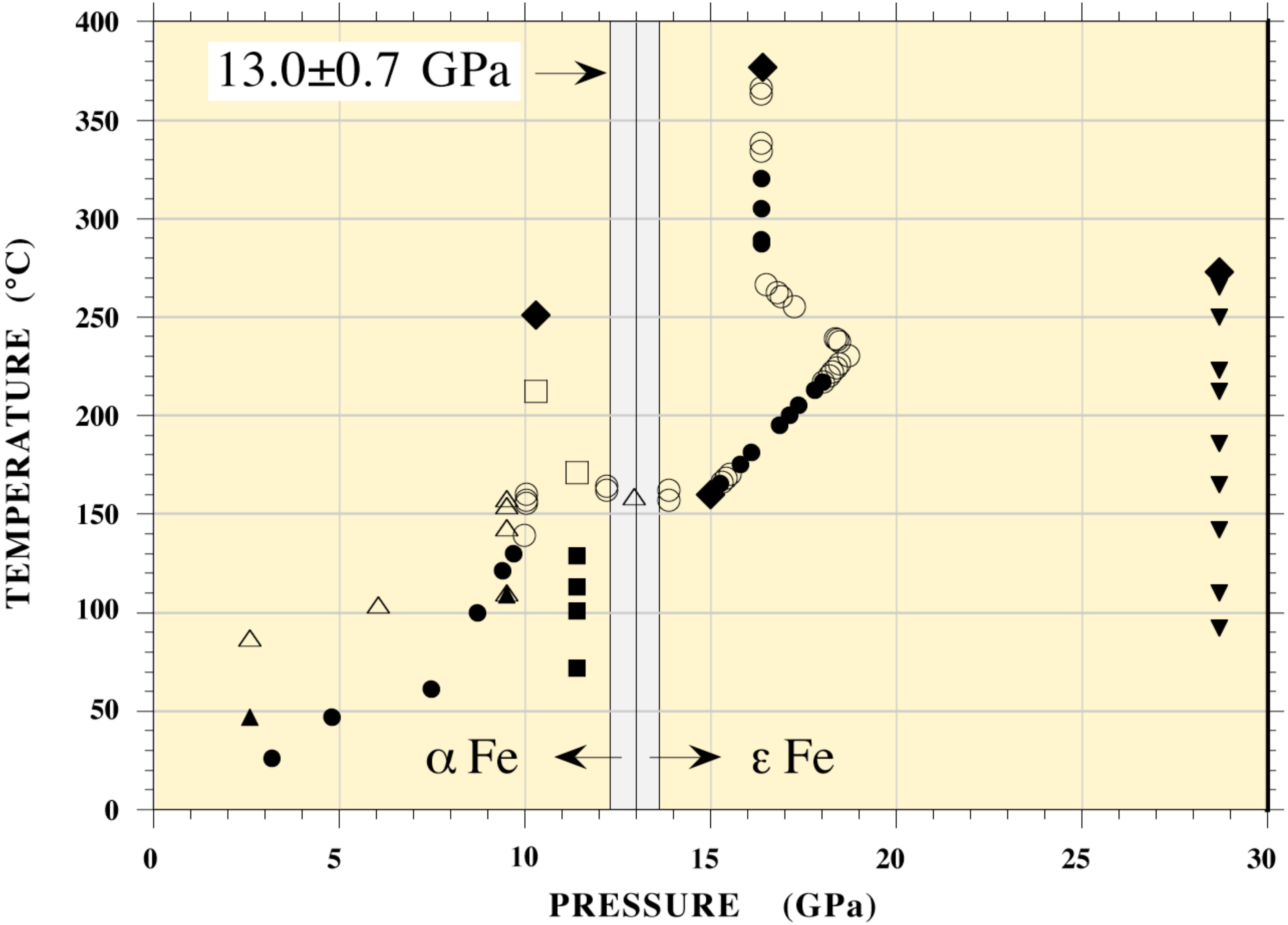


Spherical iron (>99.9%) particles with diameters of 1 to 5 μm were loaded together with ruby and a pressure medium into a ~100 μm sized hole formed in a Re gasket. Resistive heaters (not shown) surround the diamonds. The transparent pressure medium allows the iron particles to be imaged with a microscope.



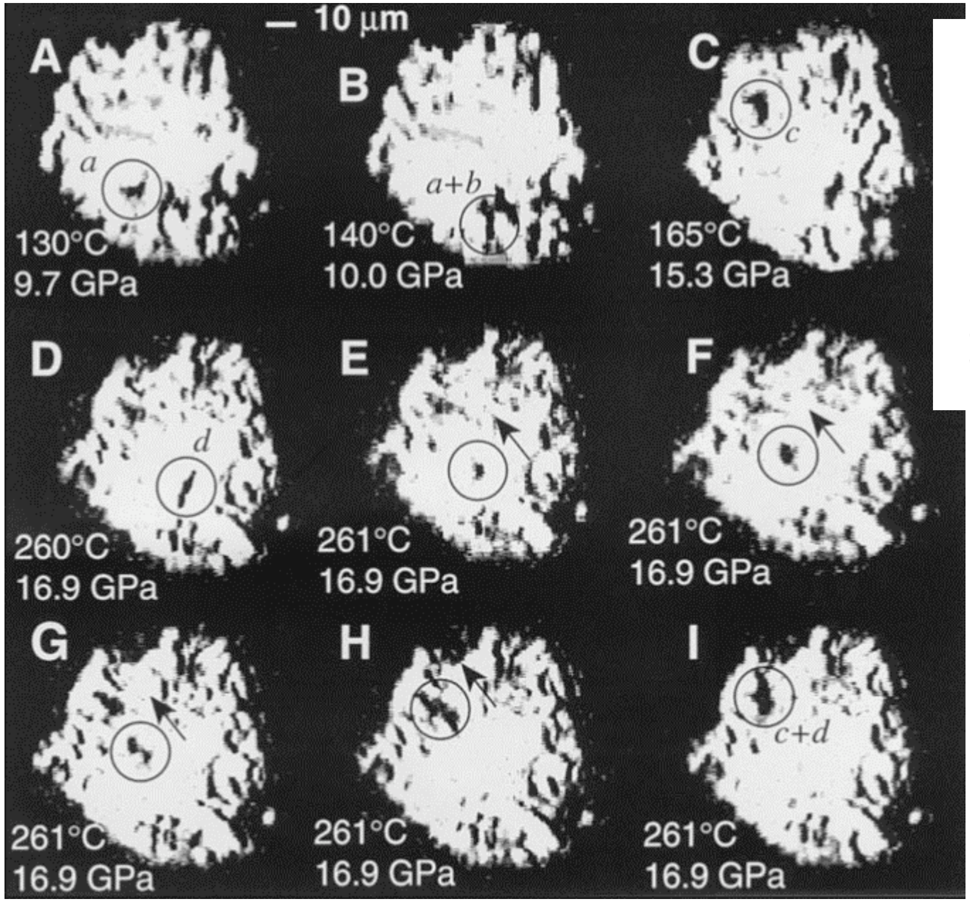


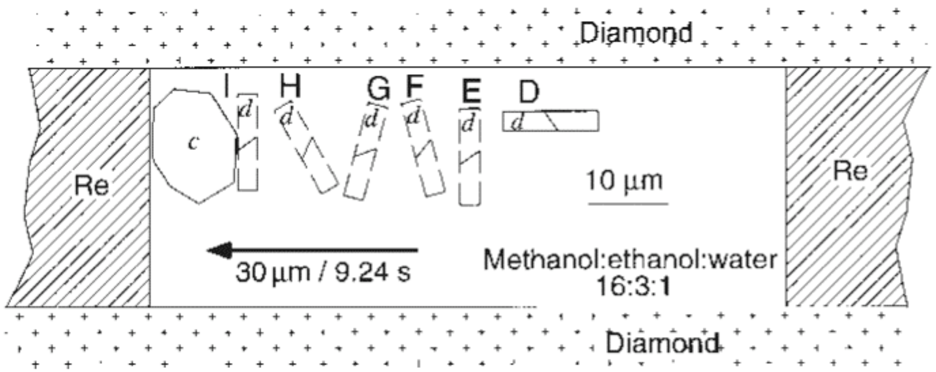
Movement of iron induced by a magnet



Open symbols = movement Closed symbols = no movement

Gilder and Glen (Science, 1998) Diamonds = failure

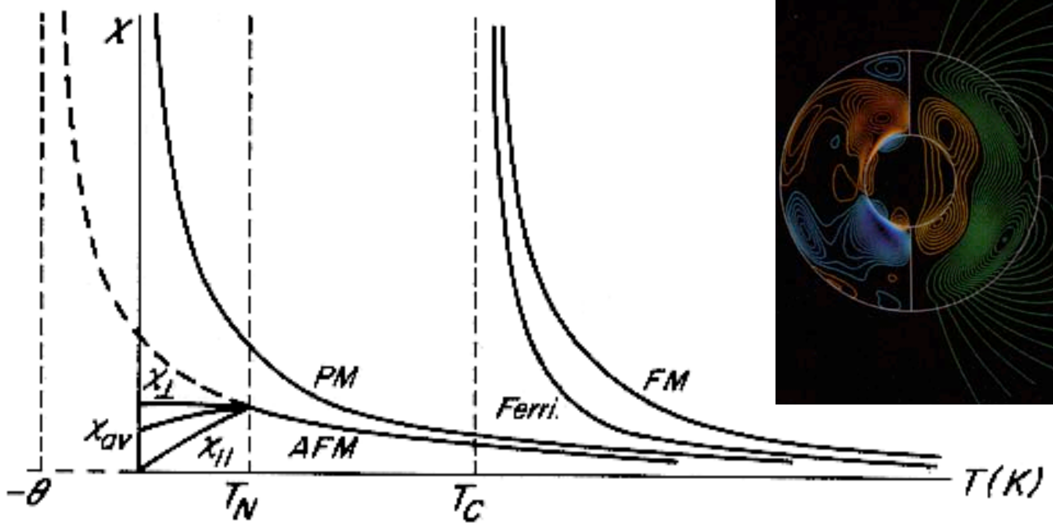


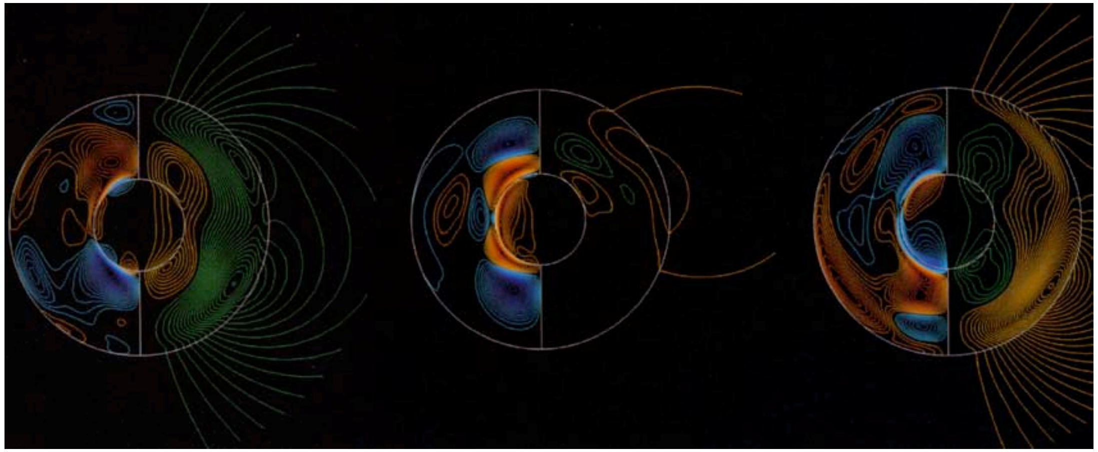


At 17 GPa and 260°C, we observed movement that allowed us to establish an equation of force couples between the magnetic attraction in one sense and viscous forces in the opposite sense.

Two possibilities can explain the motion :

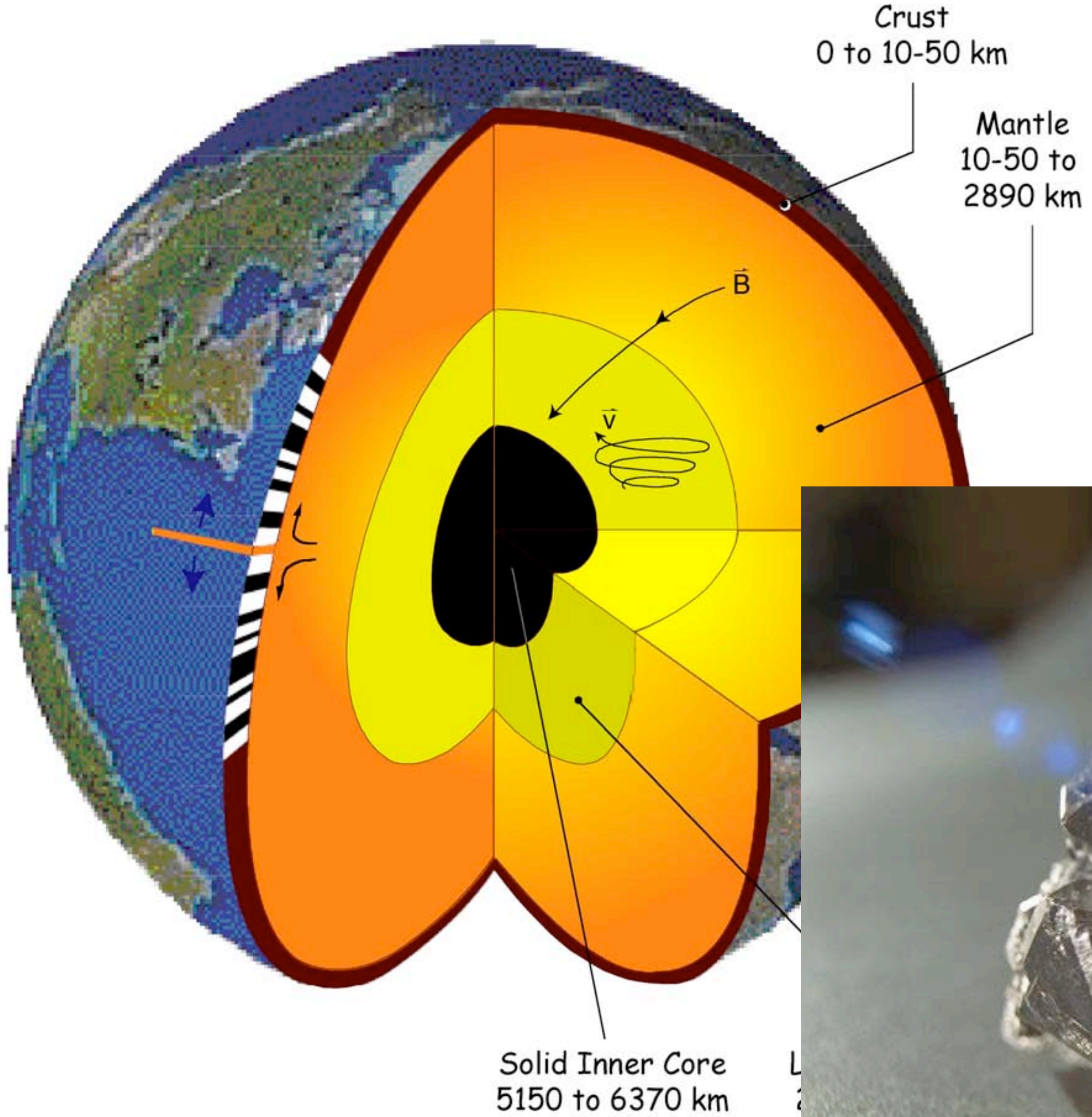
- Either hcp Fe is ferromagnetic.
- Or hcp Fe is paramagnetic with a very high bulk susceptibility with high crystalline anisotropy.





If our minimum susceptibility estimate (>10^{-3} SI) is extrapolated to inner core temperatures (4000°C to 8000°C) and pressures (330 to 360 GPa), the inner core would still have a high bulk susceptibility.

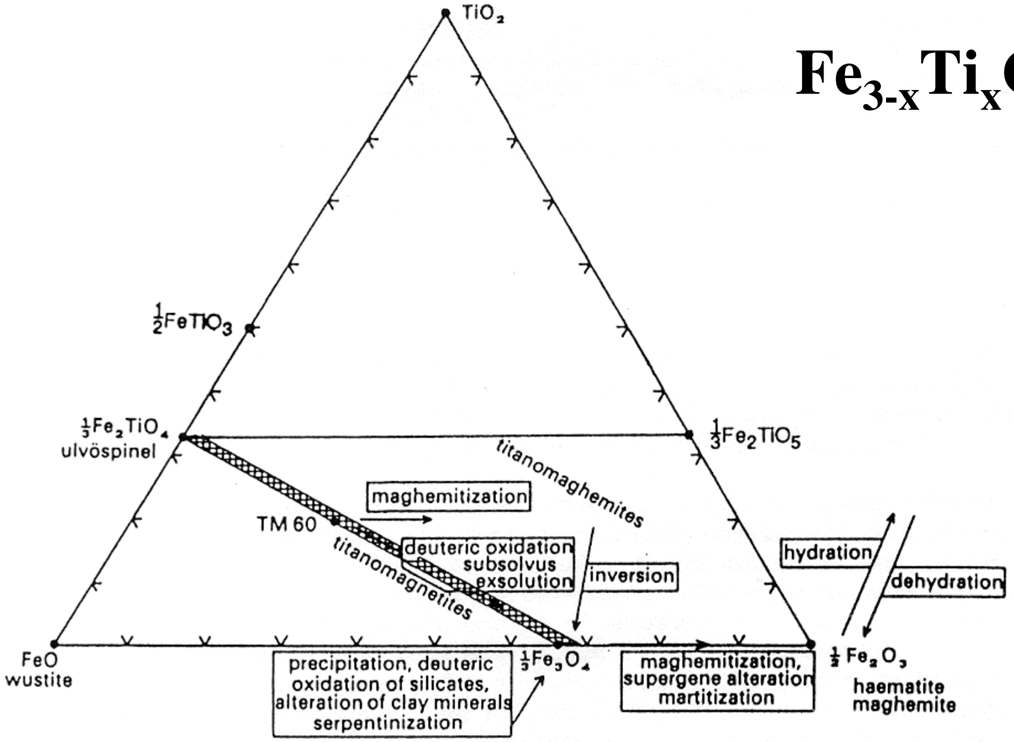
An inner core with a high paramagnetic susceptibility, and with a paramagnetic relaxation time acting slower than field changes coming from the outer core, could also attenuate short frequency fluctuations and stabilize the geodynamo, just as an electrically conducting inner core could stabilize the geodynamo (Hollerbach and Jones, 1993), because the inner core would have a magnetic diffusion constant independent of the outer core .



