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Mars' Ancient Dynamo and Crustal Remanent Magnetism

A presentation to the 2021 National Academies Decadal Survey of Planetary Science

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Why is the crustal magnetic field important?

1. The formation and evolution of the crust, including its mineralogy and modification over the past ~4.5 Gyr, by tectonic, impact, fluvial, hydrothermal and magmatic processes (MEPAG Goal III A+B)

2. The evolution of the core dynamo, and its implications for core composition and dynamics, interior evolution including early global heat flow, mantle dynamics and tectonic regime (e.g., whether Mars had an early phase of plate tectonics) (MEPAG Goal III B)

3. The link between atmosphere evolution and the extinction of the martian dynamo and thus important information on habitability (MEPAG Goal II C)

4. Implications for future human exploration (MEPAG Goal IV A)

The crustal magnetic field holds broad implications for Mars' early habitability, interior structure, thermal history, for the fundamental physics of planetary dynamos, and human exploration.

Towards new science opportunities exploring the martian magnetic field

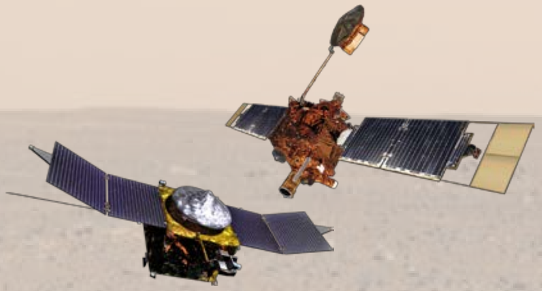
(1) What do(n't) we know?

Nature of martian crustal magnetism?

Magnetization acquisition processes?

Characteristics of the martian Dynamo?

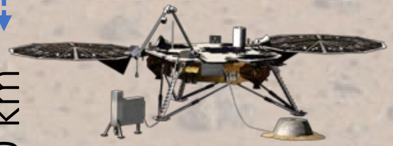
Exploration



> 100 km

No coverage

0 km

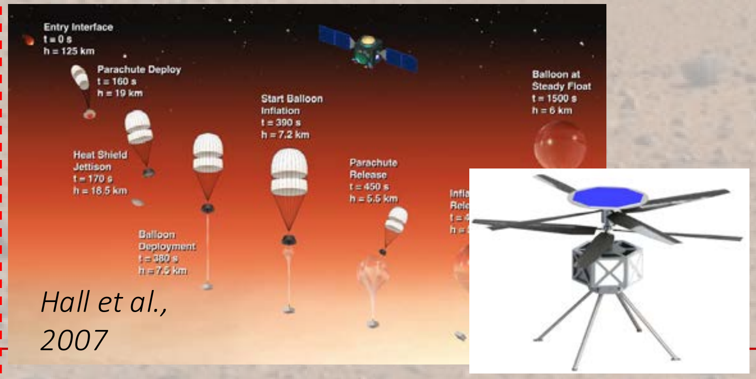


\+ Meteorites

(2) Available Data / Current Limitations

(3) Recommendation:

Planning and implementation of magnetometers on **aerial platforms** such as **airplanes, drones and/or long-lived balloons** to obtain low-altitude magnetic measurements over kilometers to hundreds of kilometers.

