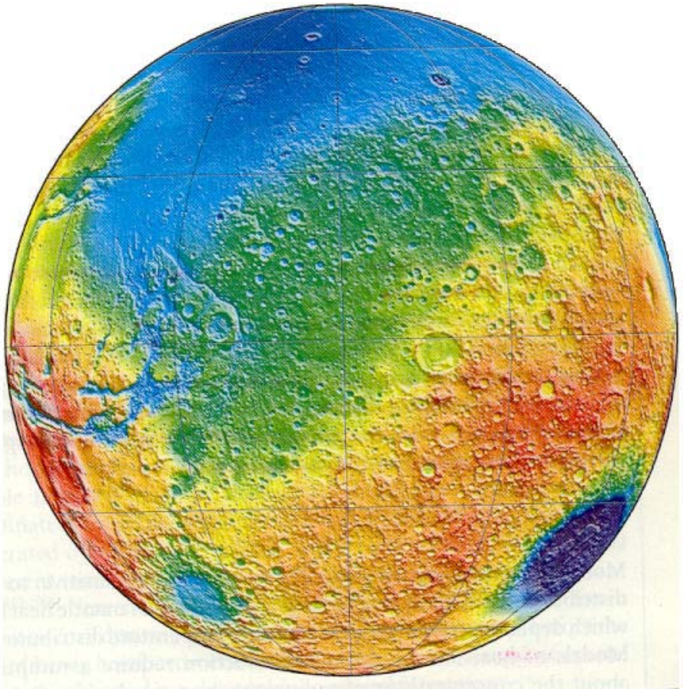
Magnetism of the Earth, Moon and Mars



David J. Dunlop

University of Toronto

Magnetism of the Earth, Moon and Mars

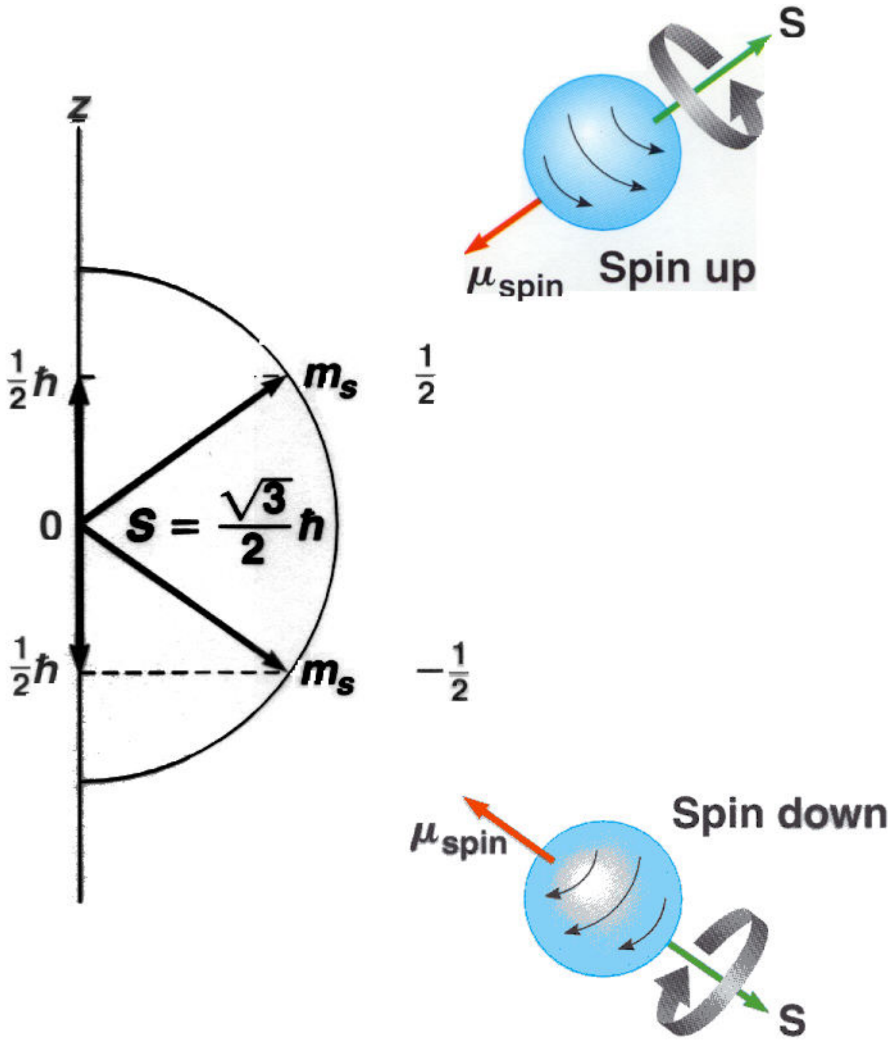
- *Magnetism*
- *Magnetic domains*
- *Magnetic fields*

- *Earth's magnetism*
- *Moon's magnetism*
- *Mars' magnetism*

Collaborators:

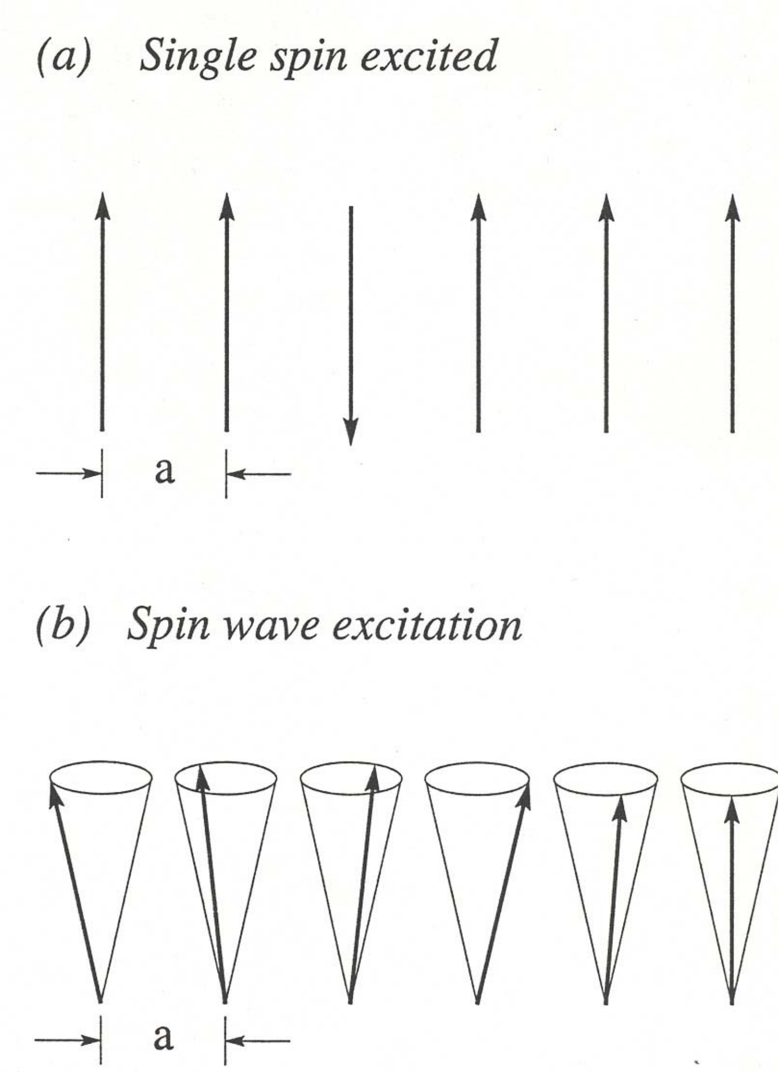
Jafar Arkani-Hamed	***McGill & U. of T.***
Özden Özdemir	***U. of T.***
Gunther Kletetschka	***NASA Goddard***
Michael Purucker	***SFC***

Spin magnetic moments



Electron spins have magnetic moments proportional to S_z and directed along the magnetic field.

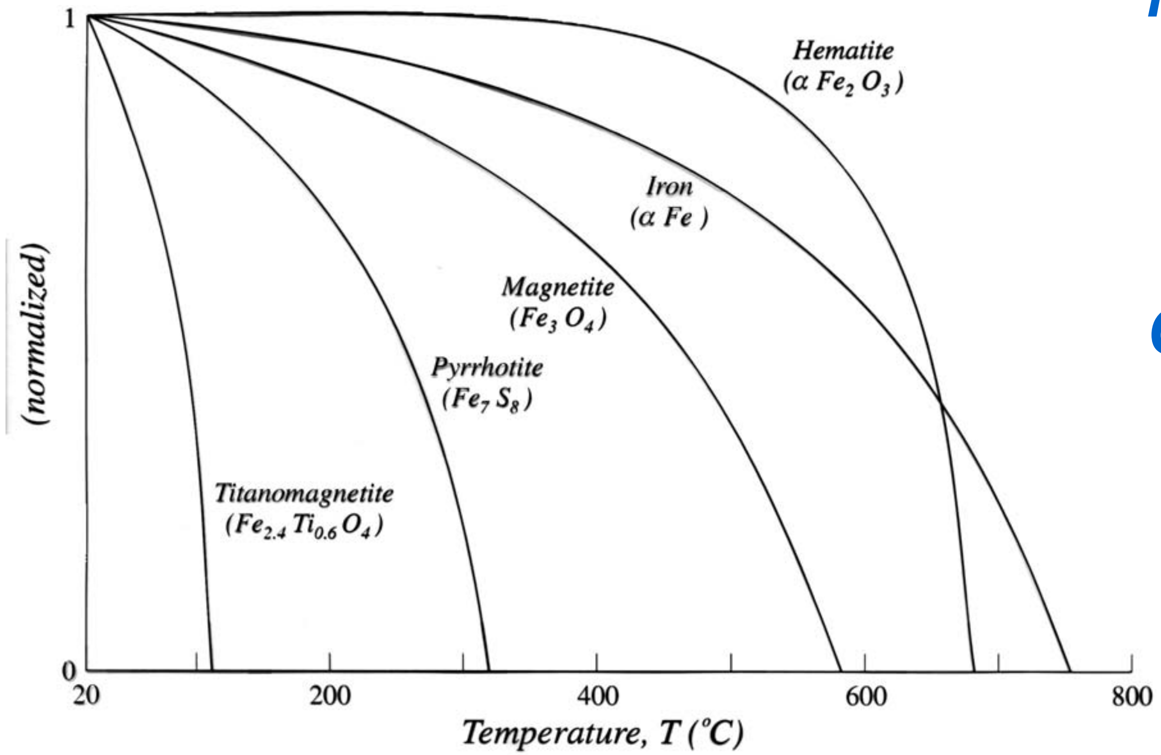
Exchange coupling and ferromagnetism



Spins and magnetic moments of 3d electrons in iron compounds are exchange coupled (Heisenberg, 1928).

This creates a strong spontaneous magnetization M_s.

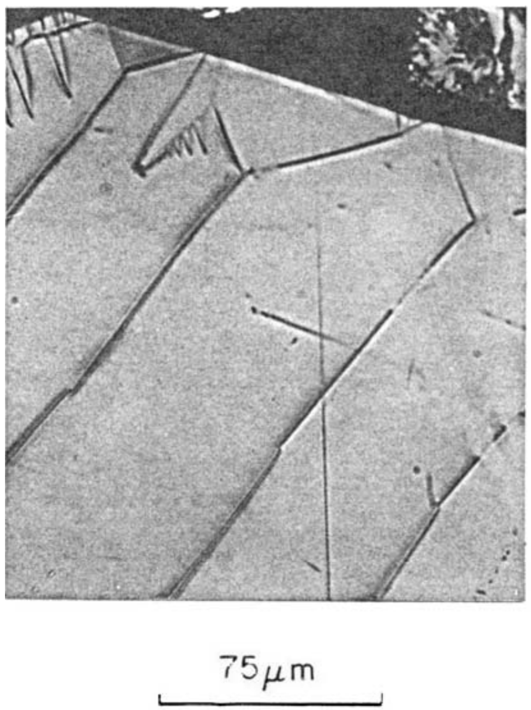
$M_s(T)$, the Curie point, and TRM

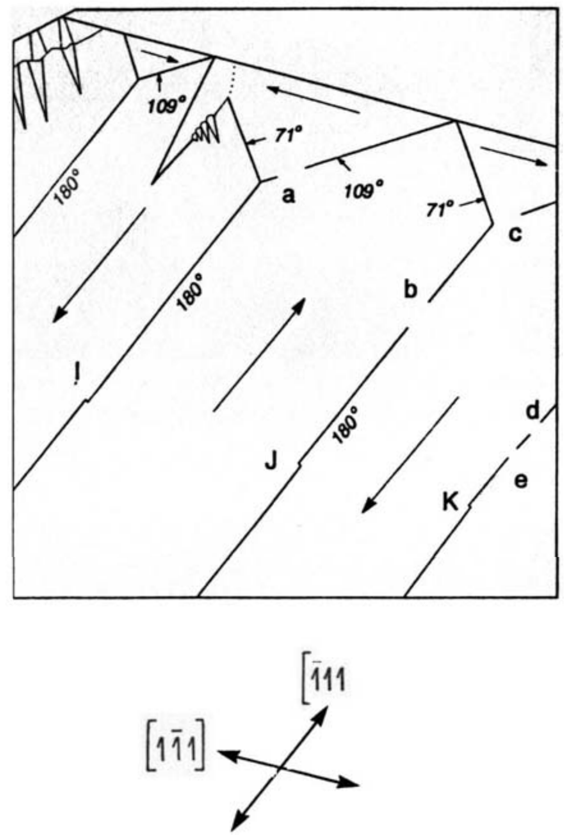


M_s is temperature varying, going to zero at the Curie point T_c.

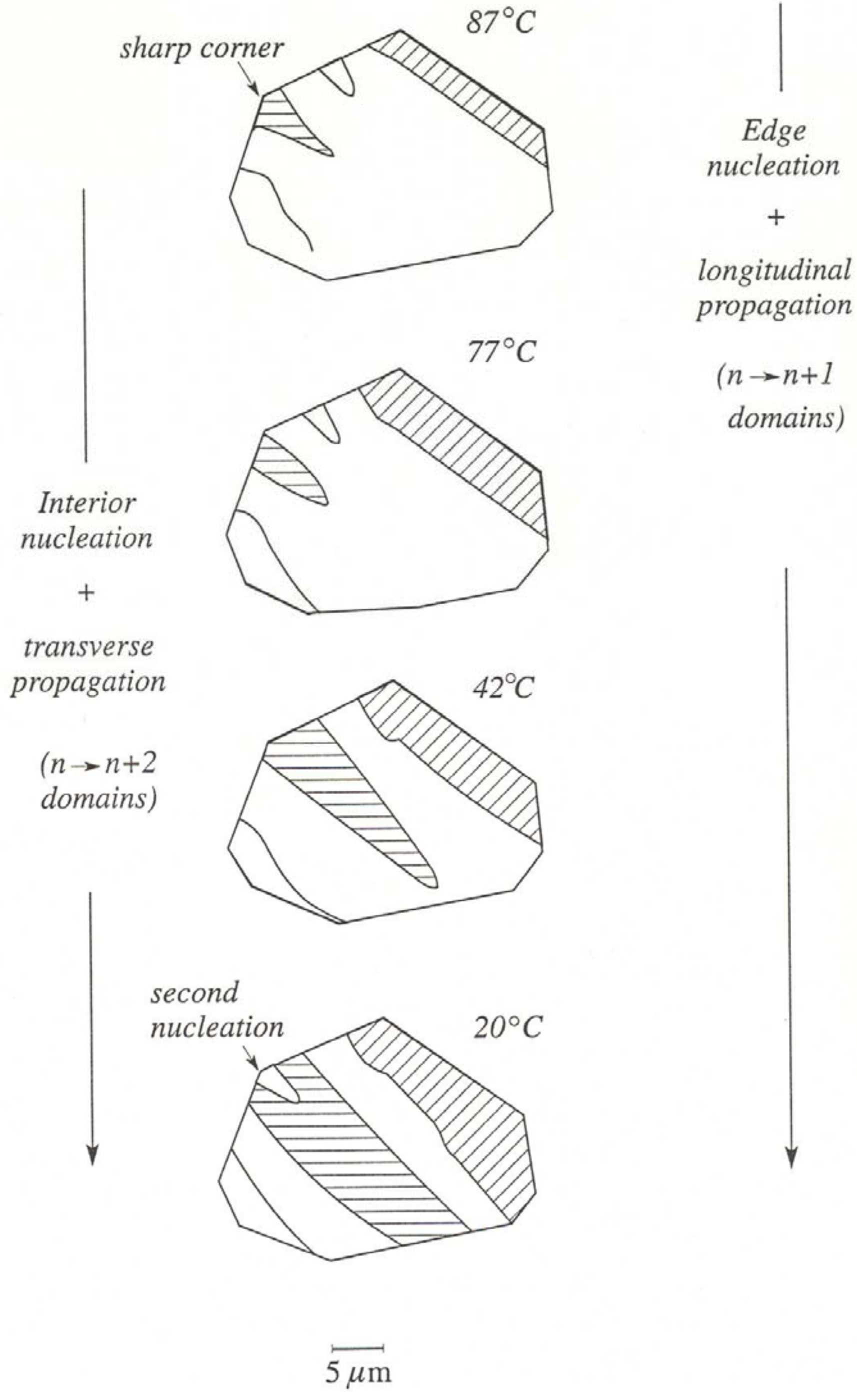
Cooling from T_c in even a small magnetic field produces a thermoremanent magnetism (TRM).