✸ ***Importance of induction in the crust ?***

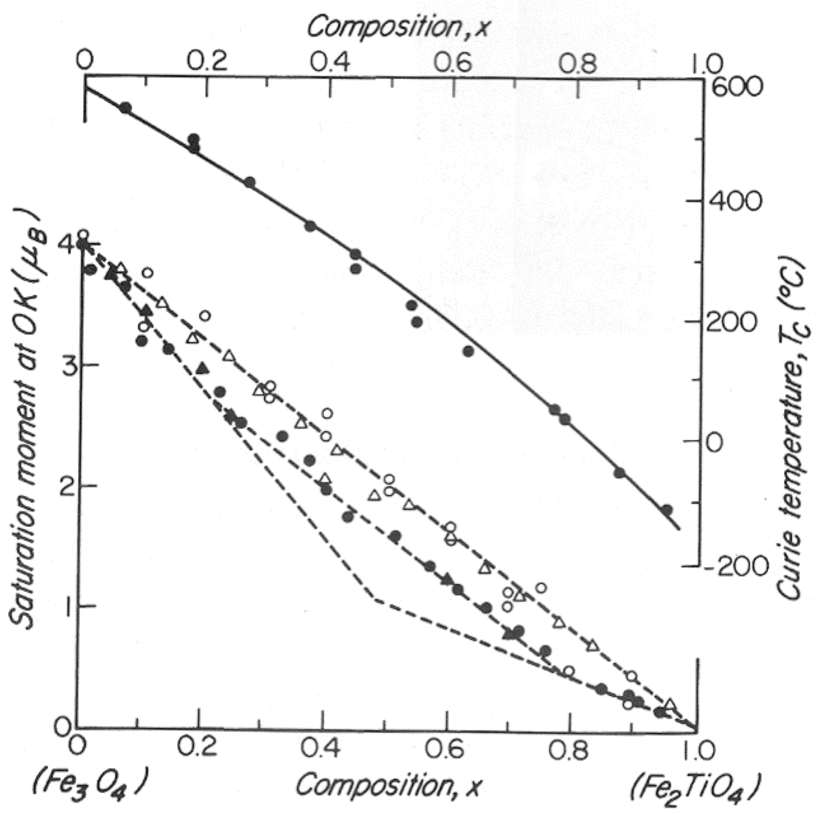
✸ ***Depth of magnetic anomalies ?***

TITANOMAGNETITE

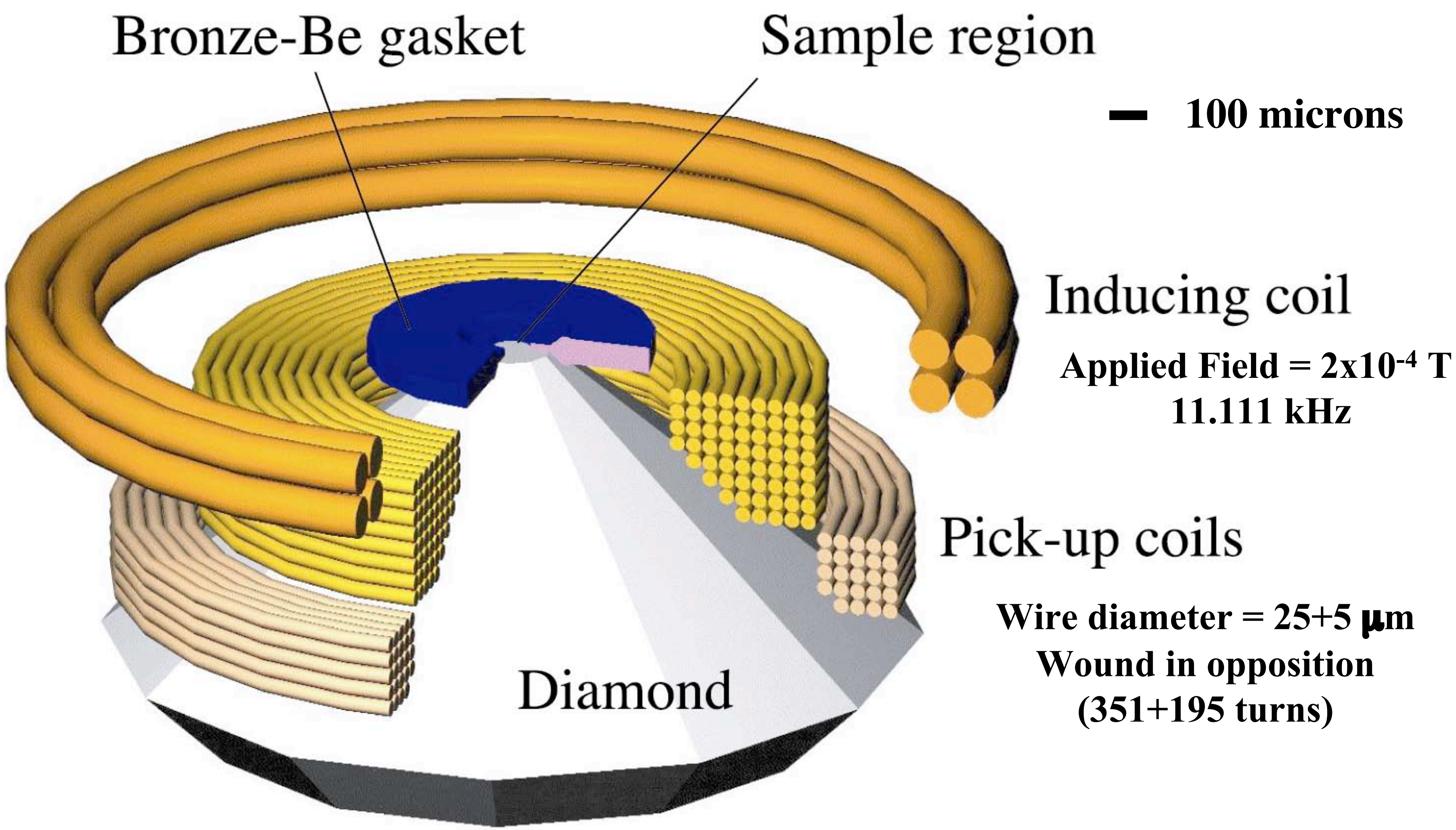


$$Fe_{3-x}Ti_xO_4 = xFe_2TiO_4(1-x)Fe_3O_4$$

(x = 0.6 => TM60)

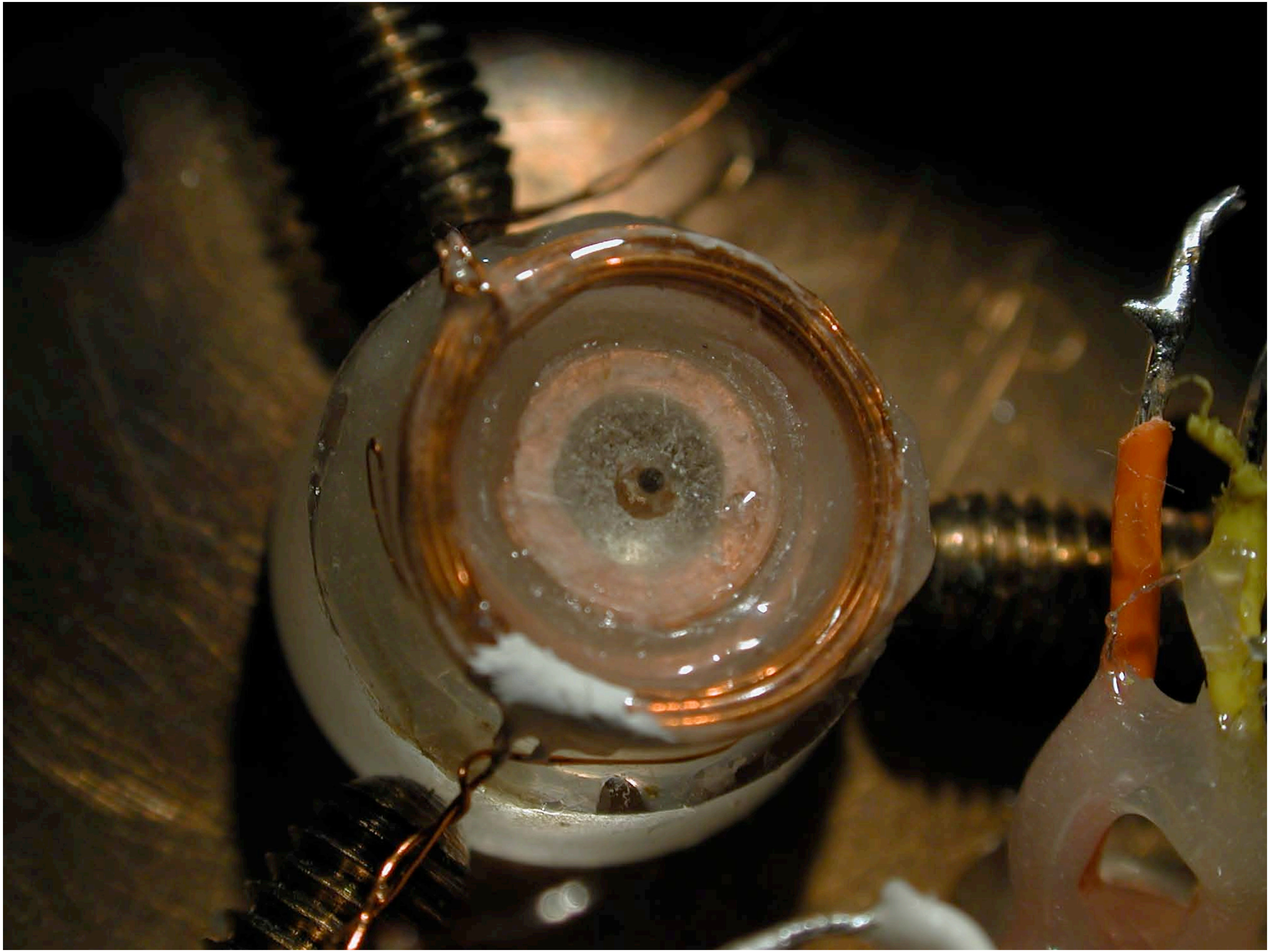


(Dunlop and Özdemir, 1997)

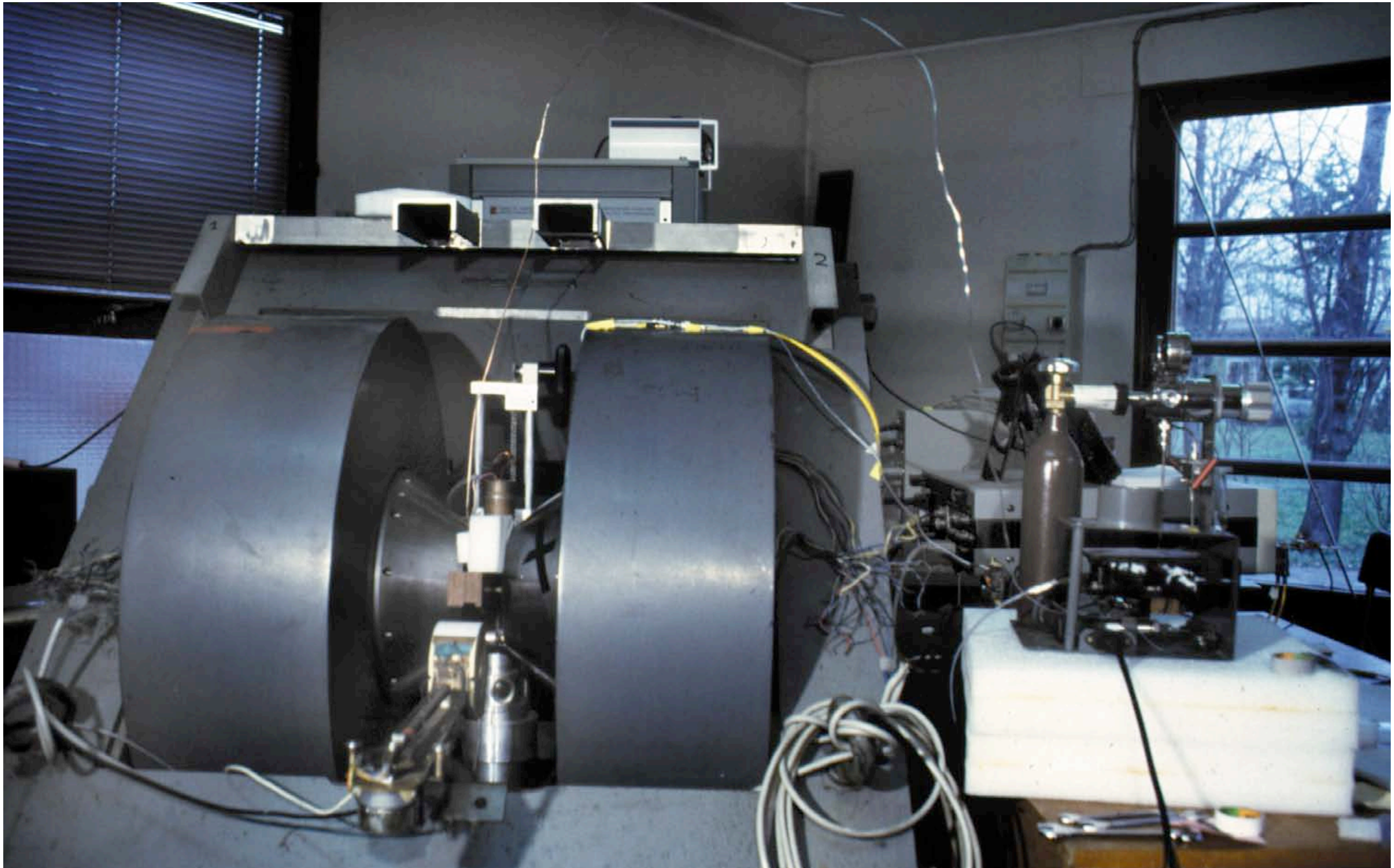


When a sample is placed in the measure region, it induces :

- **An in-phase alternating current proportional to its susceptibility.**
- **A quadrature voltage that depends on its electrical conductivity and on its magnetic viscosity.**