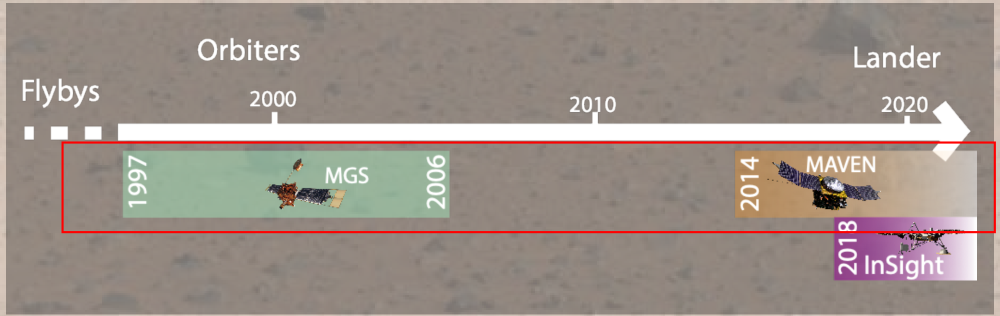


Hall et al., 2007

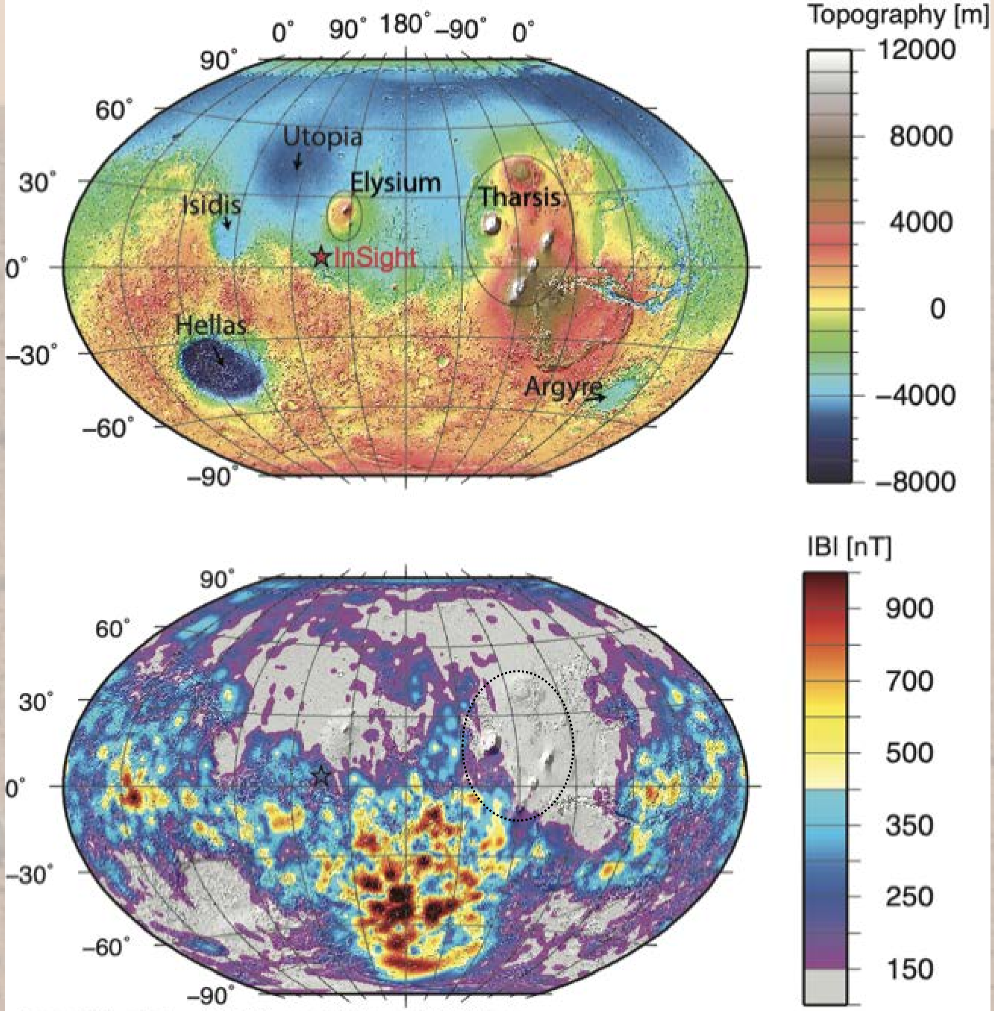
The global crustal magnetic field

- No current global field (Acuna et al., 1999; 2001)
- Strong crustal fields
- Inhomogeneous distribution

What can we learn from this?



Models:
Cain et al., 2003; Langlais et al., 2004; 2019; Morschhauser et al., 2014; Mttelholz et al., 2018

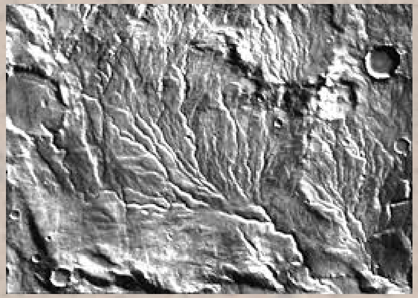


Langlais et al., (2019) prediction at 130 km

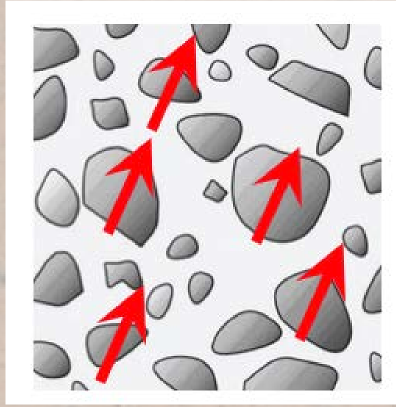
Some MAG background

Rocks acquire remanent magnetization when exposed to a magnetic field via these mechanisms:

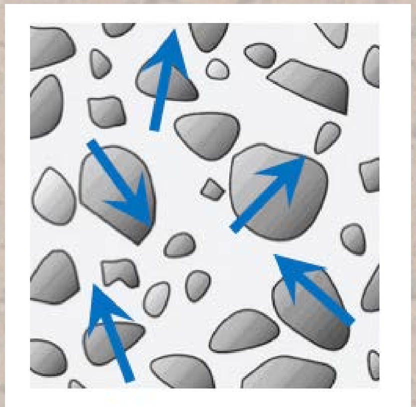
1) Thermal (TRM) → cooling below Tc
2) Shock (SRM) → impact
3) Chemical (CRM) → magnetic alteration products



