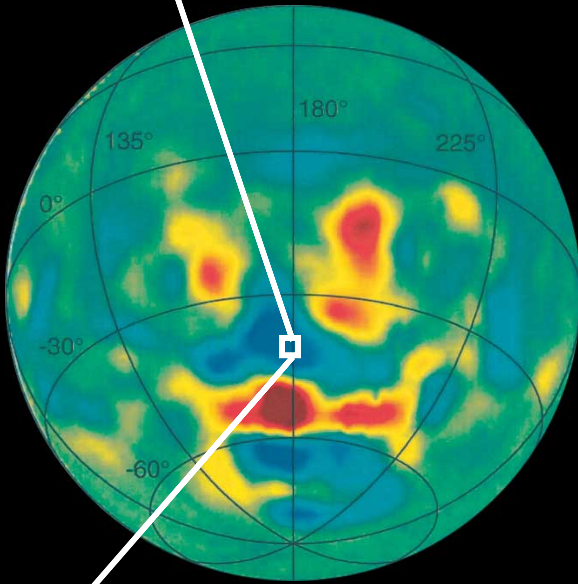
Records of Martian Paleotemperatures and Paleofields in Meteorites

Benjamin Weiss

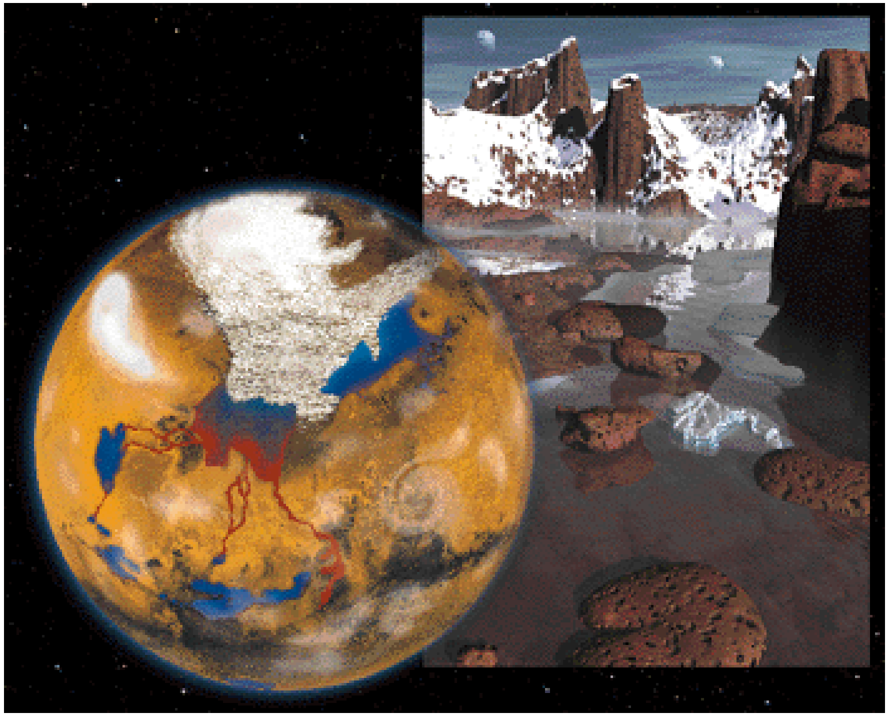
Viking Orbiter
(1976)

250 km across
24 °S, 182 °W

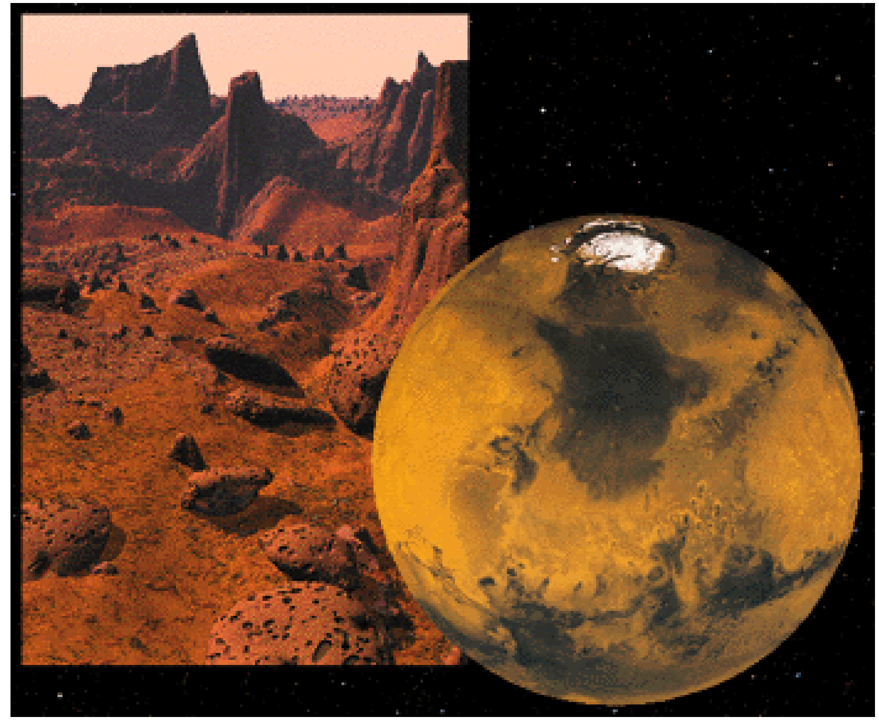


Crustal Magnetic Fields

4 Billion Years Ago



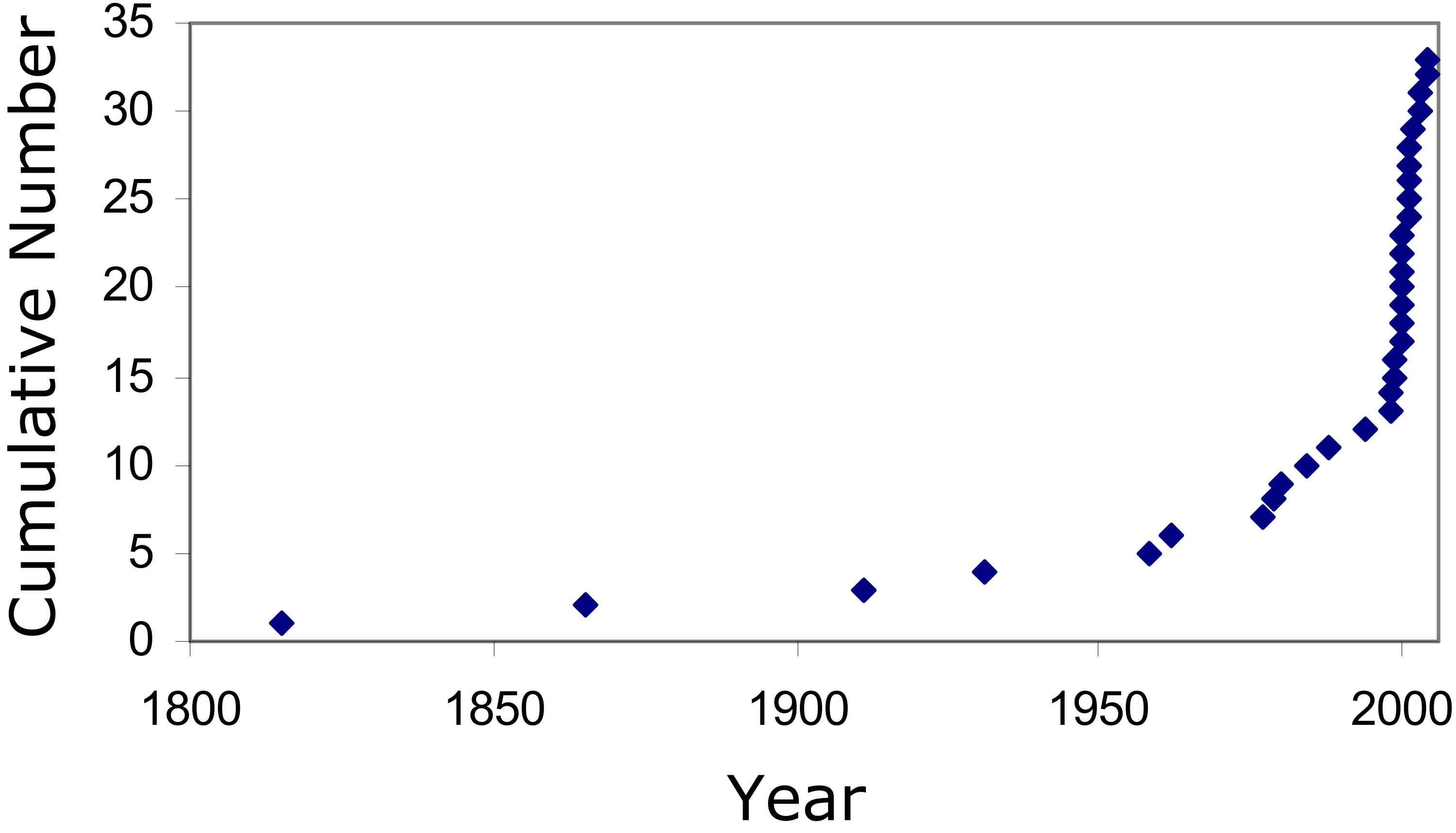
Today



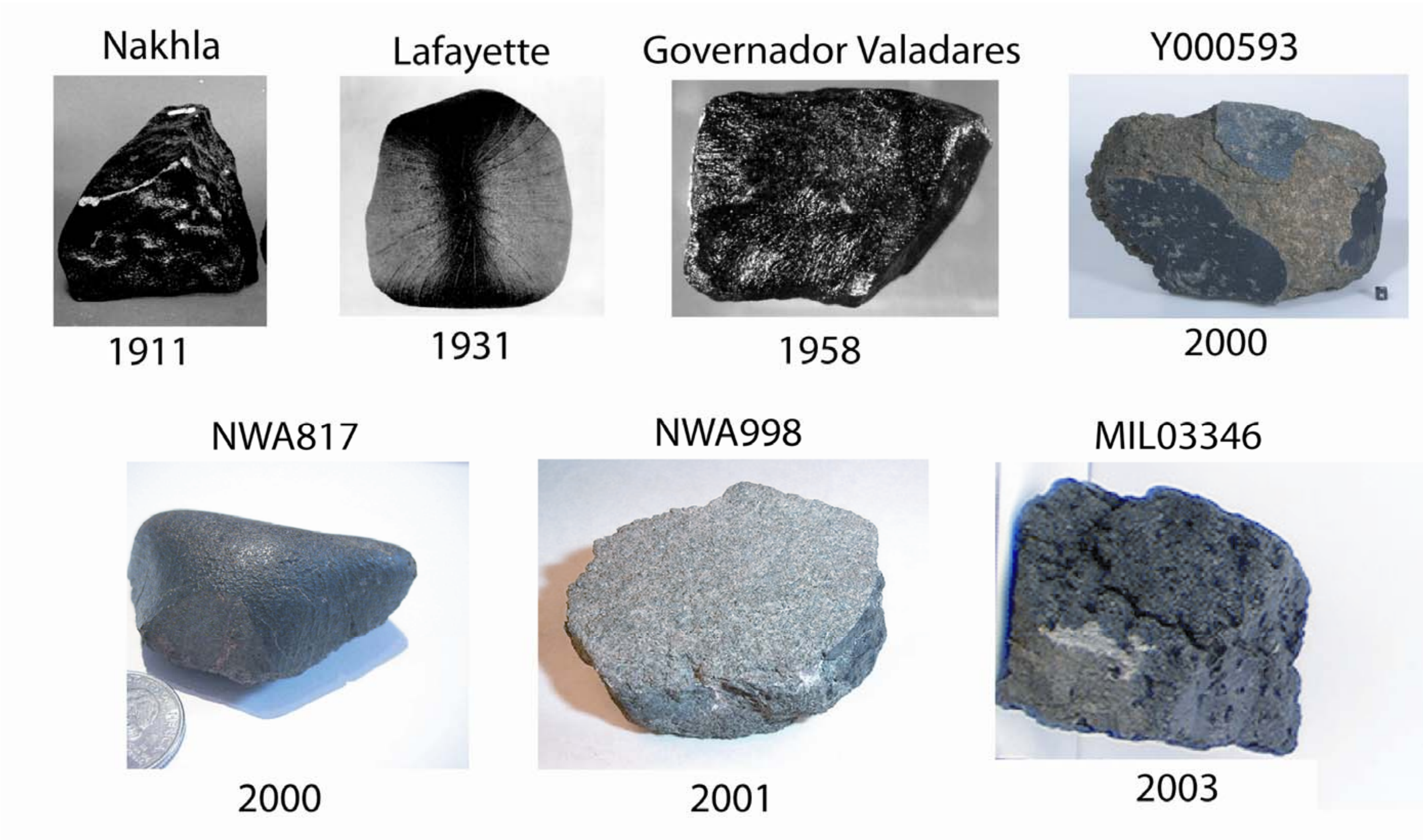
From J. Kargel's webpage

When was there a field and how strong was it?
Did atmospheric loss result from loss of magnetic field?
When and how much of the atmosphere was lost?
Was Mars really warmer and wetter in the past?
Did life evolve on Mars and could it have come to Earth?

Cumulative Number of Martian Meteorite Discoveries with Time

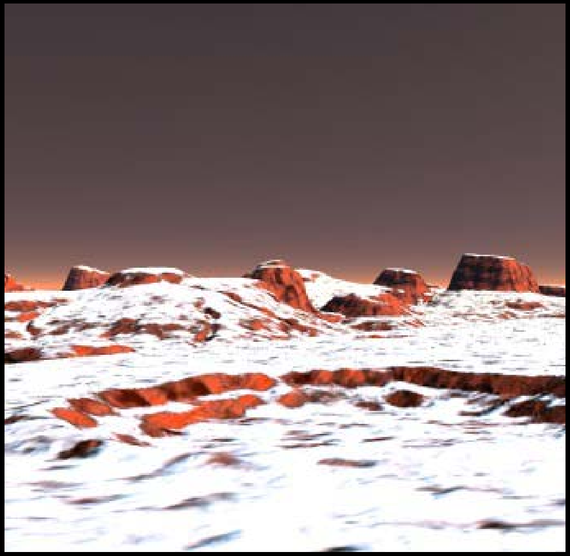


The Nakhlites (1.3 Billion Years Old)



ALH84001 (4.5 Billion Years Old)

I. Martian Paleotemperatures



Ar/Ar Dating

- $^{40}K \rightarrow {}^{40}Ar$. Half-life = 1.25 billion years
- In a reactor, convert $^{39}K \rightarrow {}^{39}Ar$.
- Since $^{39}K/^{40}K$ is constant in nature, ^{39}Ar is a proxy for ^{40}K in the sample
- $^{40}Ar/^{39}Ar$ ratio therefore gives the sample age
- Because ^{40}Ar is a noble gas, it is readily lost by diffusion.
- By estimating amount of missing ^{40}Ar, we can determine how much meteorites were heated since their Ar/Ar ages were reset.

$^{40}Ar/^{39}Ar$ Dating of Nakhlites

- $^{40}Ar/^{39}Ar$ ages of all seven known nakhlites: 1.3 billion years (Ga) (15 published studies!)
- These are within error of nakhlite crystallization ages (e.g., U/Pb).
- No major heating since 1.3 Ga.
- We quantify this using $^{40}Ar/^{39}Ar$ data of Swindle and Olson (2004).

Assumptions

- All ^{40}Ar lost by diffusion
- Ar diffusivity inferred in the lab can be extrapolated to the possibly different pressures and temperatures in nature.
- Ar diffusivity has not changed with time

What is the Peak Temperature During Ejection?

- Assume meteorite heated to some peak temperature during ejection and then cooled diffusively.
- During cooling it would degas ^{40}Ar, with amount depending on peak temperature and diffusivity.
- Calculate amount of degassed ^{40}Ar for various peak temperatures (Need: $D(T)$)
- The actual peak temperature is that which degases the same amount of Ar as that estimated to be missing from the sample.

Thermally Activated Diffusion

$$D(T) = D_0 \exp(-E_a/RT)$$

D = diffusivity of Ar in meteorite

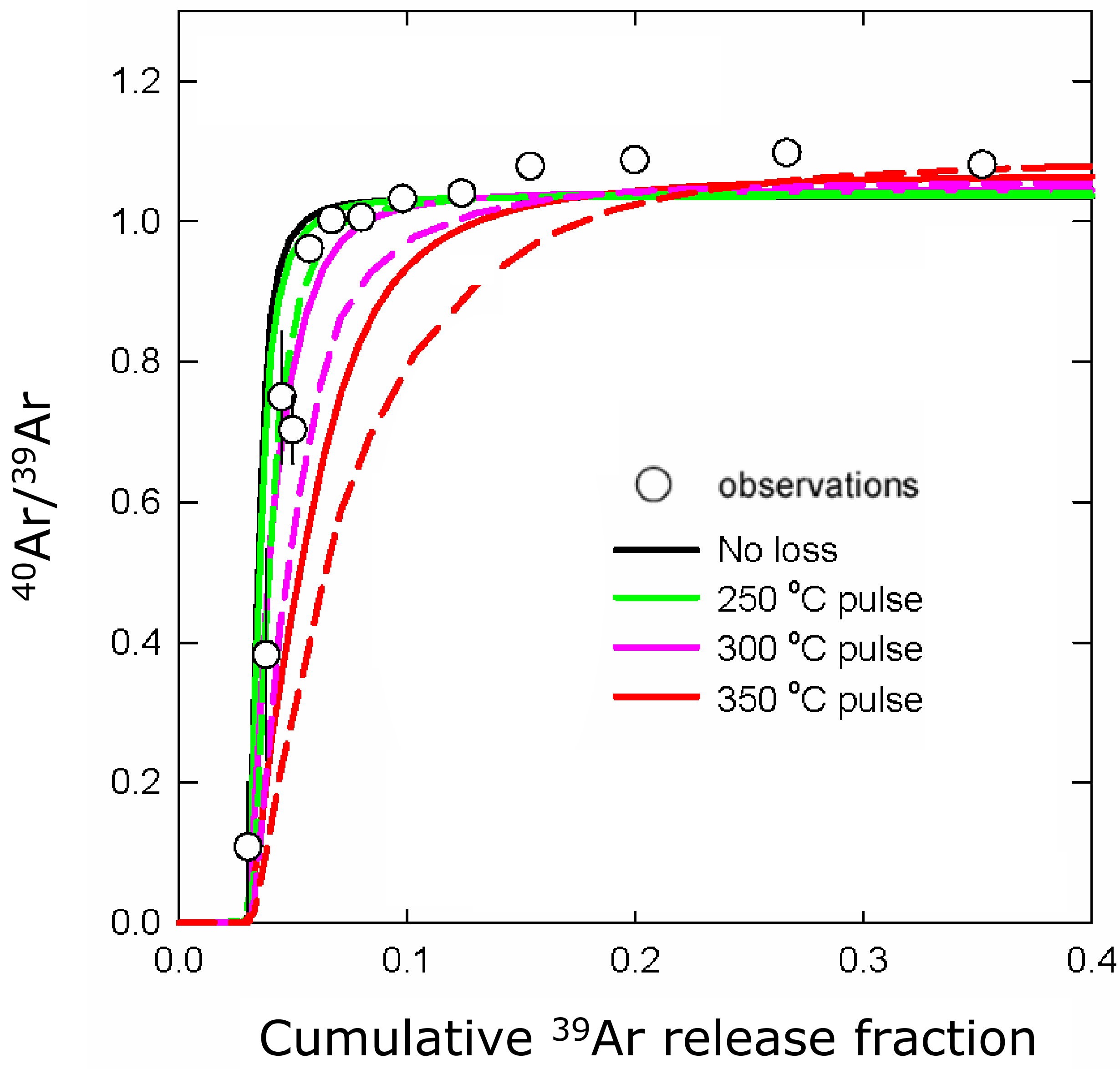
T = temperature

R = gas constant

D_0 = *diffusivity at infinite temperature*

E_a = *activation energy*

Age Spectrum of Nakhla



Using data from Swindle and Olson, 2004

Nakhla Results

- Similar results for a second Nakhla subsample and for Lafayette (another nakhlite).
- Nakhlites <<300 °C during ejection from Mars and transfer to Earth.
- These results consistent with nakhlite petrographic studies showing:

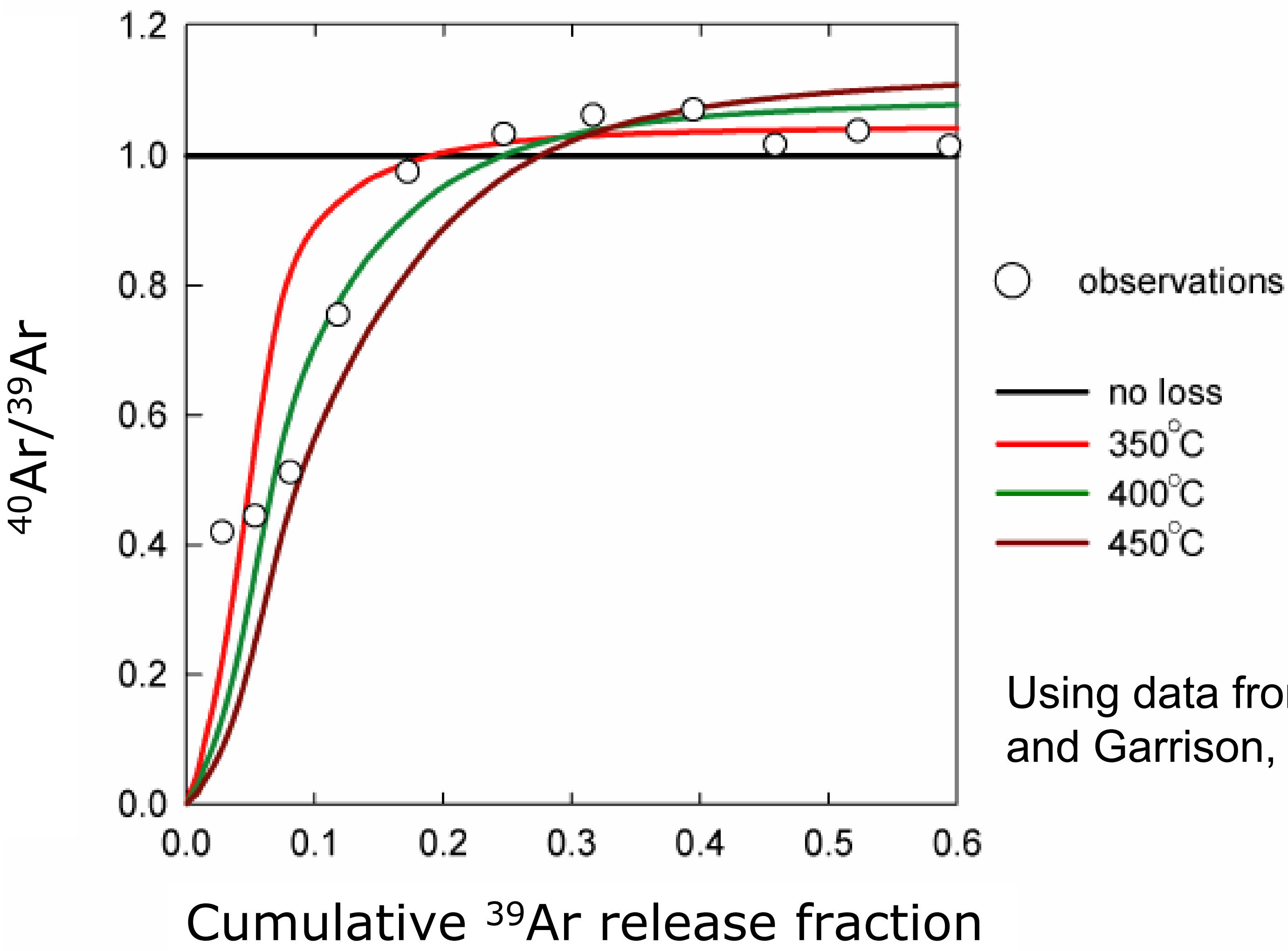
  peak shock pressures < 15 GPa (Fritz et al. 2003)

  → *peak shock temperatures < 0 ℃ (Artemieva and Ivanov, 2004)*

$^{40}Ar/^{39}Ar$ Thermochronometry of ALH84001

- Crystallization age: 4.5 Ga
- $^{40}Ar/^{39}Ar$ age of ALH84001: 4.1 $\pm$ 0.2 Ga (5 published studies)
- We used data of Bogard and Garrison (1999) to infer peak temperatures during ejection.

Age Spectrum of ALH84001



Using data from Bogard and Garrison, 1999

ALH84001 Results

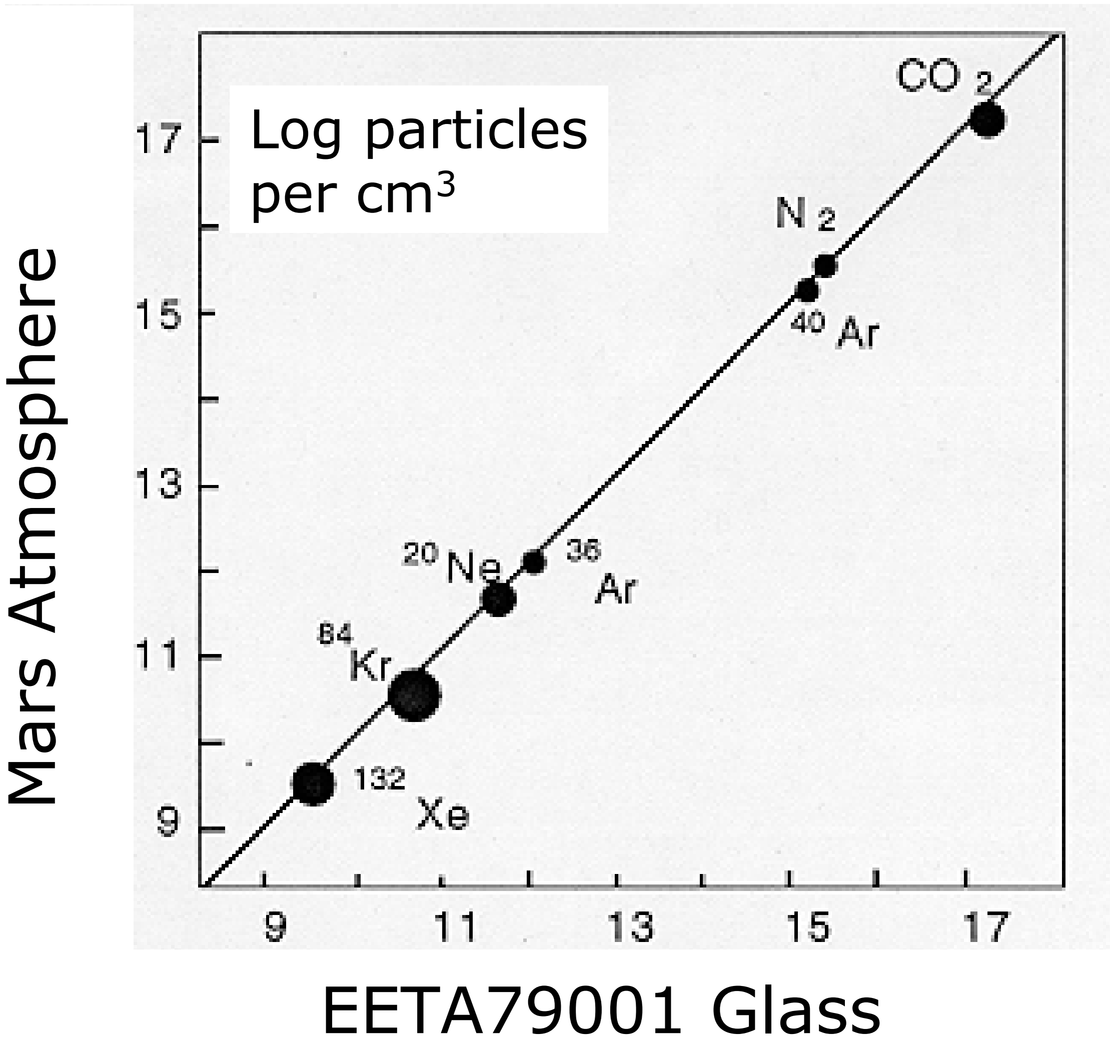
- ALH84001 was <<350 °C during ejection at 15 Ma.
- Shock petrographic data suggest ALH84001 < 30 GPa (*peak shock* temperatures < 30 °C) since 4 Ga (Weiss et al. 2002, Artemieva and Ivanov, 2004).

Meteorites not strongly heated during ejection and so should retain records of ancient geophysical processes on Mars.

At least 1/4 by mass of known Martian meteorites not heat-sterilized during ejection from Mars and transfer to Earth!

Elephant Moraine Martian Meteorite (EETA79001)

Shock-Implanted Gases in EETA79001 Meteorite



Pepin, R. O. (1991) *Icarus* **92**, 2-79

Trapped Atmospheric Gases in ALH84001?

- To implant atmospheric gases into a rock, probably need to melt the rock.
- Thus, atmospheric gas in ALH84001 should have been last implanted 4 billion years ago.
- ALH84001 could contain ancient atmosphere!
- Atmospheric loss → this gas should be less enriched in heavy isotopes, less enriched in radiogenic isotopes

Measurements of Martian Atmospheric Gases

	ALH84001 (4 Ga)	EETA79001 (0.18 Ga)	Viking (present)
D/H	**3 x**	5.4 x	5.5 ± 0.25 x
$^{15}N/^{14}N$	**1.007 x**	<1.50 x	1.62 ± 0.16 x
$^{38}Ar/^{36}Ar$	≤**0.2**	≥0.26	0.19 ± 0.06
$^{40}Ar/^{36}Ar$	≤**128**	~1800	3000 ± 500
$^{129}Xe/^{132}Xe$	**2.16**	2.4-2.6	2.3-2.6

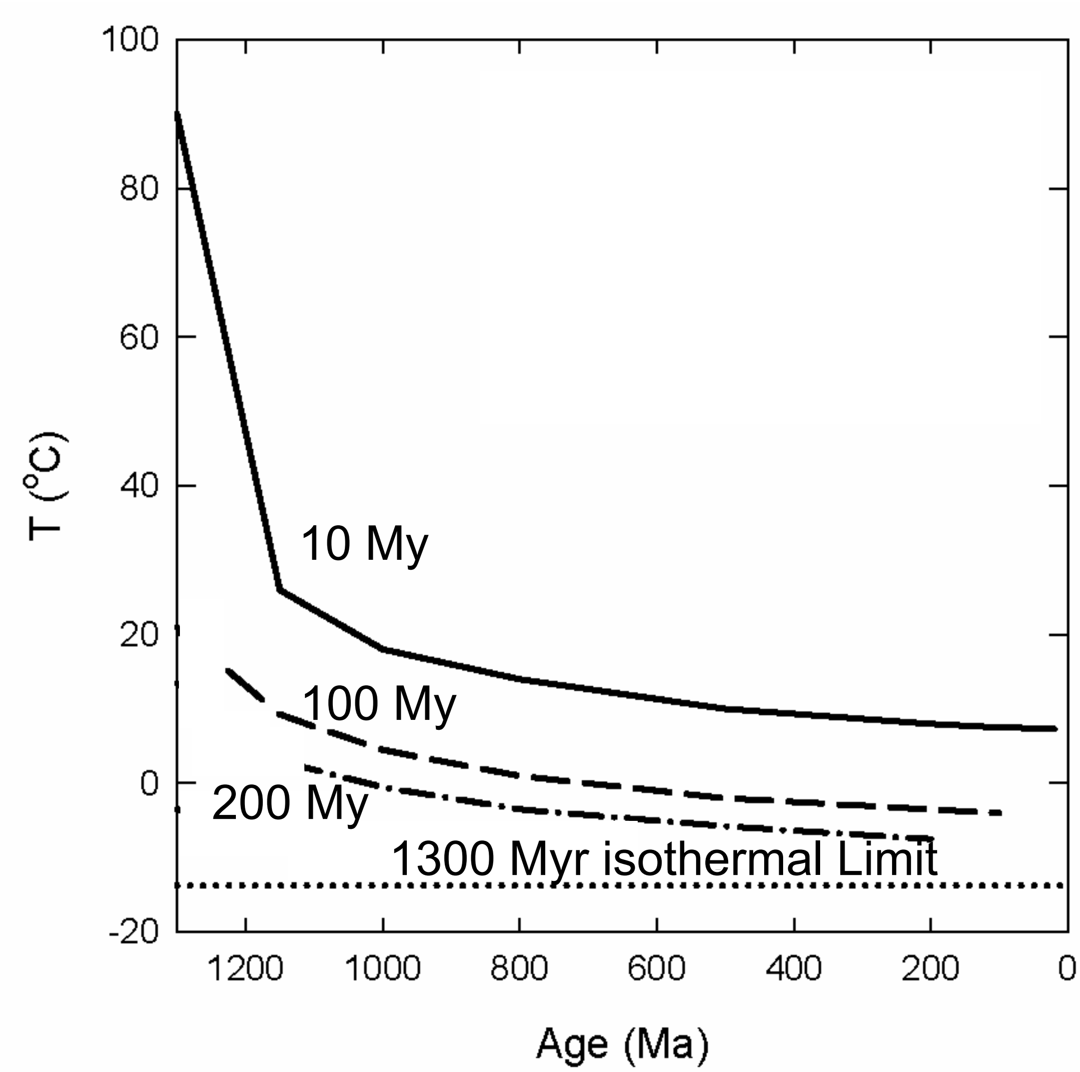
x = times Earth's atmospheric ratio

(See papers by Bogard, Marti, Mathew, Marty, Gilmour, Grady, Sugiura, Eiler, Garrison, Murty…)

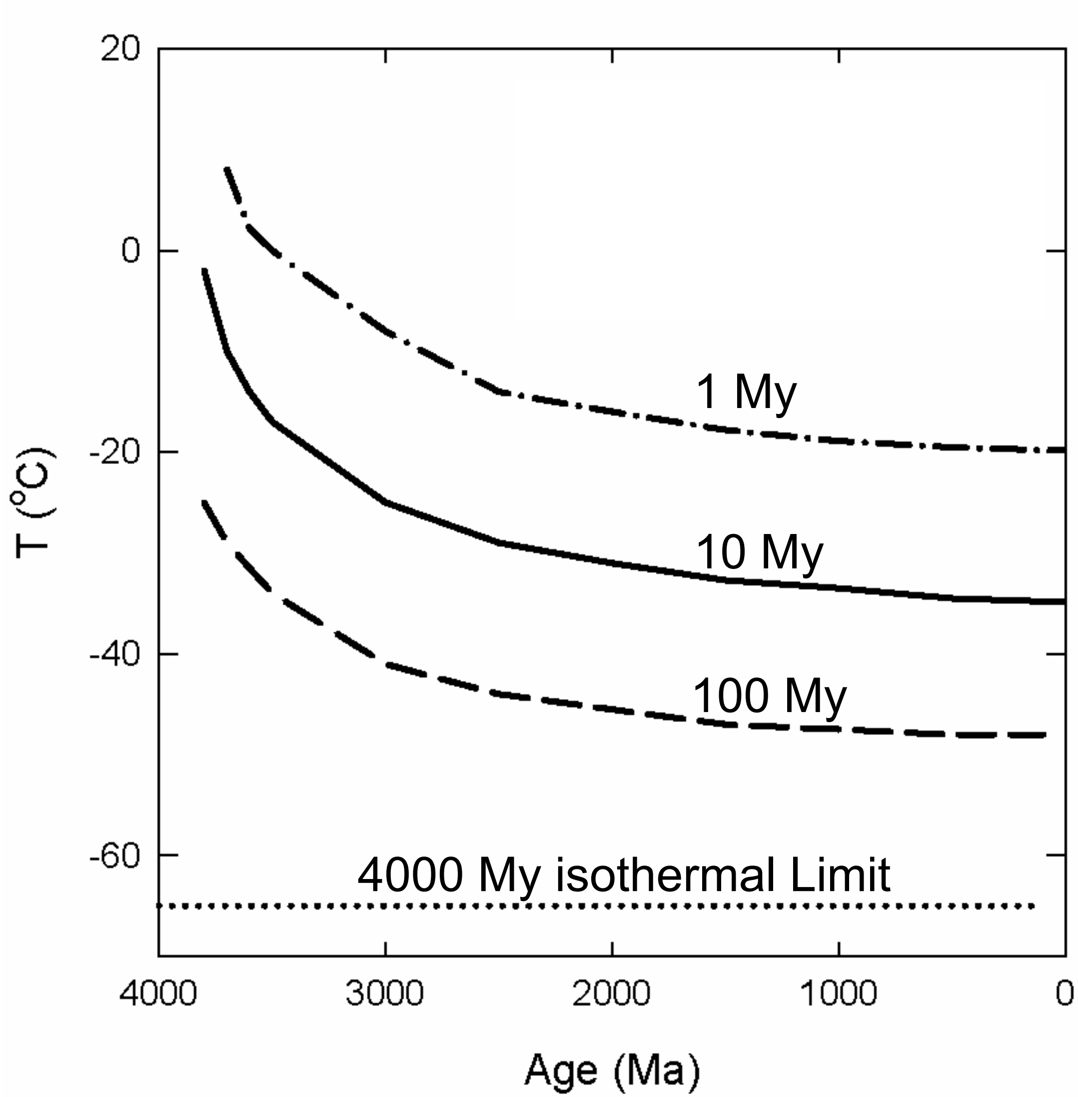
Ar/Ar data support hypothesis that ALH84001 contains a sample of 4 billion year old Martian atmosphere.

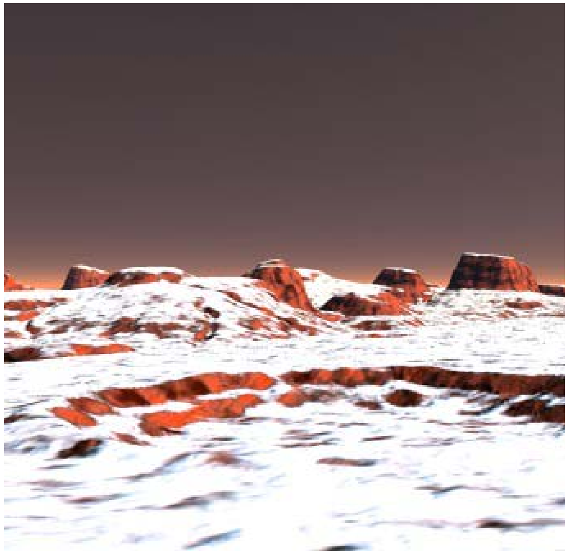
Gas composition supports theory that atmospheric loss has occurred on Mars since 4 billion years ago.

Time-Temperature Constraints on Mars from the Nakhlites



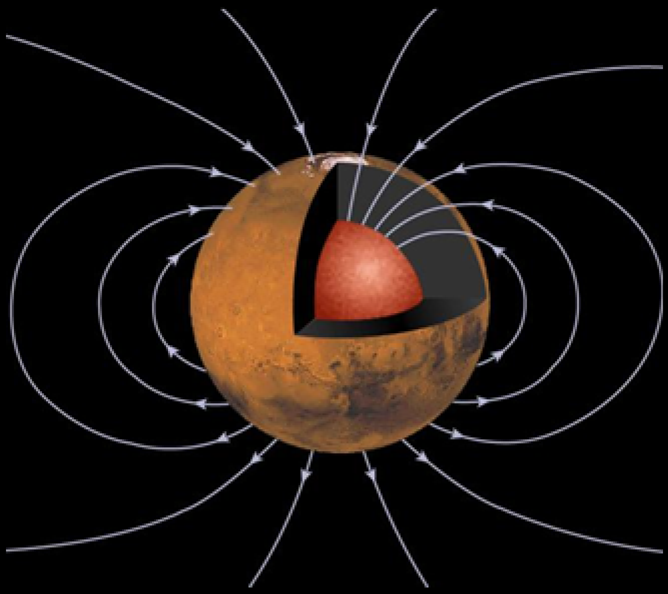
Time-Temperature Constraints on Mars from ALH84001





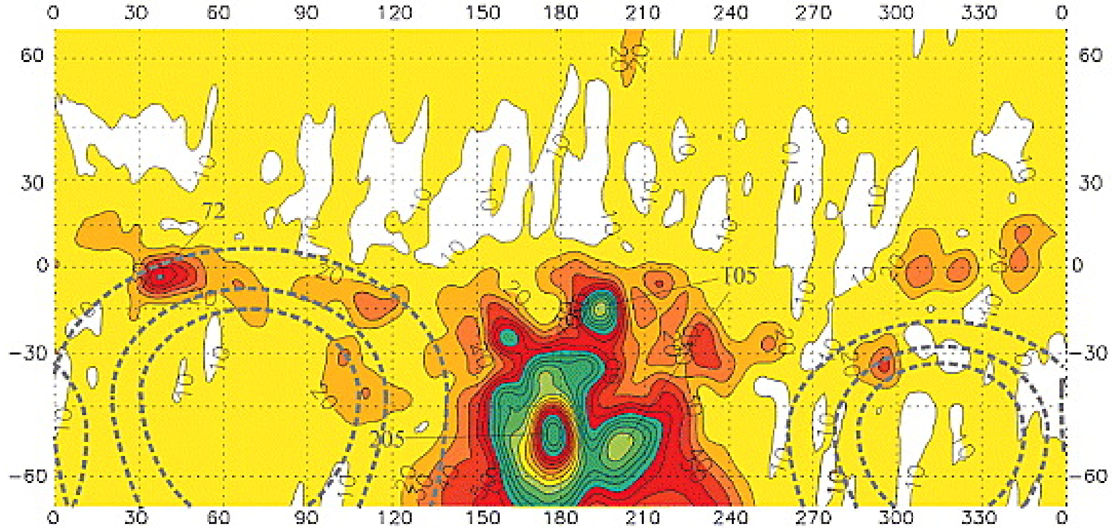
- >20% of all known Martian meteorites have been in the deep freeze for most of their histories.
- Martian near-surface < 0 °C for all but the briefest (<1 My) amounts of time since 3.5 Ga!