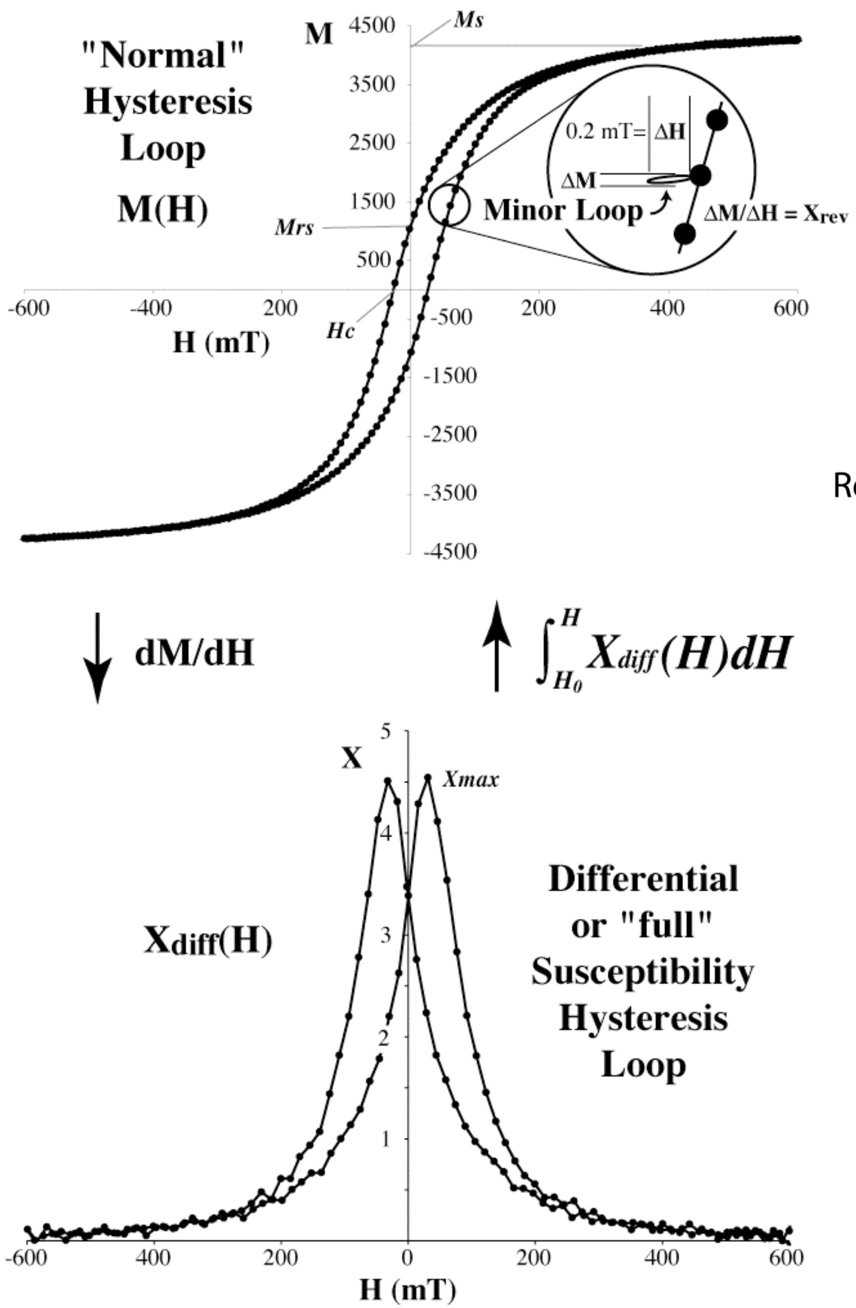


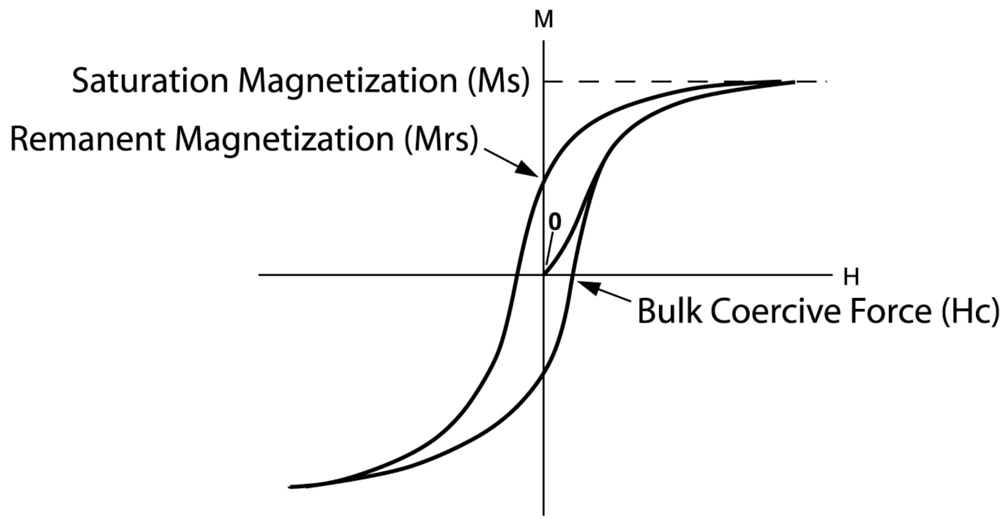
BeCu Diamond Anvil Cell



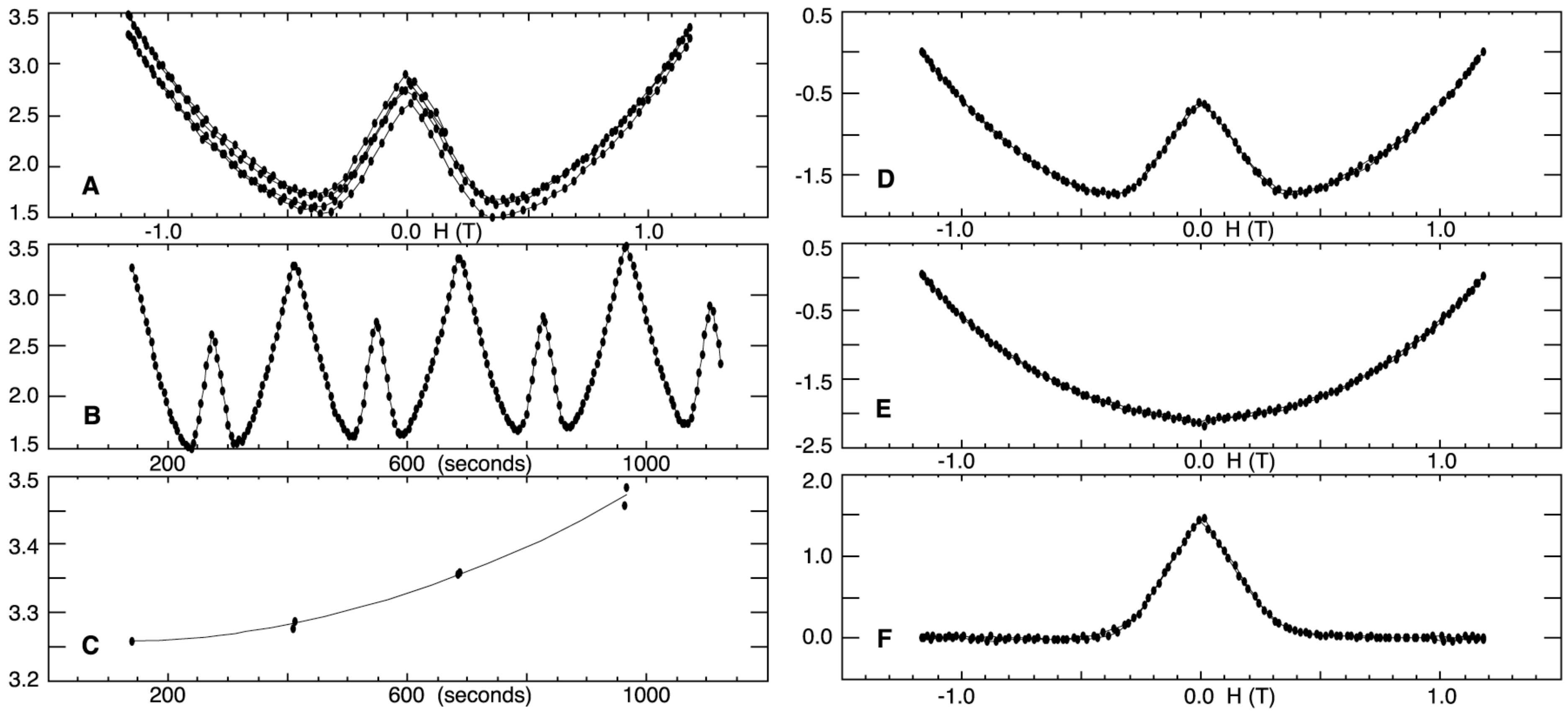
Electromagnet : maximum field = 1.4 T

Magnetic Hysteresis Loops

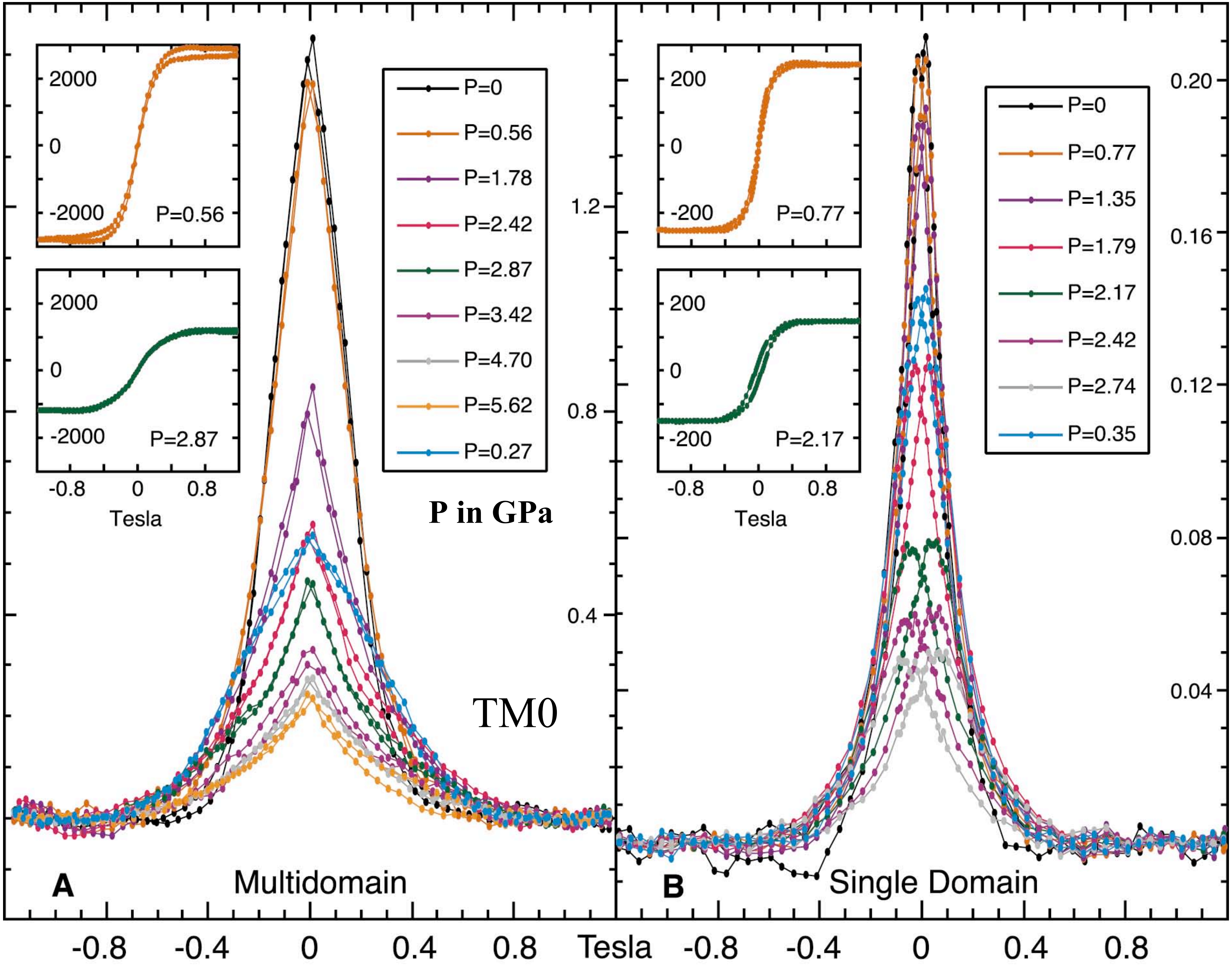




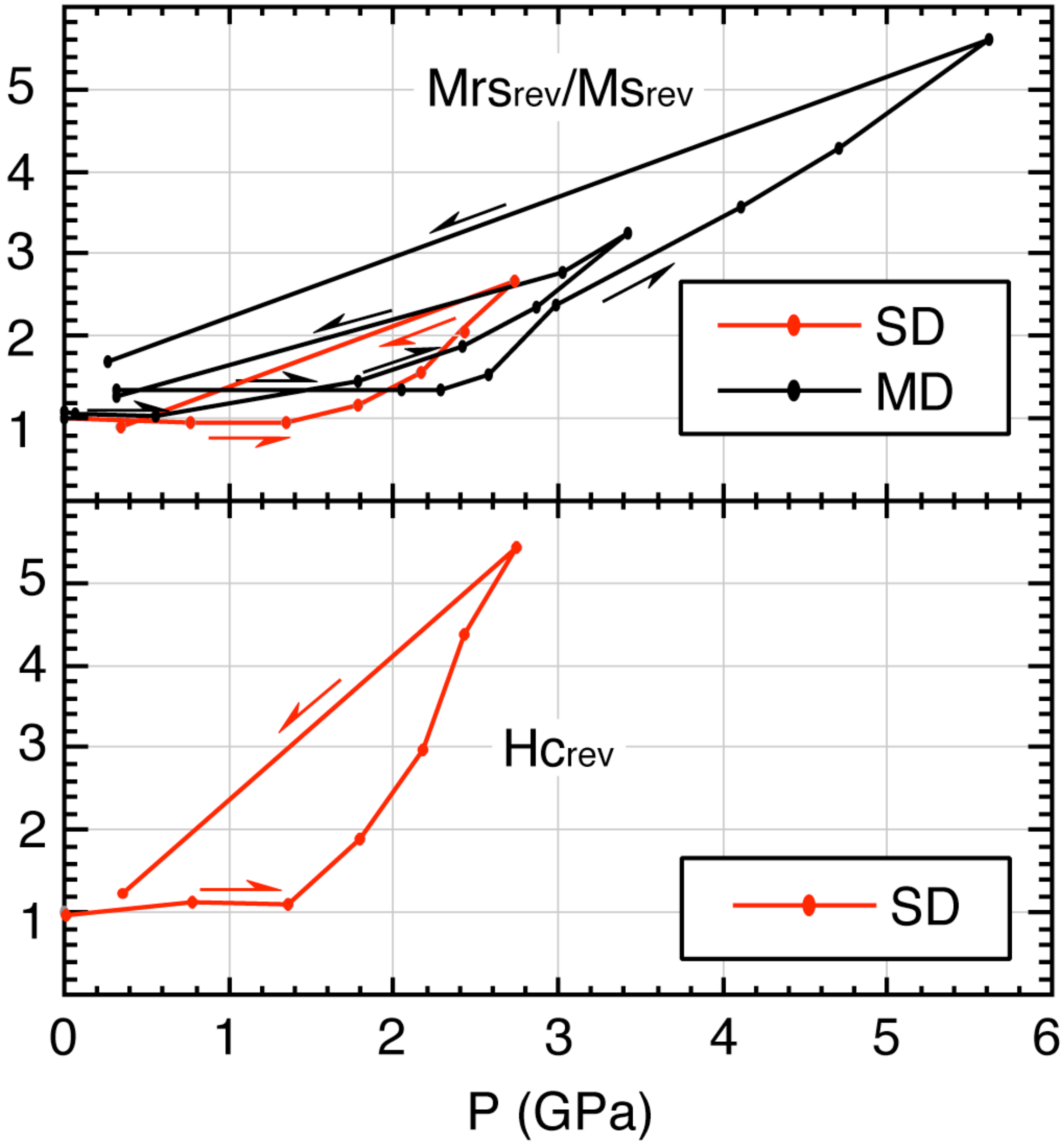
$$X_{diff} = X_{rev} + X_{irr}$$



Experiment on multidomain magnetite



2000
0
-2000
P=0.56
2000
0
-2000
P=2.87
-0.8
0
0.8
Tesla
P=0
P=0.56
P=1.78
P=2.42
P=2.87
P=3.42
P=4.70
P=5.62
P=0.27
P in GPa
TM0
A
Multidomain
1.2
0.8
0.4
200
0
-200
P=0.77
200
0
-200
P=2.17
-0.8
0
0.8
Tesla
P=0
P=0.77
P=1.35
P=1.79
P=2.17
P=2.42
P=2.74
P=0.35
0.20
0.16
0.12
0.08
0.04
B
Single Domain
-0.8
-0.4
0
0.4
0.8
Tesla
-0.8
-0.4
0
0.4
0.8



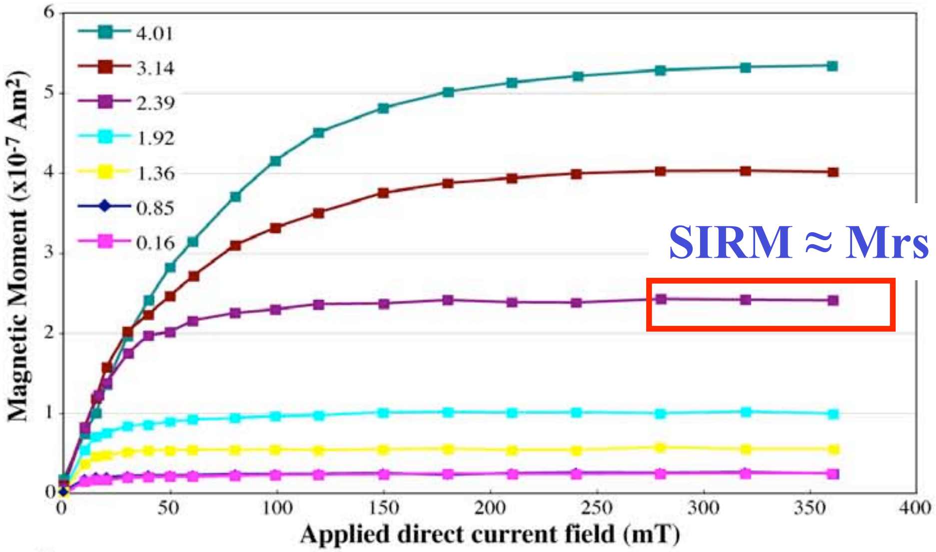
From 1 to 3 GPa, Mrs/Ms in single domain magnetite increases three times and Hc increases five times.

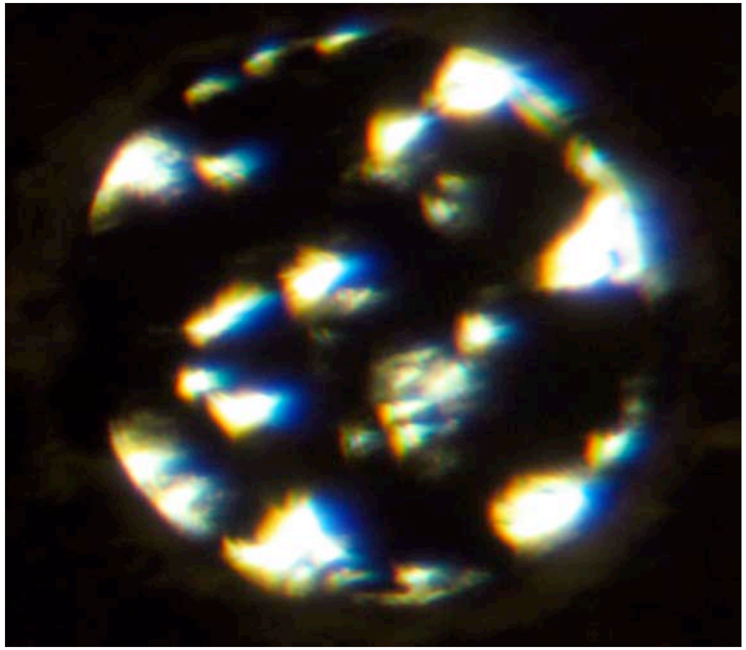
Pressure transforms magnetite into a more perfect magnet.