Magnetic



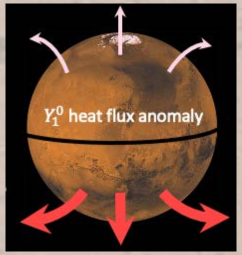
OR: Not Magnetic

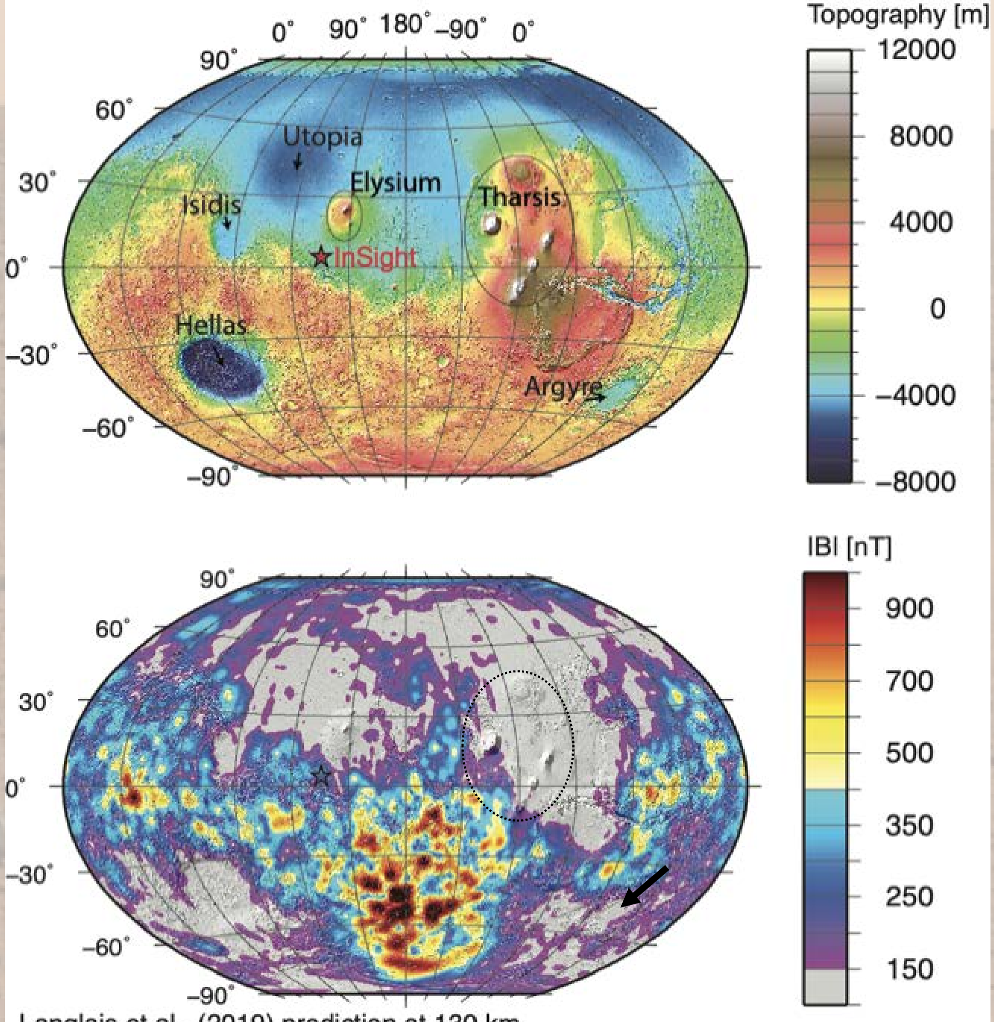


The global crustal magnetic field

- Inhomogeneous distribution

Observation	What can we learn from this?
Southern hemisphere	One-hemisphere dynamo? (Stanley et al., 2008) Difference in mineralogy? (Quesnel et al., 2009) Crustal thickness? (Neumann et al., 2004)



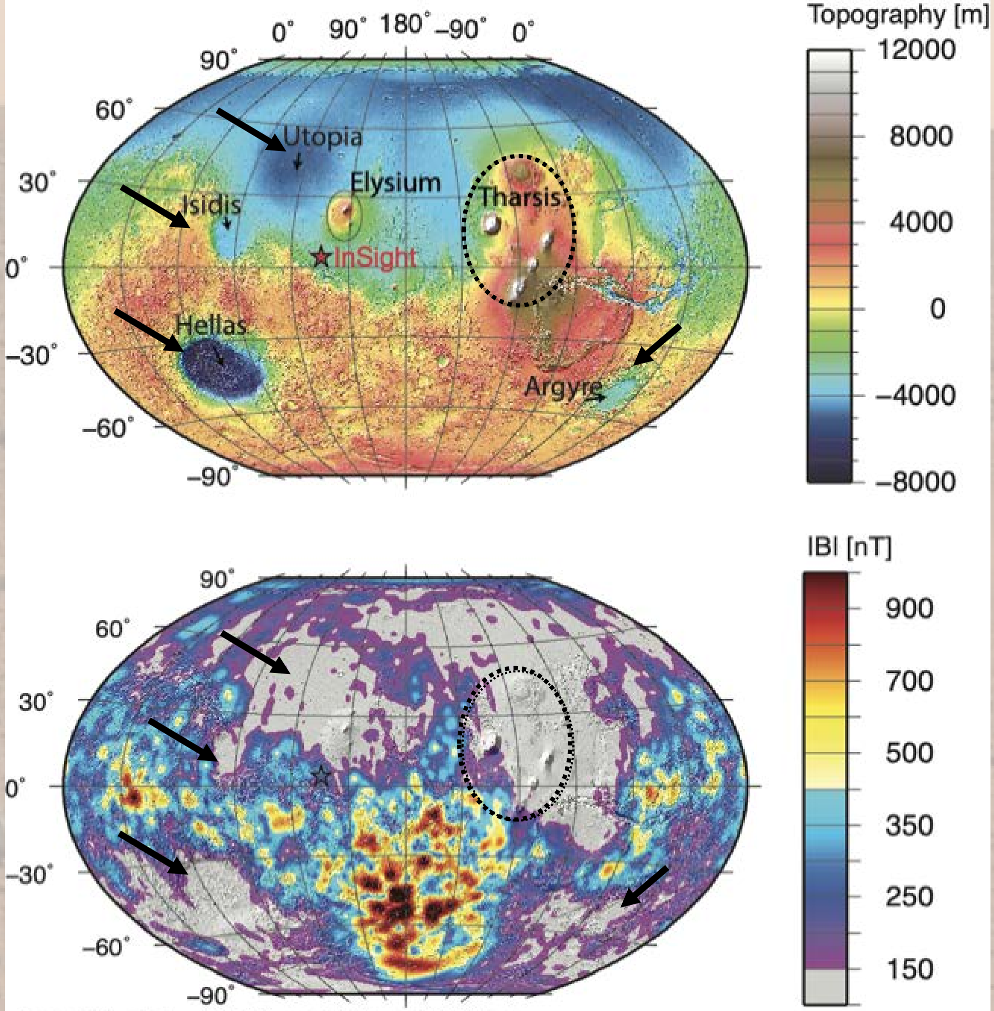


Langlais et al., (2019) prediction at 130 km

The global crustal magnetic field

- Inhomogeneous distribution

Geologic Features	**What can we learn from this?**
Southern hemisphere	One-hemisphere dynamo? (Stanley et al., 2008) Difference in mineralogy? (Quesnel et al., 2009) Crustal thickness? (Neumann et al., 2004)
- Tharsis - HUIA - + other craters and volcanoes	Correlations of magnetic field with geological features that can be associated with a heat and/or shock (de)magnetization process → Timing! (Mittelholz et al., 2020; Vervelidou et al., 2017; Hood et al., 2013; Lillis et al., 2013)