Magnetic domains are regions of parallel spins and strong spontaneous magnetization





Body and closure domains in magnetite have M_s along [111] axes (Özdemir et al., 1995)



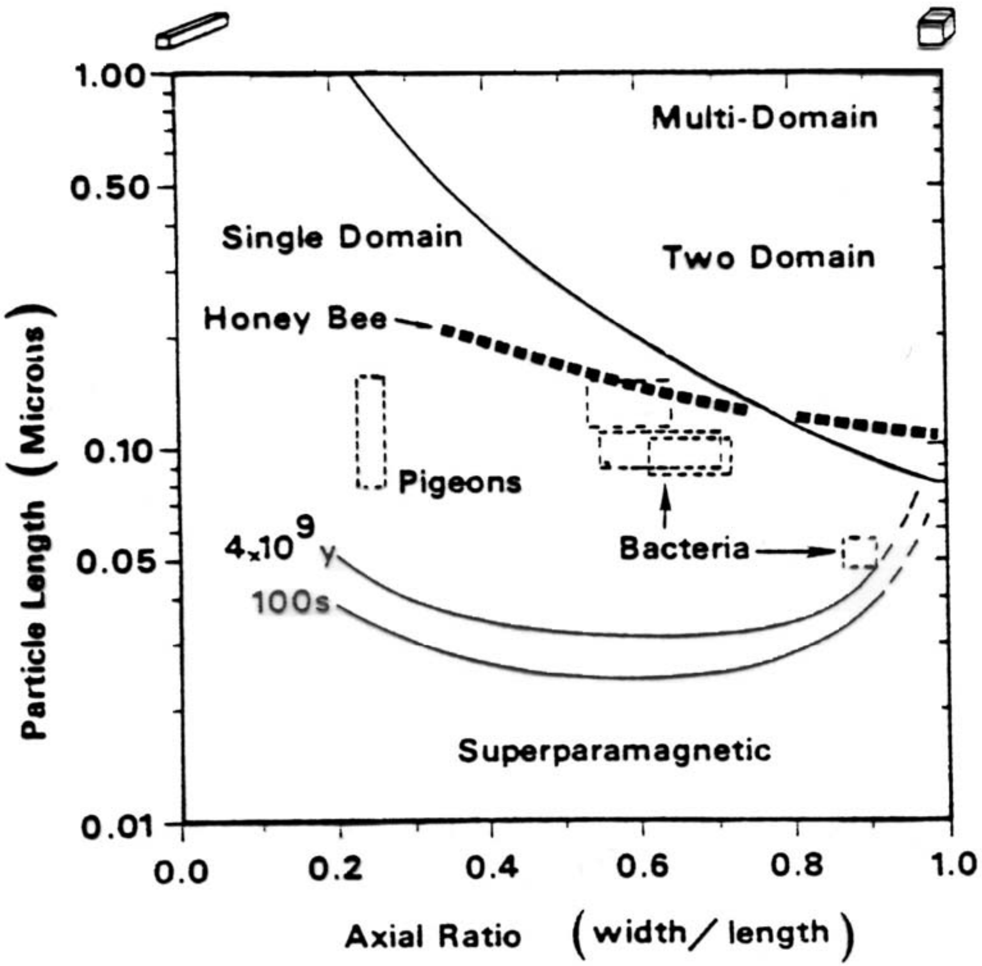
Domains change with temperature

As temperature drops, domains enlarge or shrink. New domains nucleate and grow.

Domains adjust so as to minimize energy (self-demagnetization). This limits TRM intensity.

Domain images: Heider et al. (1988)

Single-domain particles



Particles smaller than the width of a domain only have room for a single domain.

Bacteria, bees and pigeons produce single-domain biomagnetite for navigation.

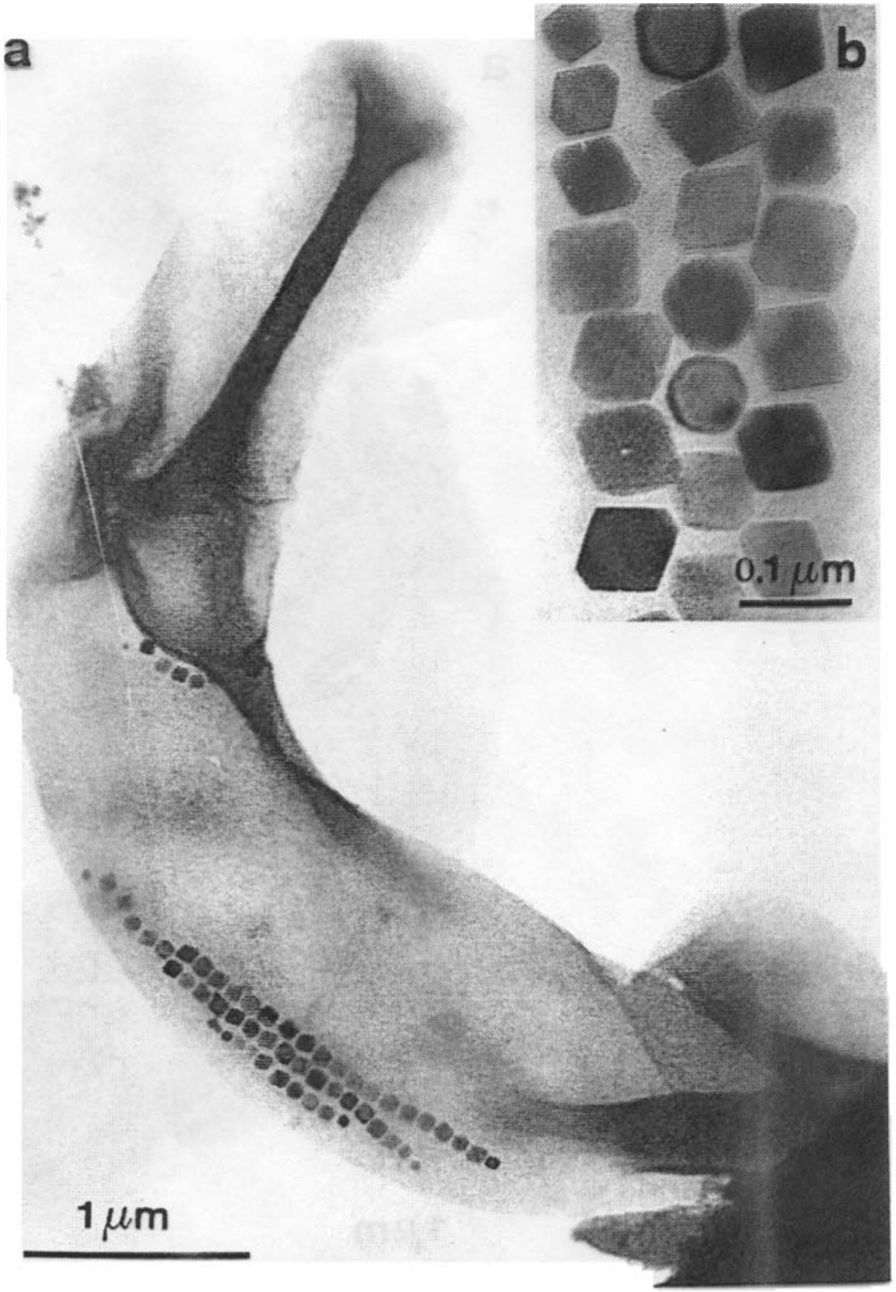


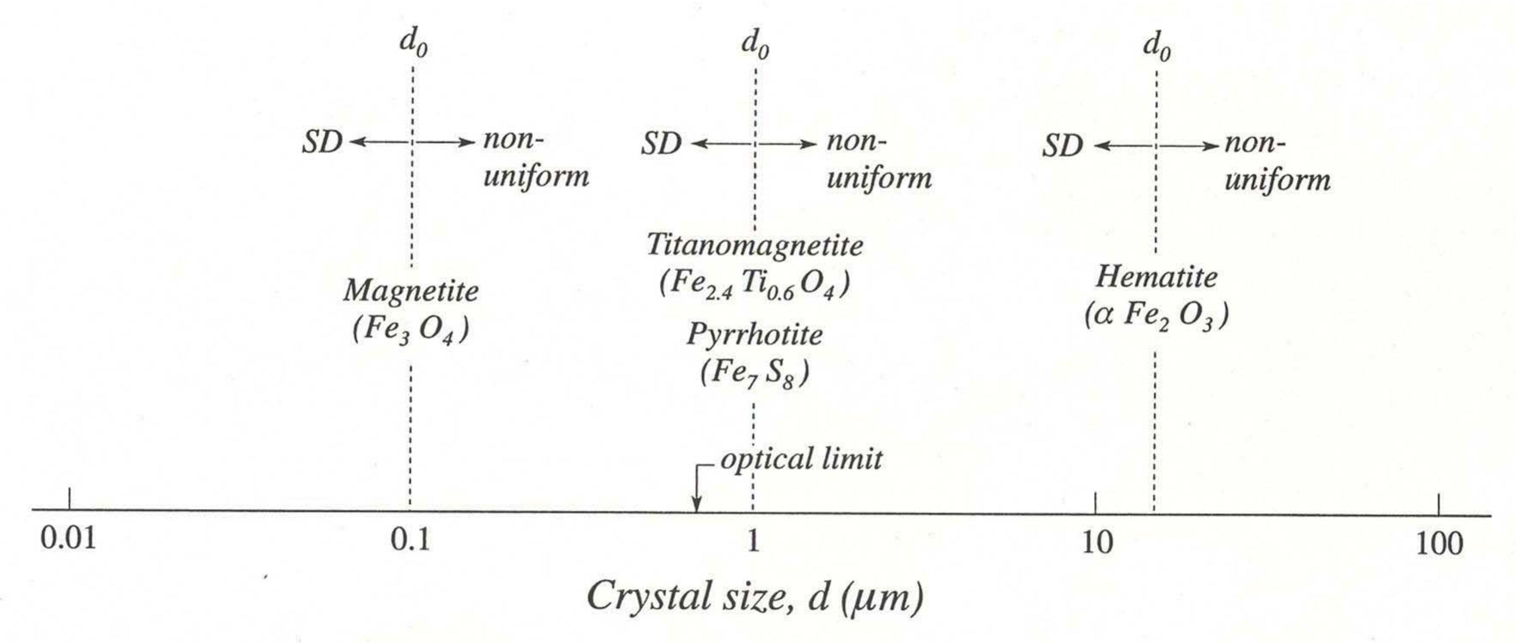
Fig. 3. (a) "Spirillum" after 4 months; (b) octahedral magnetosomes.

Aquaspirilum magnetotacticum **produces chains of magnetite octahedra -- *a compass*!**

The advantage of single-domain particles: *they do not self-demagnetize*.

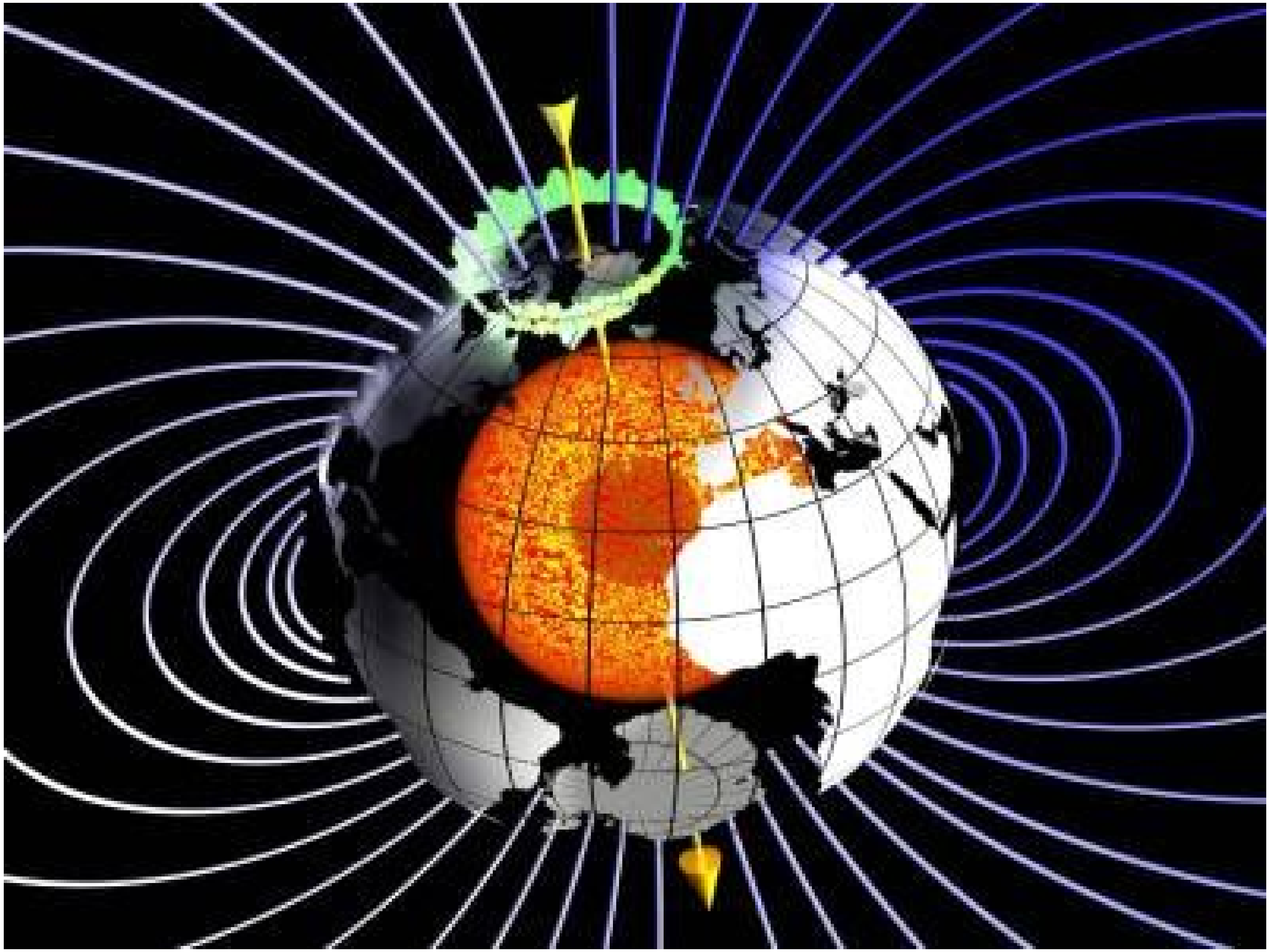
In rocks, this results in *intense and stable TRM*.

Critical single-domain sizes

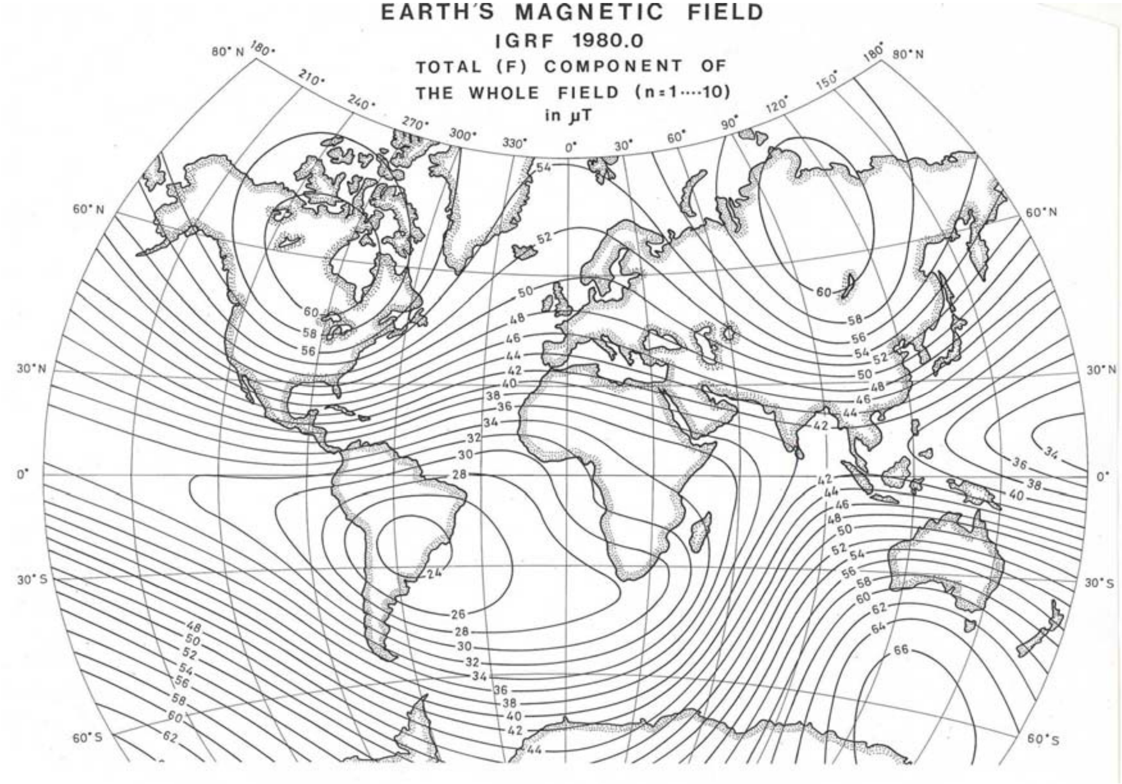


Critical sizes for single-domain behavior vary a good deal. For magnetite, $d_o \approx 0.1\ \mu m$, for pyrrhotite $d_o \approx 1\ \mu m$, for hematite $d_o \approx 20\ \mu m$.