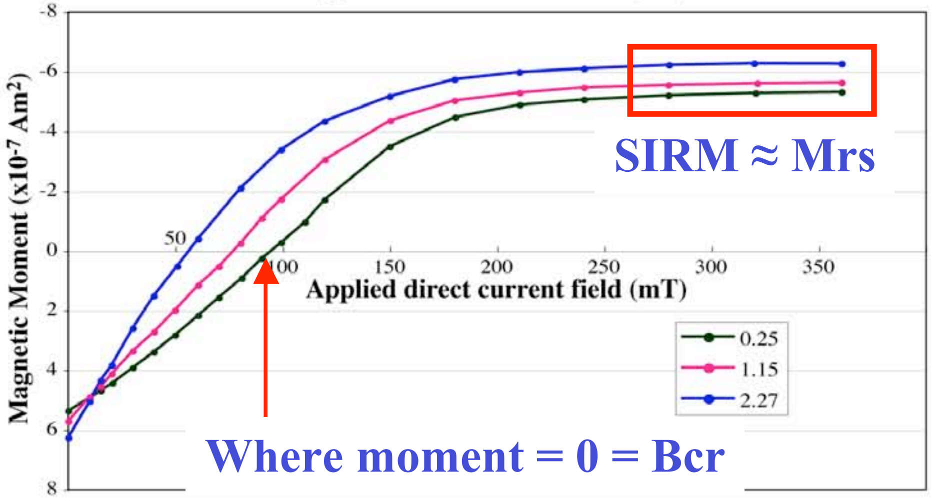
Geophysical Research Letters, 2002

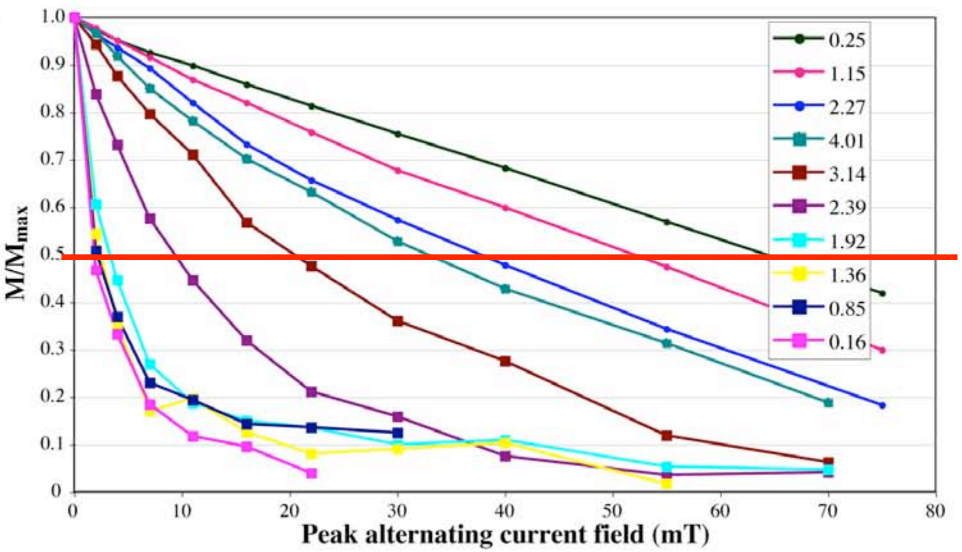
We now insert the diamond cell into a 3-axis, superconducting magnetometer to directly measure the full magnetic vector of material under pressure.

Full vector measurements: IRM acquisition and AF demagnetization

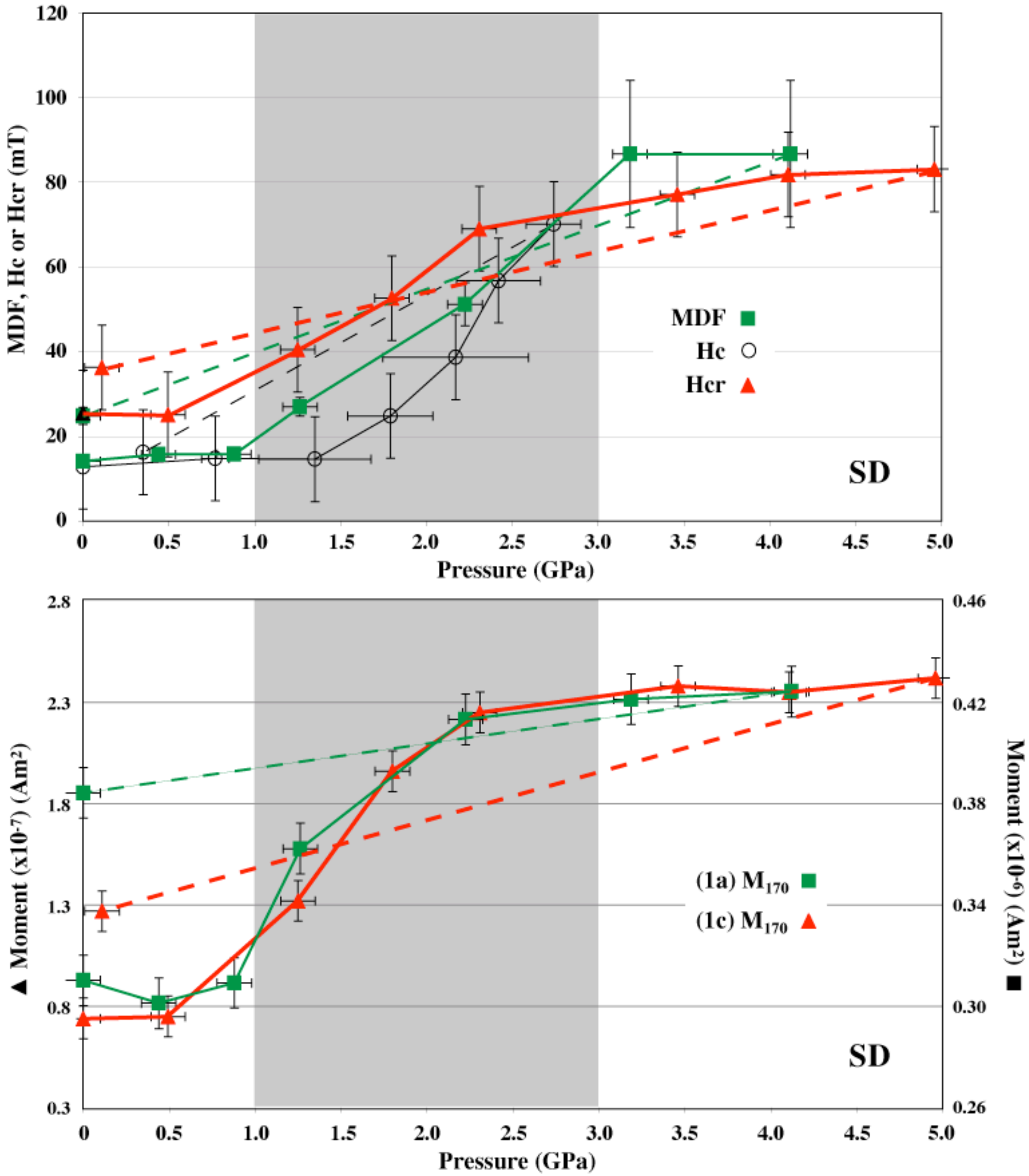








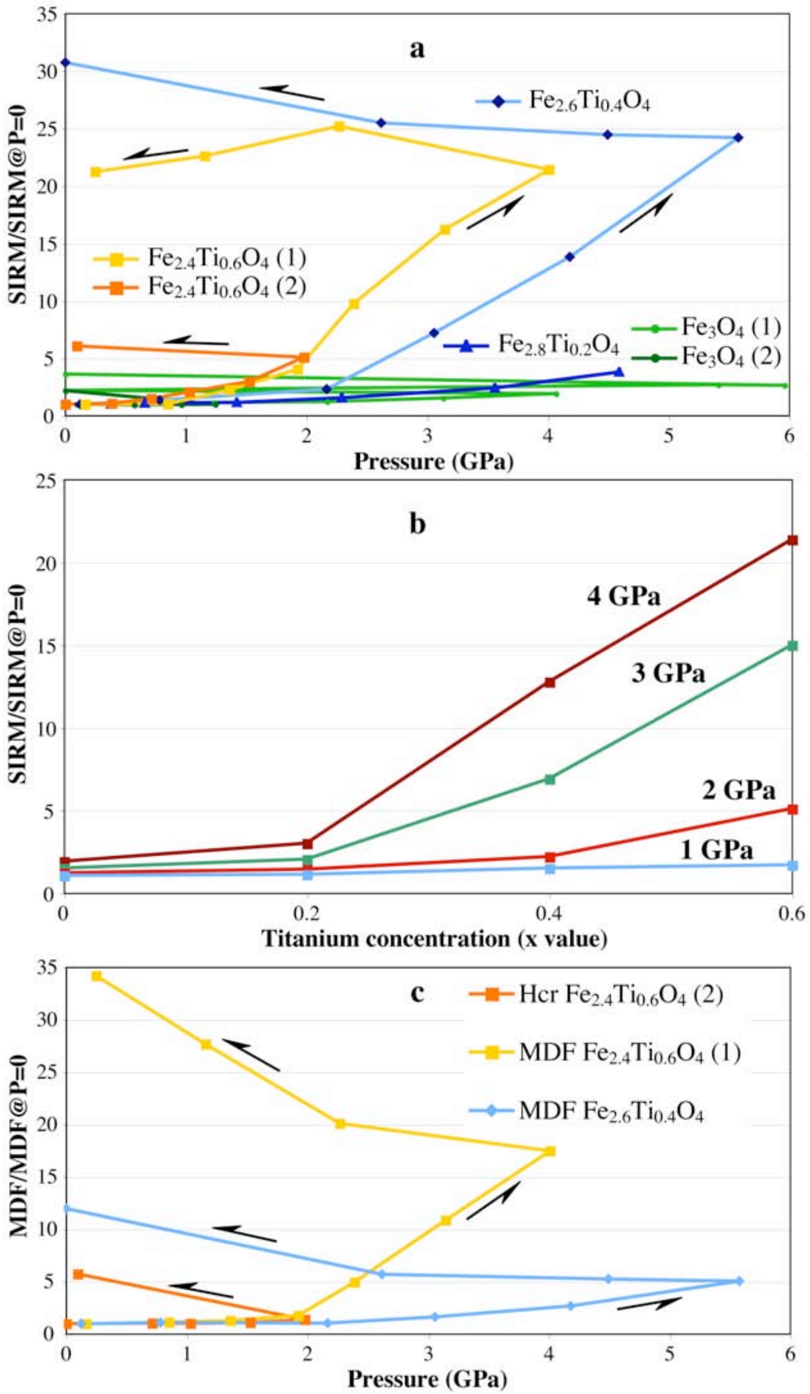
Median destructive field (MDF)



Two independent experimental methods show that the magnetic properties of single domain magnetite (TM0) change significantly between 1 and 3 GPa.

Magnetic phase transition?

Geophysical Research Letters (2004)

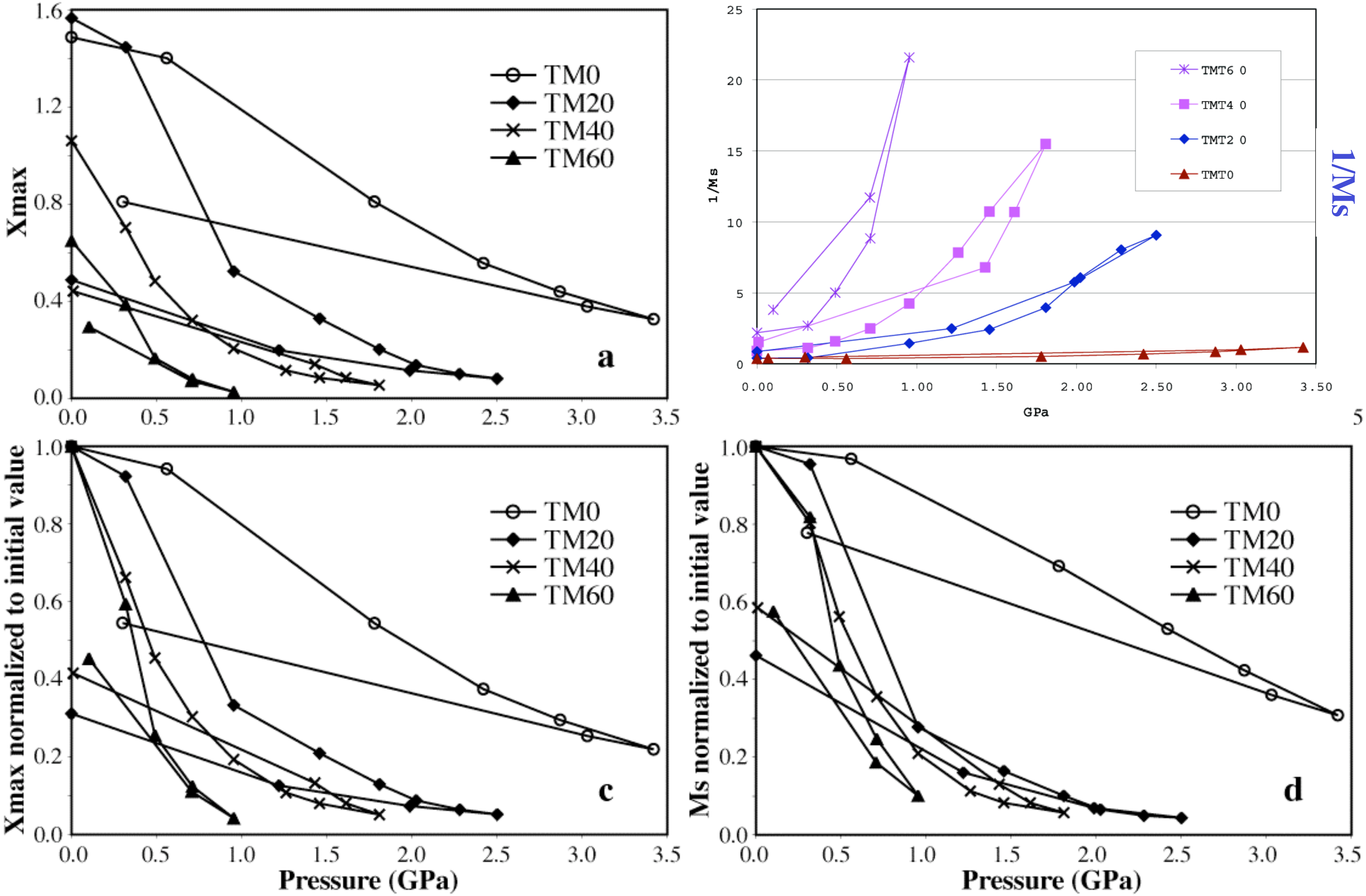


Pressure systematically enhances the magnetic properties of multidomain titanomagnetite, which are the principal carriers of magnetic remanence in nature.

Pressure makes multidomain titanomagnetite more single domain-like. This can potentially explain the origin of deeply rooted magnetic anomalies on Earth and other planets.