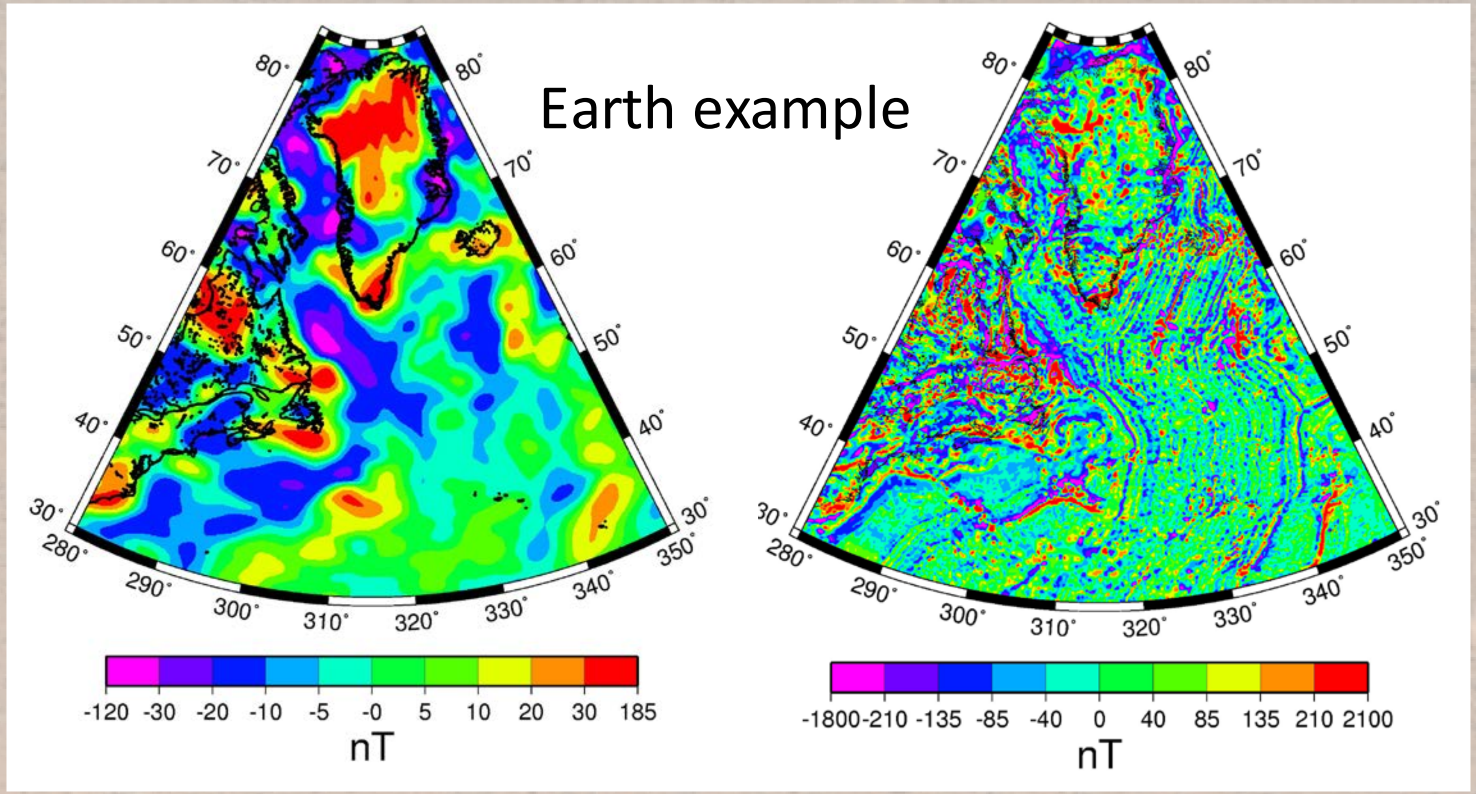
Langlais et al., (2019) prediction at 130 km