II. Martian Paleofields

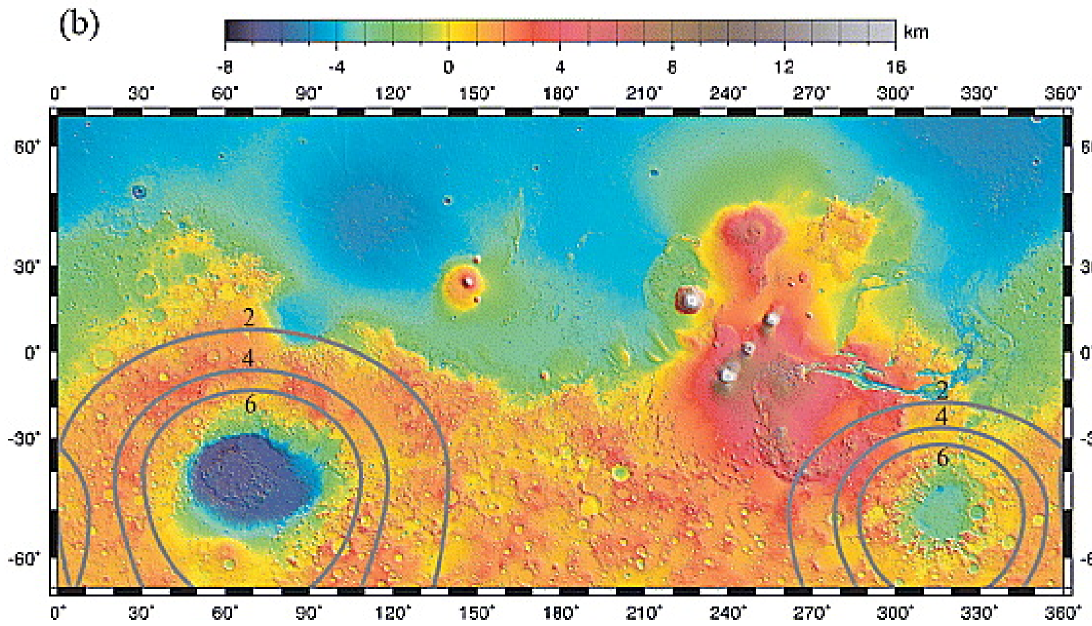


Martian Crustal Fields

Fields

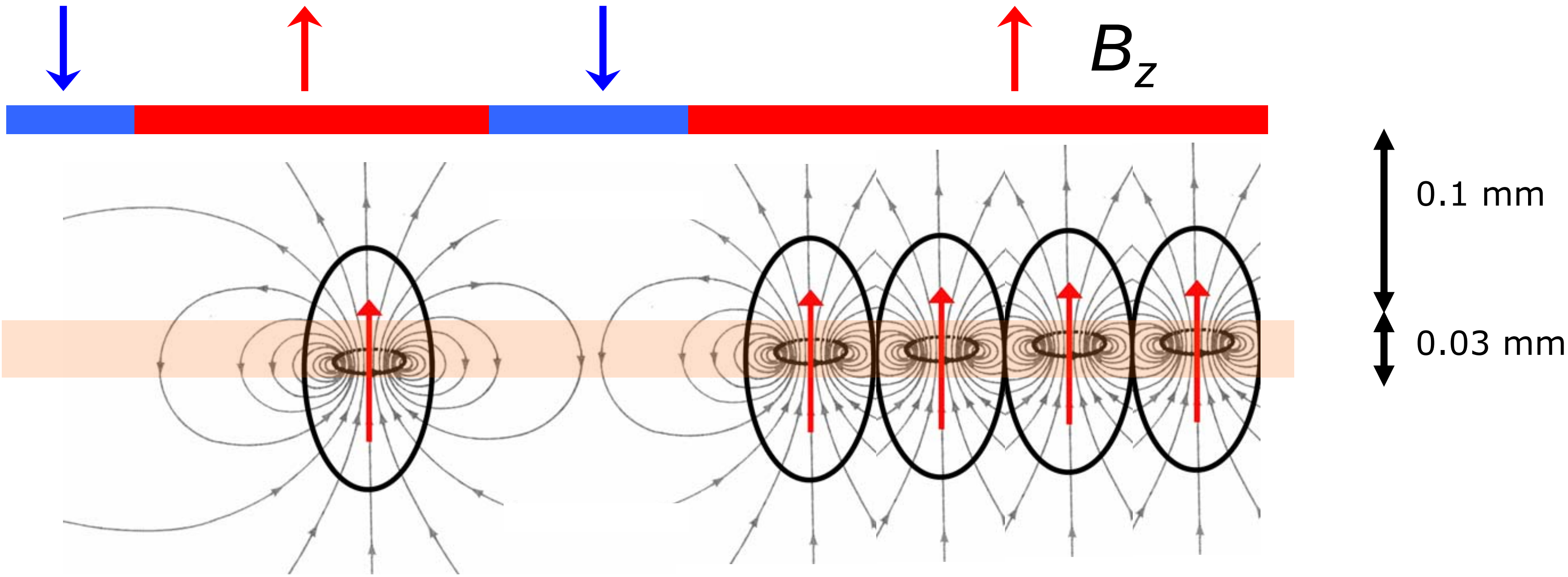


Topography

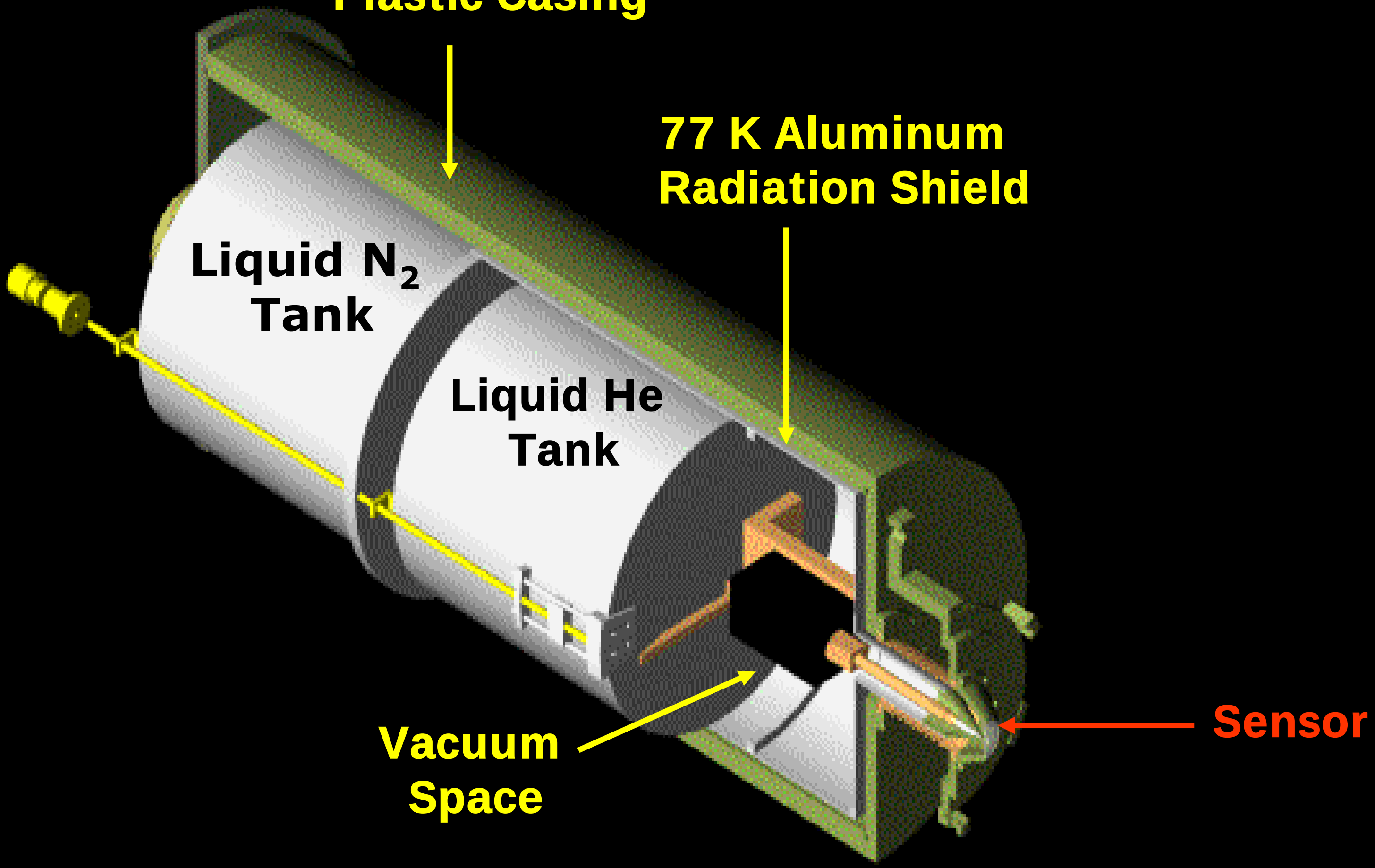


Hood et al. 2003

Orientation of Demagnetizing Fields



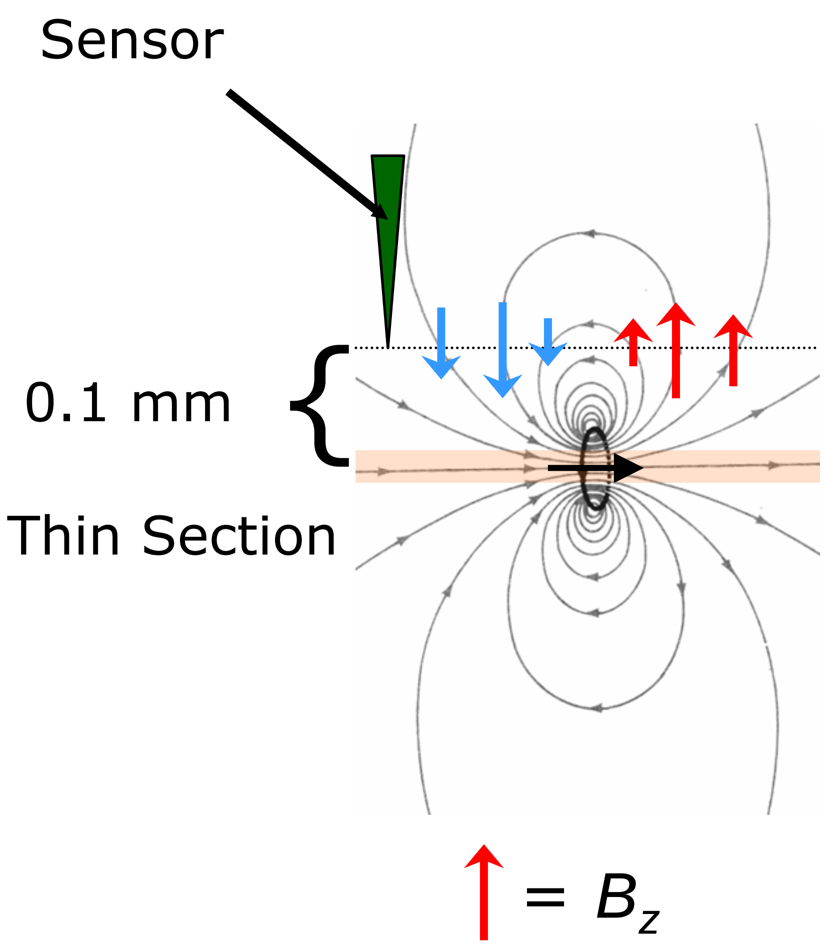
SQUID Microscope

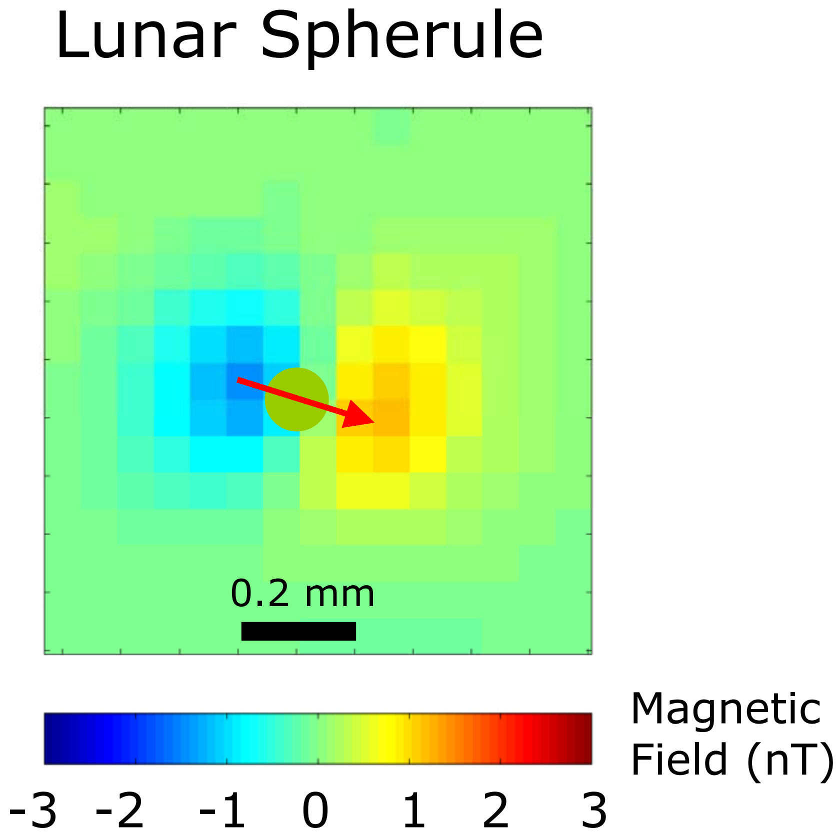


Compared to conventional SQUID magnetometers:
Sensitivity 10,000x Resolution ~100x

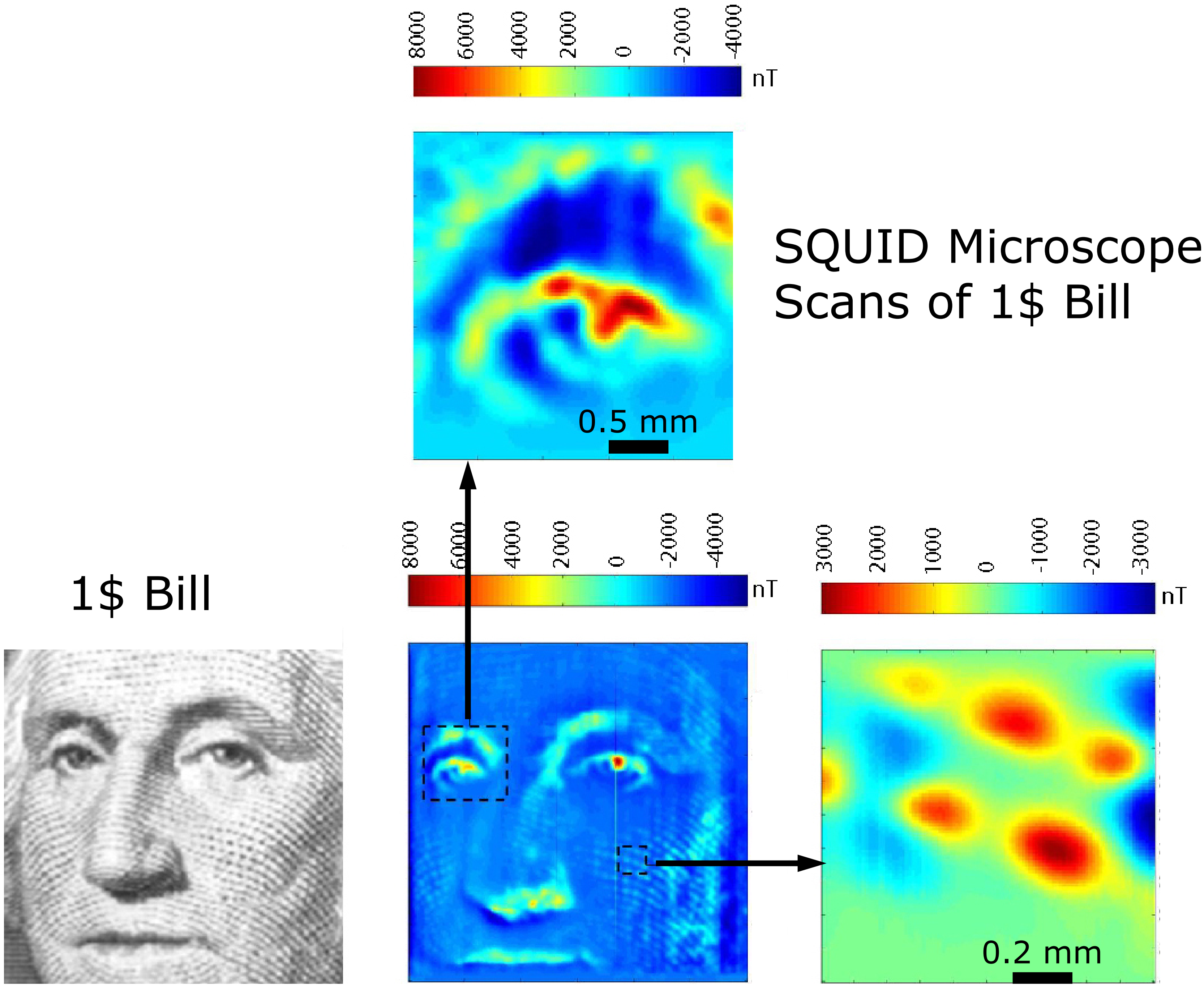
Images magnetic field!

What the SQUID Microscope Measures



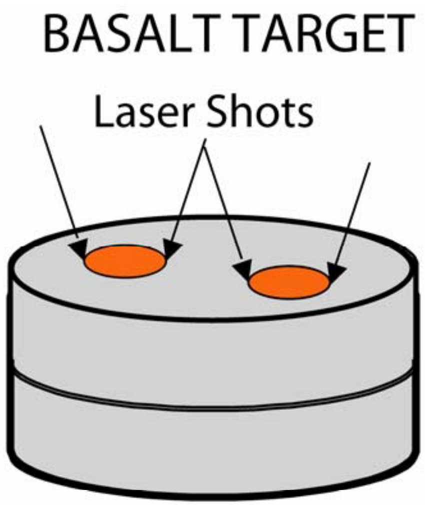


Moment=10^{-13} Am^2 !!