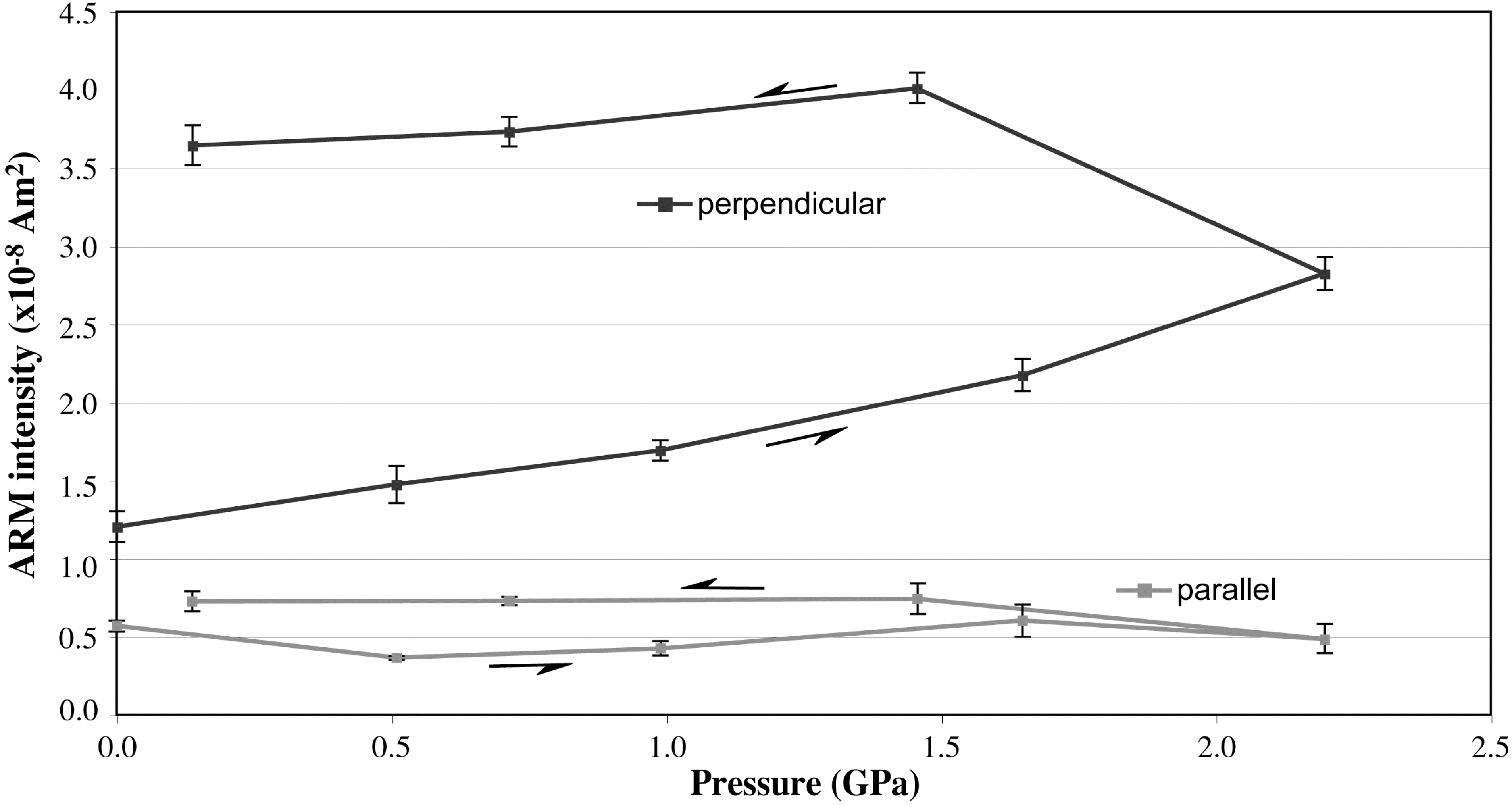
Gilder and Le Goff (GRL, 2008)

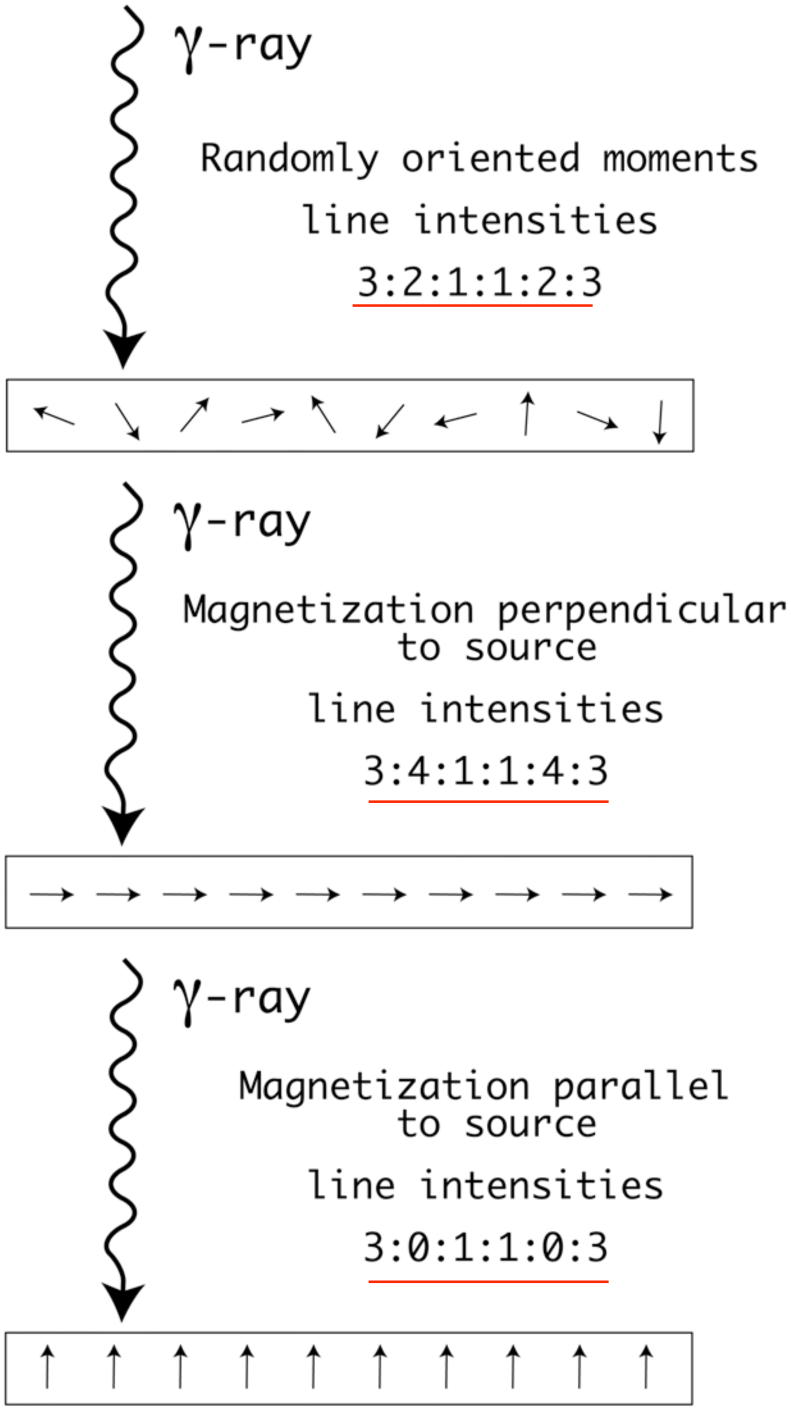
Advances in High-Pressure Technology for Geophysical Applications, Elsevier (2005)



Adding titanium (Ti) makes magnetite more sensitive to pressure. For MD grains, Mrs/Ms varies roughly as 1/Ms

Anhysteretic Remanent Magnetization (ARM) of MD TM0 (peak AF = 70 mT and 1 mT DC field)

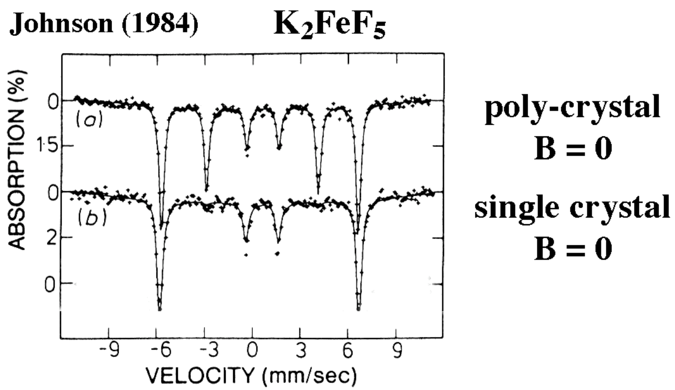




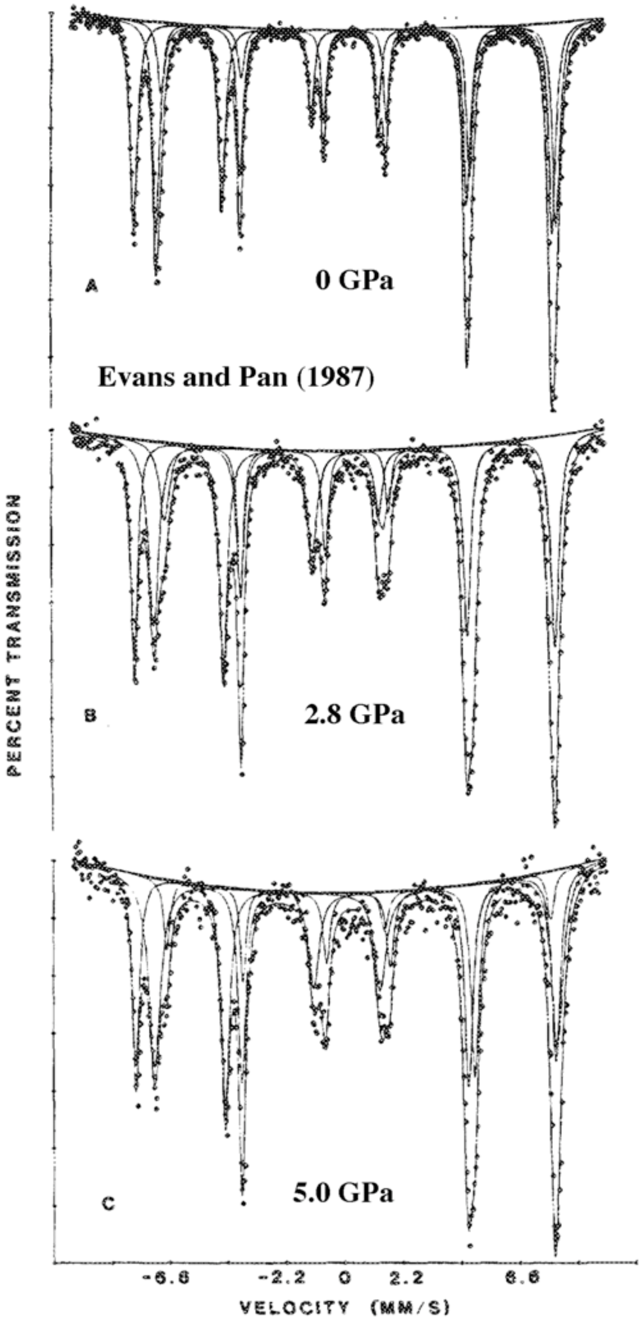
Mössbauer spectra change relative to the direction of the gamma ray source with respect to the magnetization direction of the sample.

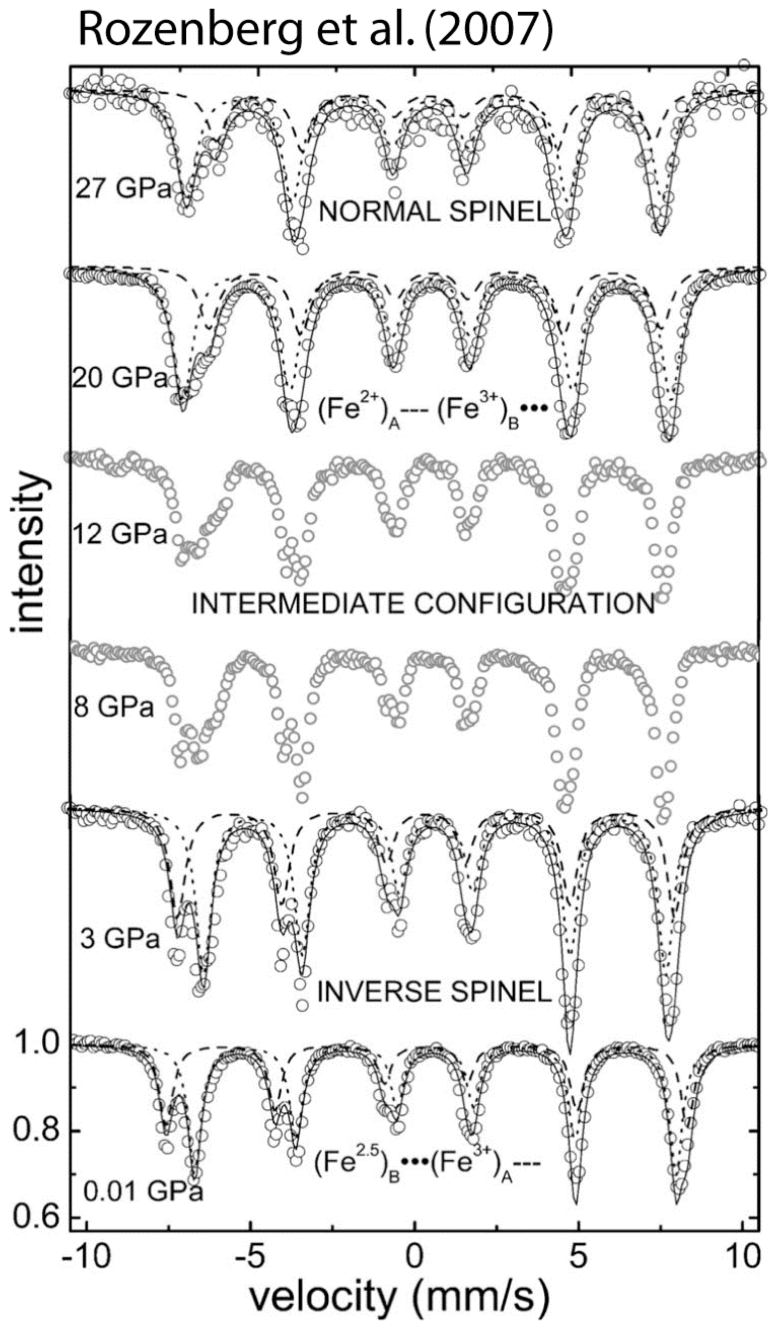
Our ARM experiments predict 2:1 (5:6) line intensities will increase with pressure.

The degree of magnetic alignment in magnetic tape can be determined by comparing the areas of the 2nd and 5th lines to the 1st and 6th lines ($A_{2,5}/A_{1,6}$).



Mössbauer spectra on "pure" magnetite





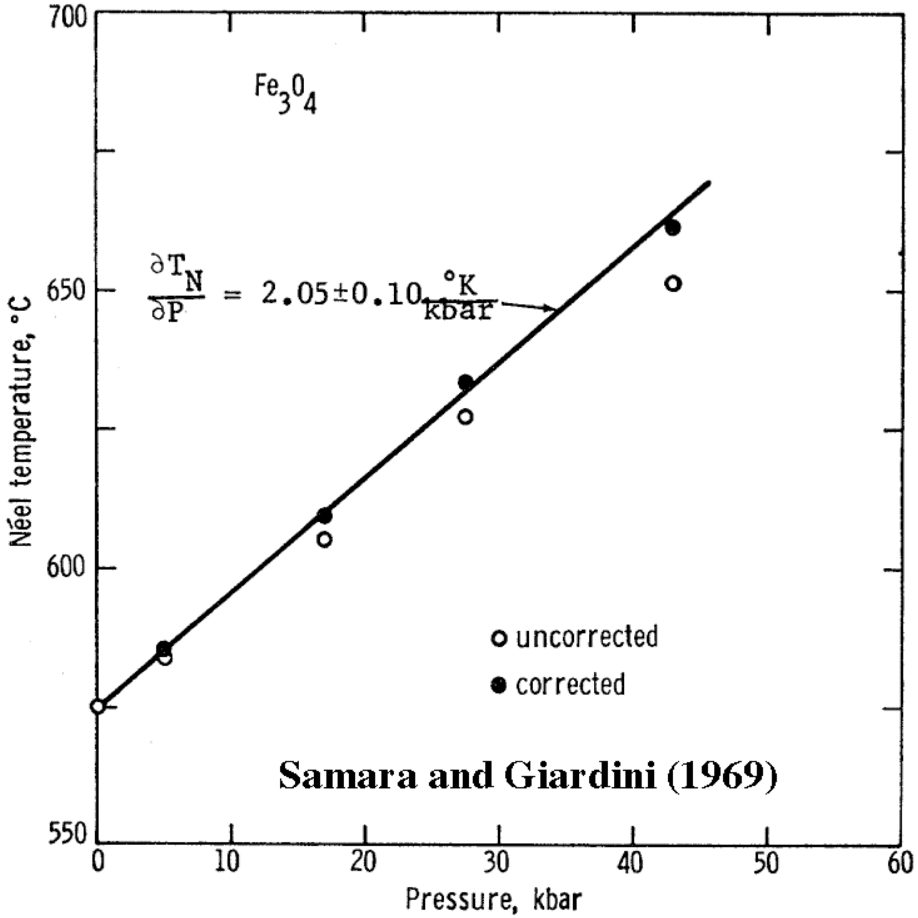
Relative area of 2:1 peaks

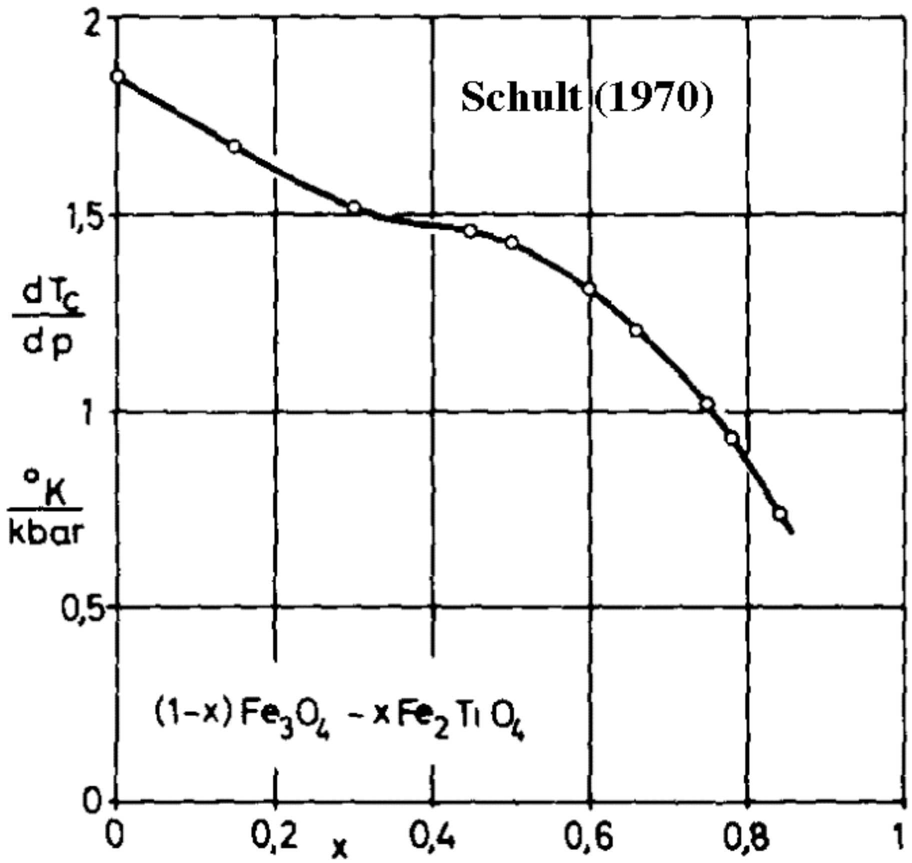
P (GPa)	R2007	E&P 1987
0.0	0.76	0.76
2.8		0.94
3.0	0.92	
5.0		0.93
20.0	1.05	
27.0	1.08	

2:1 peaks grow with pressure as expected from our ARM experiments.