The global crustal magnetic field

Resolution matters

150 km altitude

~ 3km altitude



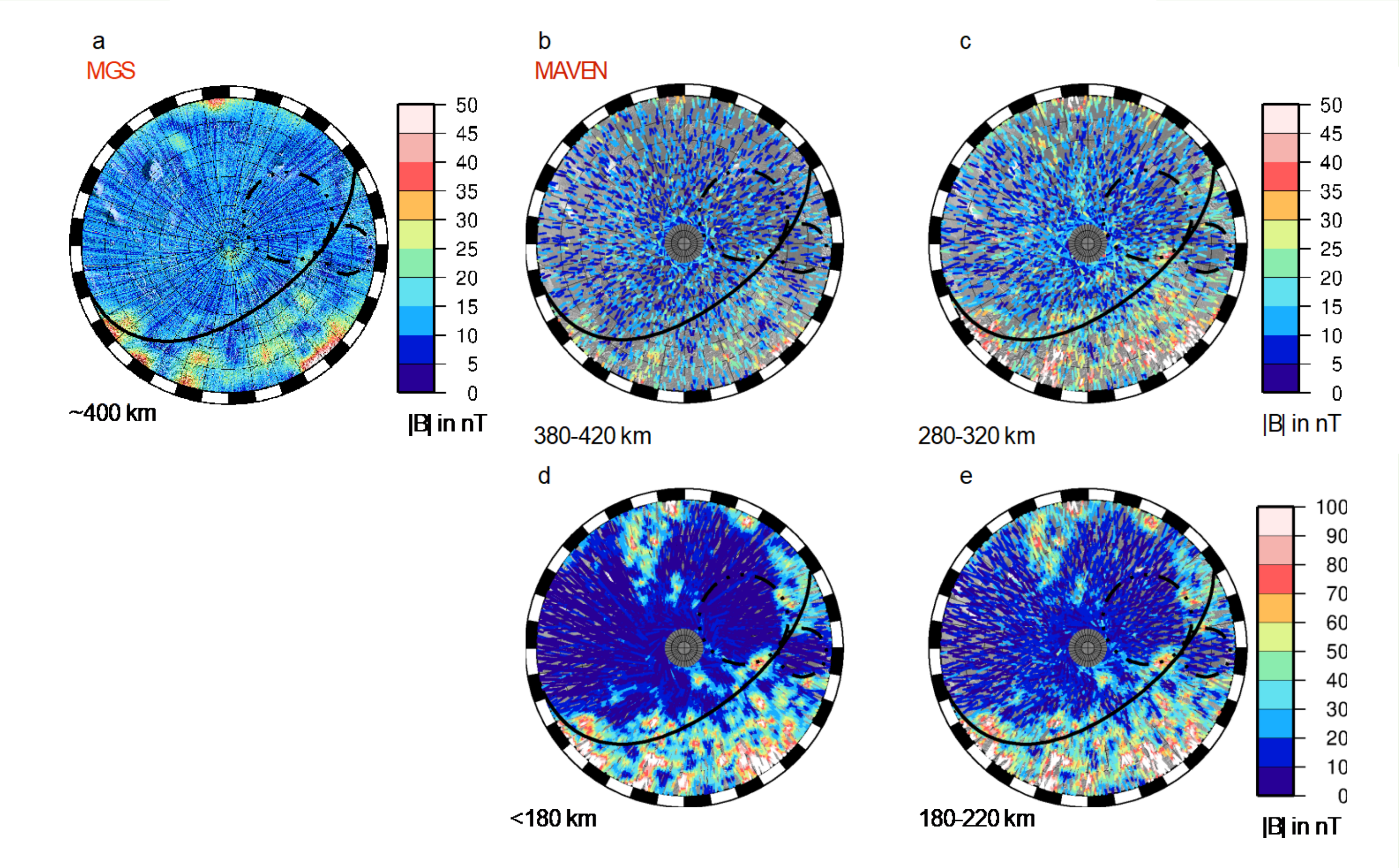
Spatial resolution of these models is approx. the altitudes of orbital observations.

→robust modeling of crustal magnetic fields globally is currently limited to spatial scales of ~135 km.

→Value of low altitude measurements: near-surface magnetic surveys detected the prominent north-south magnetic "stripes" along mid oceanic ridges.

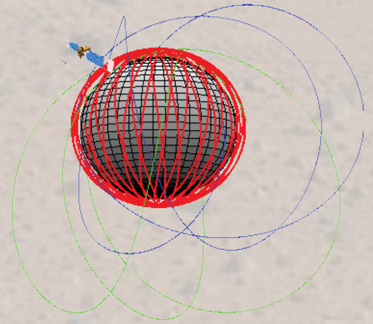
The global crustal magnetic field

Resolution matters



MGS (1997-2006): mainly in a circular orbit at 400 km (Mapping Orbit = MO) in 2am/pm orbit

MAVEN (since 2014): elliptic orbit covering variety of altitudes (periapsis: 135 km) and local times