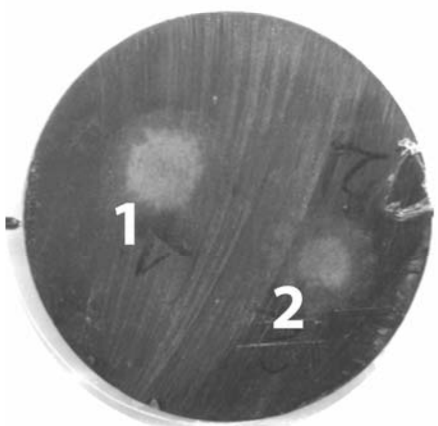
SQUID Microscope
Scans of 1$ Bill
1$ Bill
8000
6000
4000
2000
0
-2000
-4000
nT
0.5 mm
3000
2000
1000
0
-1000
-2000
-3000
nT
0.2 mm

Shock Demagnetization of Basalt



10 mm

TOP VIEW

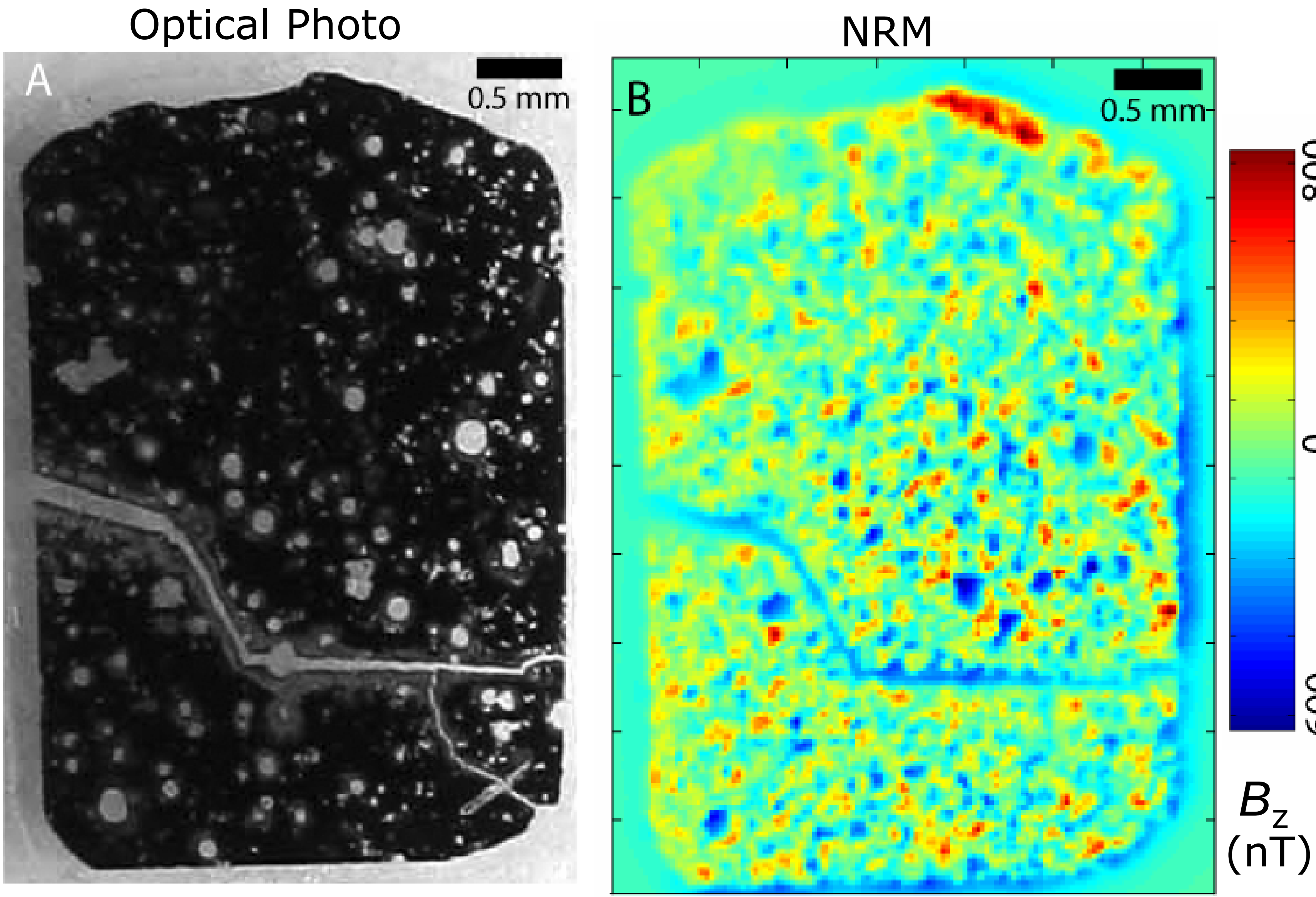


10 mm

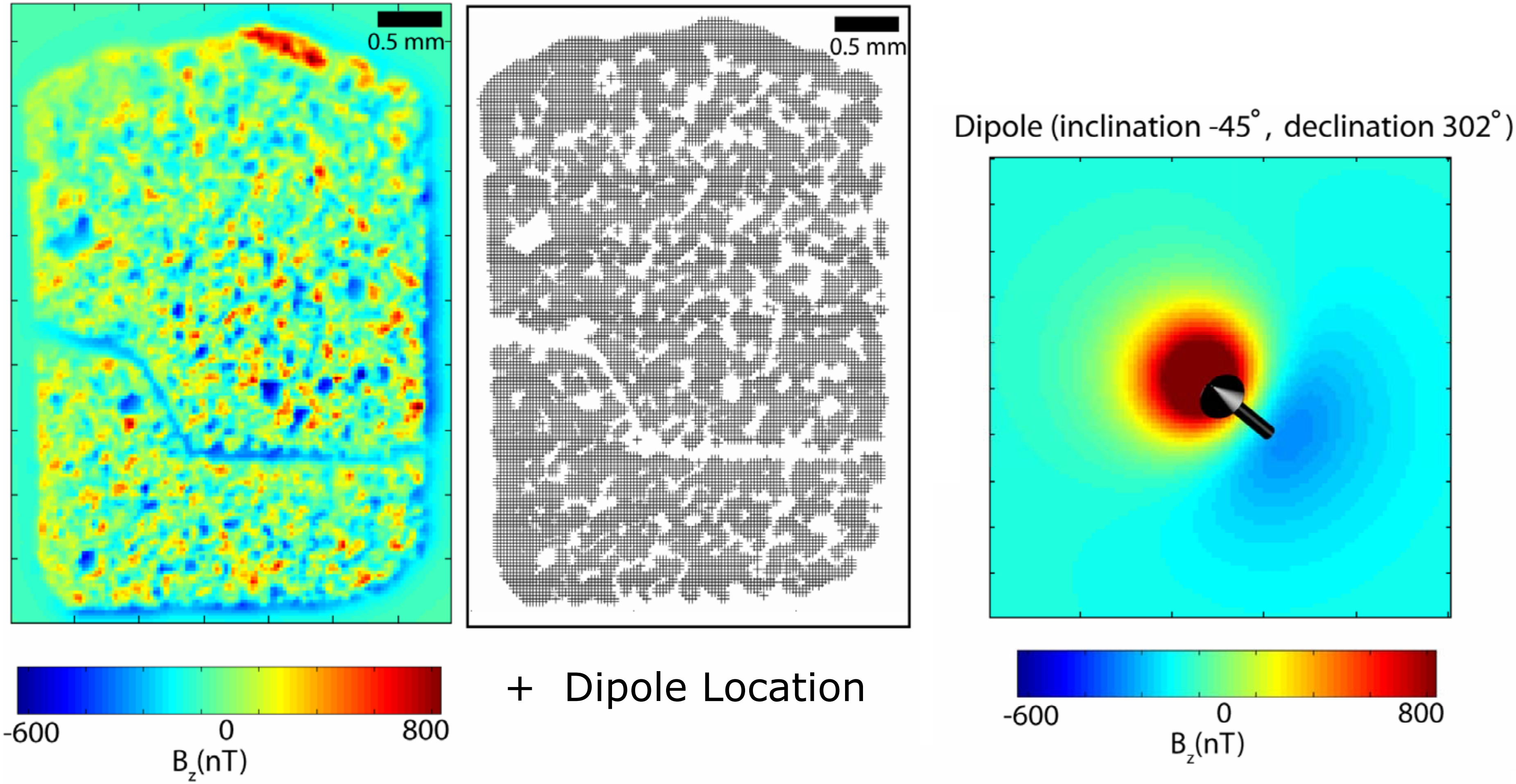
Paleointensity Technique

- NRM: natural remanent magnetization
- sIRM: magnetization after exposure to a saturating field
- Way to measure field: NRM/sIRM method
- NRM/sIRM roughly proportional to paleofield intensity (Kletetschka et al. 2003, 2004, Gattacceca and Rochette 2004)
- Earth field (~ 50 μT) produces NRM/sIRM ~ several %

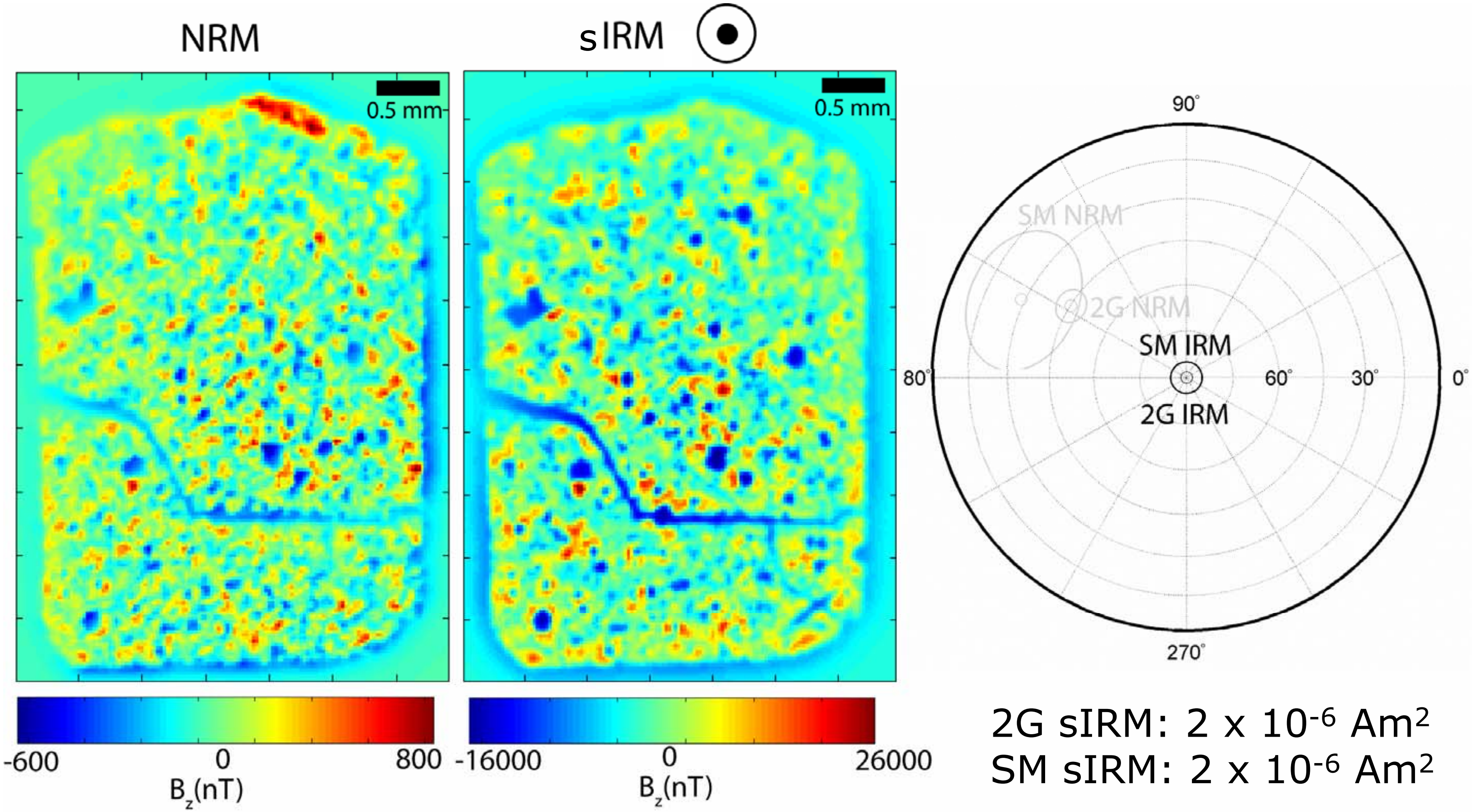
Mauna Loa Basalt Thin Section



Ground Truth: Recover 2G NRM



Ground Truth: Recover 2G Paleointensity



2G sIRM: 2 x 10^{-6} Am^2
SM sIRM: 2 x 10^{-6} Am^2

2G NRM/sIRM ~ 3%
SM NRM/sIRM ~ 3%

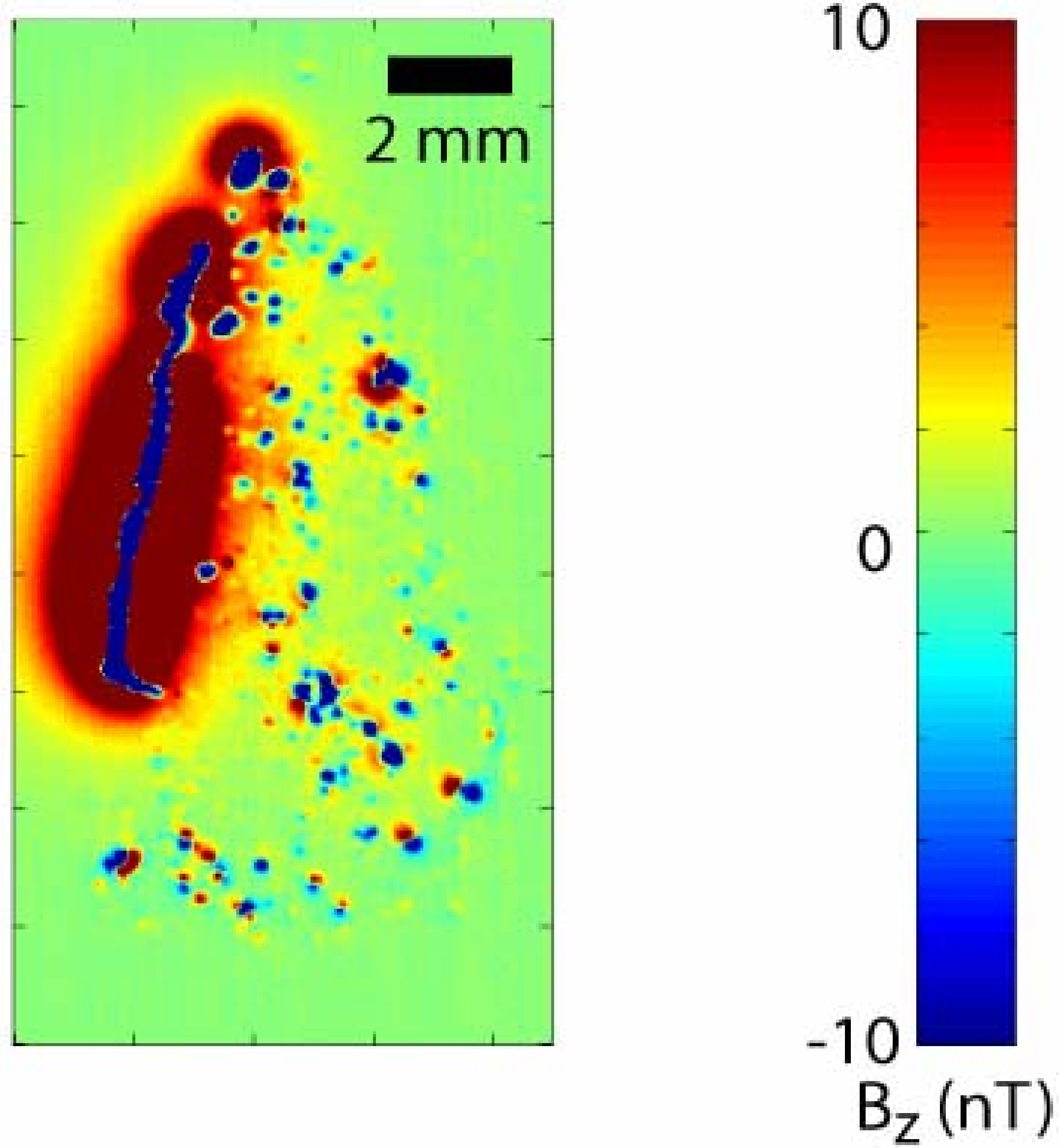
→ ~ 50 μT paleofield

ALH84001

- Crystallization age: 4.5 Ga
- K/Ar age demonstrates that ALH84001 has not been heated since 4 Ga.

  (Weiss et al. 2002, Shuster and Weiss 2005)
- Records Martian paleofield at 4 Ga.