The Curie points of pure magnetite and titanomagnetite increase by 10-20°C / GPa.

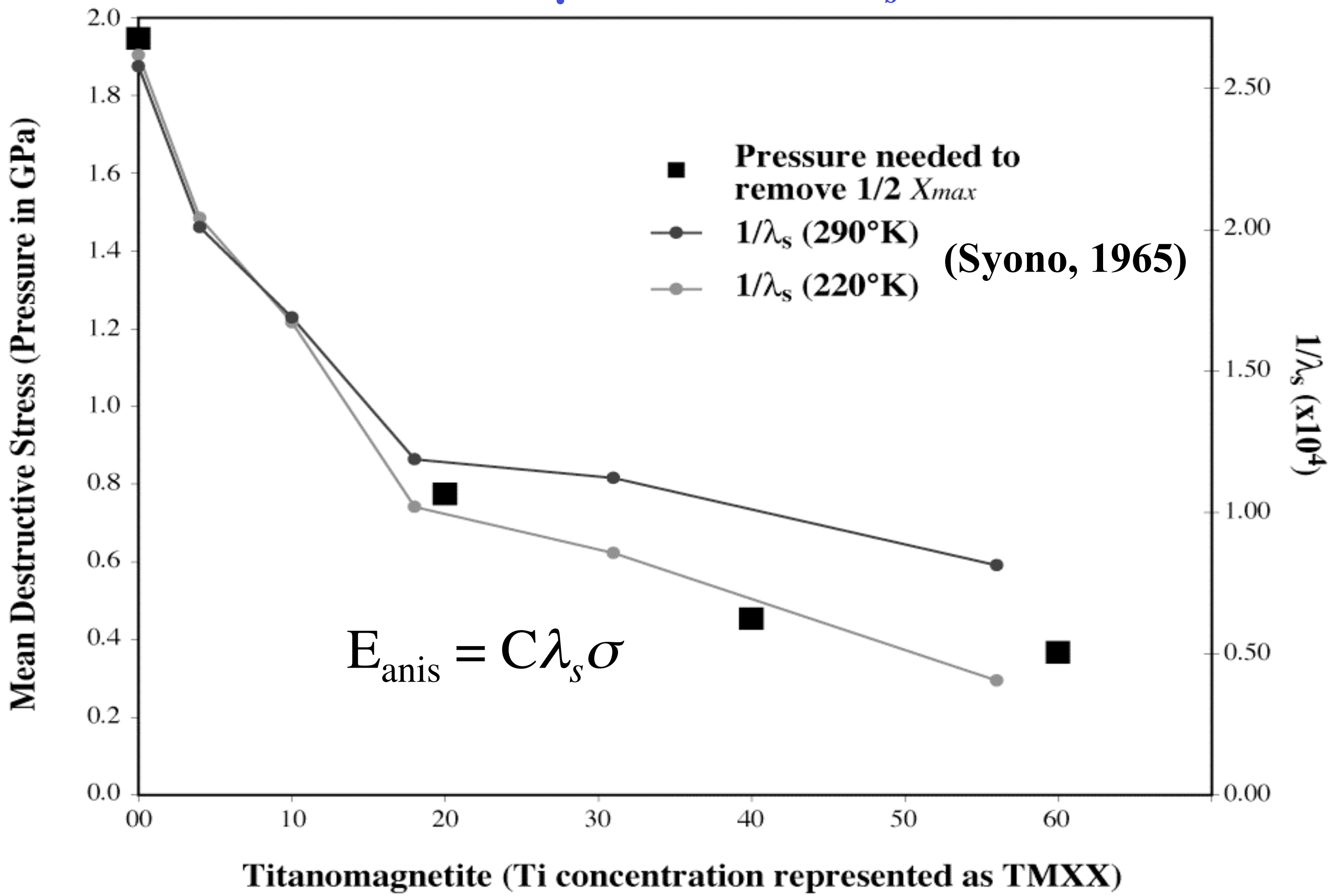
No $\partial T_c/\partial P$ data exists for other magnetic species (Fe^0, Fe_2O_3,..) or for pressures >5 GPa.





Advances in High-Pressure Technology for Geophysical Applications, Elsevier (2005)

Relationship between λ_s and σ



The higher the magnetostriction, the more sensitive magnetization will be to an external stress.

This is important for earthquake prediction !

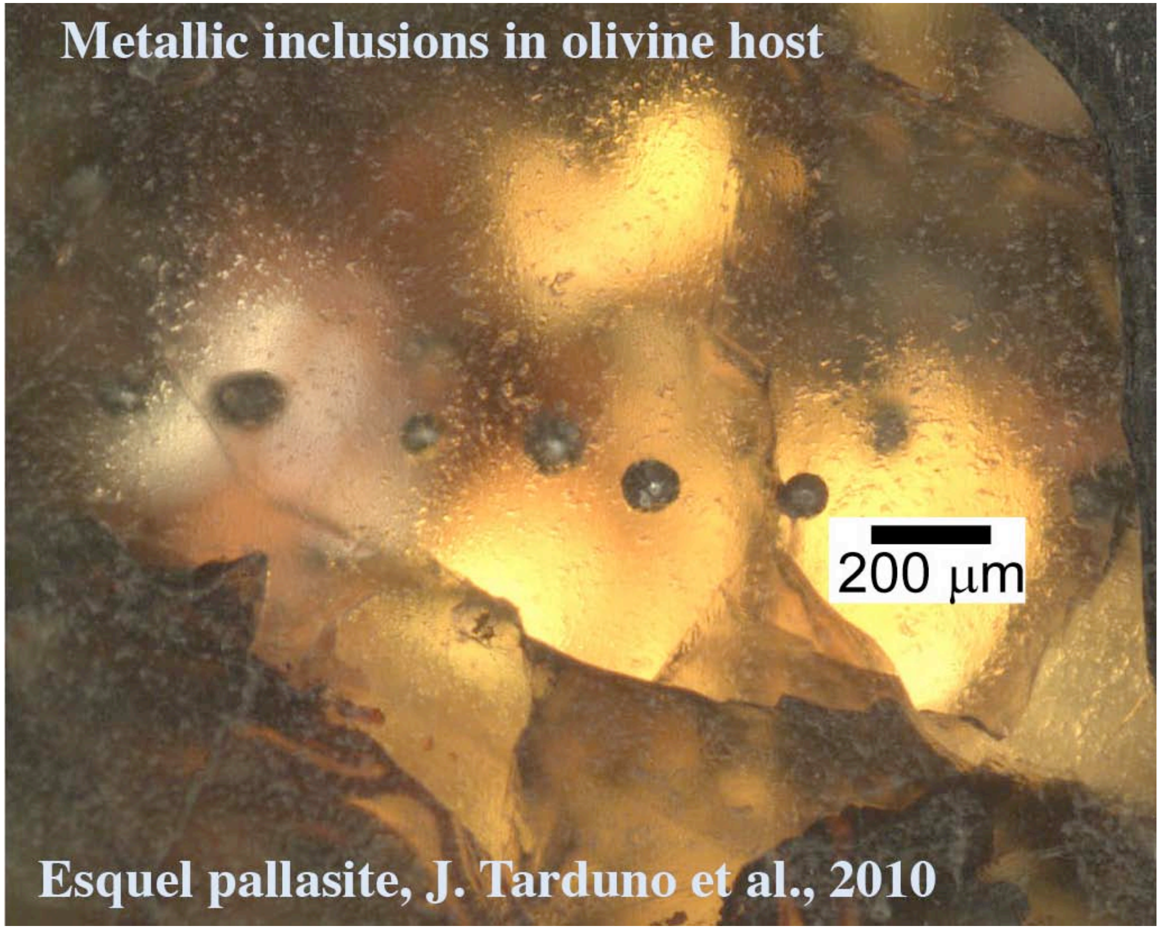
A pressure-induced, magnetic transition in pyrrhotite: Implications for the formation pressure of meteorites and diamonds

Stuart A. Gilder[1], Ramon Egli[1], Rupert Hochleitner[2], Sophie C. Roud[1], Michael W.R. Volk[1], Maxime Le Goff[3] and Maarten de Wit[4]

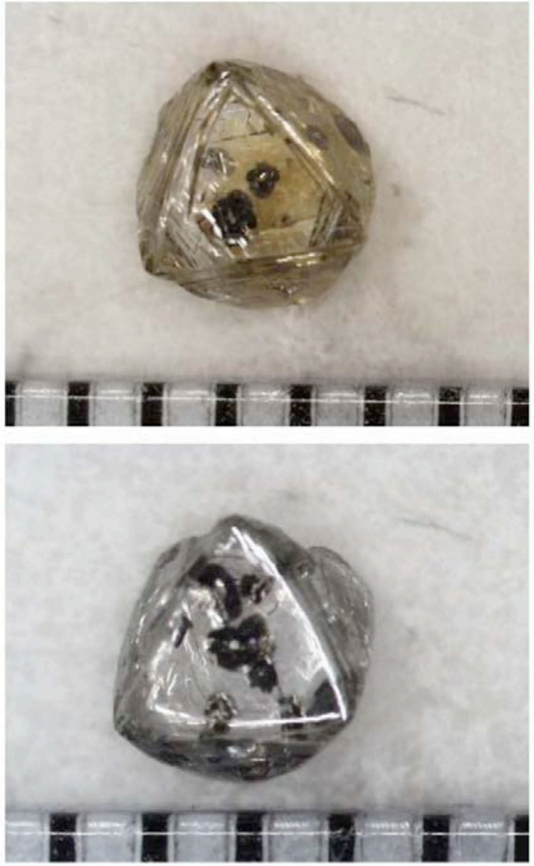
[1]Ludwig Maximilians Universität, Munich, Germany
[2]Mineralogische Staatssammlung, Munich, Germany
[3]Institut de Physique du Globe, Paris, France
[4]University of Cape Town, South Africa

JGR, in press 2011

Olivine and diamonds may contain magnetic inclusions. Differences in bulk moduli and thermal expansion coefficients between the two phases can result in an overpressure of the magnetic inclusions at ambient conditions. As magnetism is strain-sensitive, perhaps we can constrain formation pressures through a study of their magnetic properties (= magnetic barometry).



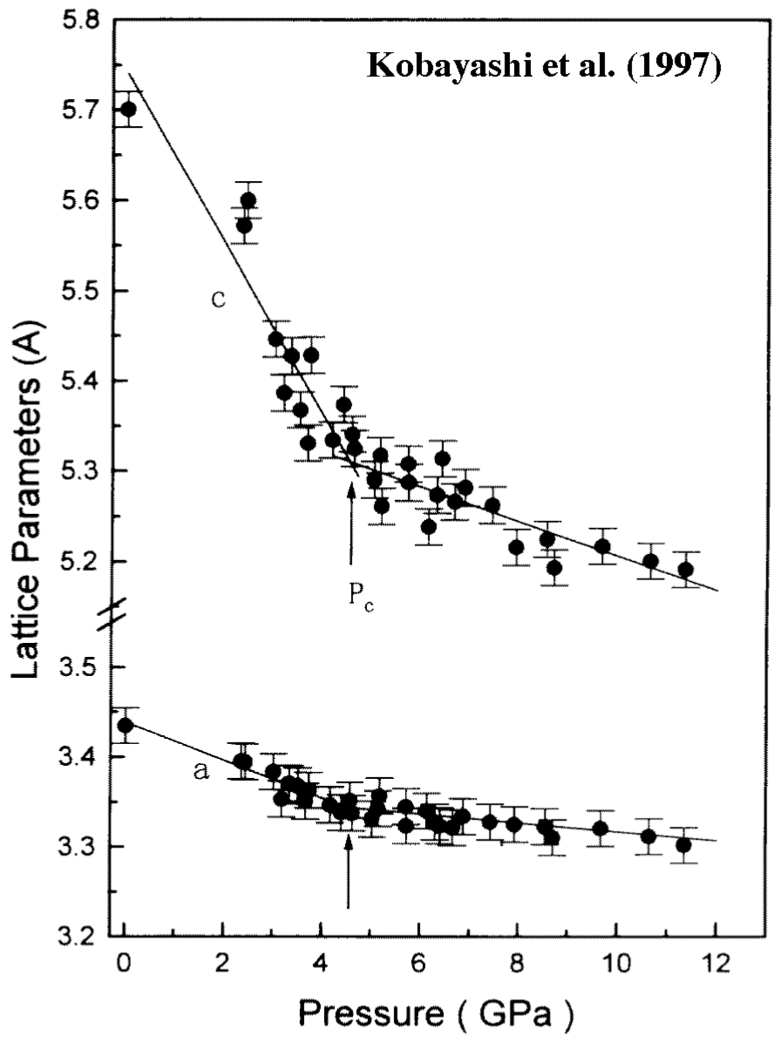
B.M. Clement et al. (2008)

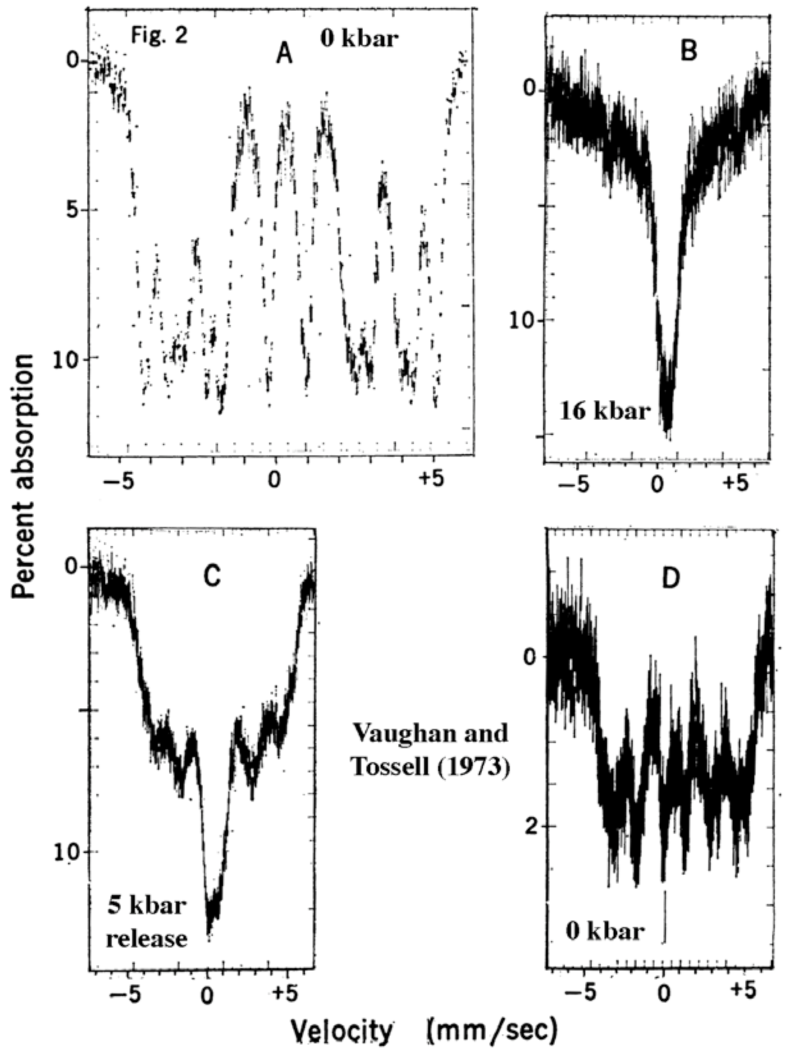


Each interval of the scale bars is 1 mm.

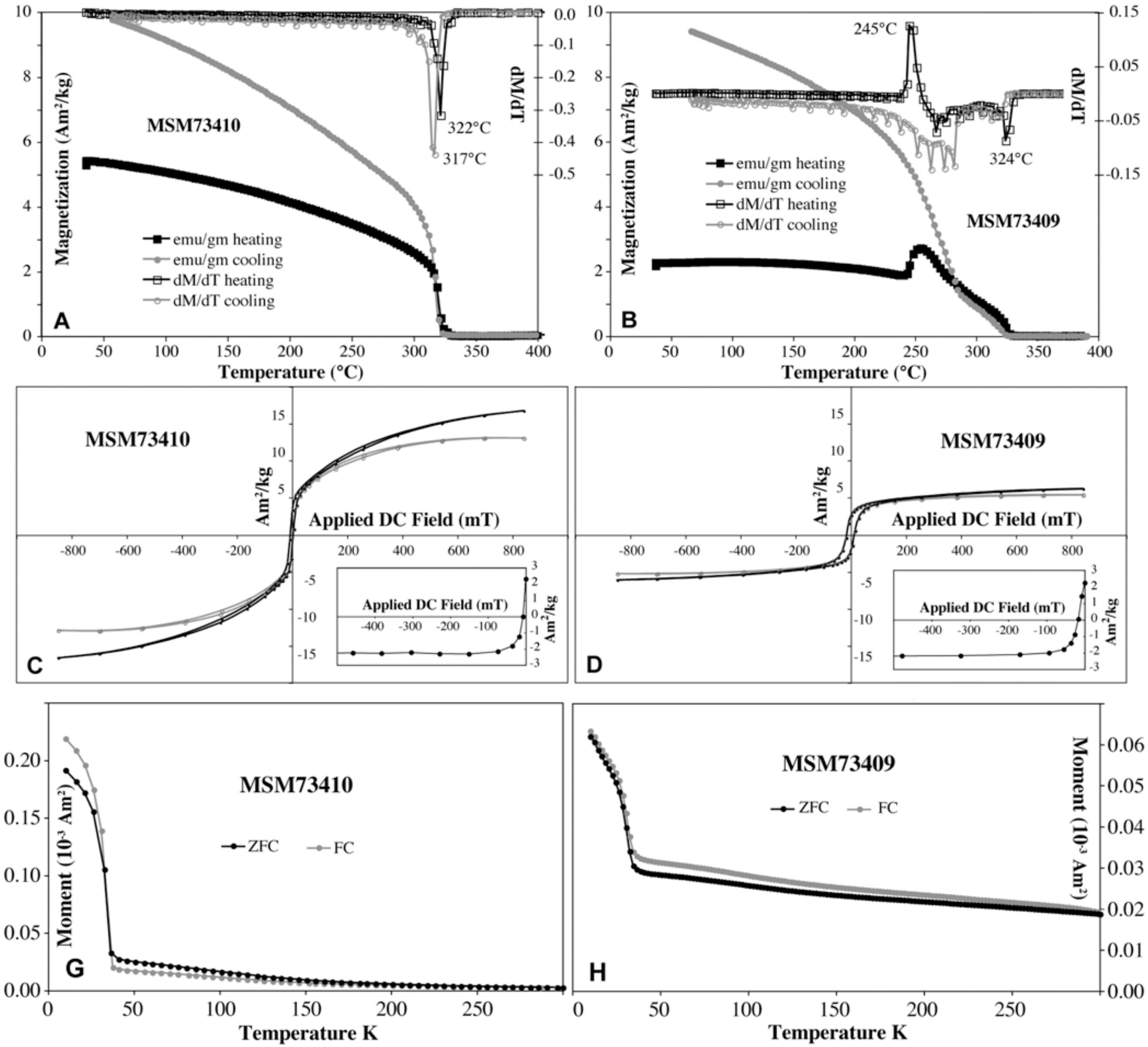
Monoclinic pyrrhotite undergoes a ferrimagnetic to paramagnetic transition under pressure. Estimates for the transition pressure range from 1.6 to 6.2 GPa. The c-axis lattice spacing likely governs pyrrhotite's electromagnetic properties (Kamimura et al., 1992).