Earth’s magnetic field: almost a dipole



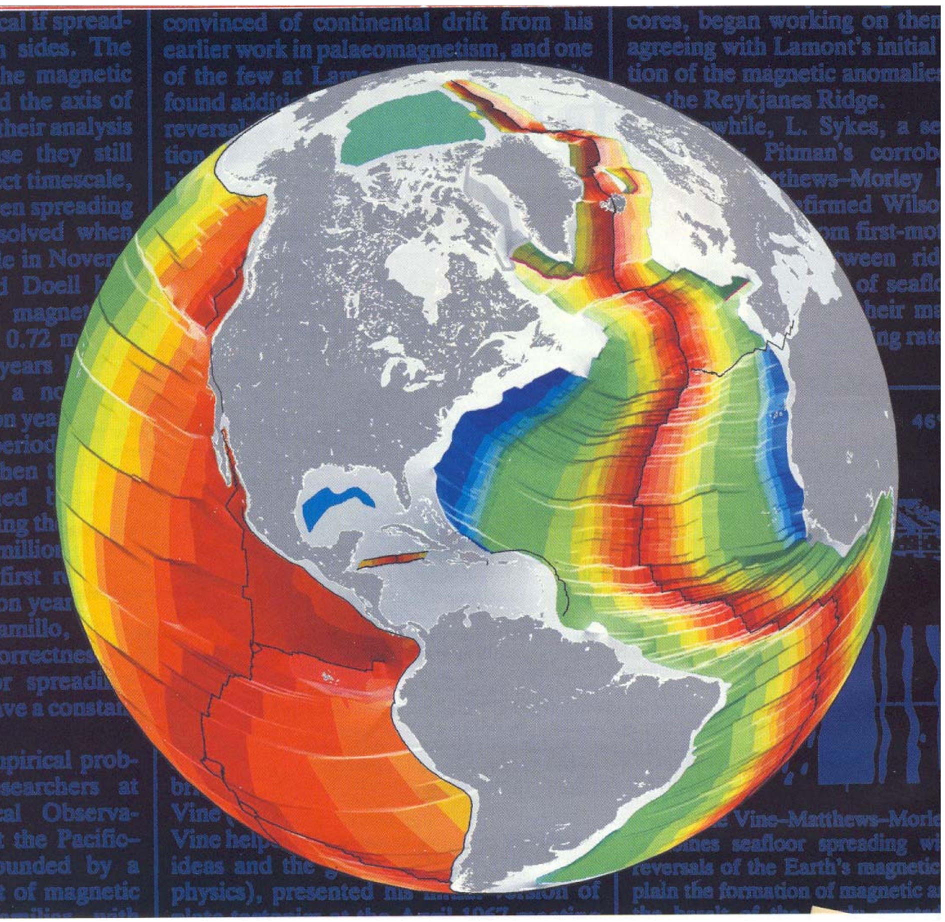
Earth's magnetic field intensity



The field is twice as strong at the poles as at the equator, as Gauss (1838) predicted for a dipole.

The residual after subtracting a multipole fit up to ~10th harmonic is a magnetic anomaly map.

Seafloor spreading resulting from crustal accretion at mid-ocean ridges



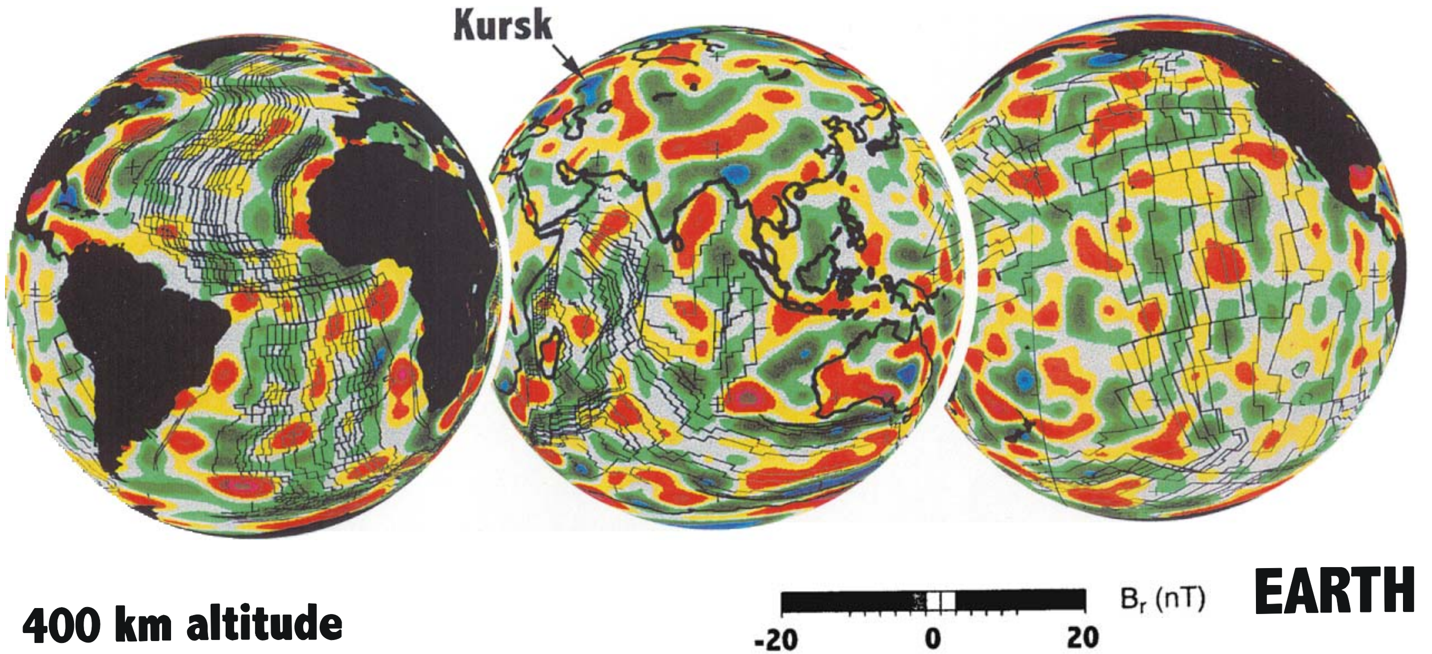
Vine & Matthews (1964):
Seafloor spreading +
Reversals of the field
→ Linear oceanic magnetic anomalies

10's of km wide
100's of km long

Source is remanent: TRM of rocks 0 to 3 km deep

Magnetic anomalies from satellite altitude

(courtesy of M. Purucker)

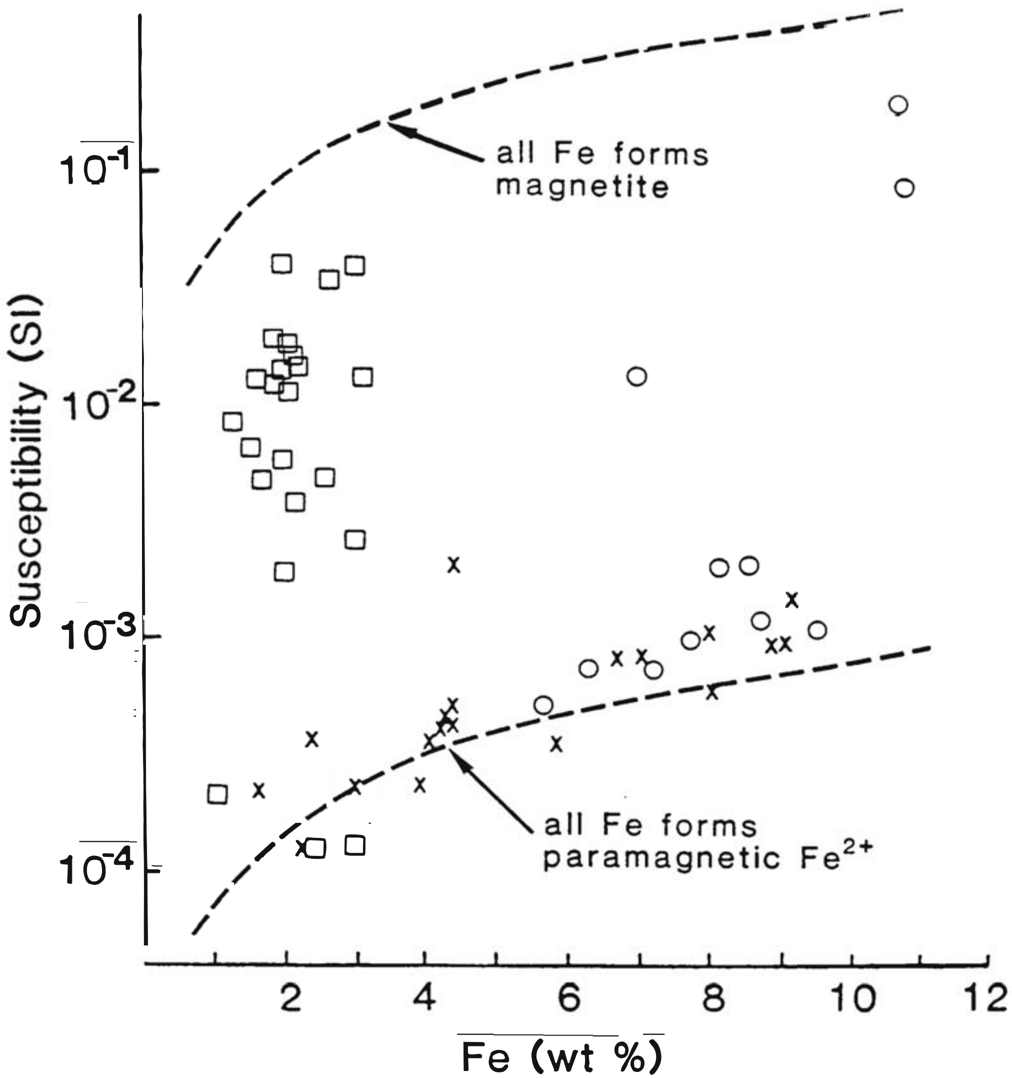


Scale size: 100's to 1000 km

Sources as deep as 50 km

Mainly induced magnetization in Earth's present field (30-70 µT)

Deep crustal rocks from Pikwitonei (Williams et al., 1985)



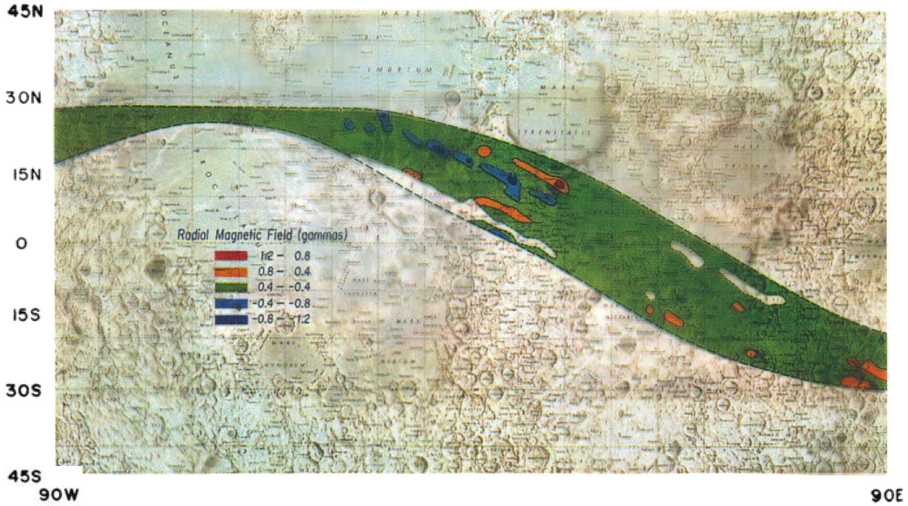
In the Earth's deep continental crust, the main magnetic mineral is 1-3% magnetite.

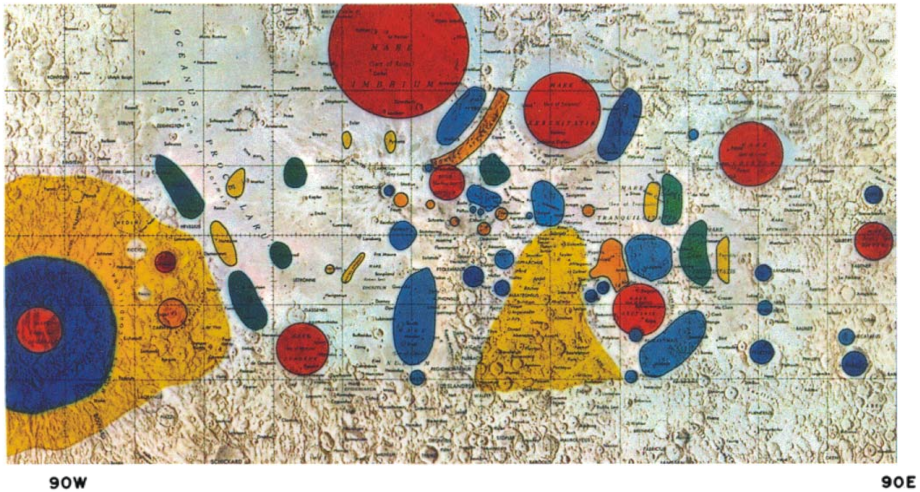
Magnetism of the Moon

The Apollo 15 magnetometer measured weak farside anomalies, not exceeding 1 nT.

This is also the level of the lunar global field.

Lunar magnetic and gravity anomalies

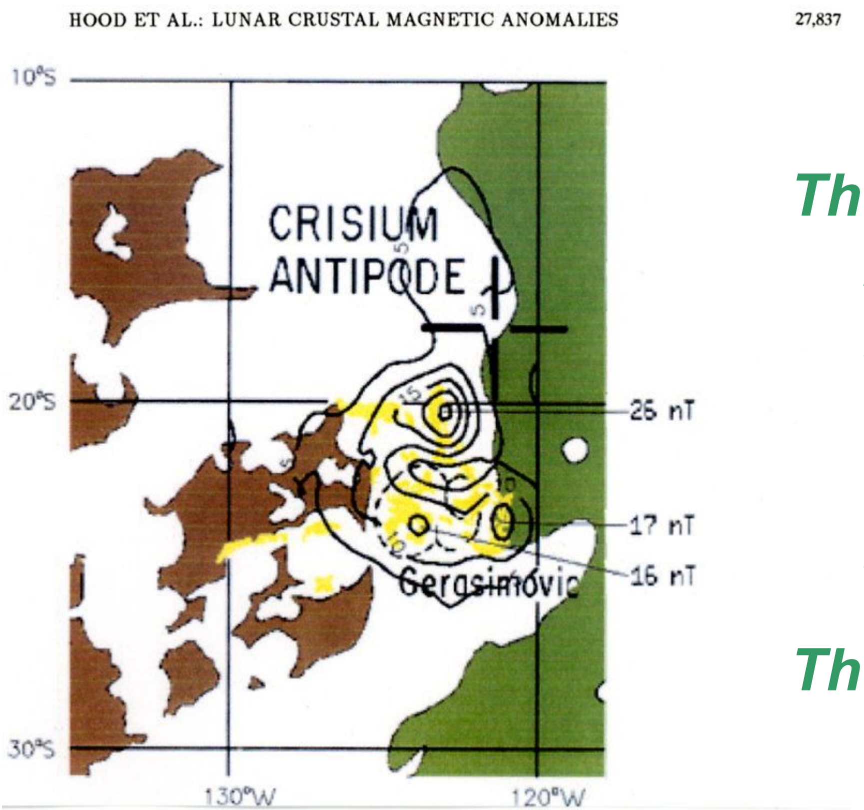




Magnetic anomalies on the nearside are also weak and do not correlate with lunar mascons.

Magnetic anomalies are low over major impact basins like Mare Imbrium and Mare Serenitatis.

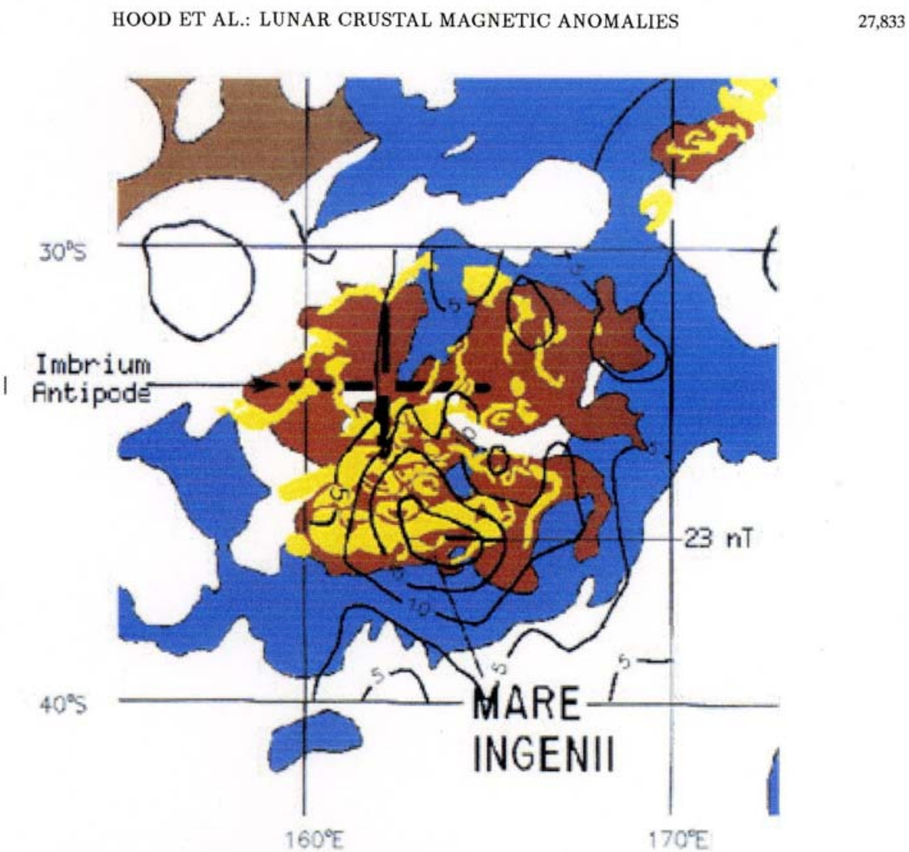
Lunar Prospector magnetic anomalies



The largest magnetic anomalies measured by the 1998-9 Lunar Prospector mission are about 25 nT. They are found on the farside, antipodal to the major impact basins.