The global crustal magnetic field

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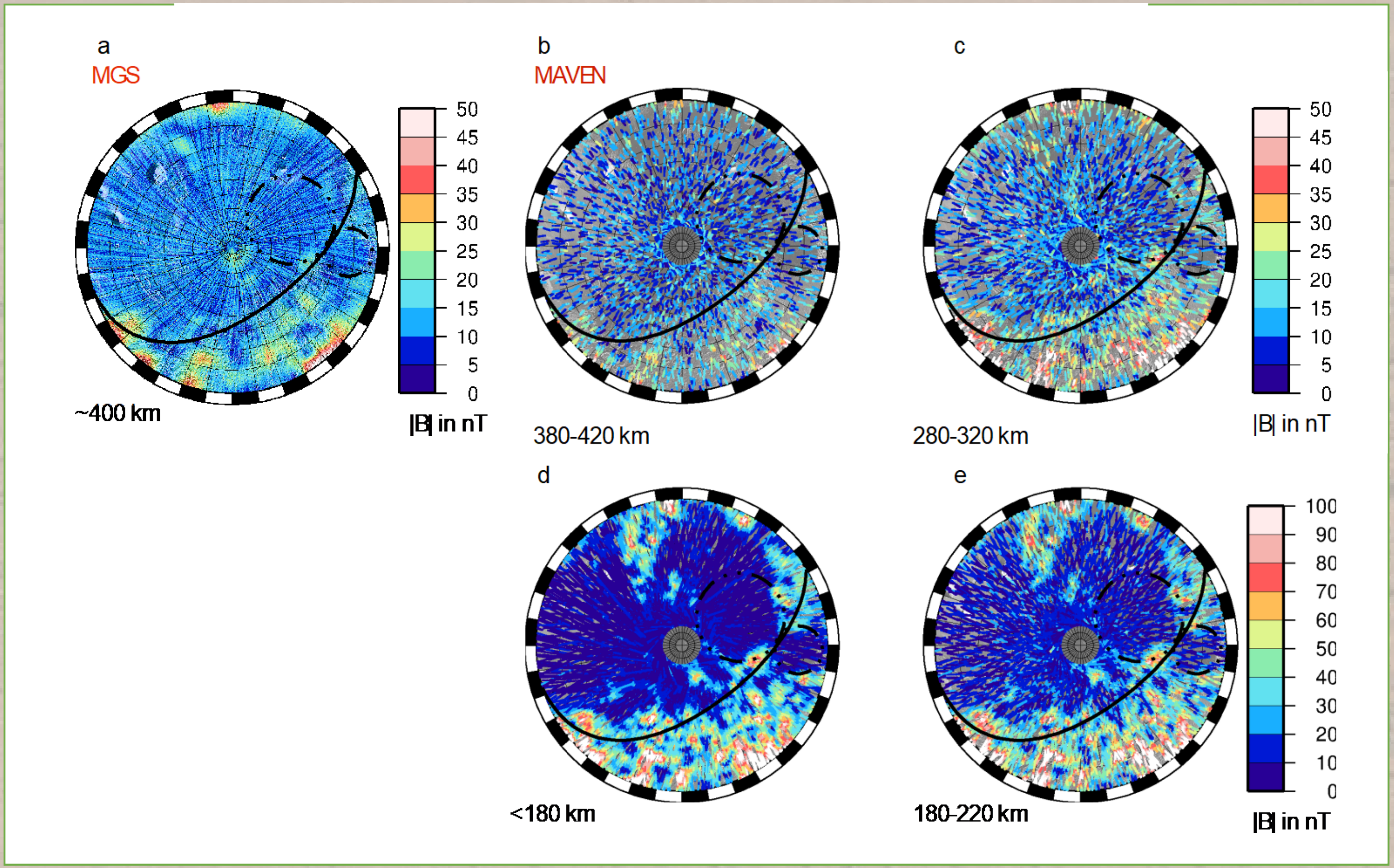
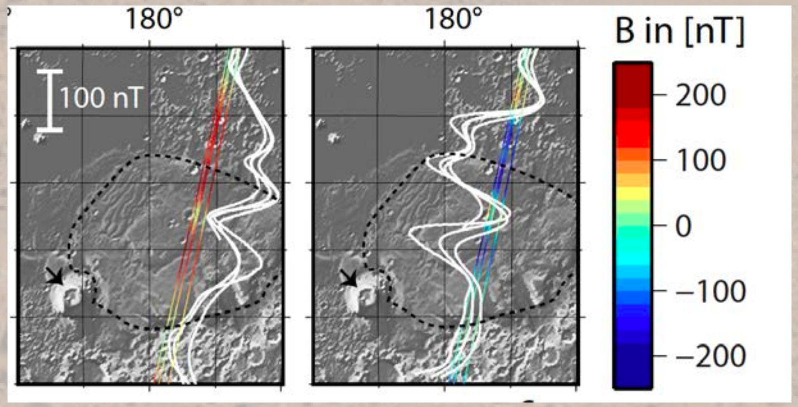


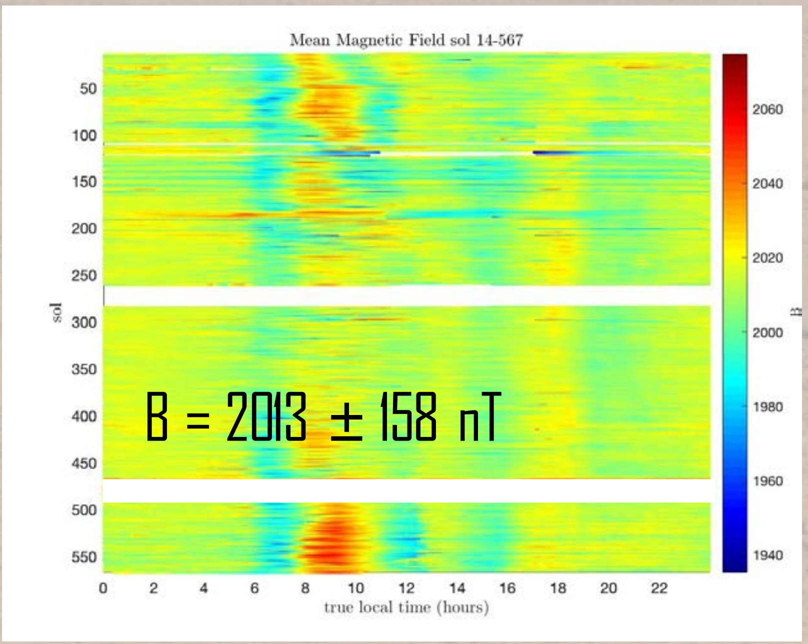
Correlations of the magnetic field with geology (age!), mineralogy, gravimetry, … allow asking questions about dynamo timing, carrier distribution, source depth, …



Recent suggestion of a dynamo at 4.5 and 3.7 Ga

Mittelholz et al., 2020

The magnetic field from the surface

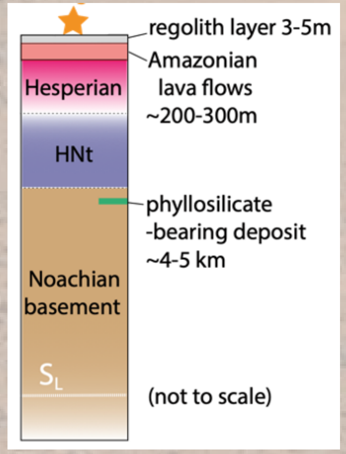


Crustal field 10x stronger than predicted from orbital data

Magnetization (*M*) age and strength?

- Free parameters are burial depth and thickness of magnetized layer. Constraints: geology & crustal thickness

1. Deep-burial, hosted by Noachian units
   - *M* > ~1.8 Am^{-1}
   - compatible with dynamo cessation by ~4.1 Ga (e.g. Lillis et al., 2008) or longer-lived, depending on basement age
2. Shallow burial, partly hosted in younger HNt units
   - *M* < 1 Am^{-1} unless magnetized layer entirely within HNt unit
   - longer-lived or restarted dynamo (*Mittelholz et al.*, 2020; Hemingway and Driscoll, 2020).