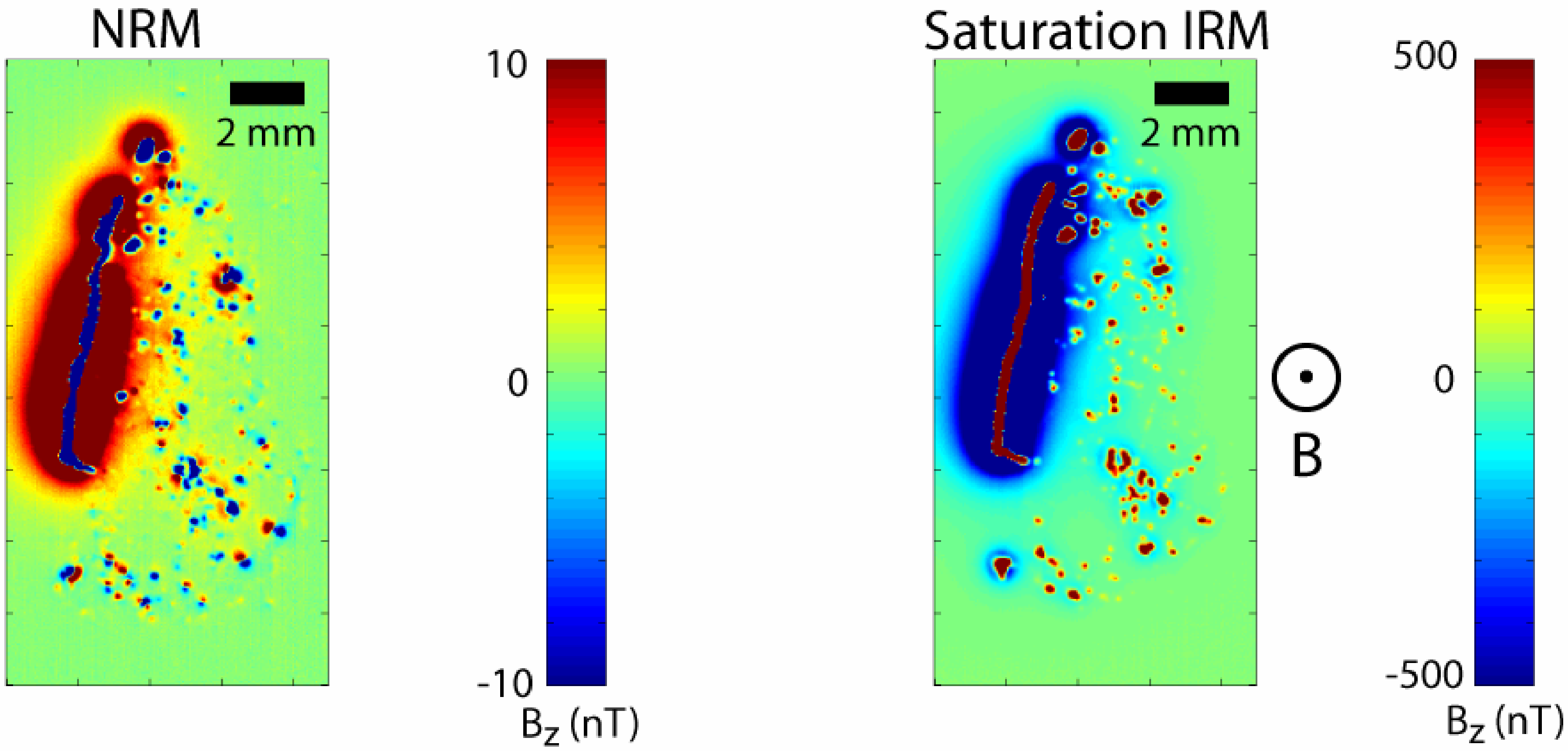
NRM Field of an ALH84001 Thin Section



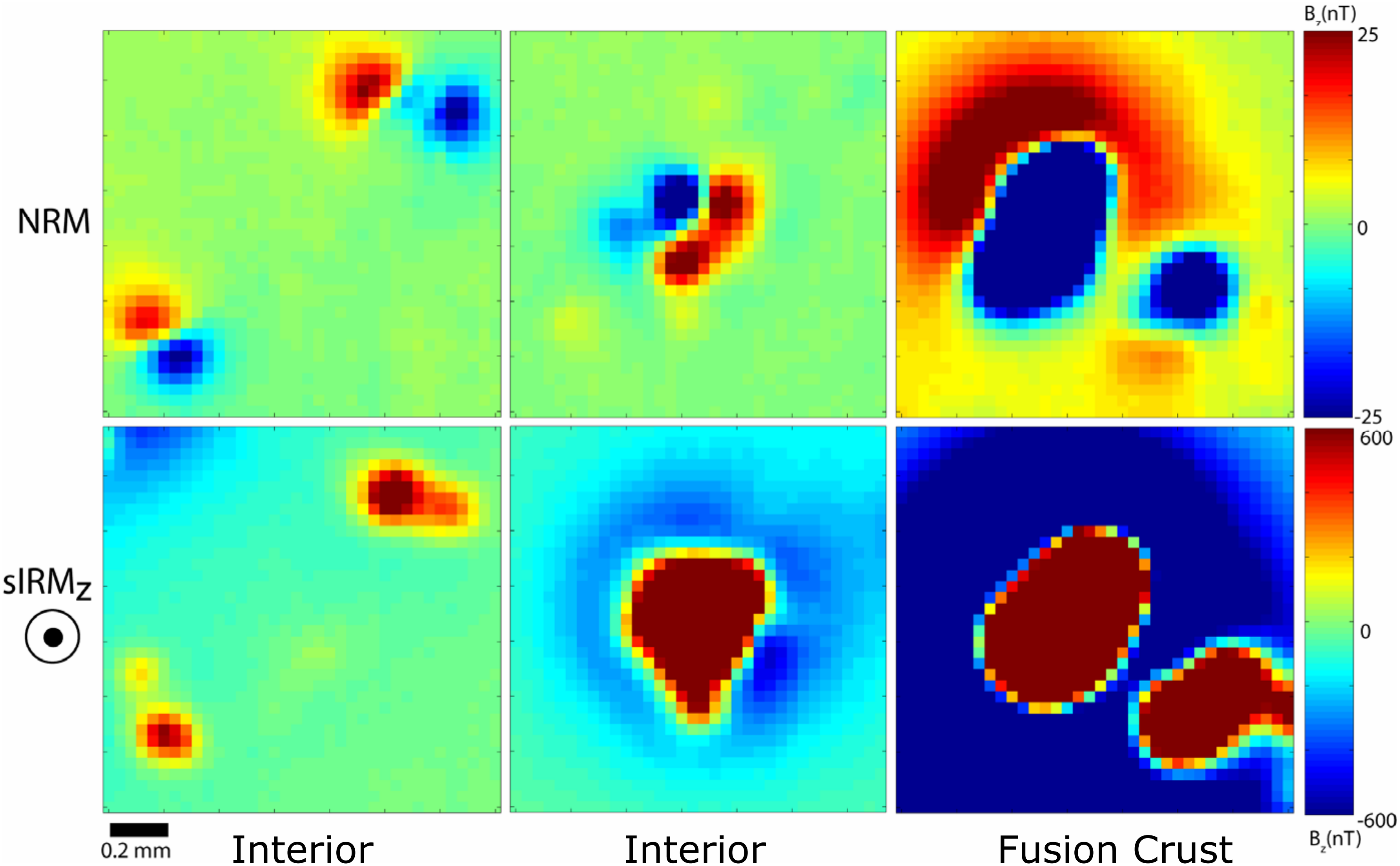
What was Intensity of the Field that Magnetized ALH84001 at 4 Ga?

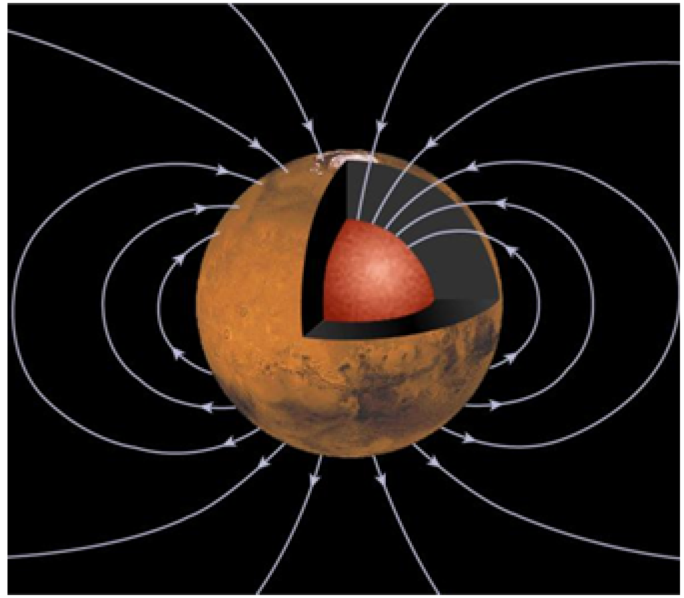
- Studies of bulk ALH84001 grains by Collinson 1997, Antretter et al. 2003: NRM/sIRM ~ 0.1%
- Implies ~5 μT paleofield.
- Lower limit because of heterogeneity of ALH84001 magnetism!!

Intensity of Martian Field at 4 Ga



Intensity of Martian Field at 4 Ga





- Field intensity: ~ 50 μT (~present Earth). 10x some previous bulk grain estimates.
- Crustal or dynamo?
- Better able to explain crustal magnetization.
- Enough to shield early atmosphere.

Conclusions

A large fraction of Martian meteorites were not heat-sterilized during ejection and transfer to Earth.

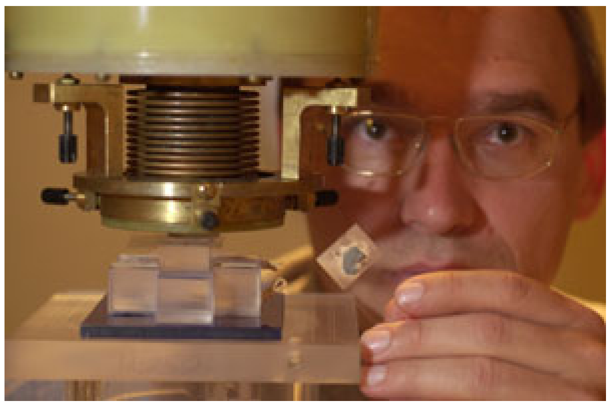
Atmosphere in ALH84001 is apparently 4 Gy old. Its composition is consistent with atmospheric loss since 4 Ga.

Subzero near-surface temperatures on Mars for all but 1 My of last 4 Gy.

50 μT field magnetized ALH84001 at 4 Ga. Much easier to explain crustal magnetization than previous bulk-grain estimates. Mars had generated a dynamo by 4 Ga.

Thanks To:

David Shuster
BGC

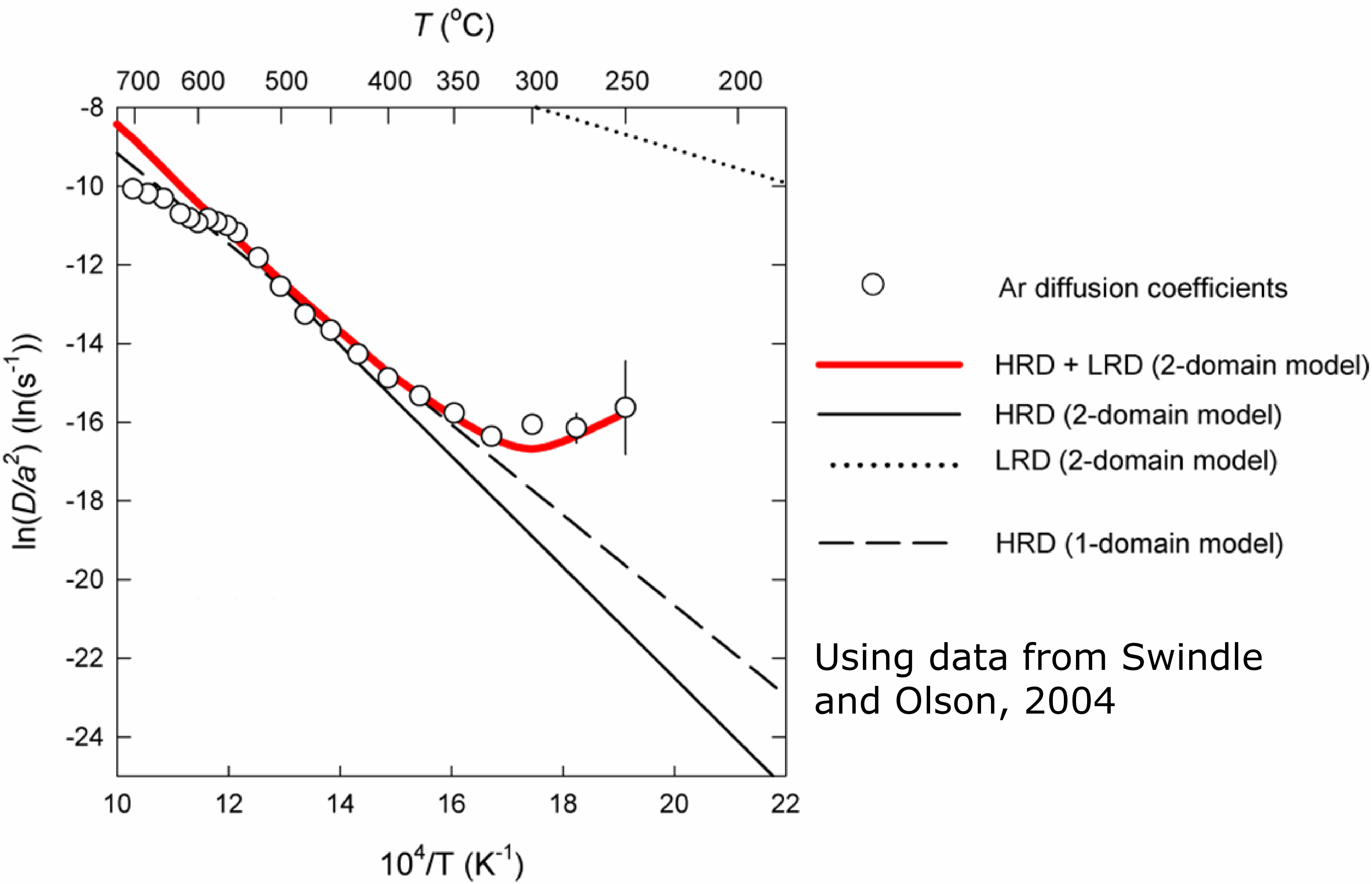


Franz Baudenbacher
Vanderbilt

J. Gattacceca
CEREGE

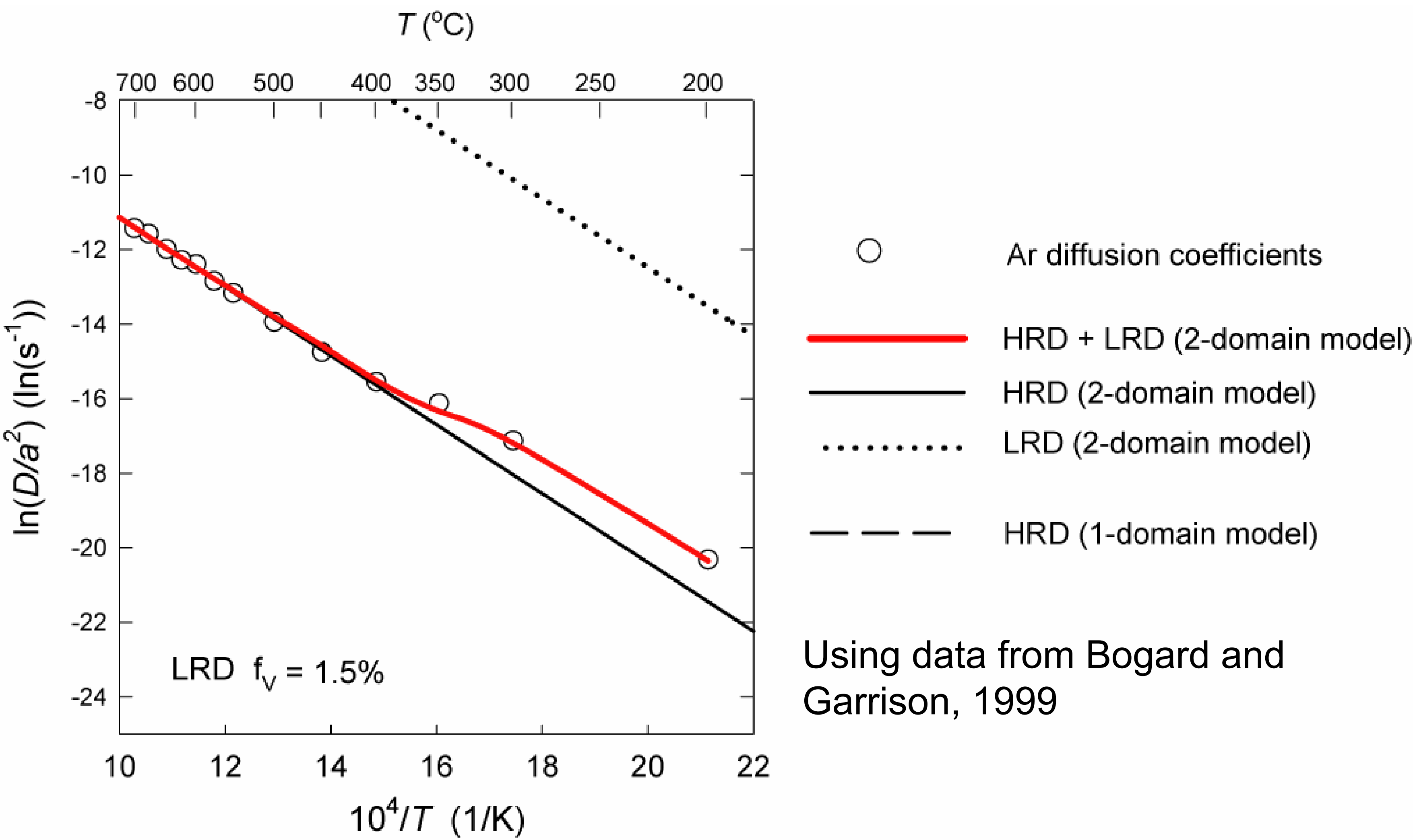
Tanja Bosak
Harvard

Diffusivity of Ar in Nakhla



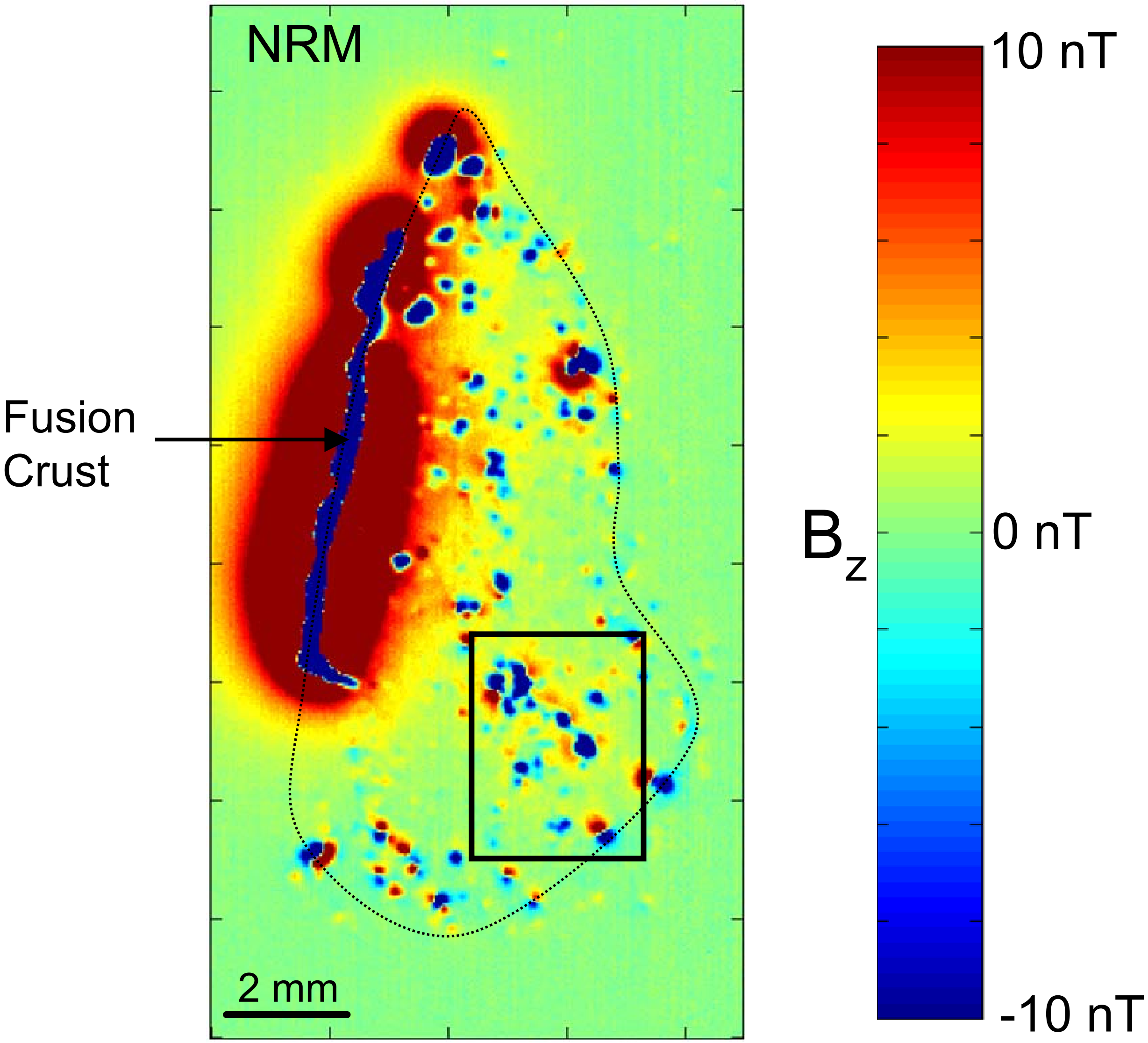
Using data from Swindle and Olson, 2004

Diffusivity of Ar in ALH84001

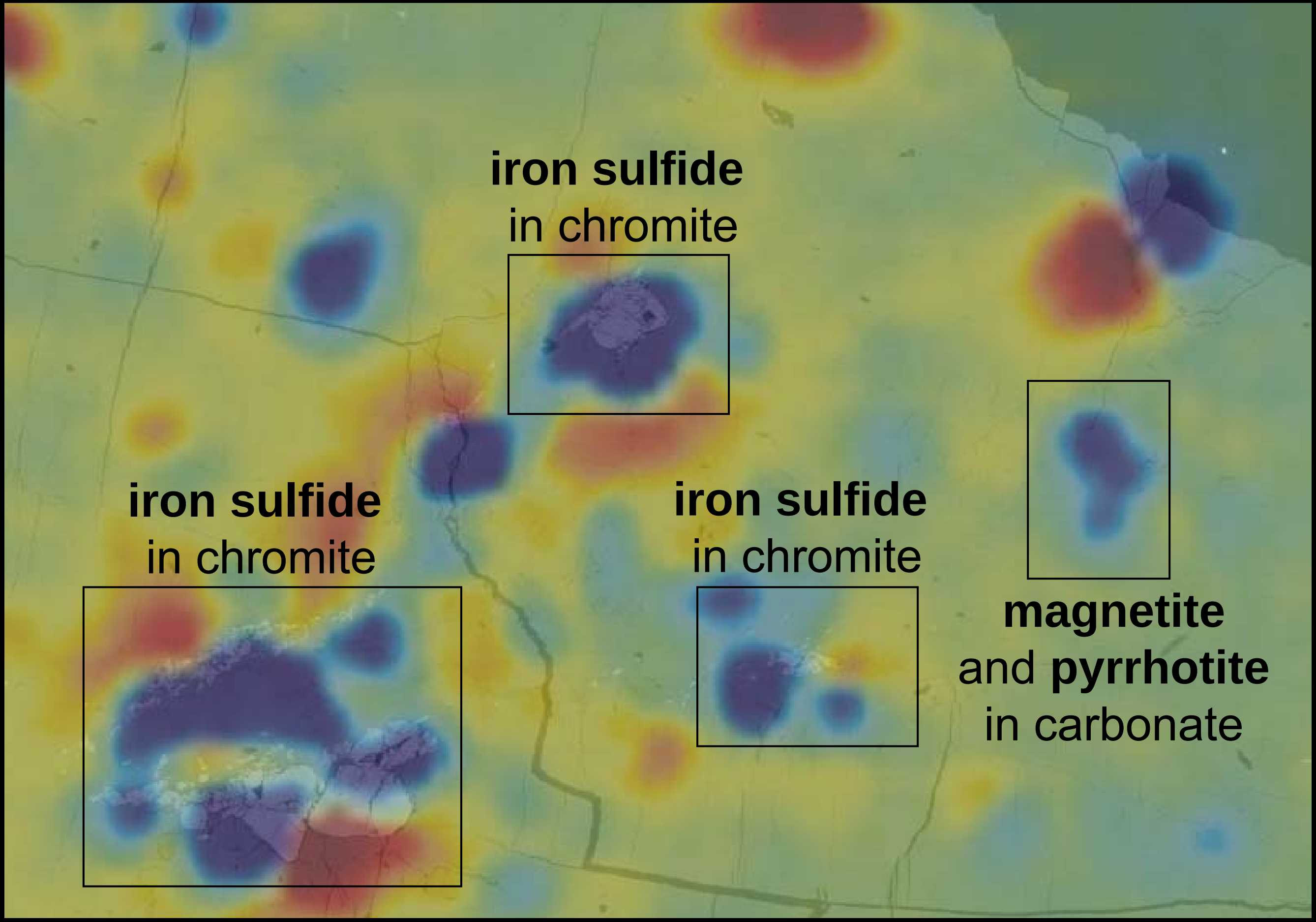


Using data from Bogard and Garrison, 1999

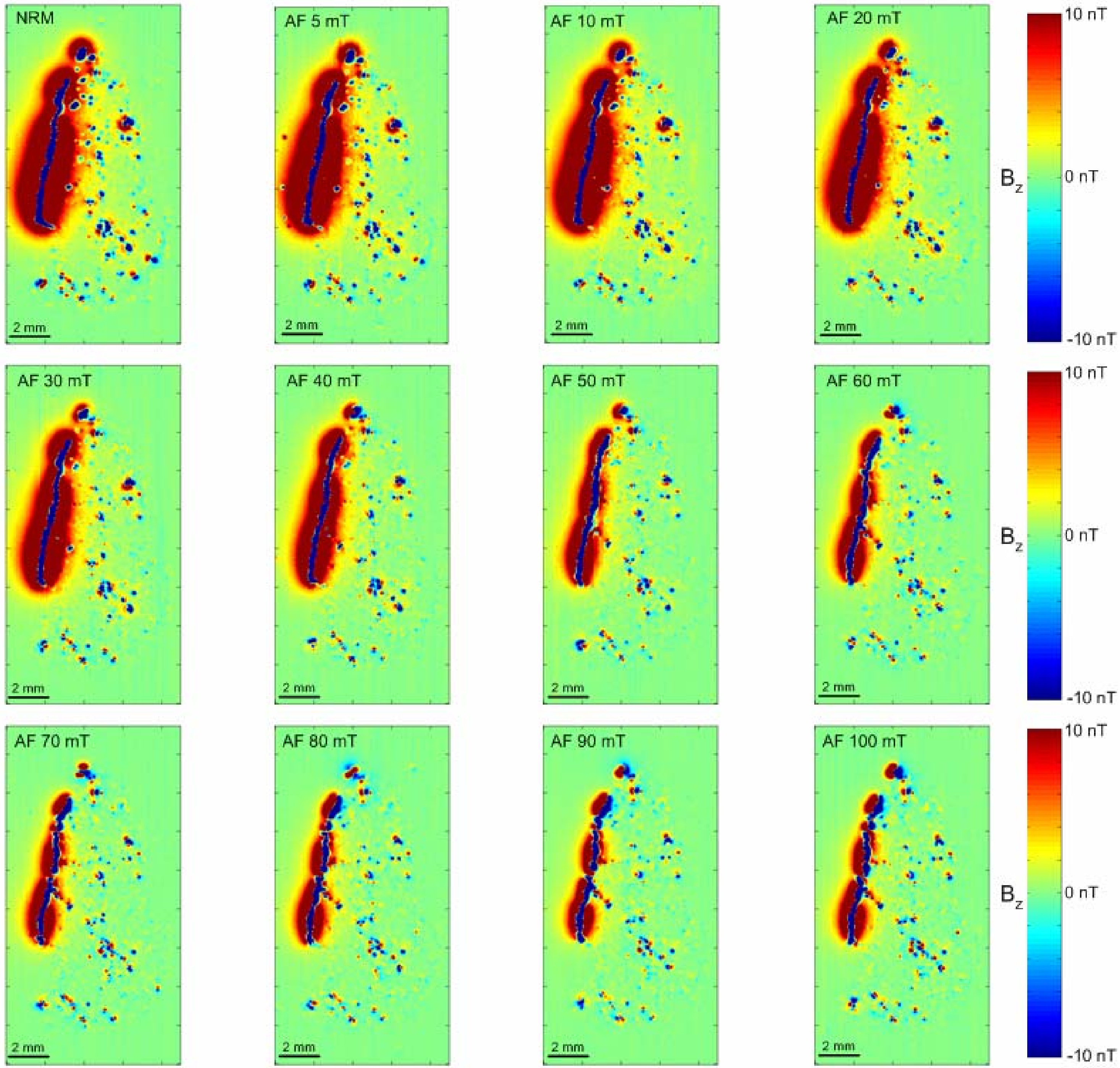
ALH84001 Thin Section



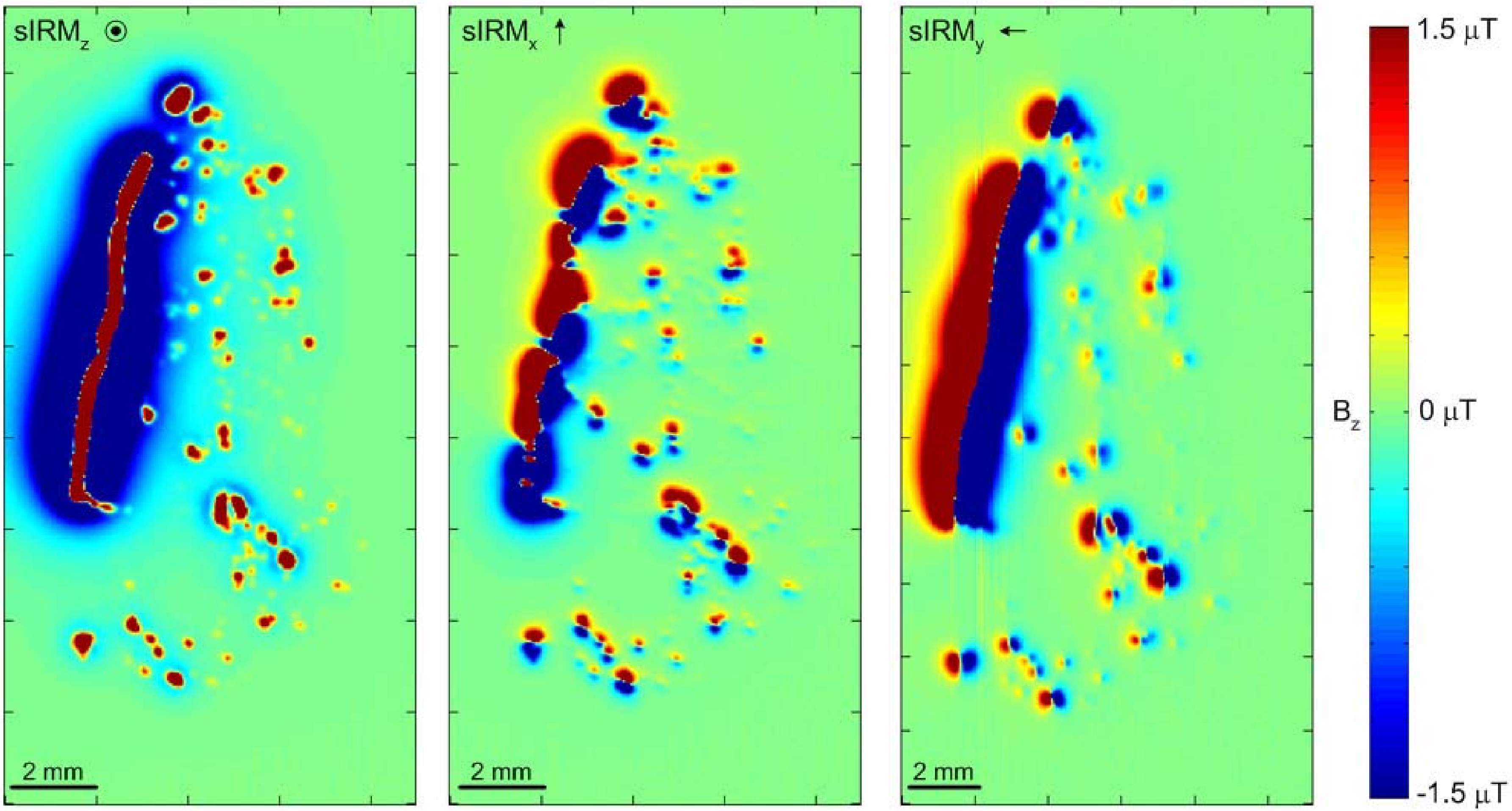
SM Map Overlaid on BSEM Image



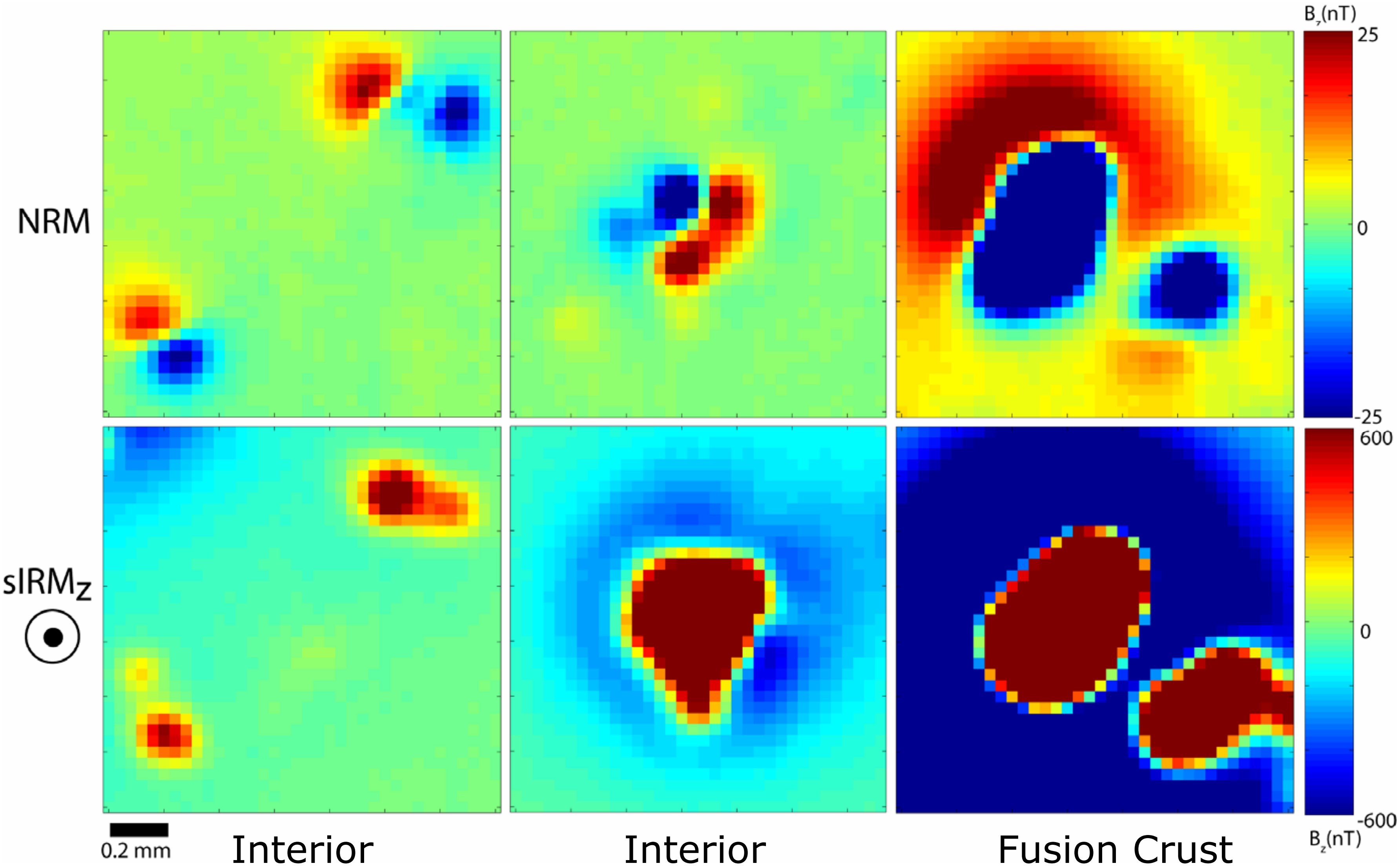
AF Demag


NRM
AF 5 mT
AF 10 mT
AF 20 mT
AF 30 mT
AF 40 mT
AF 50 mT
AF 60 mT
AF 70 mT
AF 80 mT
AF 90 mT
AF 100 mT
2 mm
10 nT
0 nT
-10 nT
B_z

Three Axis IRM:
No Appreciable Anisotropy of Remanence

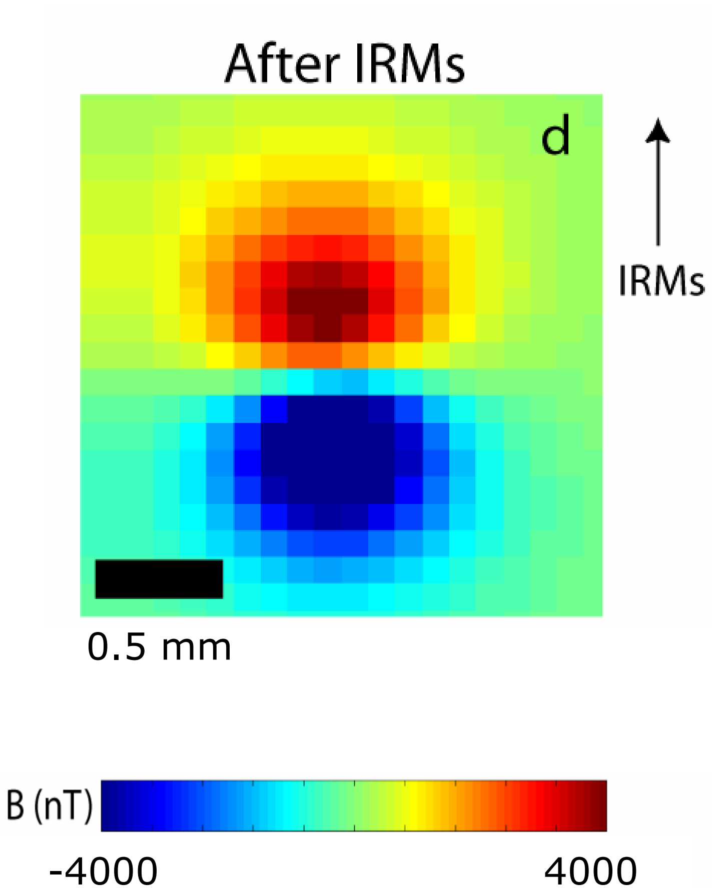


Intensity of Martian Field at 4 Ga

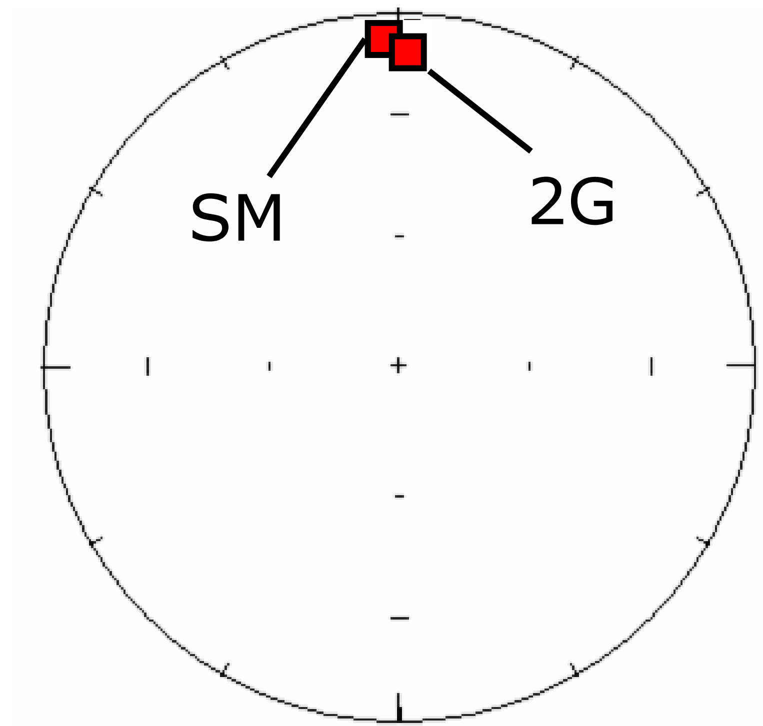


Ground Truth: Recover 2G Measurements for Point Source

SQUID Microscope Scan



Moment Direction



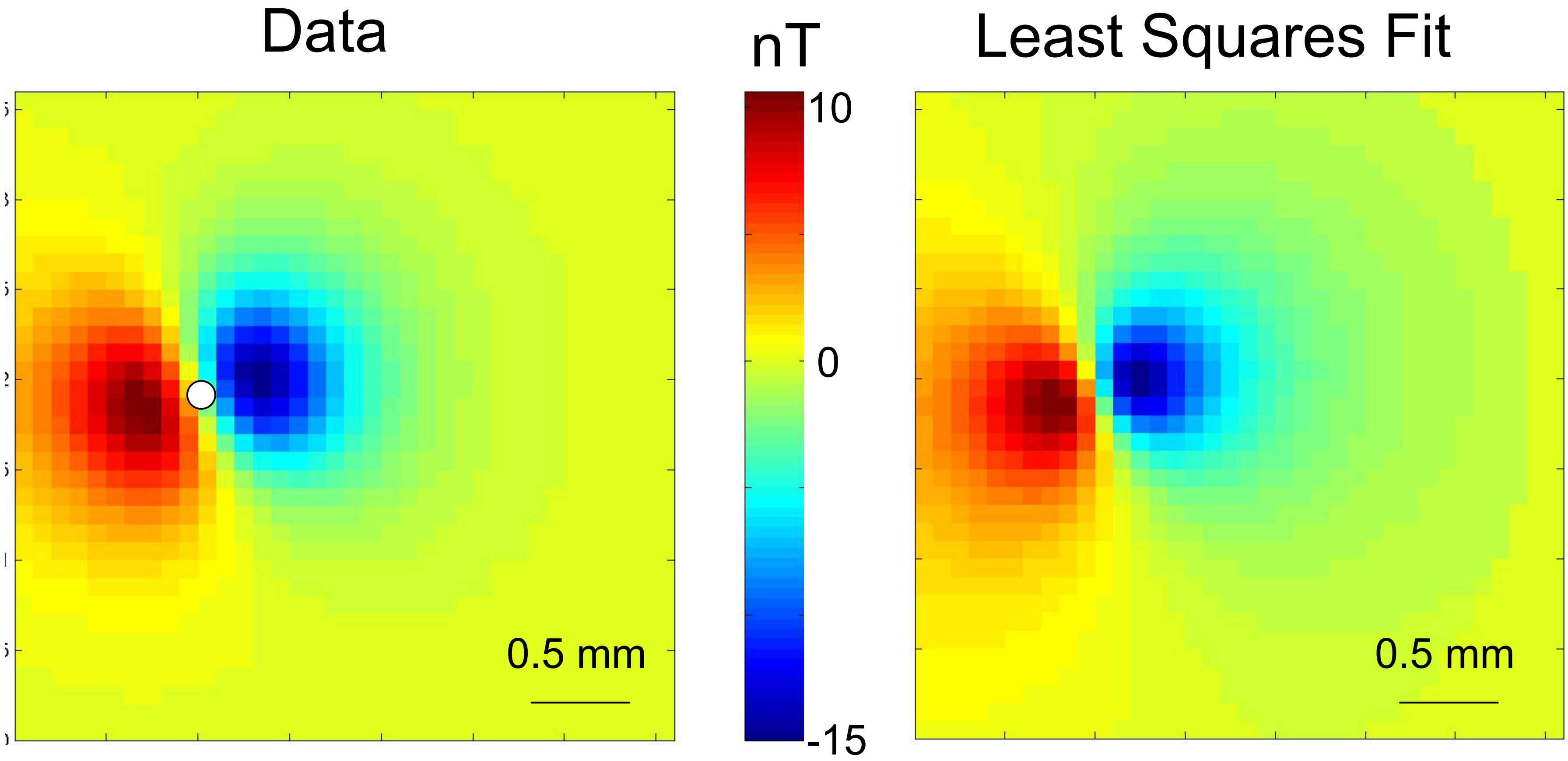
Moment Intensity:

SM: 7.6×10^{-9} Am^2

2G: 8.5×10^{-9} Am^2

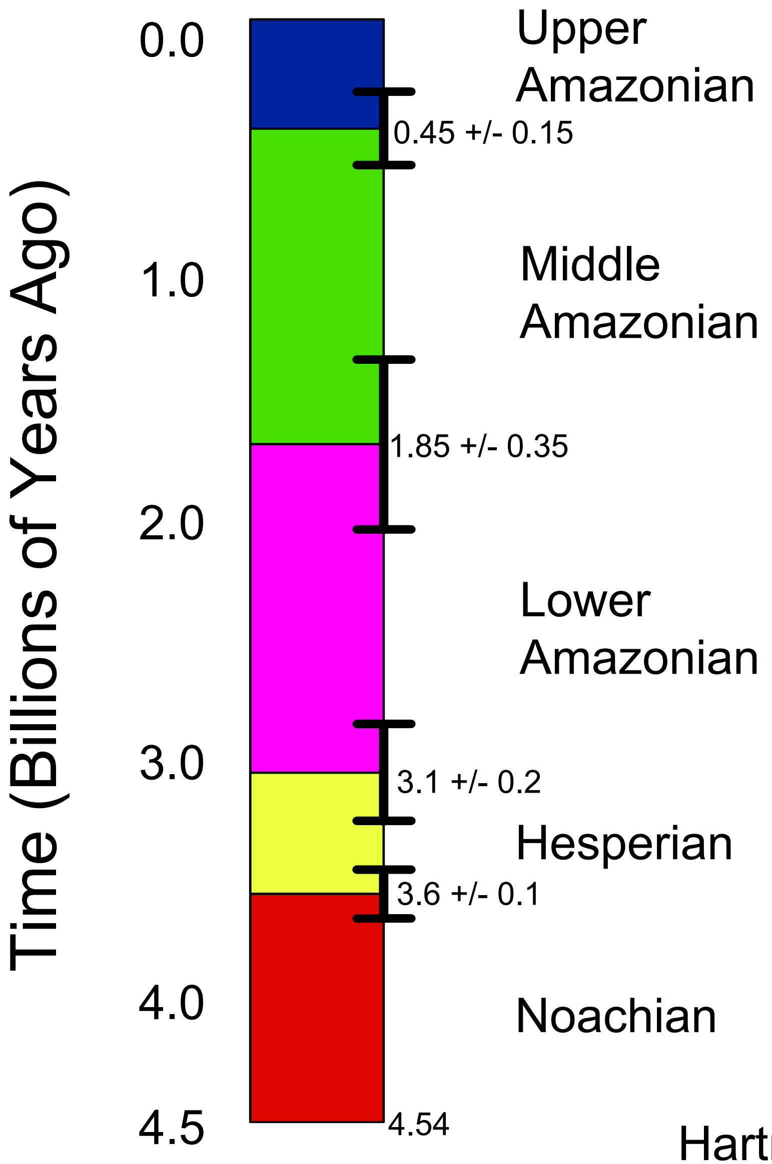
Least Squares Fit To Field For Moment

~200 μm Diameter Lunar Spherule



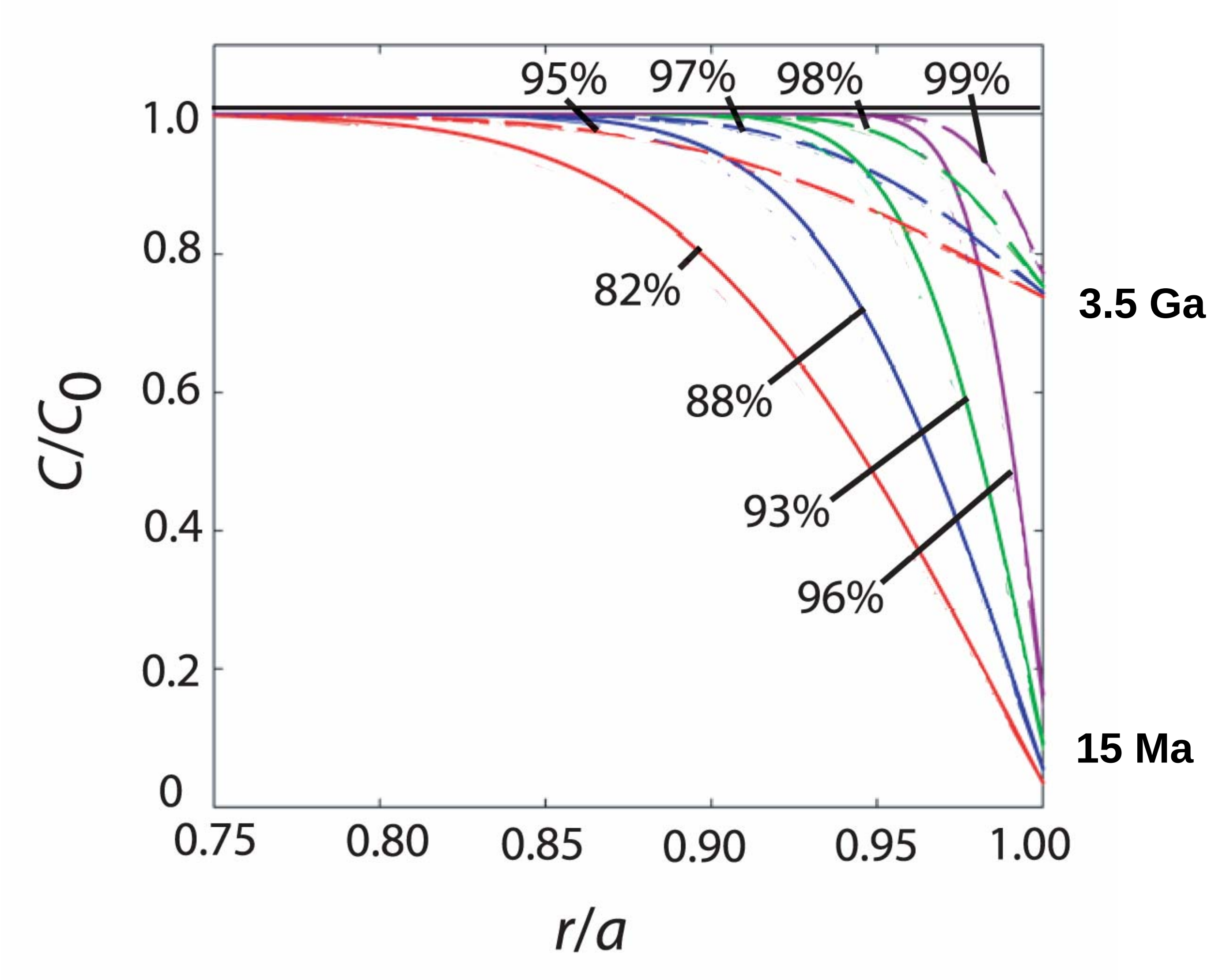
Moment: 3×10^{-12} Am^2

Martian Geologic Time

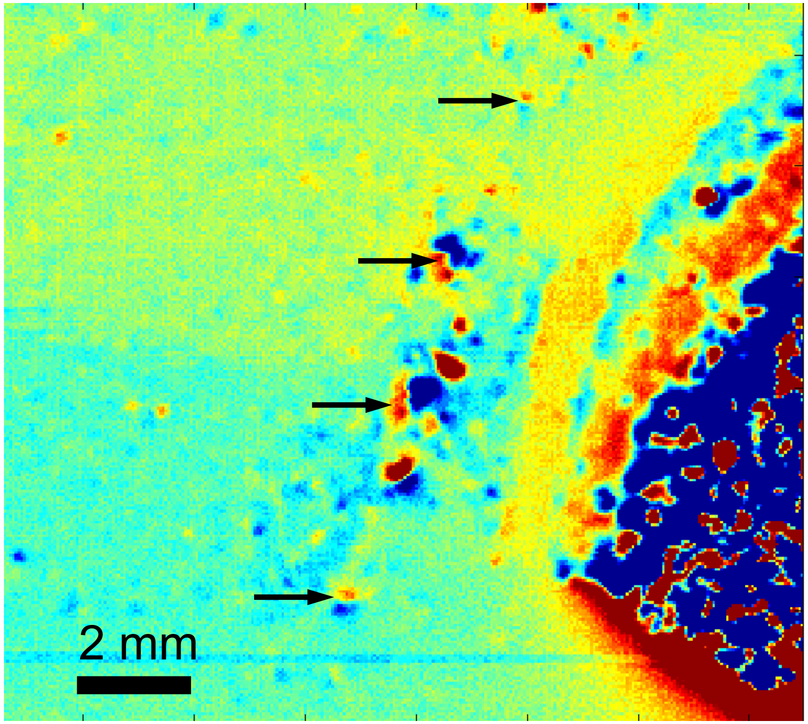


Hartmann & Neukem (2001)

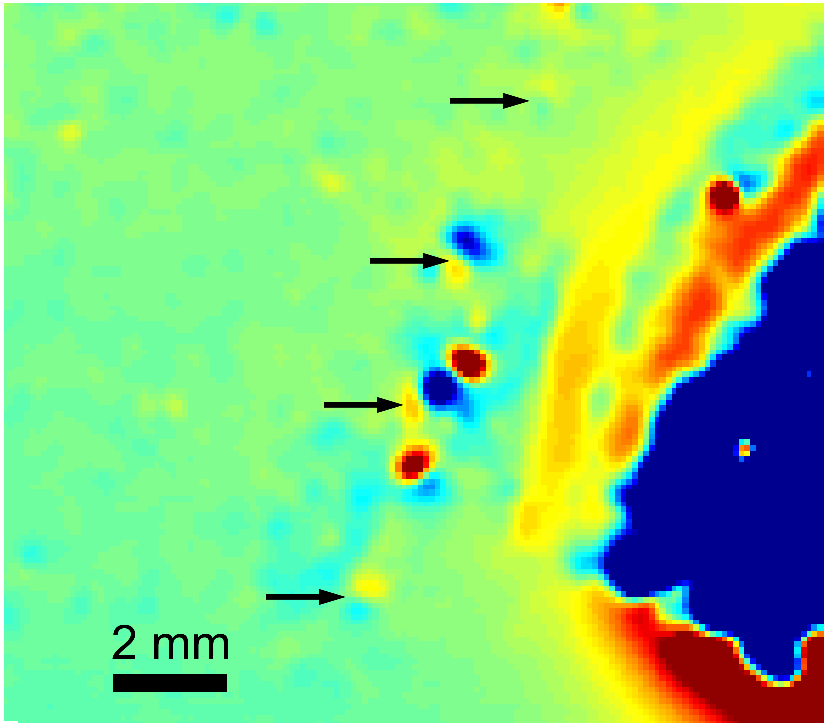
Ar Concentration After Cooling From Various Temperature Pulses



Effect of Sensor on Sensitivity and Resolution:

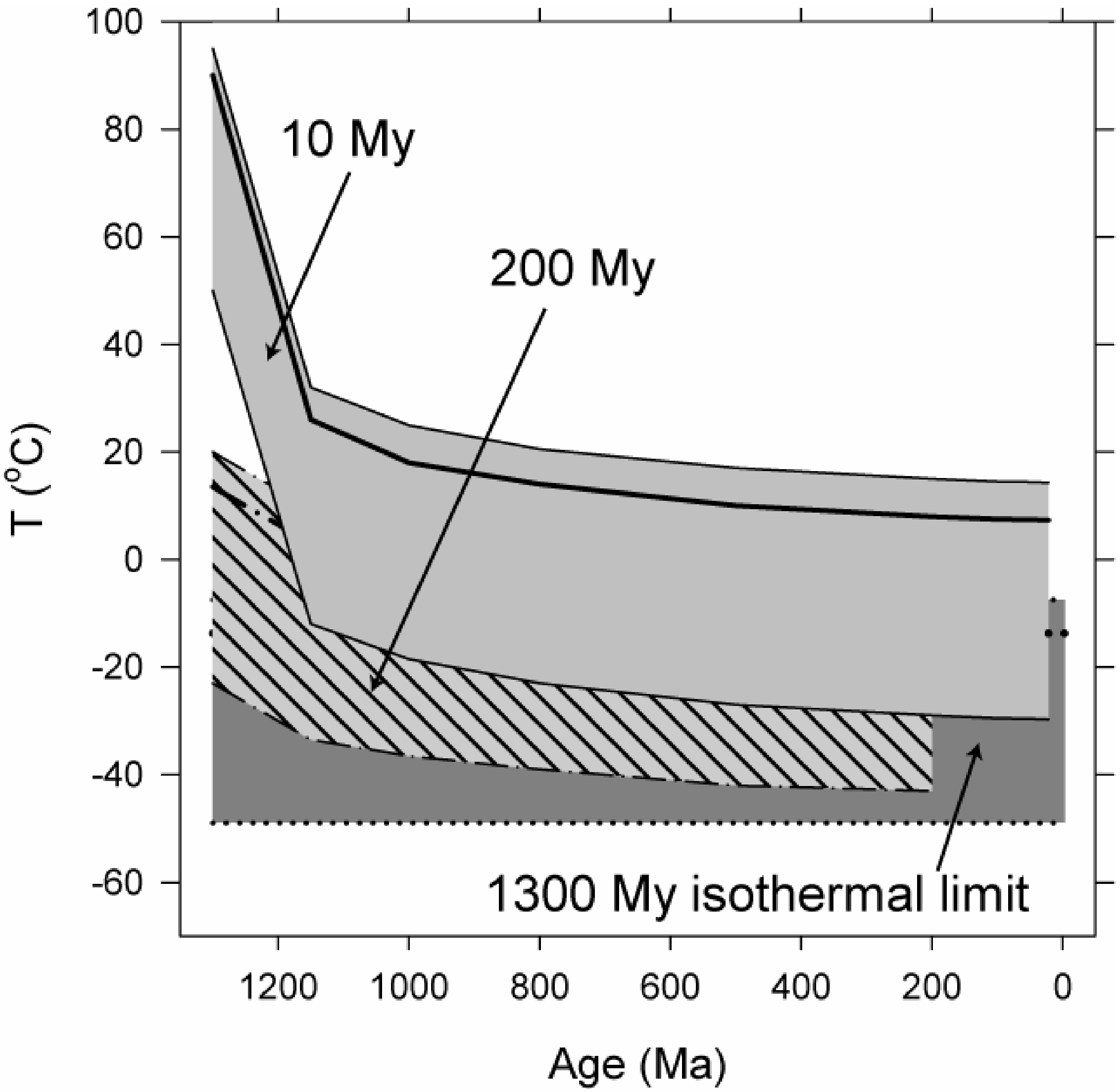


100 μm SQUID Chip

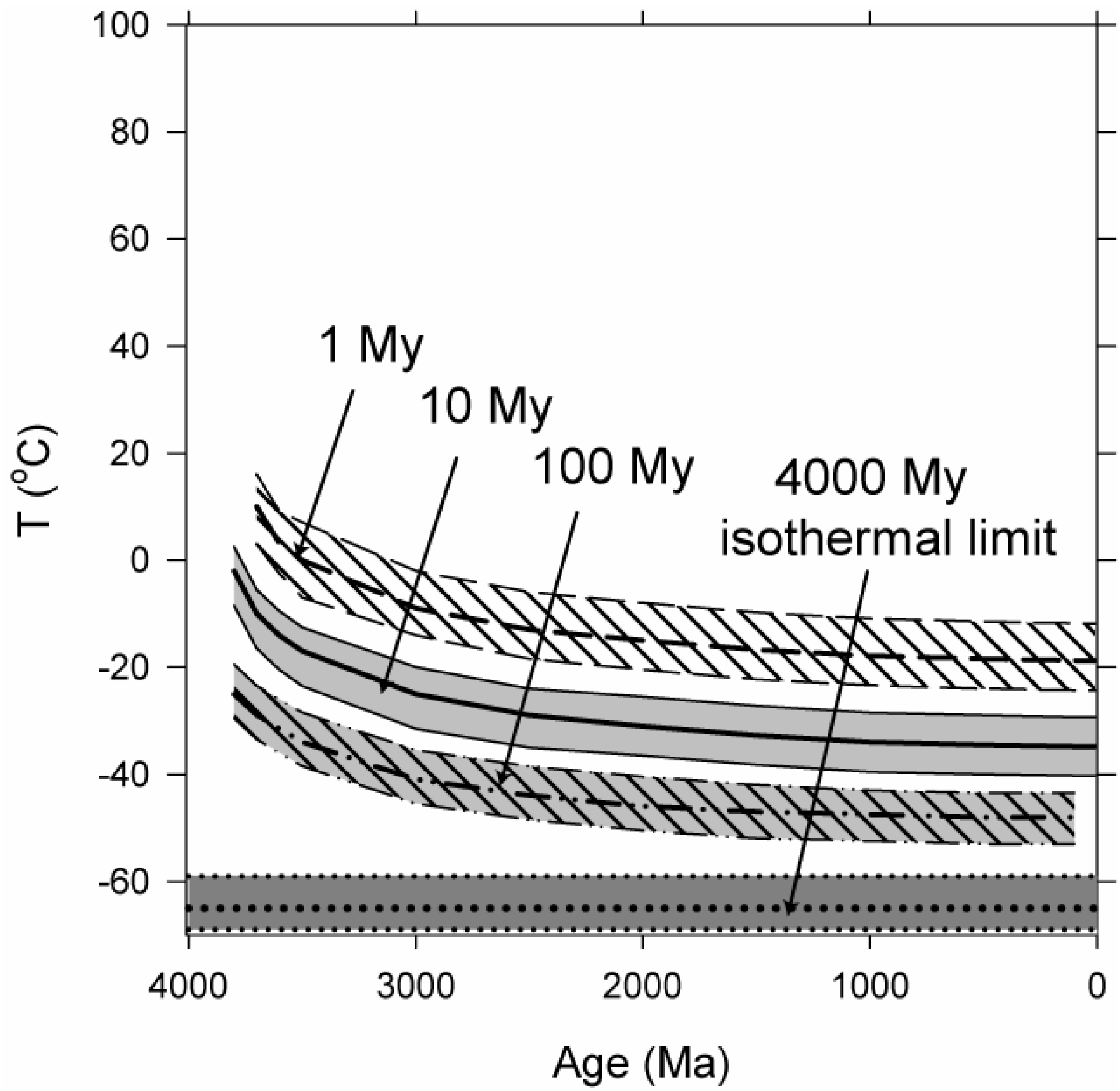


250 μm Pickup Coil

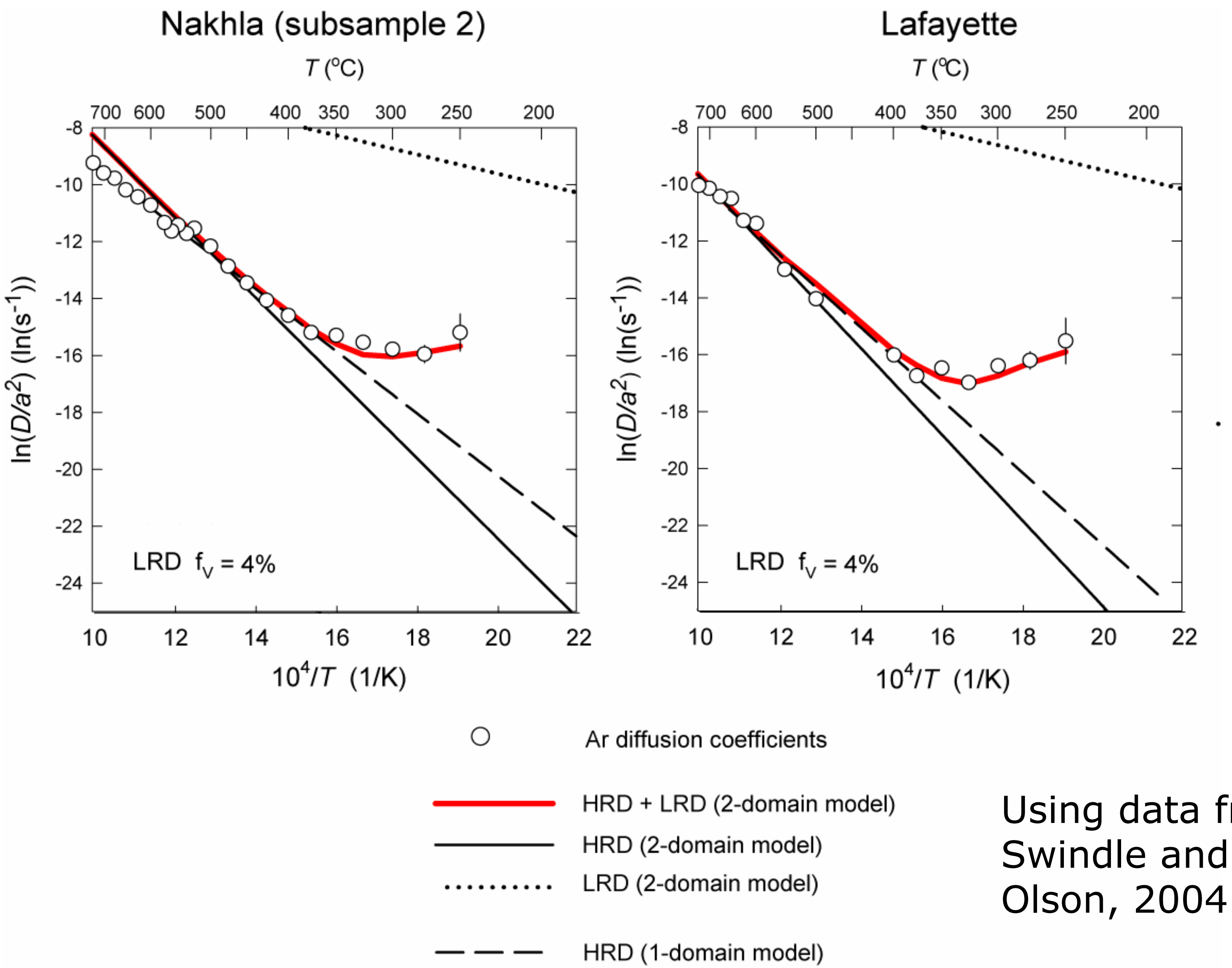
Uncertainty Envelopes on Nakhlite Time-Temperature Constraints