The Gerasimovic anomaly is antipodal to Mare Crisium.

Why are anomalies antipodal to impact basins?



Another large anomaly, over Mare Ingenii, is antipodal to Mare Imbrium.

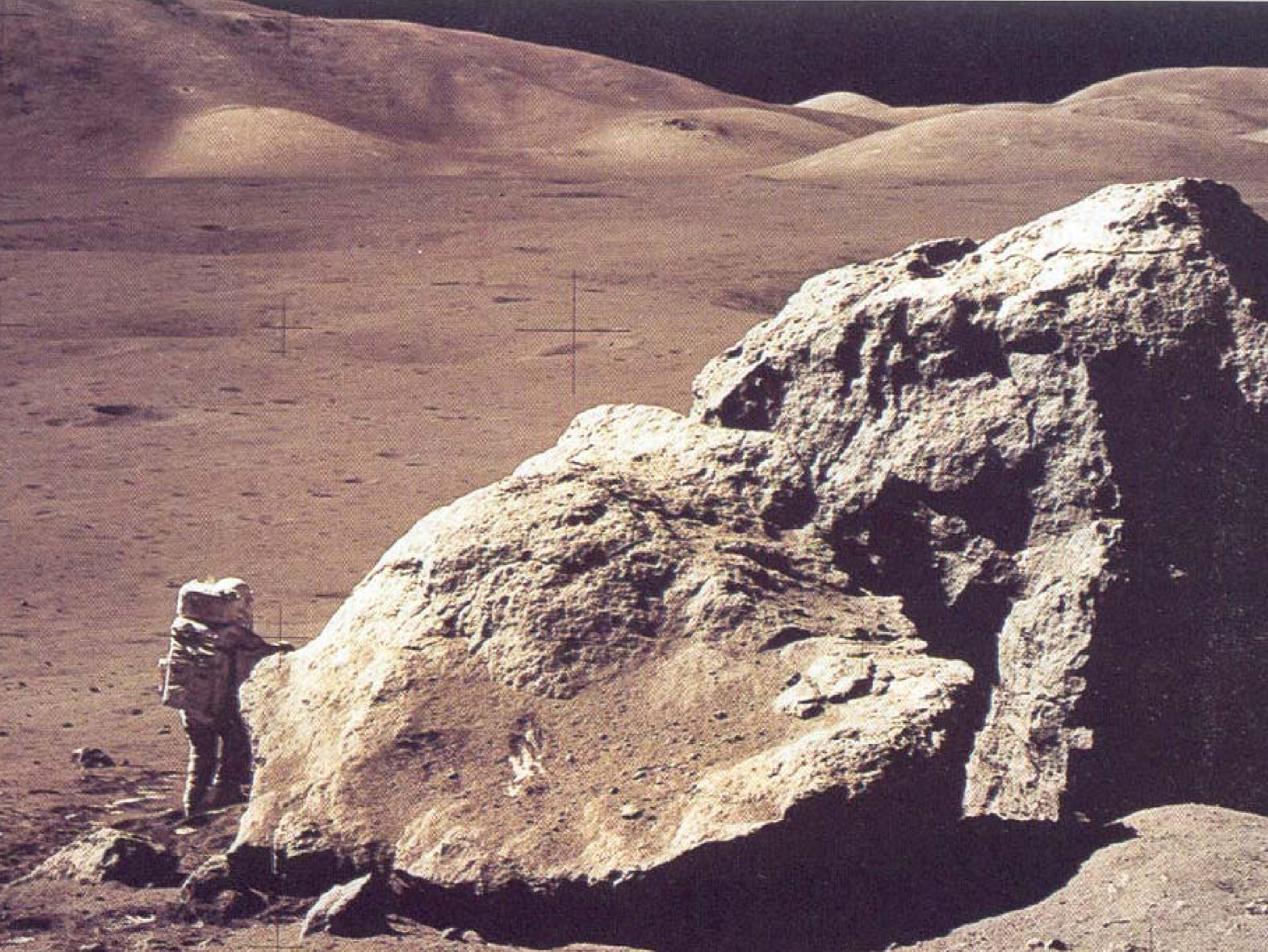
One hypothesis is that ejecta from the giant impacts that formed the nearside basins traveled completely around the Moon.

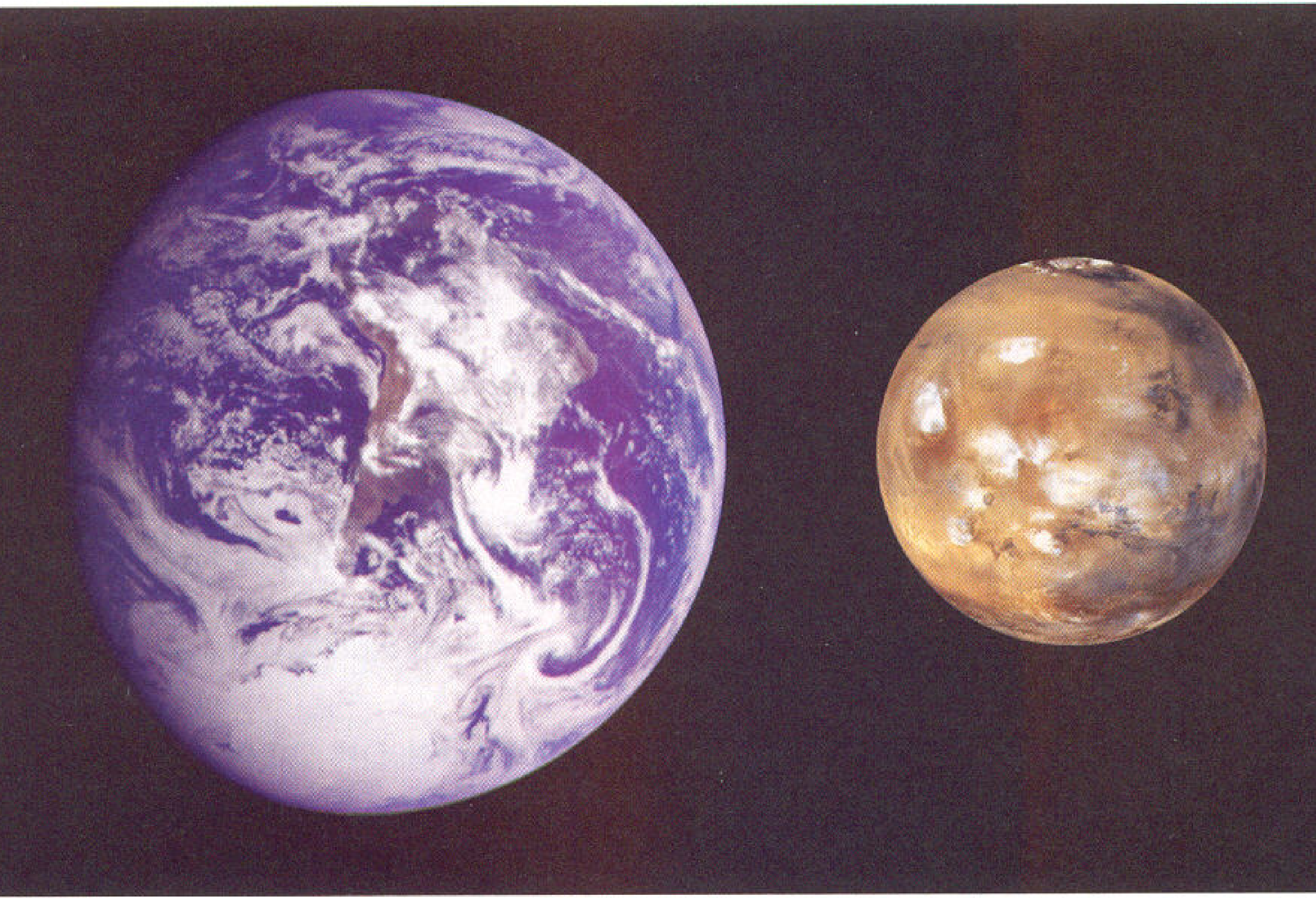
Source of the Moon's magnetism

The present-day lunar magnetic field is negligible and so is induced magnetism.

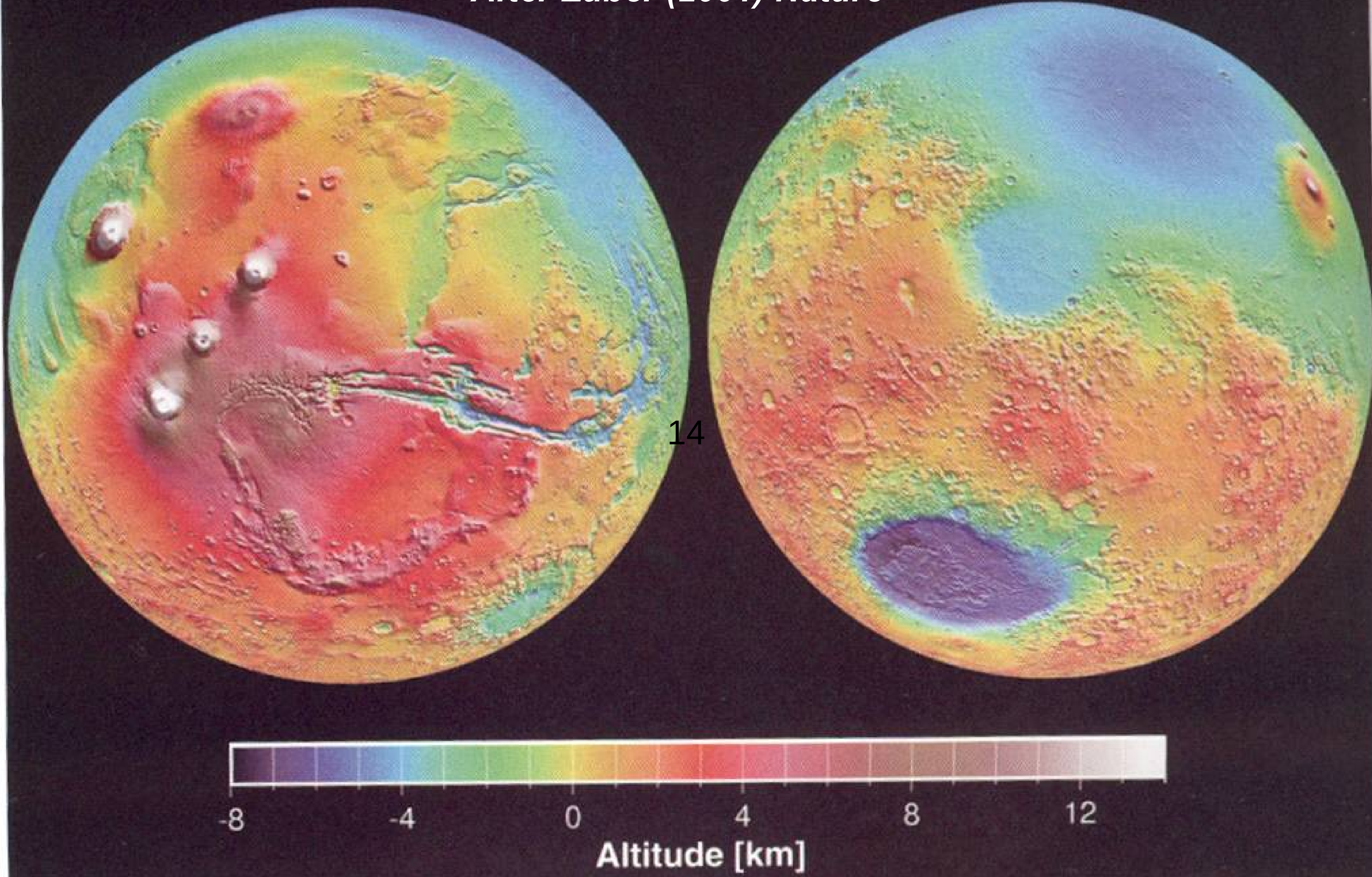
However, the ancient Moon had a field of 20-100 μT about 4 billion years ago. This is recorded by TRM of Apollo 11 through 17 samples returned to Earth.

Both highlands rocks and mare basalts are difficult to work with. The magnetic mineral is iron, usually >> single-domain size.



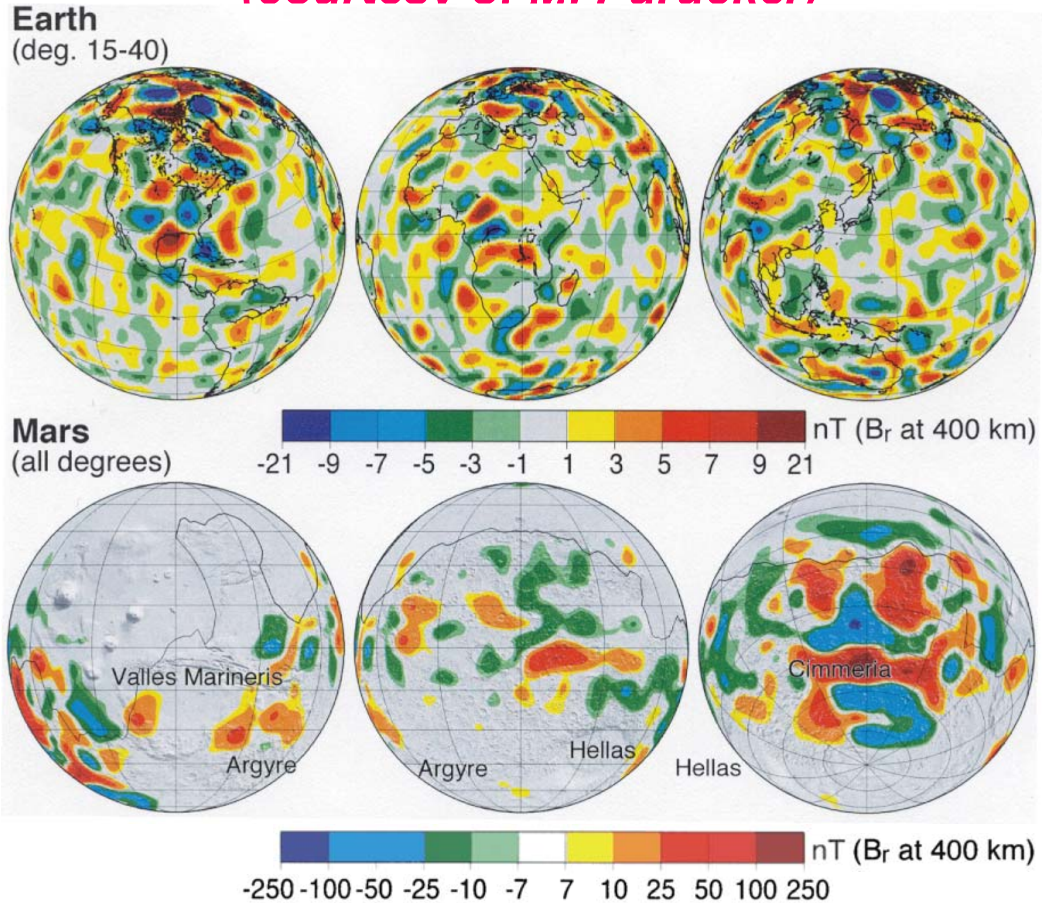


After Zuber (2001) Nature



Magnetic anomalies of Earth and Mars

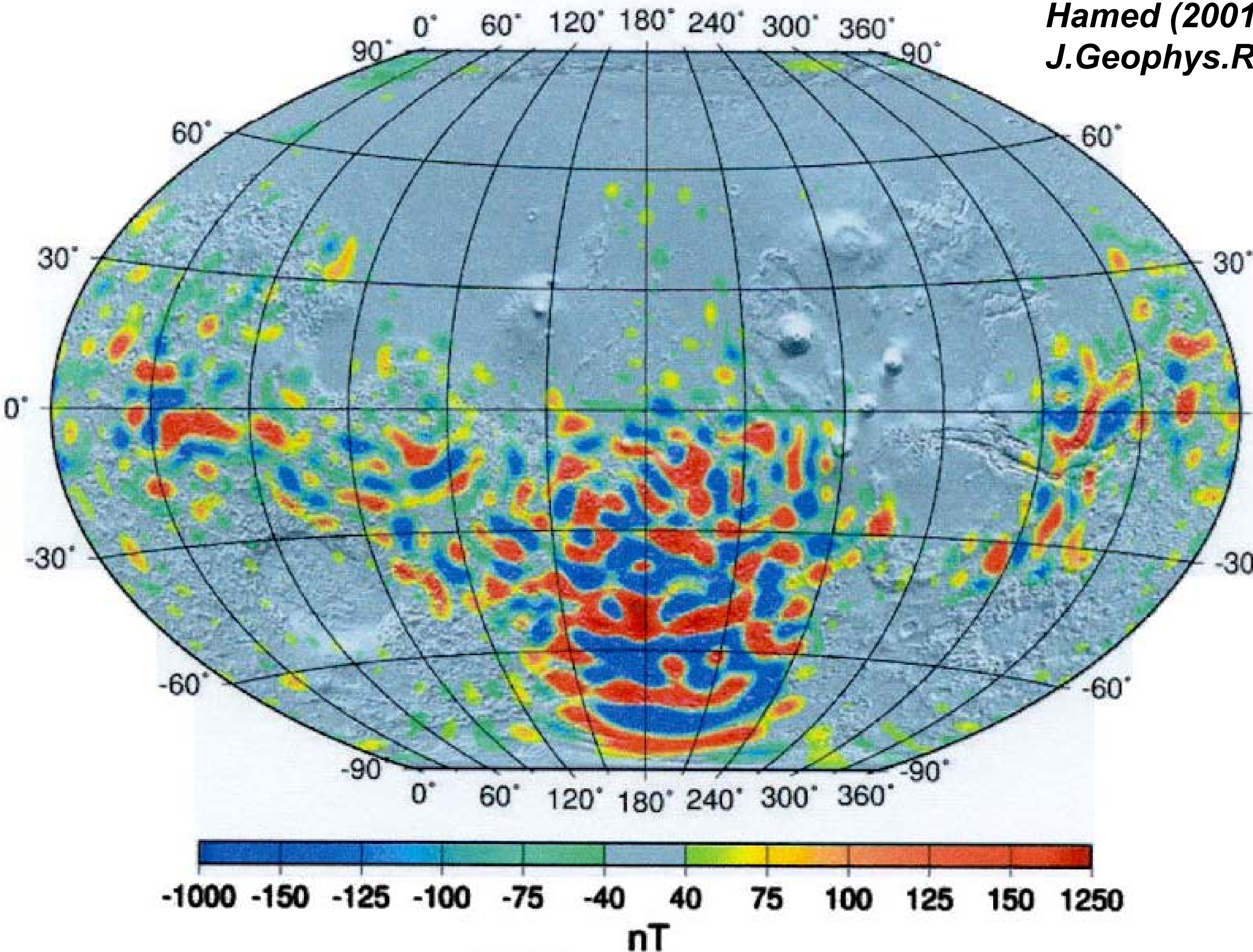
(courtesy of M. Purucker)