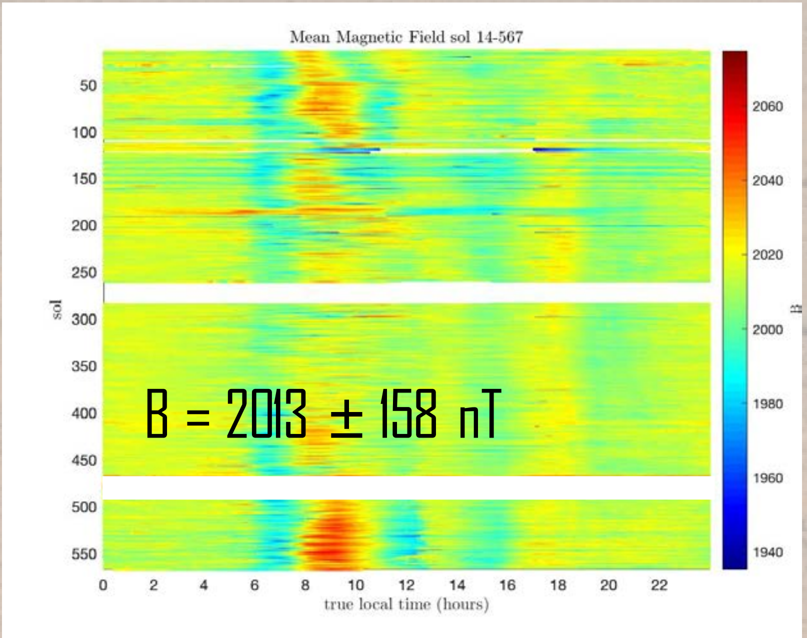


(Johnson et al., 2020; Mittelholz et al., 2020b)

The magnetic field from the surface

single data point

Crustal field 10x stronger than predicted from orbital data



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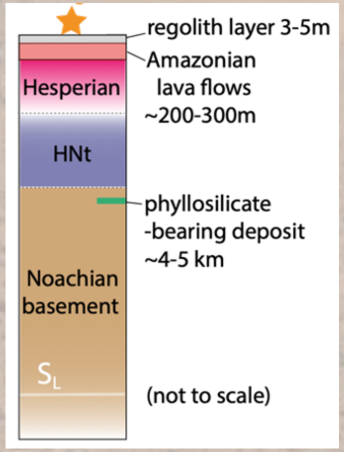
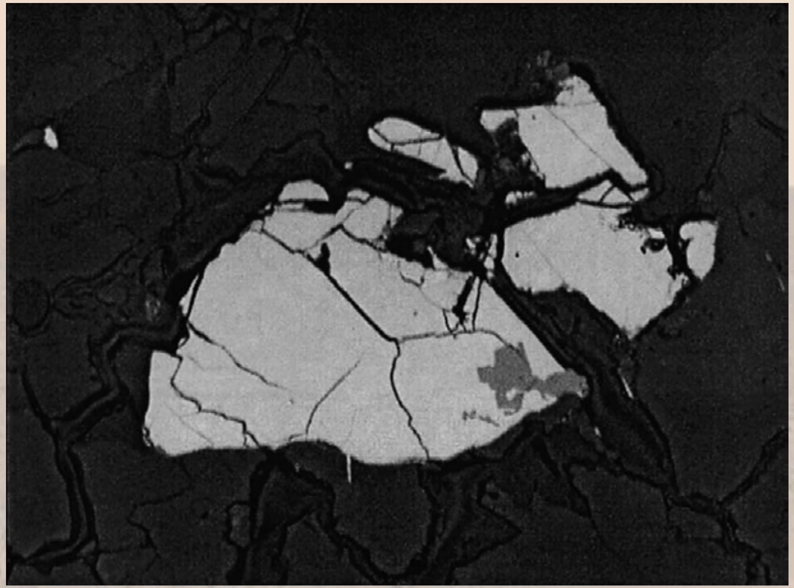


(Johnson et al., 2020; Mittelholz et al., 2020)

Meteorites

Advantage:
Radiometric dating

- Timing of the dynamo: ALH 84001 suggest Earth-like paleointensities at ~4 Ga, consistent with the hypothesis of an early dynamo (Weiss et al., 2002; 2008; Gattacceca et al., 2014)
- A variety of potential magnetic carriers suggested including magnetite, hematite, titanohematite, titanomagnetite and pyrrhotite (Dunlop et al., 2005; Rochette et al., 2005)