A Mössbauer study of FeS and Fe_7S_8 under pressure

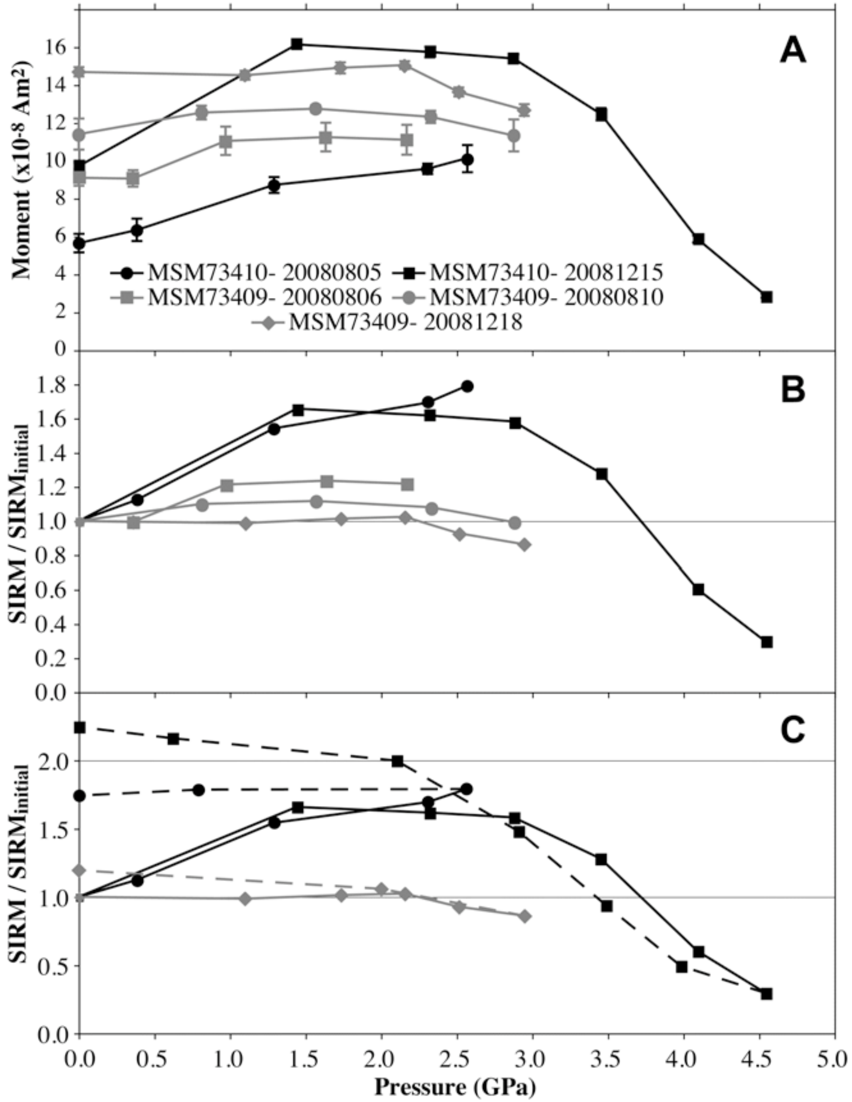


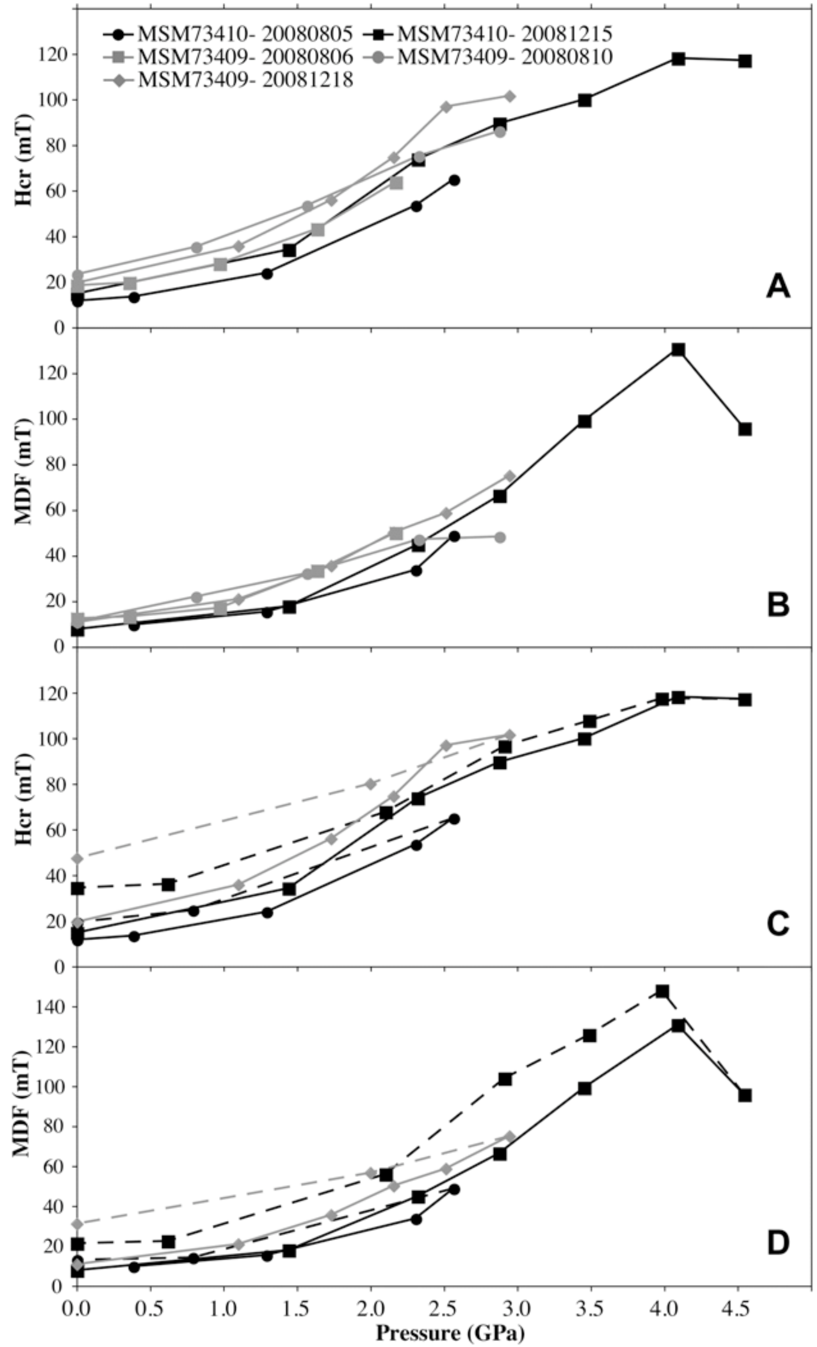


We studied natural samples of multidomain (Schmiedeberg, Germany) and single domain (Colquiri, Bolivia) pyrrhotite.

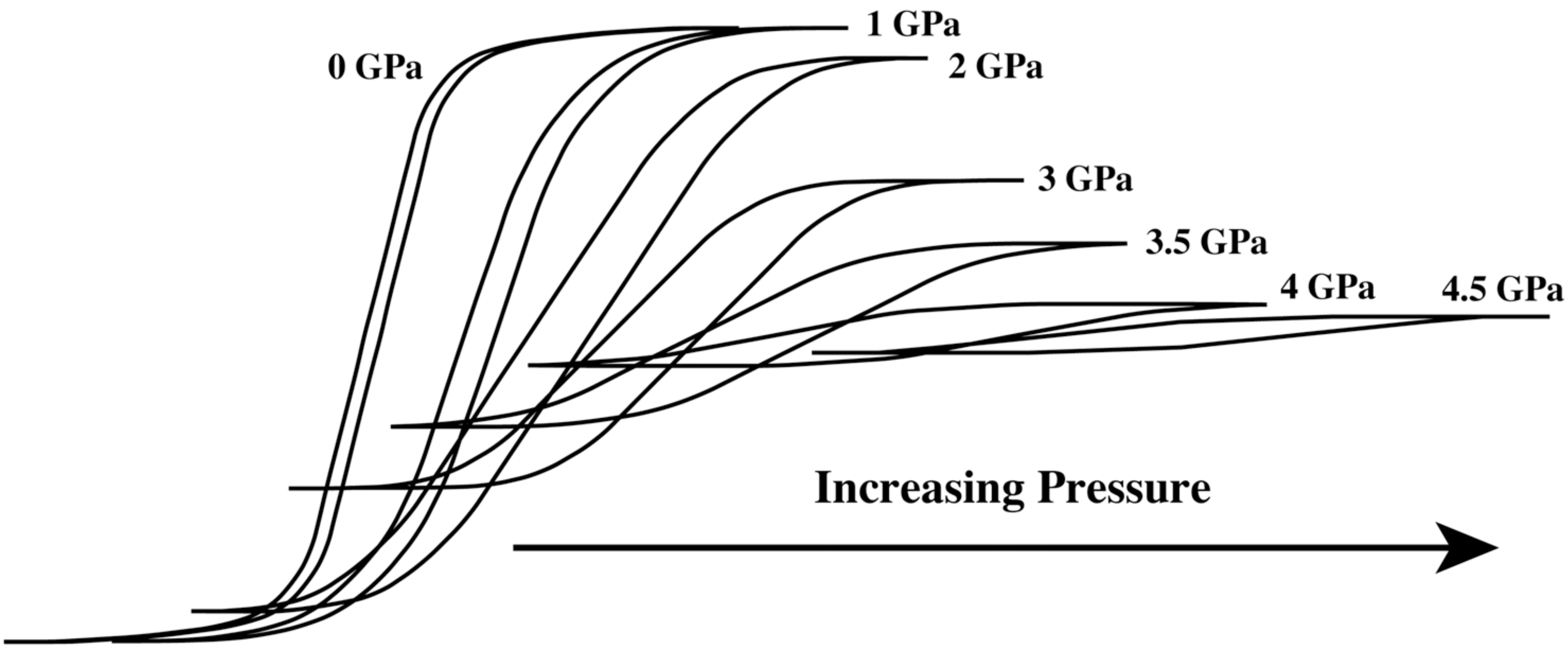


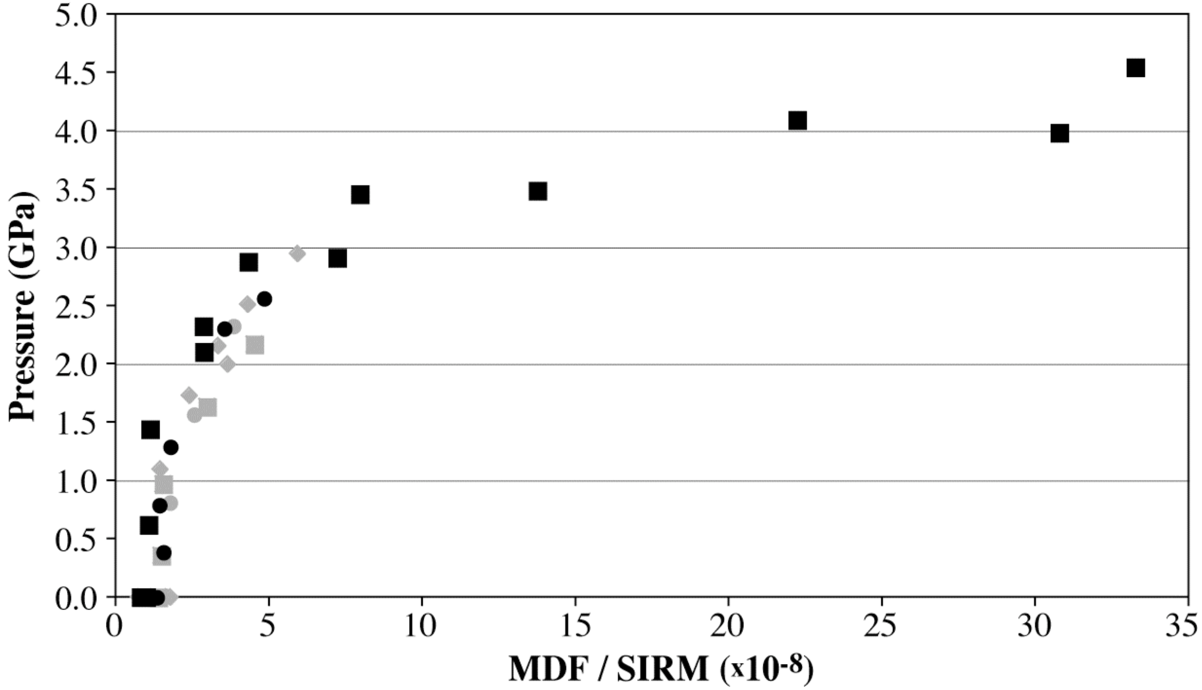
Three experiments on single domain (gray curves) and two on multi-domain (black curves) pyrrhotite

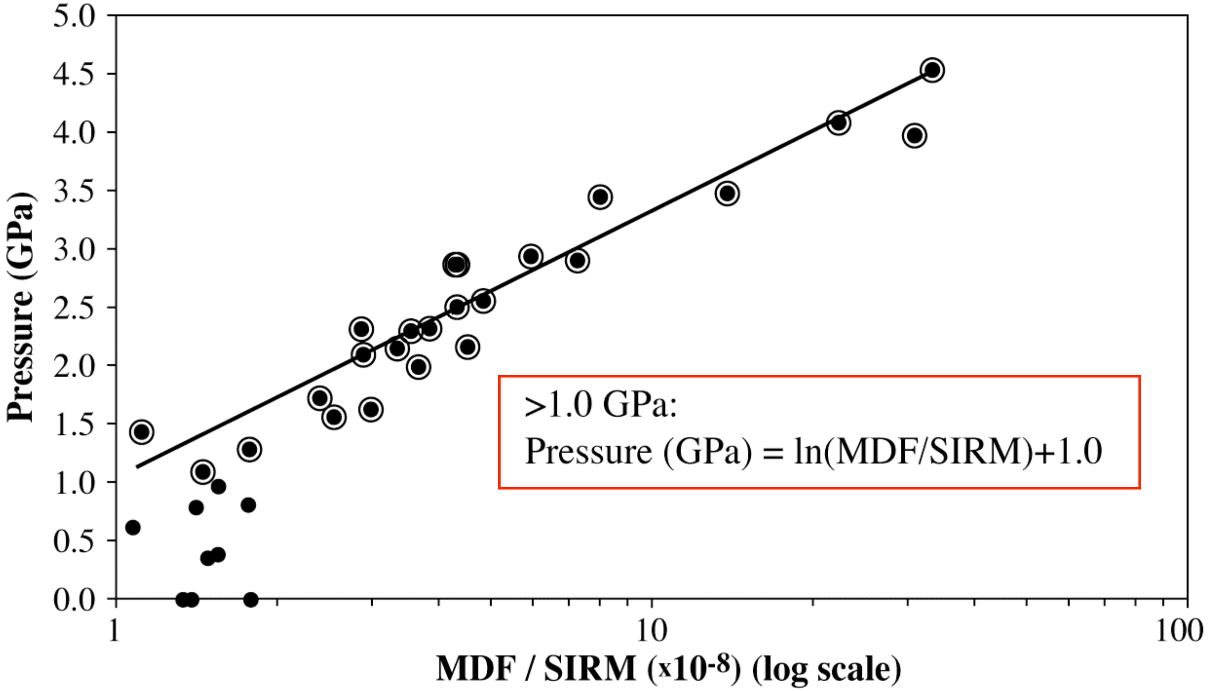




Idealized schematic of magnetic hysteresis loops of multi-domain pyrrhotite with increasing pressure. Hysteresis loops for single domain pyrrhotite follow the same overall path as for multi-domain pyrrhotite except the initial conditions begin farther to the right. Ms data scaled from neutron diffraction experiments of Rochette et al. (2003).







Above 1 GPa and regardless of domain state, the coercivity to remanence ratio follows a simple logarithmic law with respect to pressure.

Can this relationship be used to predict the formation pressures of pyrrhotite-bearing diamonds?