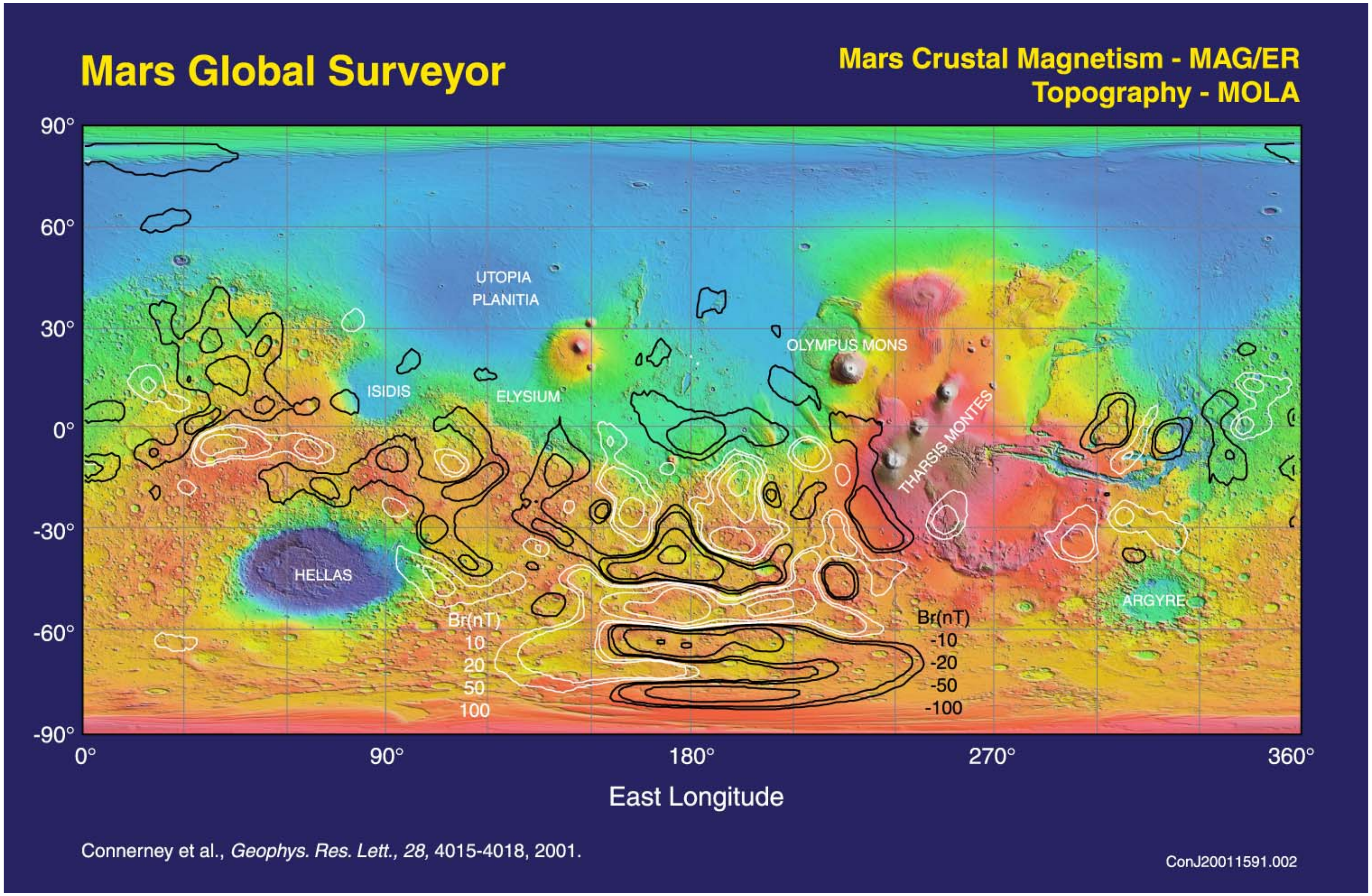


Magnetic fields measured by the Mars Global Surveyor (MGS) satellite, corrected to 400 km altitude, are an order of magnitude larger than MAGSAT anomalies over the Earth.

Radial magnetic field

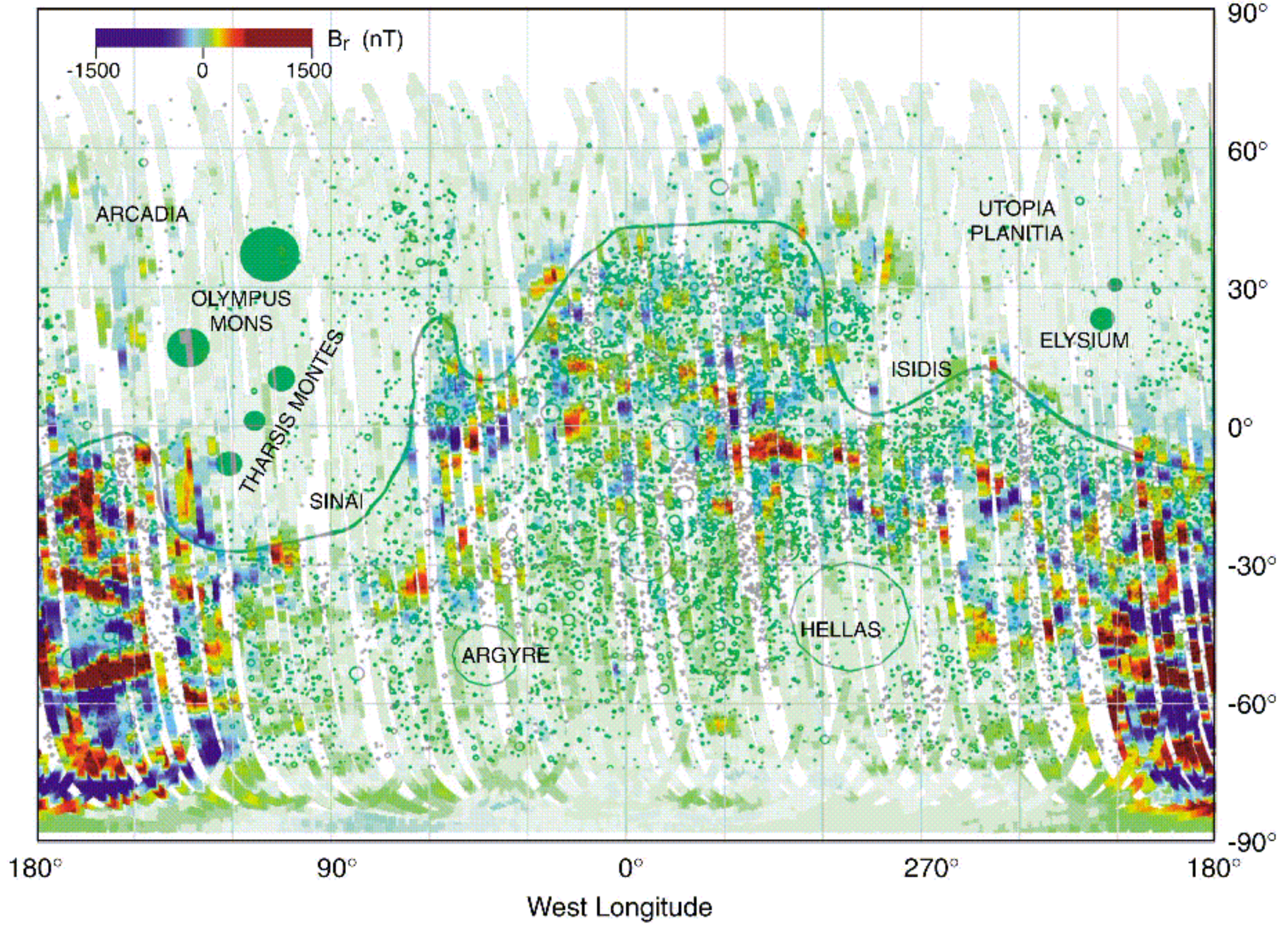
After Arkani-Hamed (2001) J.Geophys.Res



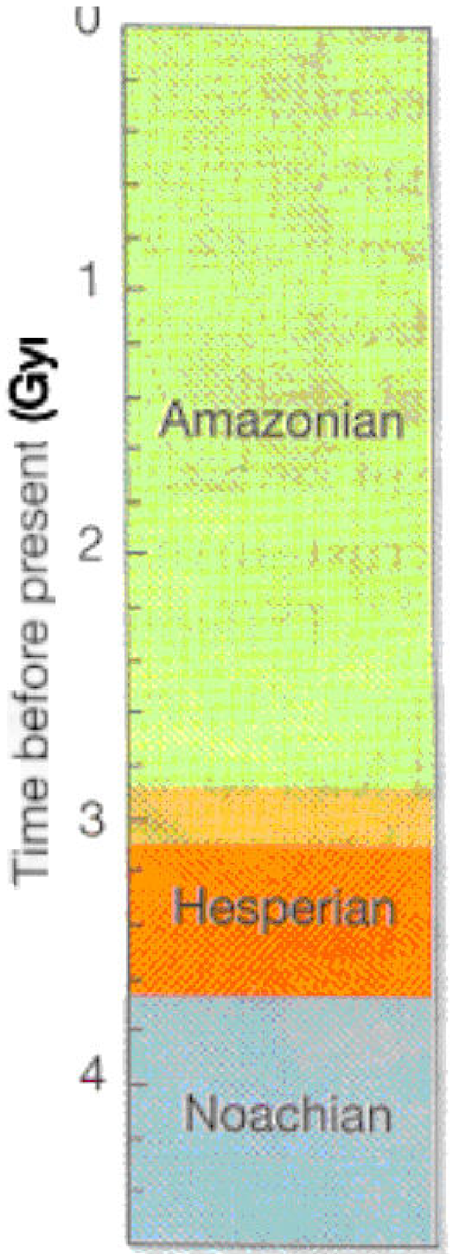


The largest Martian anomalies are over the ancient Southern Highlands crust. The Martian magnetic field seems to have died by ~4 billion years ago because basins like Hellas and Argyre have no anomalies.

There is a complete lack of anomalies over the Northern Plains (north of the dichotomy line) which are blanketed by younger volcanics, as well as over Argyre and Hellas.



After Connerney et al. (1999) Science



Timing of events on Mars

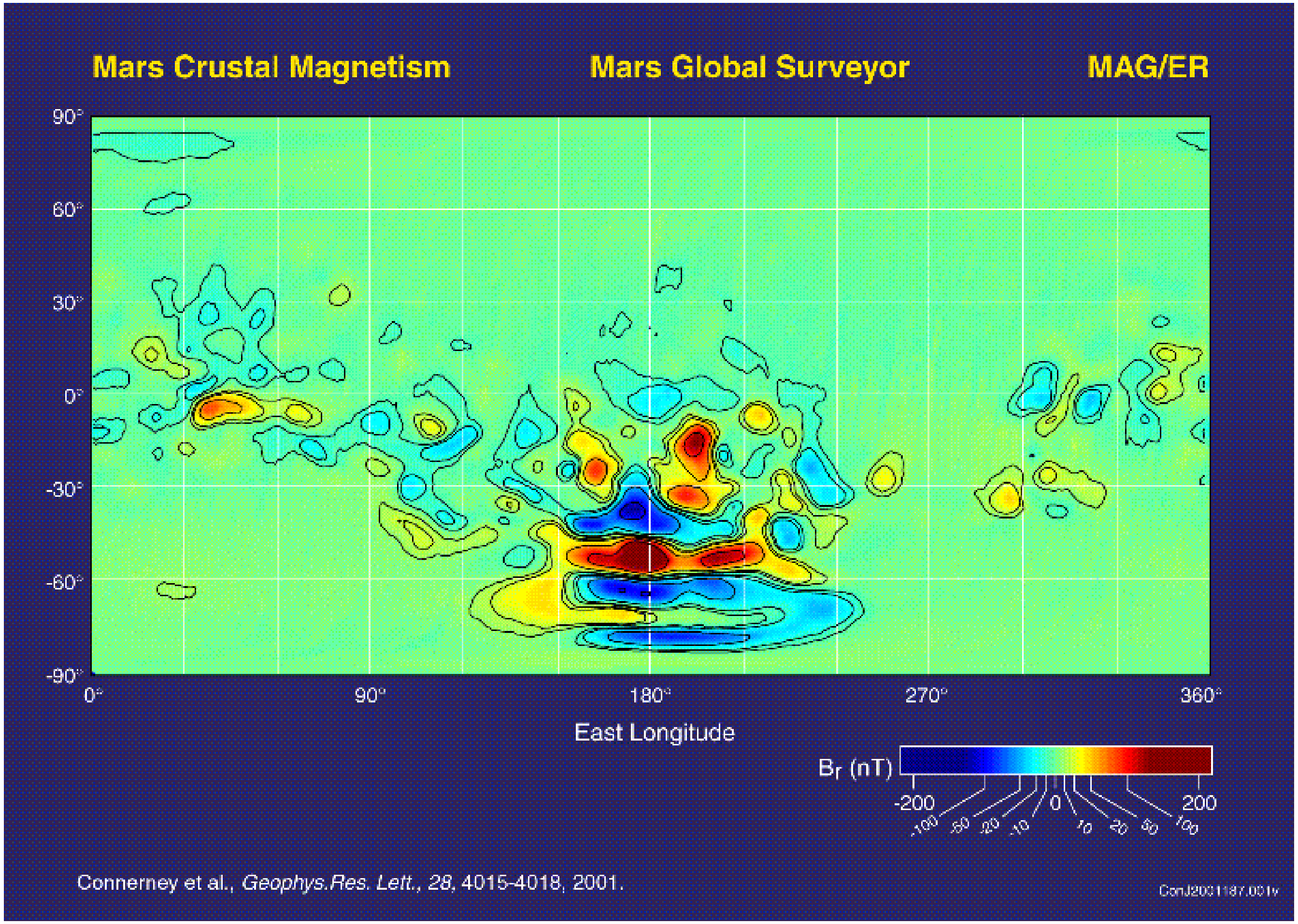
Major impacts: 4.2 – 3.0 Ga

(crater counting, comparison with lunar impact history)

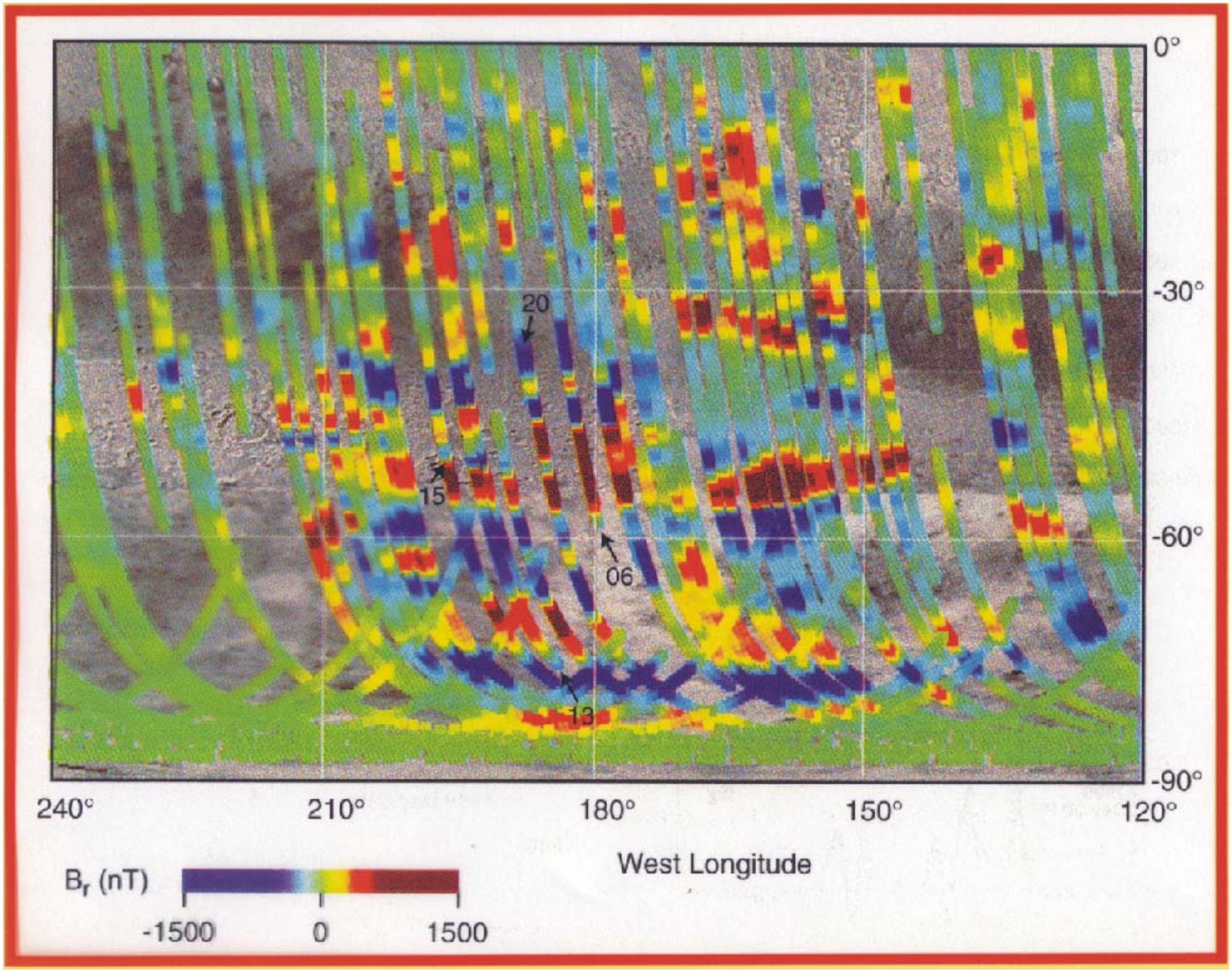
Hellas and Argyre basins and the Northern Plains are unmagnetized

Dynamo must predate ~4.0 Ga or else postdate ~3.0 Ga

Early dynamo (before 3.9- 4.0 Ga) favoured by age of ALH84001 magnetization (Weiss et al., 2002a,b; Antretter et al., 2003)



The major anomalies over Terra Cimmeria and Terra Sirenum have a stripe-like pattern.