Uncertainty Envelopes on ALH84001 Time-Temperature Constraints

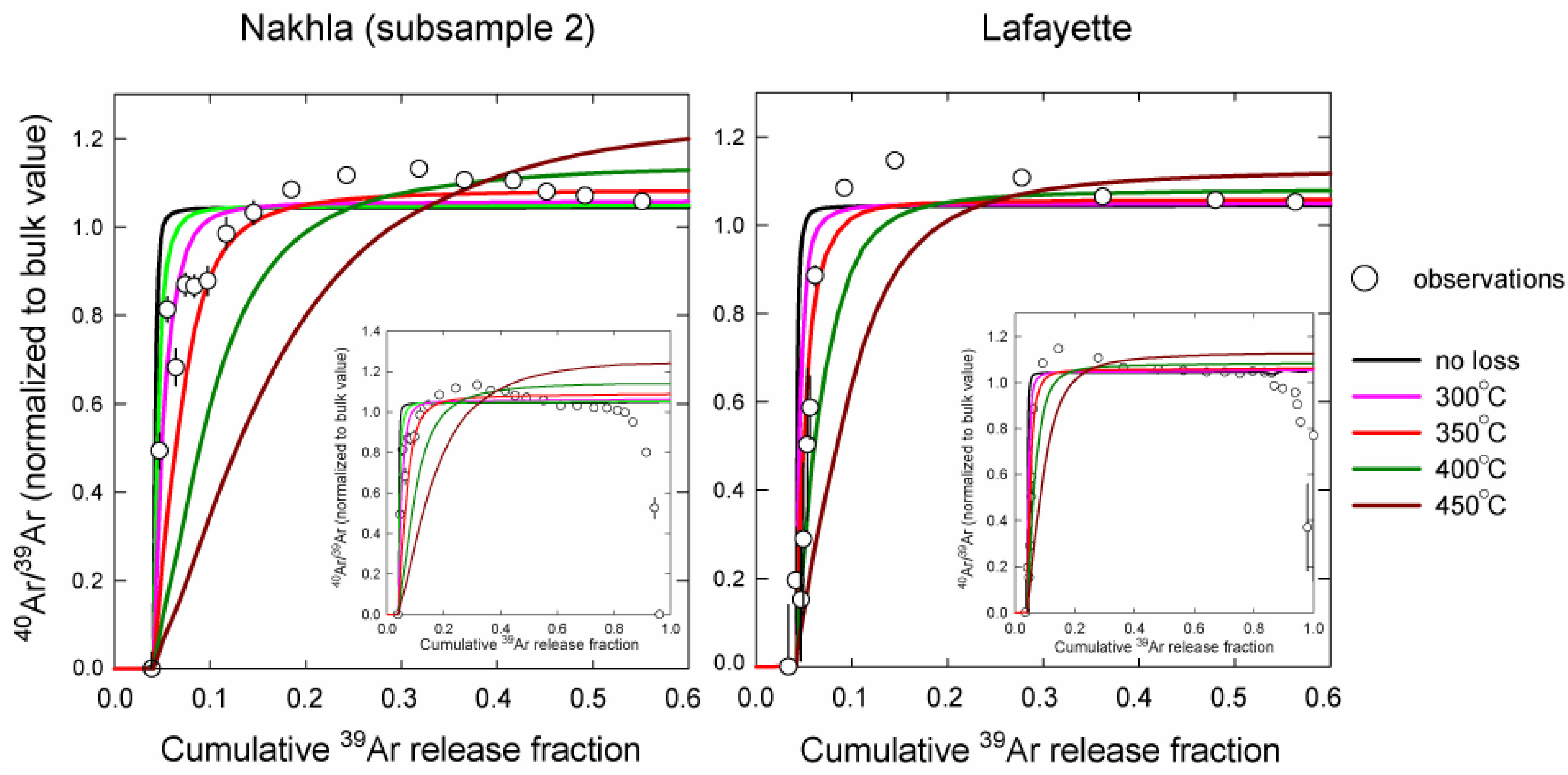


Ar Diffusivity in Other Nakhlite Samples

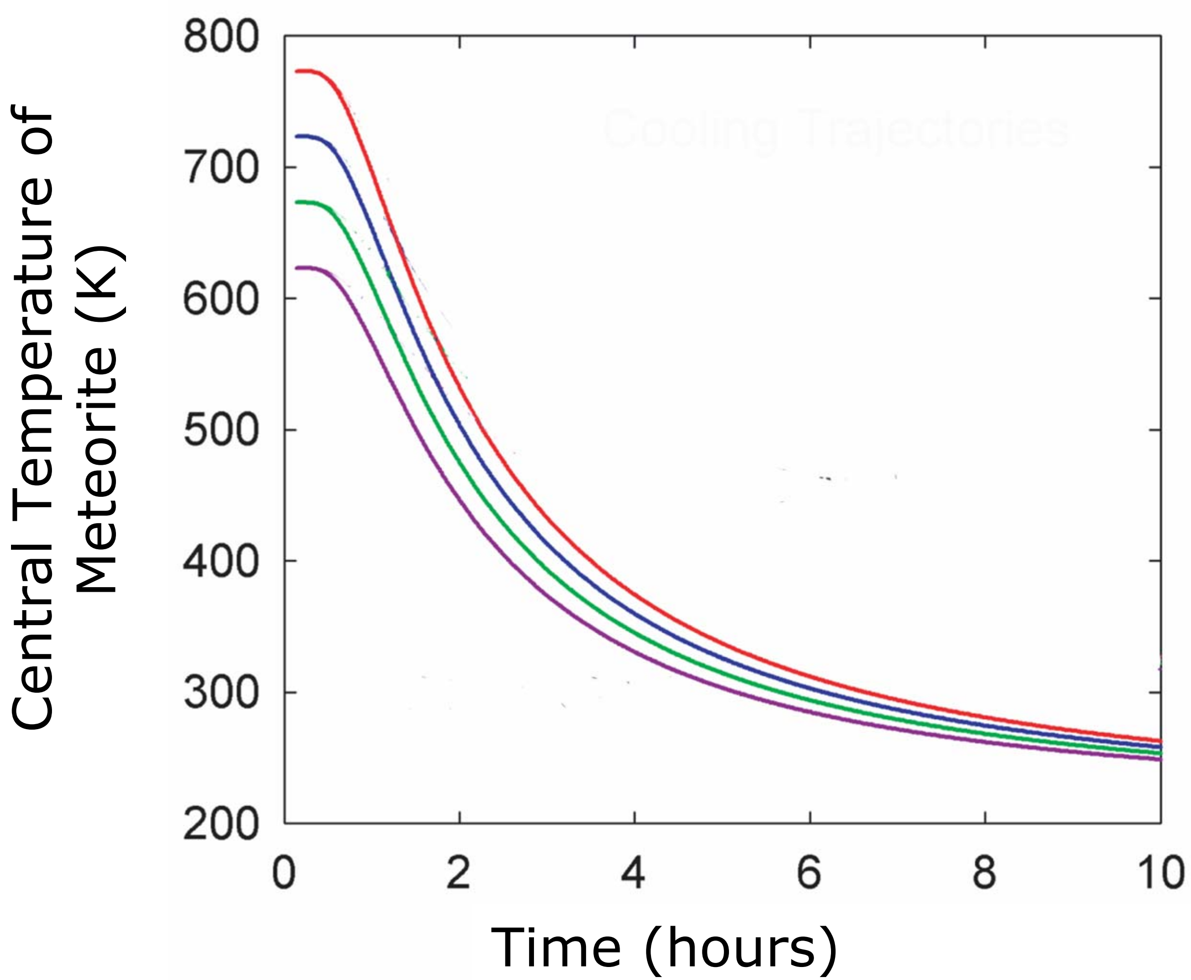


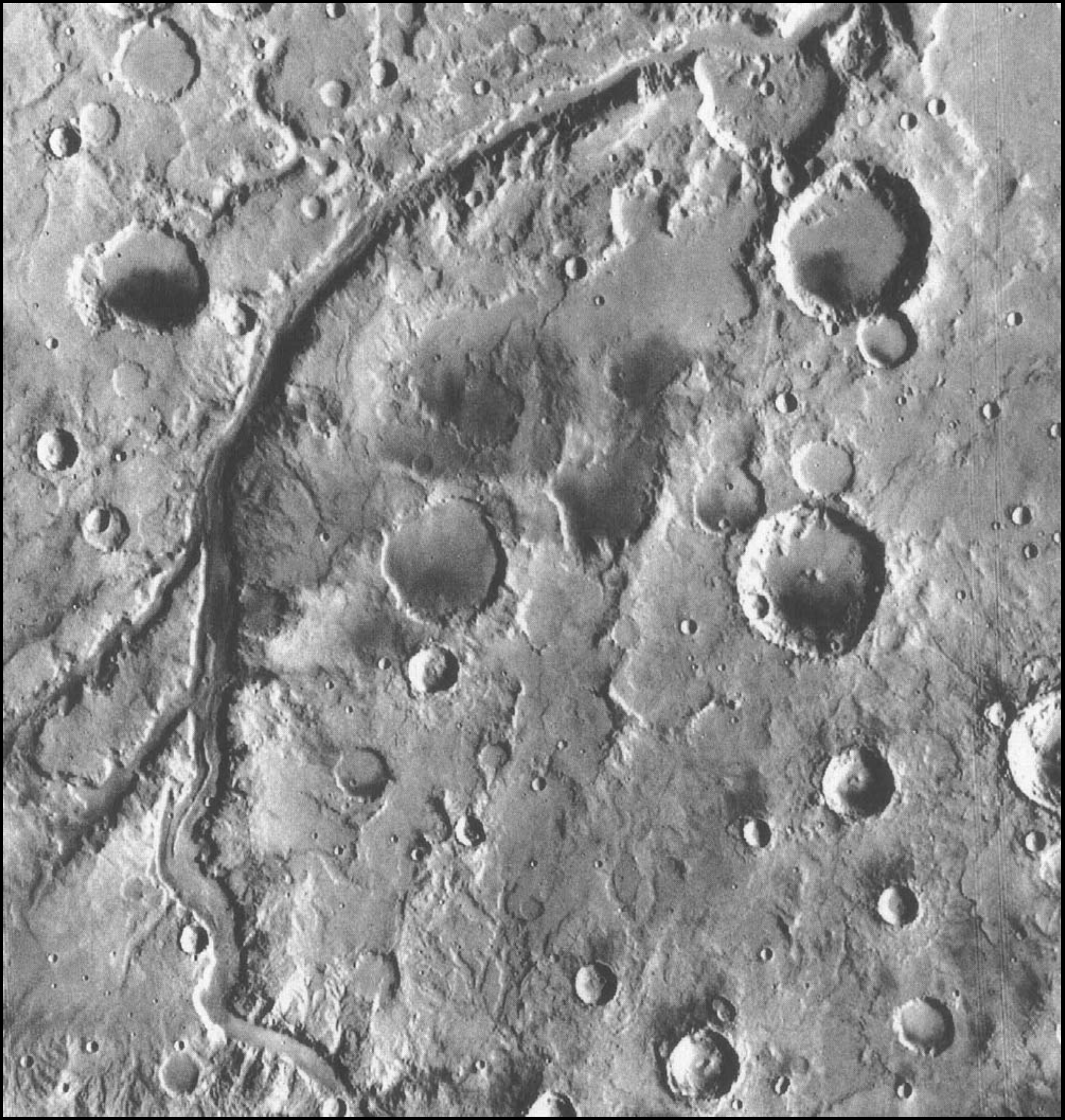
Using data from Swindle and Olson, 2004

Age Spectra for Other Nakhlite Samples



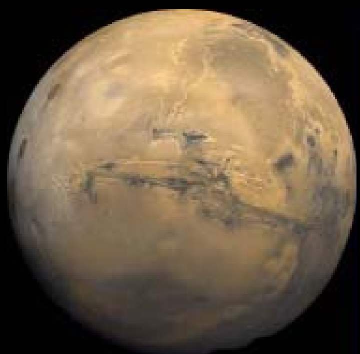
Diffusive Cooling Profiles

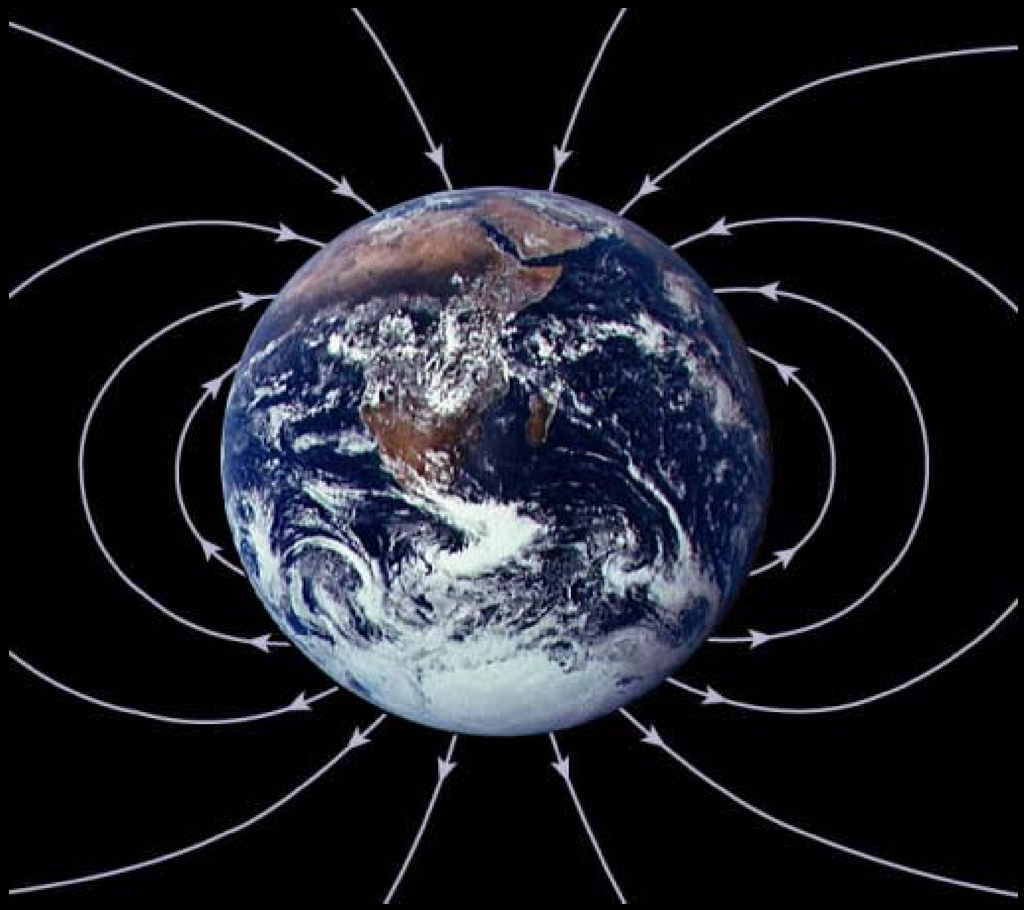




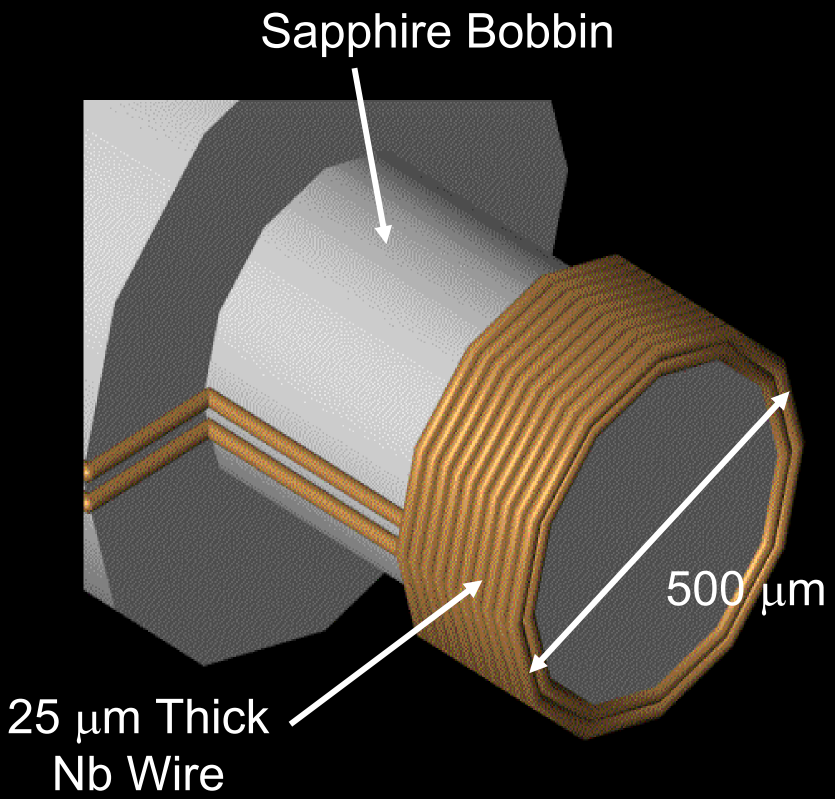
Viking Orbiter
(1976)

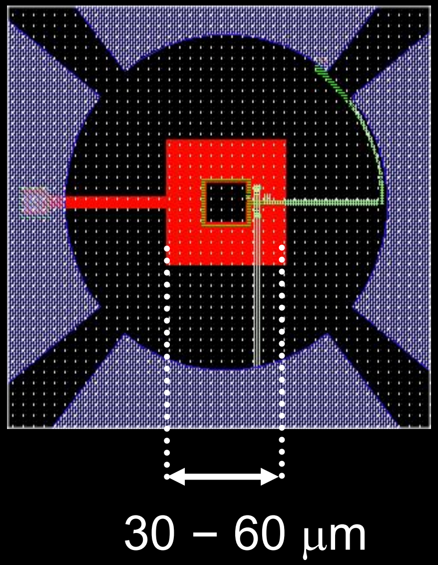
250 km across
24 °S, 182 °W





Sensors





A Few Years Ago…

Today