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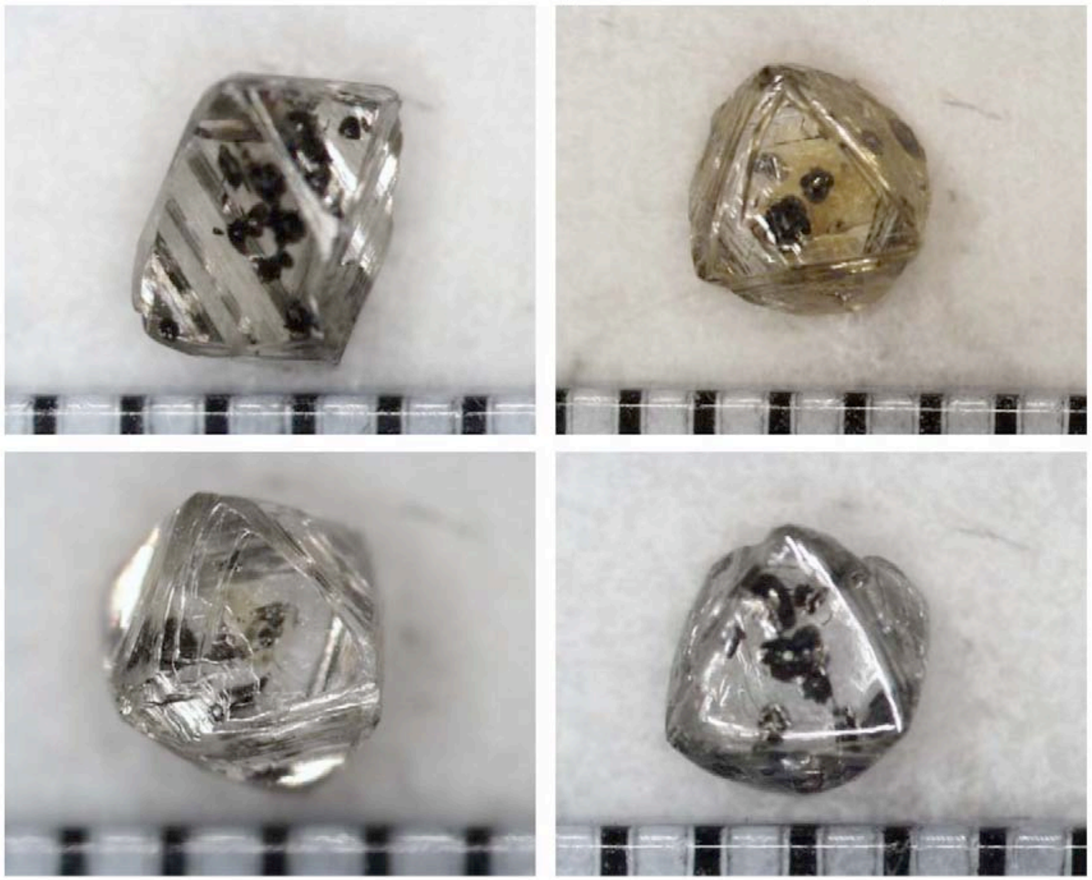


Fig. 1. Photomicrographs of diamonds showing inclusions. Each interval of the scale bars is 1 mm.

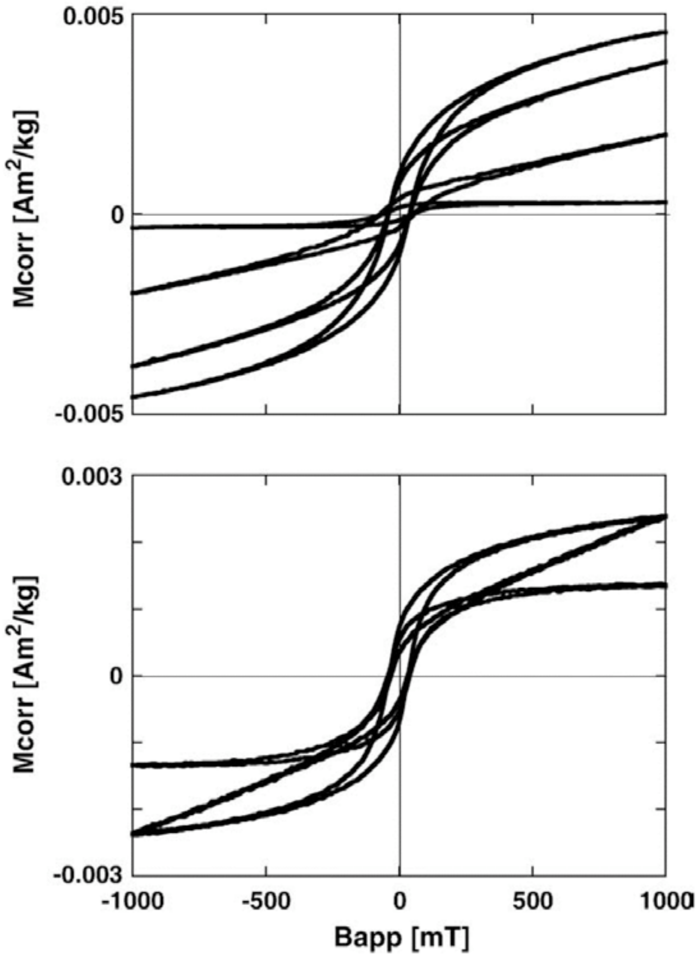


Fig. 8. Examples of hysteresis loops measured on two samples in multiple orientations documents a dramatic magnetic anisotropy (ORM-11 shown in the top panel, ORM-3 shown in lower panel). Each hysteresis loop has been corrected for the diamagnetism of diamond.

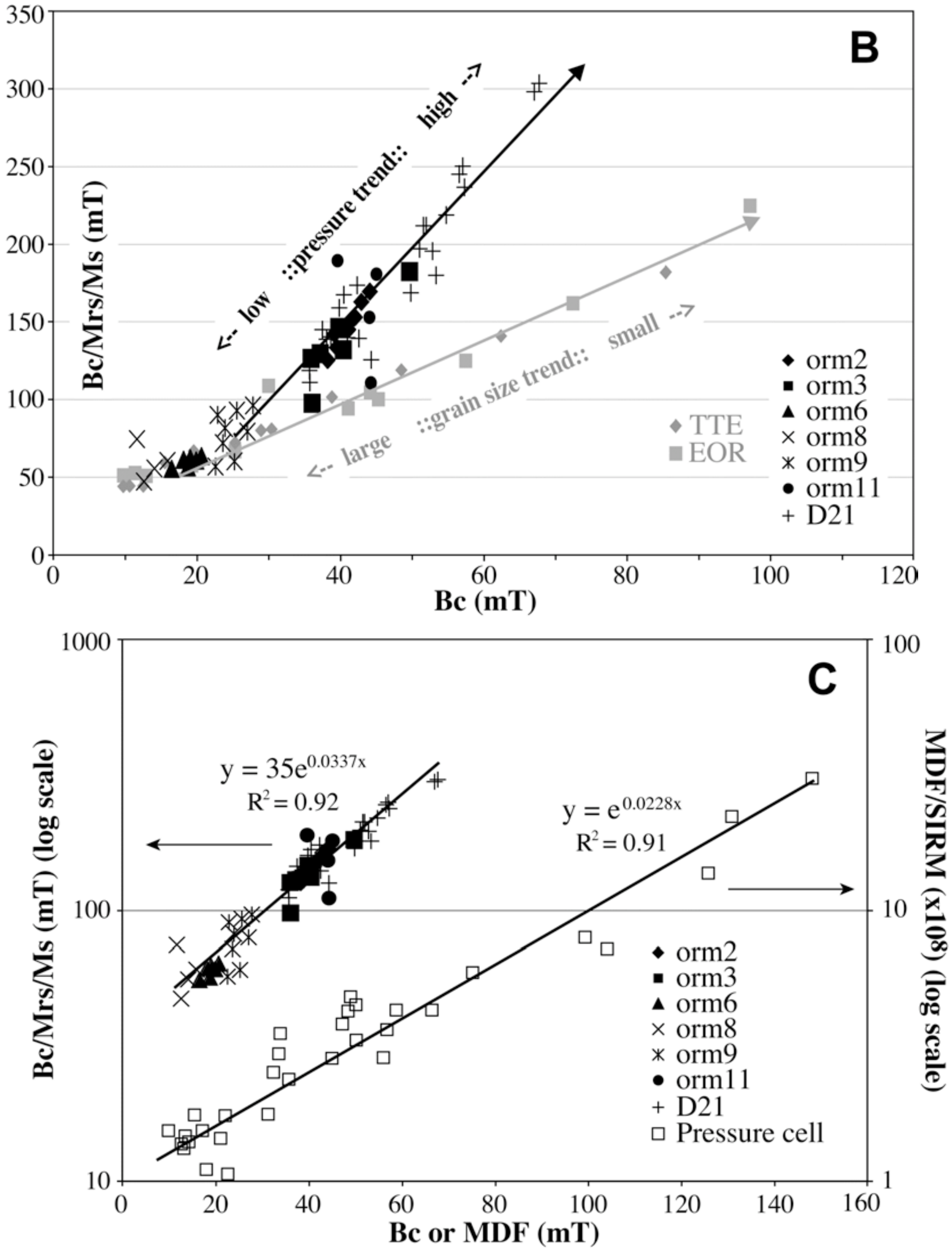
ORM- Botswana (Clement et al., 2008)

D21- Central African Republic
(this study)

Above ~1.0 GPa, the magnetic properties of pyrrhotite become distinctly different from non-pressurized pyrrhotite.

Individual magnetic hysteresis parameters for a single diamond can vary >50%, yet pressure estimates vary by <5%.

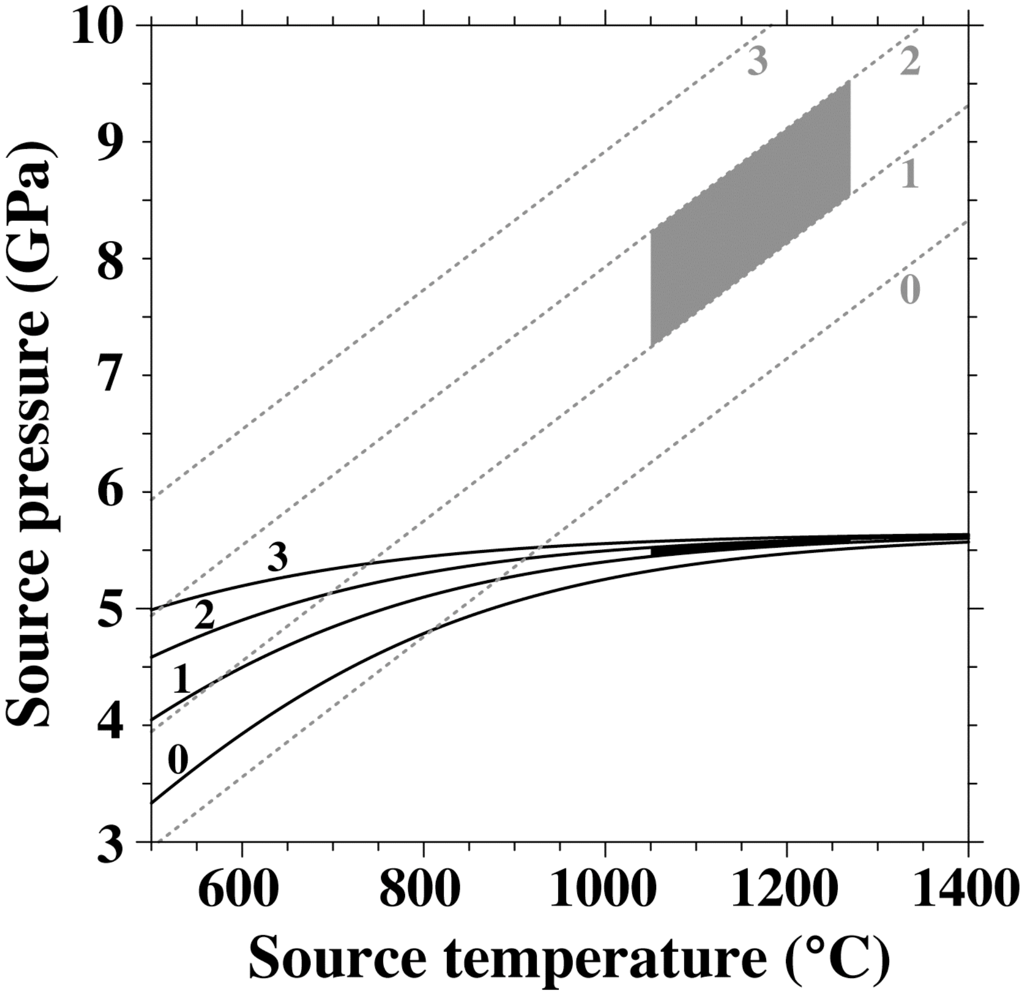
$$P\ (in\ GPa) = \frac{1}{1.478}\ln\left(\frac{HcMs}{35Mrs}\right) + 1$$



This work shows that the pyrrhotite inclusions are at pressures from 1.3 to 2.1 GPa. This corresponds to minimum diamond formation pressures of 5.4 to 9.5 GPa depending on which thermal expansion coefficients are considered.

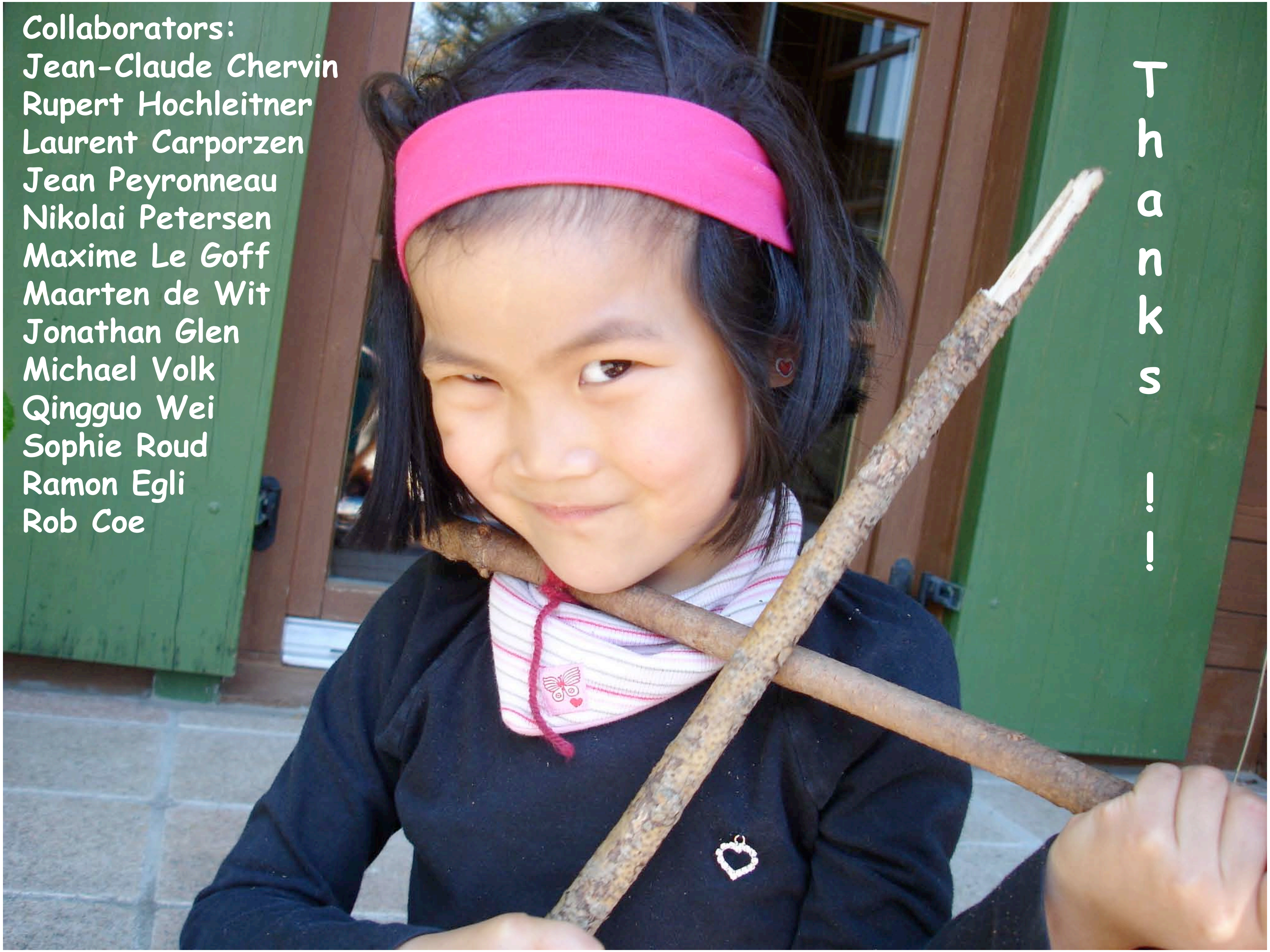
$$\frac{dP}{dT} = \frac{\alpha_i(T,P) - \alpha_d(T,P)}{\frac{1}{K_i(T,P)} - \frac{1}{K_d(T,P)}}$$

α = thermal expansion coefficient
K = bulk modulus



Conclusions

1. Iron in the solid inner core can potentially influence the geomagnetic field.
2. Magnetite's magnetic properties are more stress-sensitive with increasing titanium concentration.
3. The pyrrhobarometer can determine source pressures of diamonds and possibly meteorites if pyrrhotite forms multidomain-size inclusions in olivine or other "strong" minerals and if the formation pressure was ca. >1 GPa. For meteorites, a goal is to know what depth the meteorite originally formed at in the parent body.
4. Much more work is needed (Qingguo Wei, new PhD student):
   a) At high temperatures (Curie temperature)
   b) On Fe-Ni-S-Si phases relevant to planetary cores
   c) Varying grain sizes and oxidation states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Thanks !!