For comparison, these are the raw data from successive MGS tracks.

Are there magnetic stripes (… ancient crustal spreading …) on Mars?

Stripe widths of 100's of km

Stripe lengths up to 2000 km

Field magnitude at 100-200 km altitude: up to 1,500 nT

Proposed source thickness: ≈30 km

TRM required: ≈20 A/m – fresh MORB!

How can we explain such a thick and strongly magnetic source?

1. *Mars had a large magnetic field when TRM was acquired (4 Ga BP)*
2. *Mars' lithosphere has magnetic mineral concentrations >> Earth's*
3. *T_c is high, giving a deep Curie point isotherm in the juvenile lithosphere*
4. *The minerals have large M_s and a domain state giving intense TRM*

A strong ancient Martian magnetic field?

Mars probably had an internal dynamo field soon after accretion, with a strength like that recorded by the Earth, Moon and non-Martian meteorites: $\leq$ 50 μT.

ALH84001 records a 5-50 μT field at 4.1-3.9 Ga

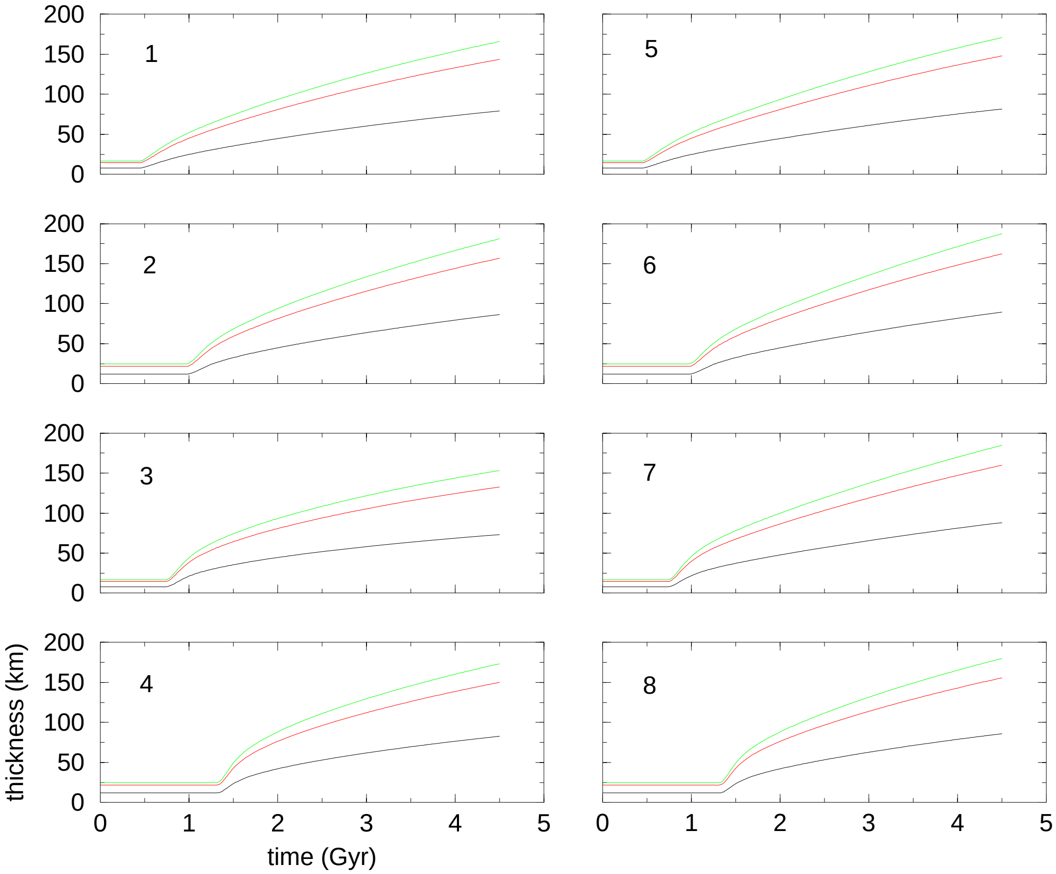
Mars' dynamo field was not unusually strong

Mars' magnetic lithosphere: a best guess

Based on Fe in Martian meteorites, magnetic mineral concentrations are probably no more than 3 times those on Earth: ≲10% by weight.

Calculations of a stagnant lid overlying convecting mantle, with 40-60% of radioactive elements in the crust and a brittle → ductile transition at 600-800 ℃, yield ≈30 km thick early magnetic lithospheres.

How thick is Mars' magnetic lithosphere?



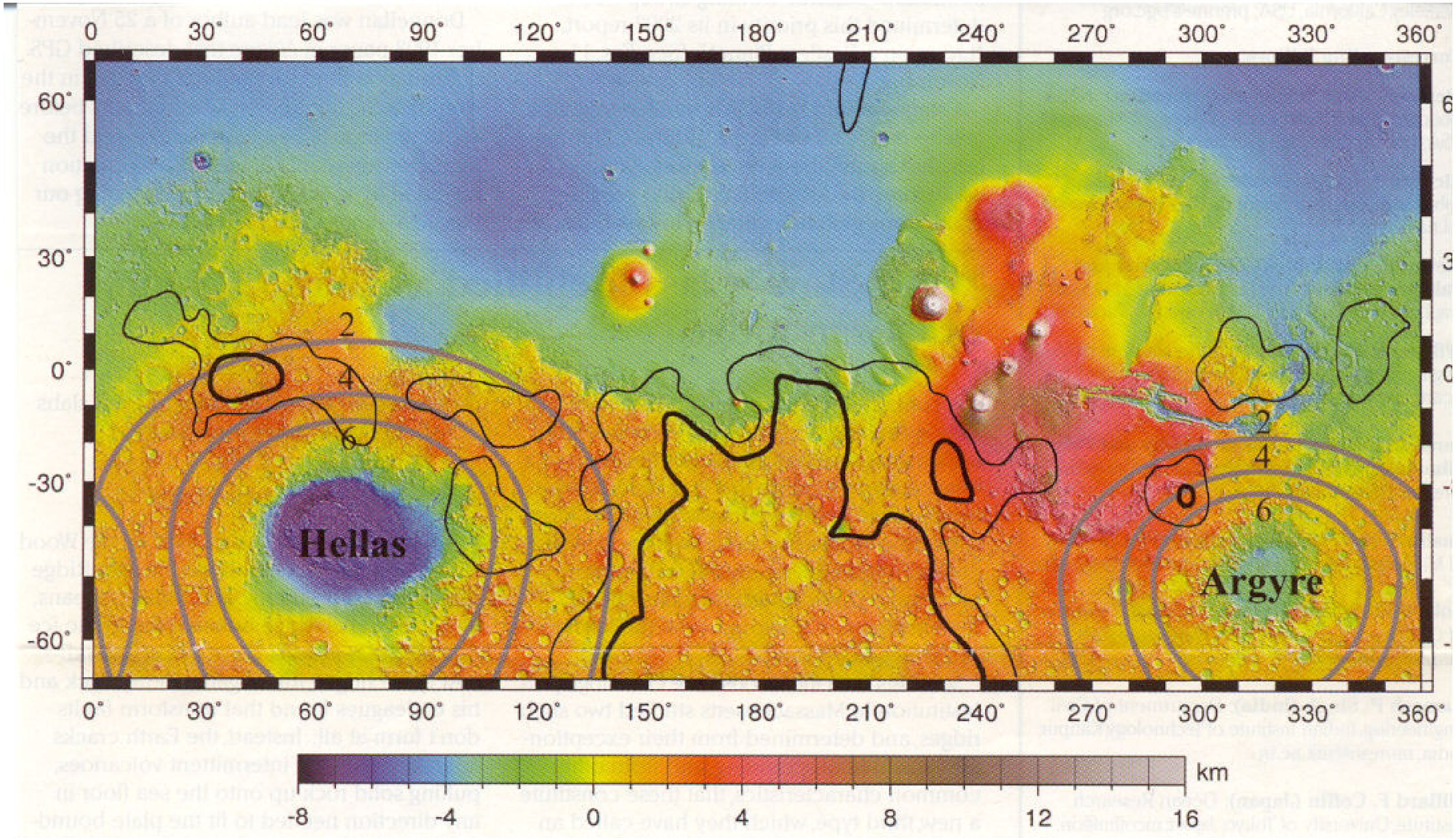
The Curie point isotherm was 20-30 km deep for the first 0.5-1.5 Ga gradually growing to 150-200 km (magnetite, hematite) or 50-100 km (pyrrhotite) now. (Calculations: J. Arkani-Hamed)

Which mineral?
Pyrrhotite?

Pyrrhotite (Fe_7S_8) is found on Earth mainly in massive sulphide ores and in reduced sediments. It is also found in many SNC meteorites from Mars.

Pyrrhotite is 6 times less magnetic than magnetite ($M_s \approx 80$ kA/m) and its Curie point $T_C = 320$°C is quite low. Pyrrhotite's Curie point isotherm on Mars is shallow, requiring a higher TRM to compensate.

Evidence for pyrrhotite?



Are Hellas and Argyre basins shock demagnetized "holes"?

Why shock demagnetization?
Why pyrrhotite?

Mars' dynamo had died by ~4.0 Ga. Impact heating raised magnetic minerals above the Curie point. Without a field, no new TRM was produced.

But demagnetization goes beyond the heated region. Shock demagnetization could be the answer.

Pyrrhotite has a phase transition to a non-magnetic phase at 2.8 GPa (Hood et al., 2003; Rochette et al., 2003, 2004).

Which mineral?
Magnetite?

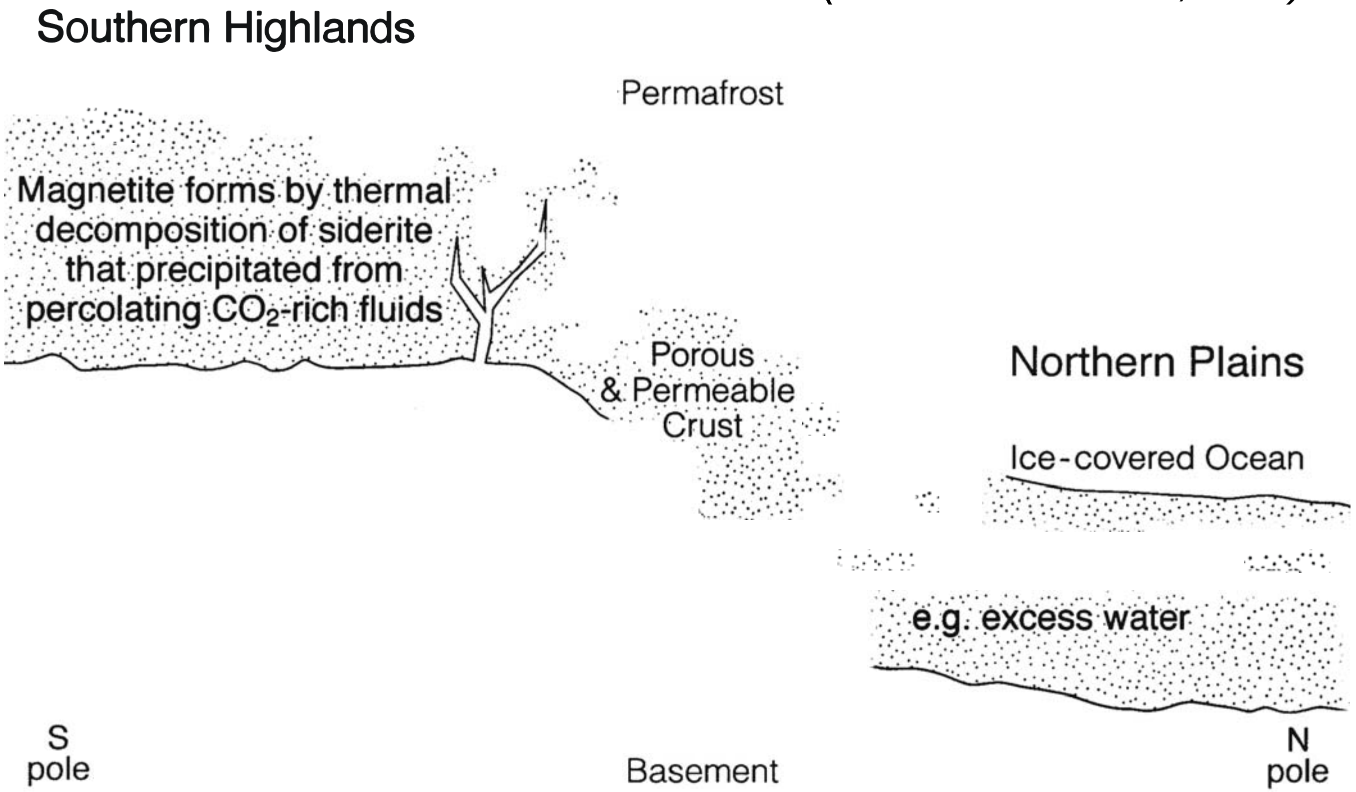
Magnetite (Fe_3O_4) is common on Earth. It occurs in virtually all igneous, sedimentary and metamorphic rocks, in substantial concentrations.

It is Earth's most magnetic mineral (M_s = 480 kA/m) and its T_C is high (580 ℃).

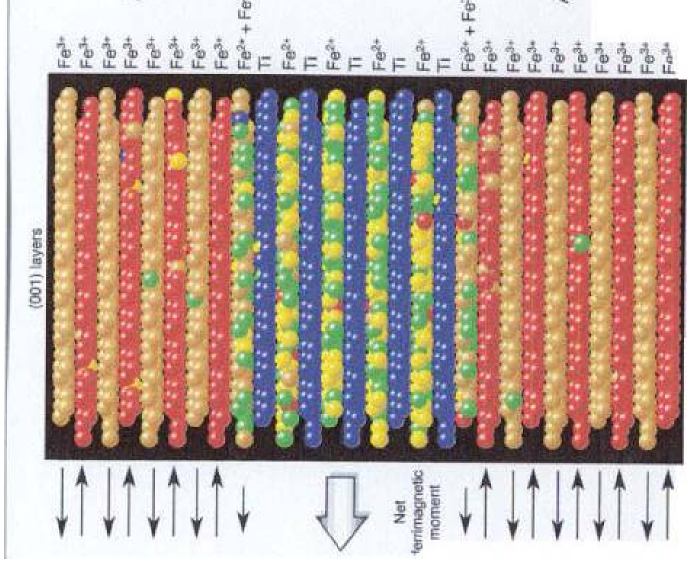
Magnetite's Curie point isotherm on early Mars was ≈30 km deep, requiring a TRM of ≈20 A/m.

Does siderite ($FeCO_3$) produce single-domain magnetite through heating by deep intrusions?

(E. Scott & M. Fuller, 2003)



but source layer is only 10-15 km thick at most...



Which mineral?

Hemoilmenite?

(lamellar magnetism)

Finely exsolved (nm-scale) hematite-ilmenite lamellae may have an interfacial net magnetism with $M_s \approx$ 55 kA/m, 10% that of magnetite (Robinson et al., 2002).

Metamorphic rocks with finely exsolved hemoilmenite have high T_C (530-650 ℃) and high coercivities similar to single-domain hematite.

Coupling of the ferromagnetic layers to host hematite produces a hybrid, 20 times more magnetic than hematite but with high thermal and field stability.

Which mineral?
Hematite?

Hematite (αFe_2O_3) is very common on Earth, as a primary mineral in some igneous rocks but more often as an oxidation product.

Hematite's T_C = 675℃ is high, but $M_s \approx 2.5$ kA/m, 200 times less than magnetite's.

On the face of it, hematite is not a viable candidate for the source of Martian anomalies, but several factors conspire to keep it in the running.

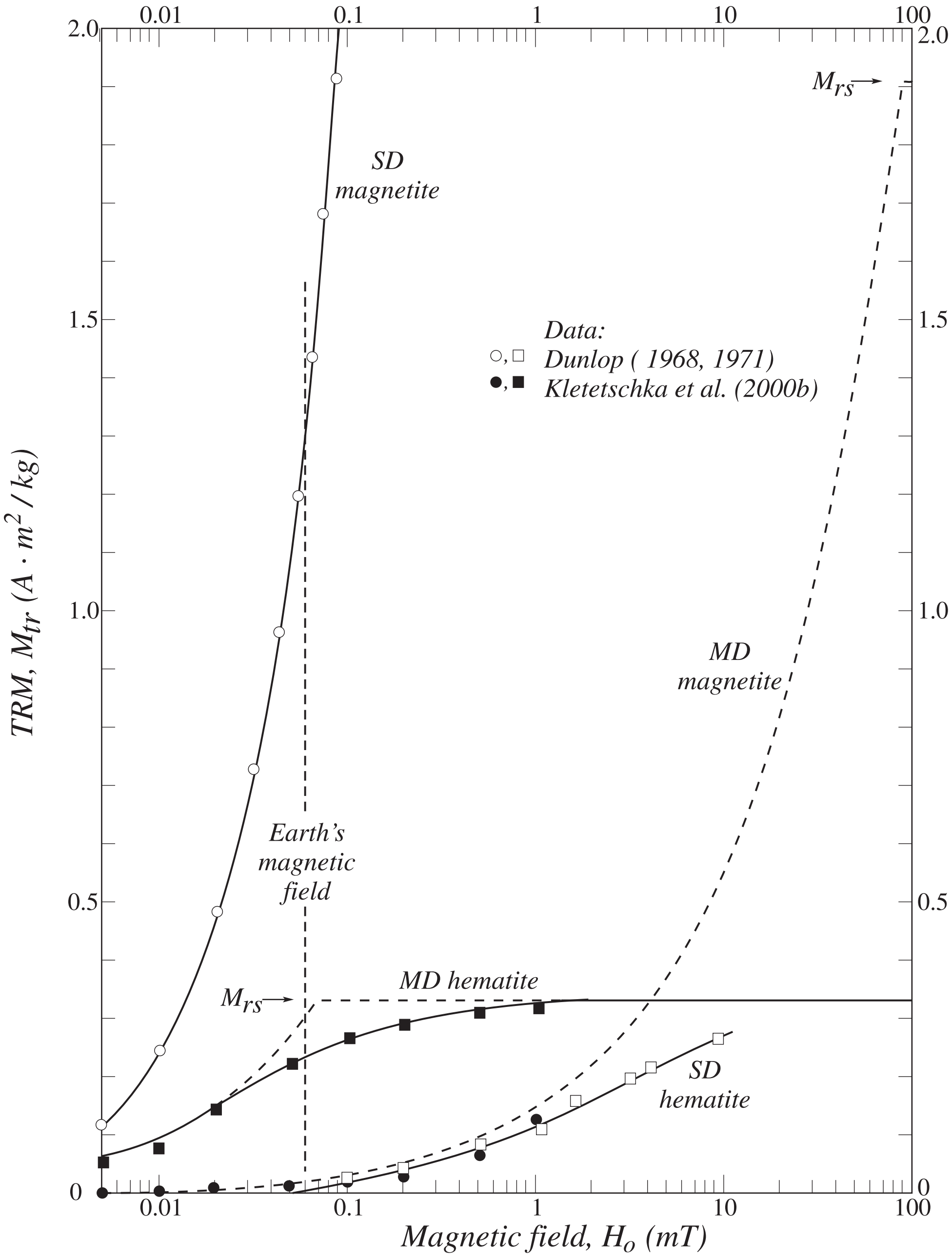
Which mineral?

Why consider hematite?

Mars, the red planet, owes at least part of its distinctive colour to hematite on its surface.

For example, large concentrations of >5-10 µm crystalline hematite occur in Sinus Meridiani (MGS thermal emission spectrometer data).

Magnetite and pyrrhotite are inferred from their presence in Martian meteorites but are not directly detected on Mars.



TRM – hematite and magnetite

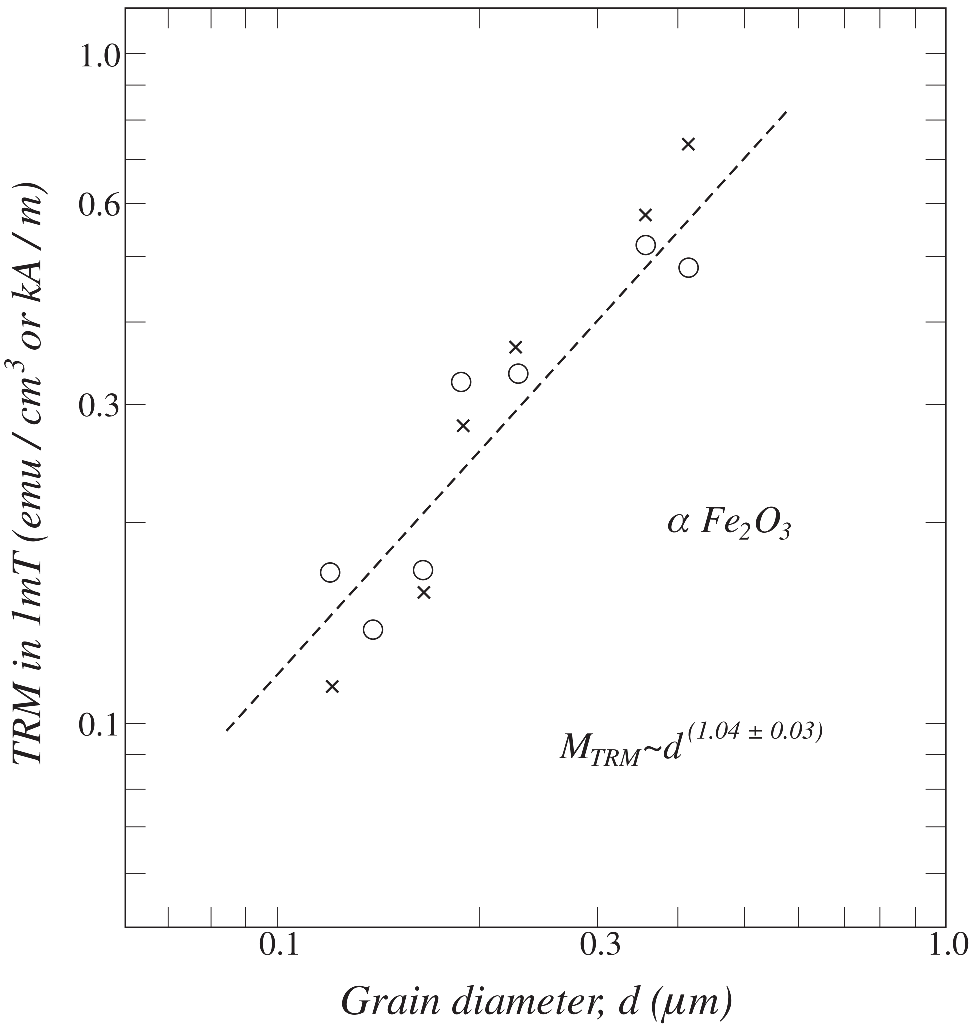
In the Earth's field, single-domain (SD) magnetite and multi-domain (MD) hematite have strong TRMs.

MD hematite does not self-demagnetize because M_s is small.

MD magnetite has a large M_s and does self-demagnetize, resulting in weak TRM.

(Dunlop & Kletetschka, 2001)

Is single-domain hematite a contender?



0.1–0.5 µm single-domain hematites have 10 times larger TRM than found previously.

Larger hematites have still stronger TRMs.

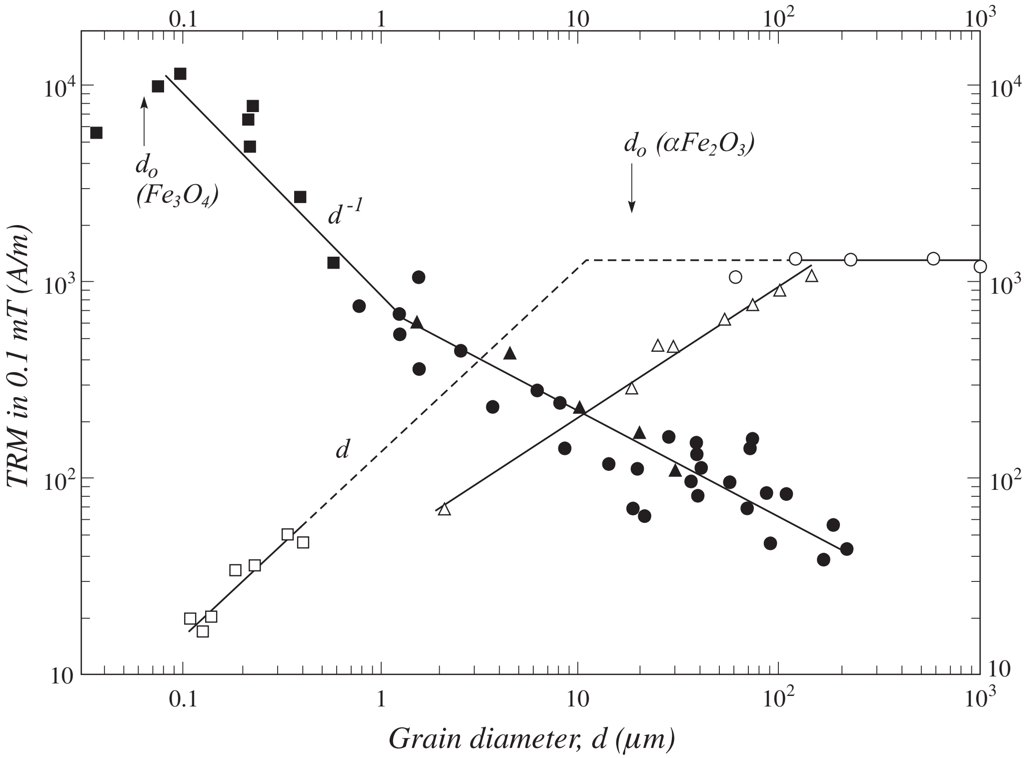
Hematite's critical single-domain size is 20 µm, compared to 0.1 µm for magnetite.

Single-domain hematite is a contender!

(Özdemir & Dunlop, 2002)

Grain-size variation of TRM

TRM of magnetite decreases as d^{-1} when grain size d increases from SD to MD...



but TRM of hematite increases when d grows from 0.1 – 20 µm across the SD range.

The larger the hematite, the stronger its TRM!

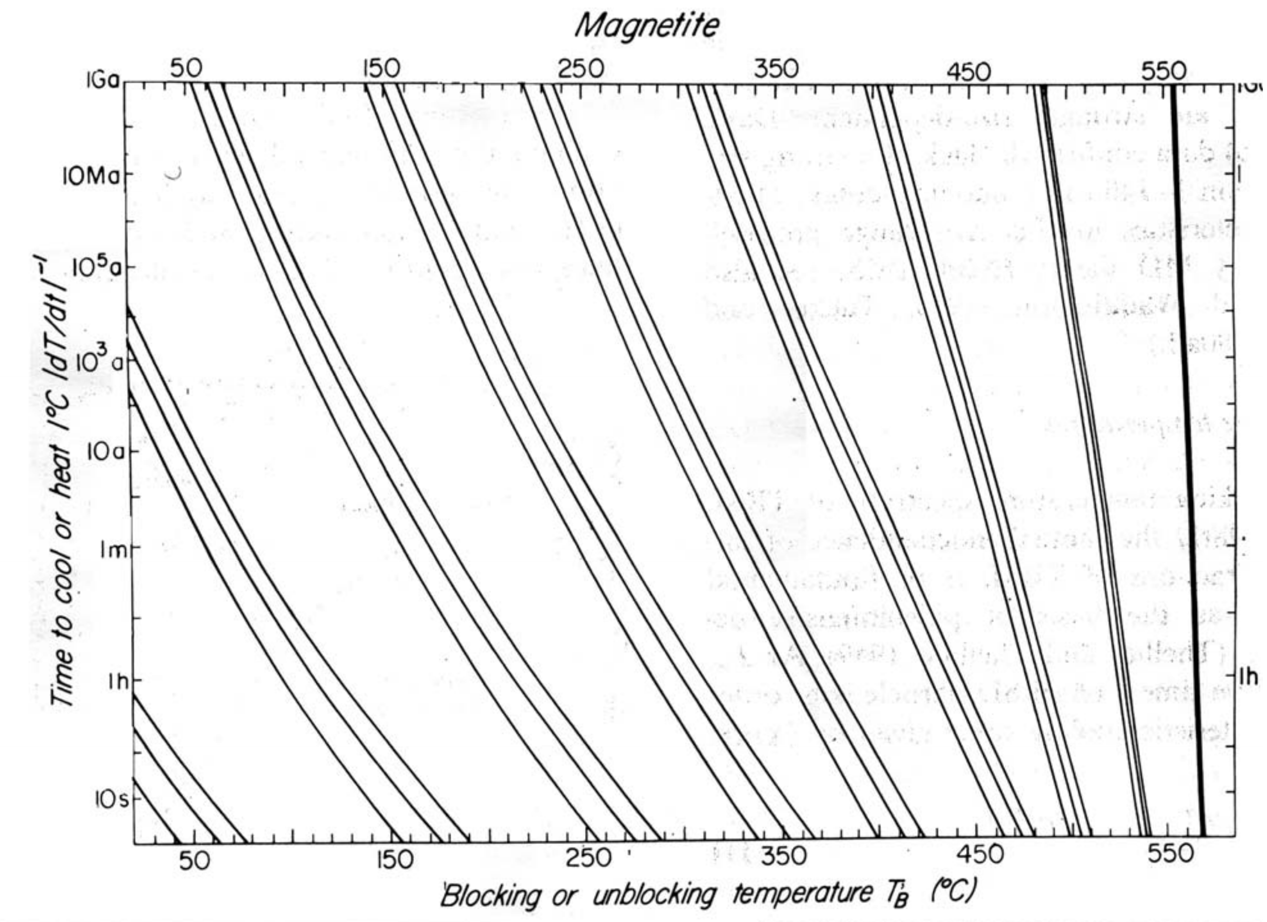
(Dunlop & Arkani-Hamed, 2005)

Candidate minerals for Mars' magnetism
(30 km @ 20 A/m)

- ***SD magnetite: need 0.2-0.4%, but <0.1 μm sizes.***
- ***SD pyrrhotite: need 1-2%, but <1 μm sizes.***
- ***MD hematite: need ≈2%, but >20 μm sizes. Poor long-term stability.***
- ***Hemoilmenite lamellae: need ≈3%.***
- ***SD hematite: need ≲ 10%. Wide size range, but most favourable if ≳ 5 μm.***

How long did it take to block TRM?

At typical magnetite blocking temperatures, 500-550℃, TRM blocking occurs over about a 5℃ interval.



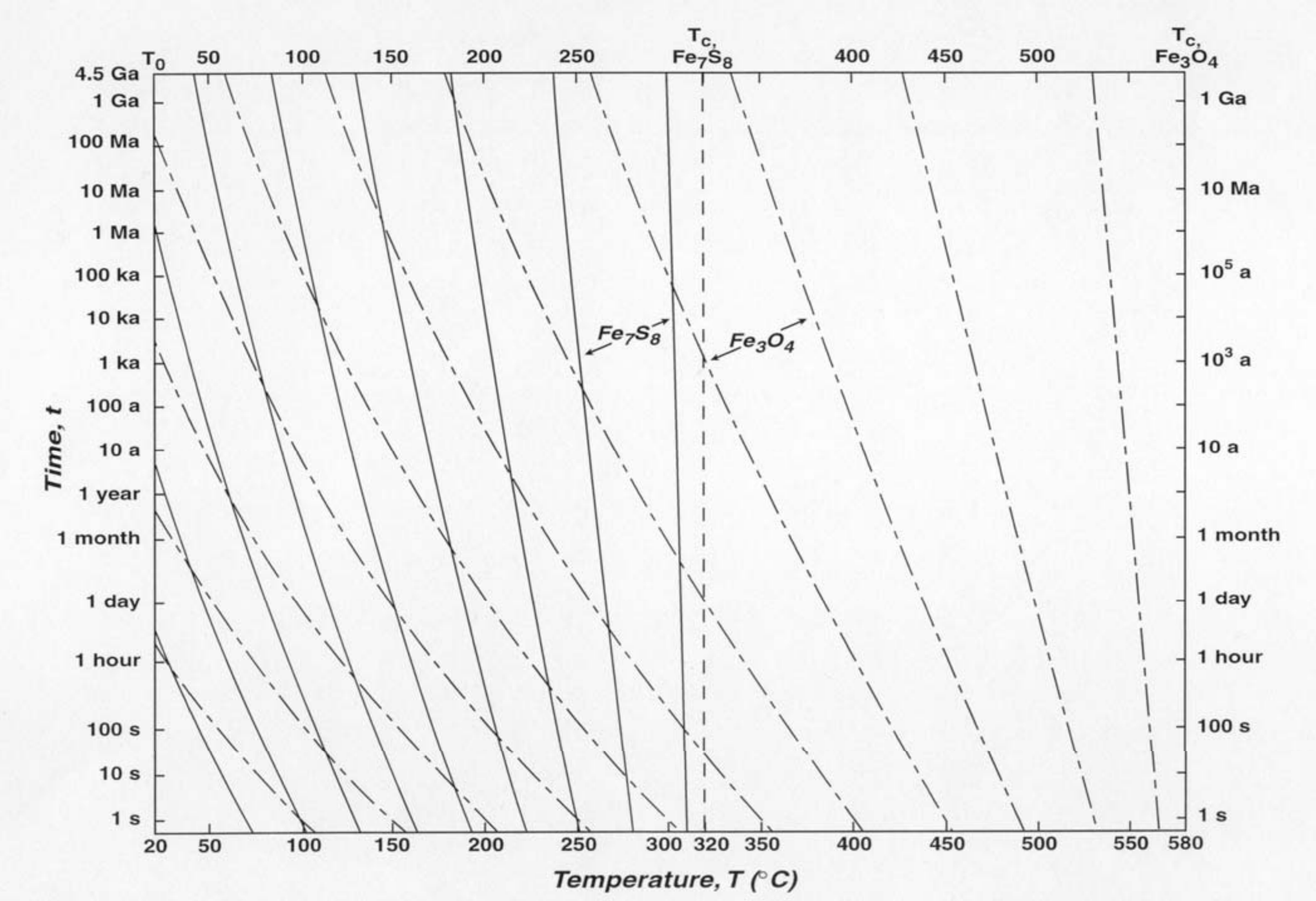
Cooling time required for blocking: ≈10 Myr

Mars' dynamo & global field likely endured 100–200 Myr

No problem in blocking TRM.

Did TRM decay after the field died?

If Mars' field died just after TRM was blocked, viscous decay could occur below the blocking temperature T_B.



But if only 10-15℃ of cooling below T_B occurred before $H \rightarrow 0$, the TRM would not decay at all for the next 3.5 Gyr.

Conclusions

The likeliest carriers of the strong magnetic signal responsible for Terra Sirenum anomalies are single-domain magnetite and pyrrhotite, on the basis of their high TRM intensities. 0.5-2% content is needed.

Hematite and finely exsolved hemoilmenite with interfacial magnetism coupled to hematite are also possible carriers, but higher contents are needed.

All these minerals except pyrrhotite had deep Curie point isotherms in Mars' earliest history.

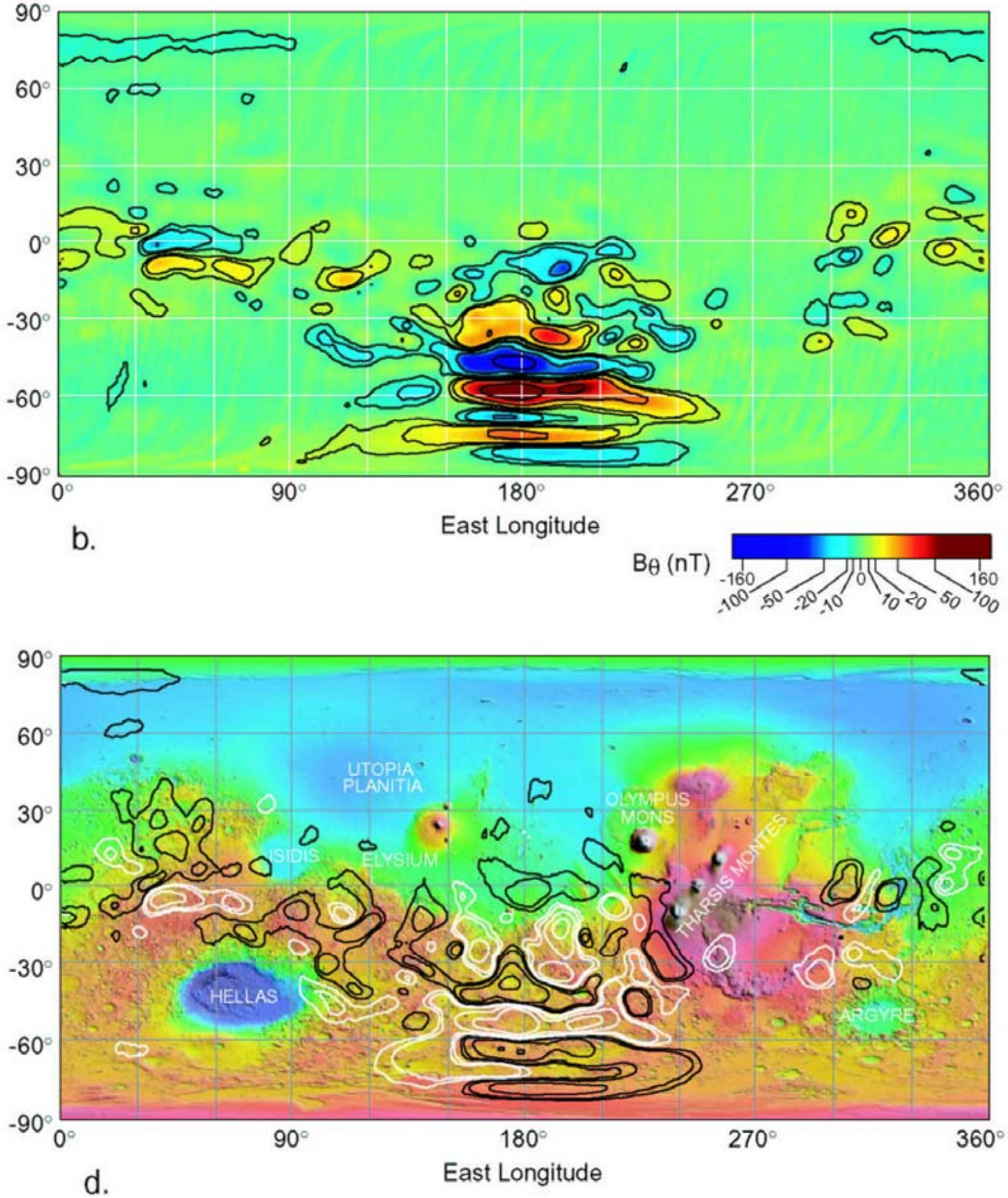
TRM blocking occurred within a 10 Myr cooling time. TRM is stabilized against viscous decay in $H = 0$ over the next 3.5 Gyr provided at least 10-15℃ of cooling below T_B occurred before the death of the dynamo.

Life on Mars ?

(Primaverda, *Botticelli*)

Was there ever spring on Mars?

Is there life now on Mars? How did it survive Mars' harsh conditions? Did life once exist but perish? Did it leapfrog to Earth?

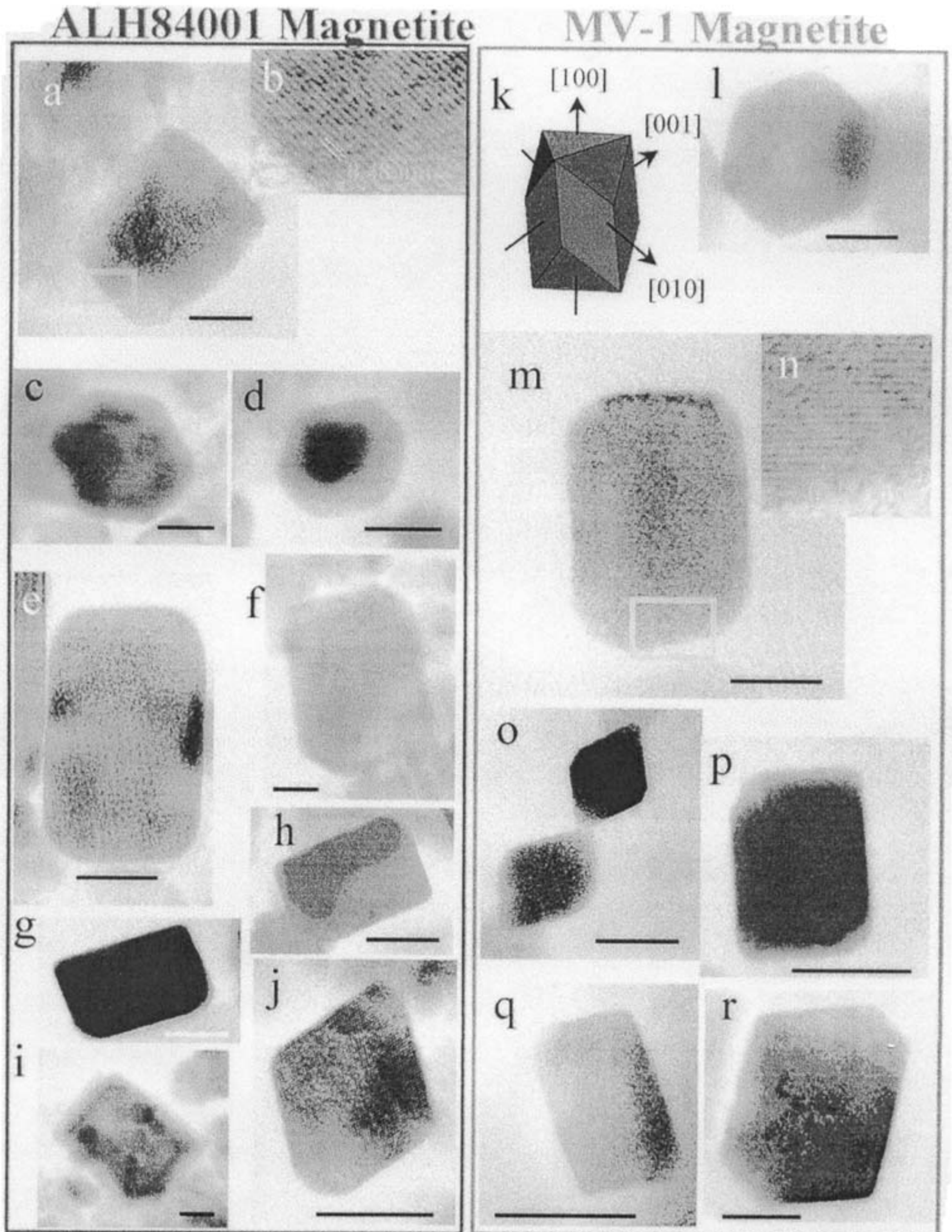


Shelter from cosmic rays

Earth's atmosphere shields us from cosmic rays, but Mars lost its early atmosphere.

Horizontal fields are a magnetic umbrella protecting life: cosmic rays spiral along field lines.

Connerney et al. (2001) Geophys.Res.Lett.



Scale bars = 20 nm

Life on Mars 4 Ga ago?
Magnetite in ALH84001

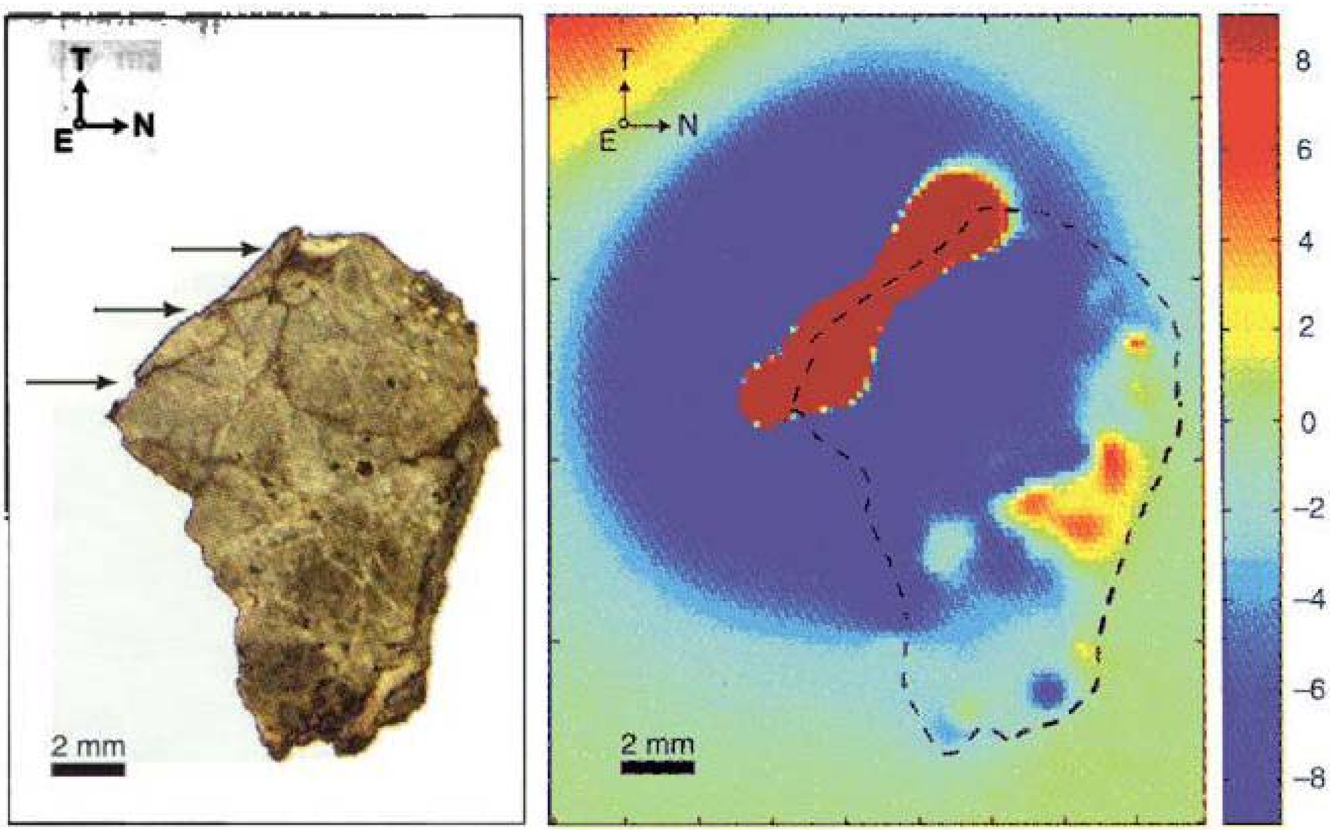
Elongated prismatic crystals of magnetite in ~4 billion year old carbonate globules in ~4.5 Ga old Martian meteorite ALH84001…

…are identical in size and morphology to biogenic magnetite produced by magneto-tactic bacterium MV1.

TEM: Thomas-Keprta et al., 2000

ALH84001 microscale magnetic anomalies measured with a scanning SQUID magnetometer

The fusion crust (arrows) of ALH84001 has been remagnetized during entry through Earth's atmosphere (peak fields are ~1,200 nT, elongated red region).



A much smaller magnetic signal of the unheated interior shows as red/yellow highs and blue lows (±8 nT).

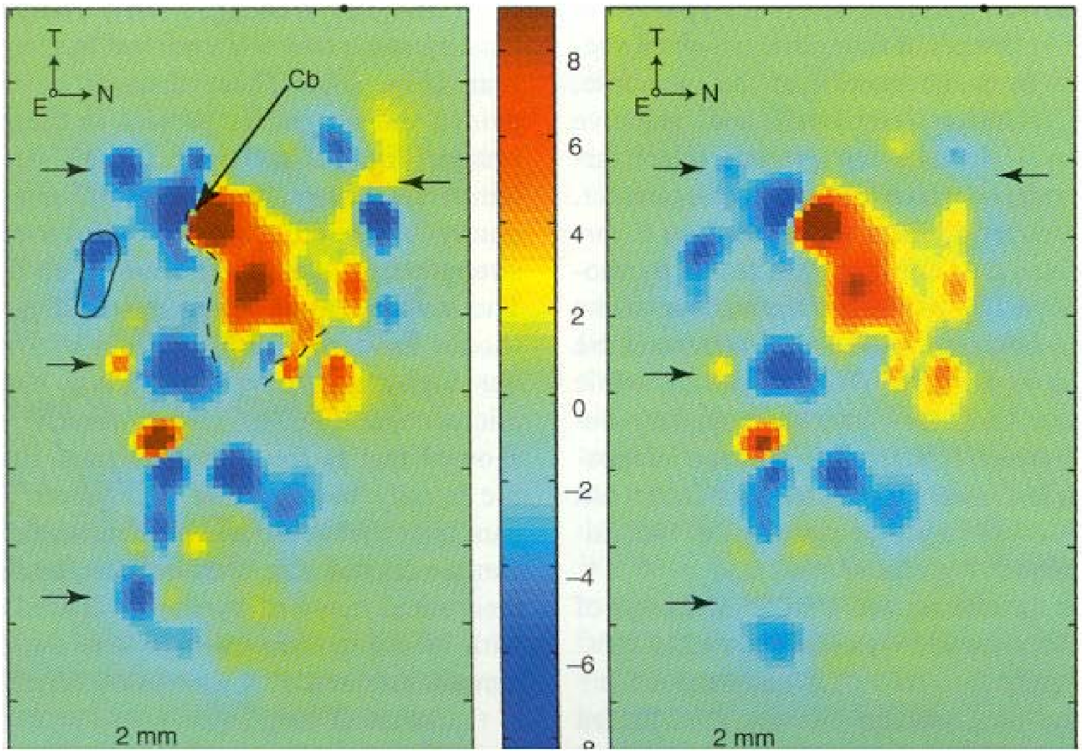
(*Weiss et al., 2000*)

Low-temperature transfer of ALH84001 from Mars to Earth?

(*Weiss et al., 2000*)

SQUID images show decay of features (arrows) after heating from 20℃ (left) to 40℃ (right)…

suggesting that the interior had not previously been heated to 40℃.



Most bacteria or eukarya are not sterilized by 40℃ heating and might have survived the journey to Earth. Cb marks a carbonate bleb containing (biogenic?) magnetite.

More conclusions about magnetism and Mars

- ***A "magnetic umbrella" may have sheltered Martian life forms from destruction by cosmic rays.***
- ***Martian meteorite ALH84001 may contain ~4 Ga old biogenic magnetite. The interior was possibly not heated above 40℃ during transit from Mars to Earth.***