From Rochette et al., 2001

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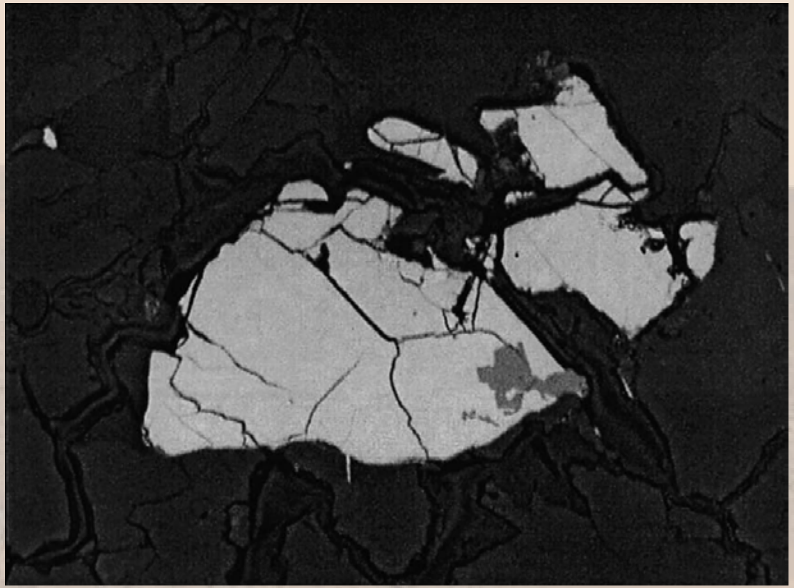
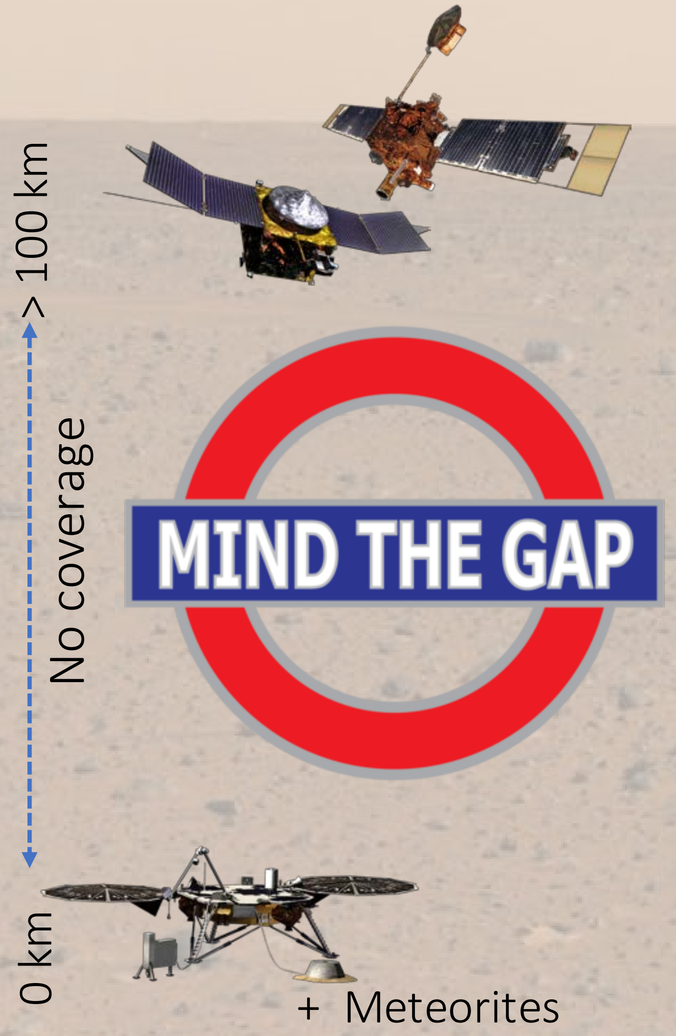


From Rochette et al., 2001

Limitations:

- limited constraints on the provenance of the samples (i.e., where on Mars they came from)
- complex histories, including exposure to shock and multiple reheating events.
- This lack of context also contributes to uncertainty as to whether the magnetization was acquired in a crustal magnetic field or dynamo magnetic field.

How can we make progress?



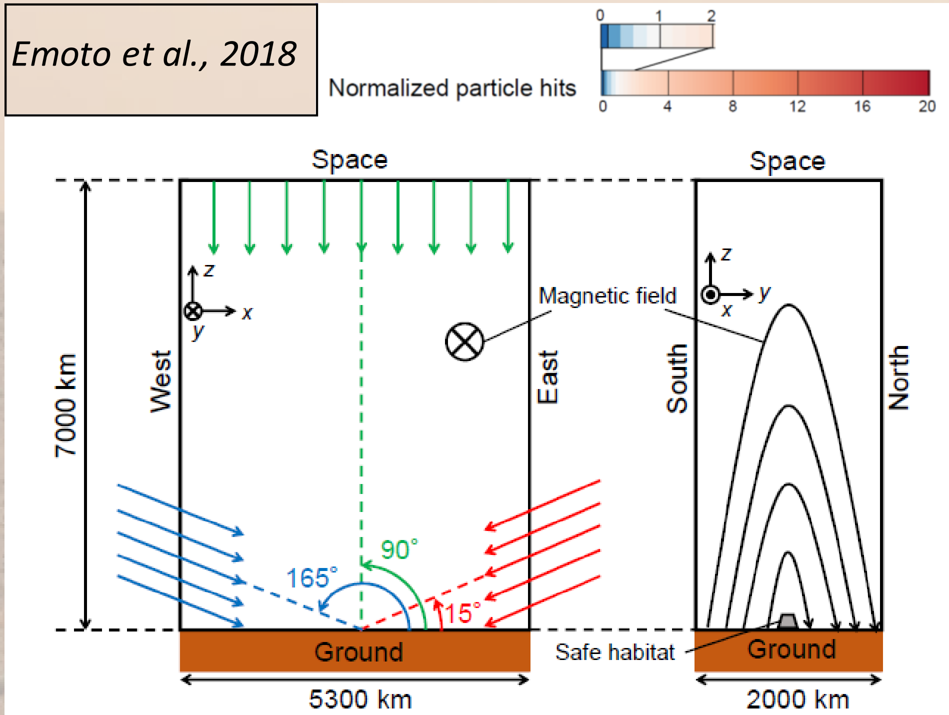
- (1) We recommend that a magnetometer be mounted on a (preferentially) **mobile surface and/or low altitude aerial platform** → spatially continuous measurements of crustal magnetic fields. → Preference: helicopter, aircraft or balloon will allow high resolution spatial coverage over spatial scales of tens to hundreds of kilometers, offering access to areas that might be hazardous or inaccessible from the surface.

- (2) Use opportunities!

  Typical phase A-D costs are only a few million $ (and even less for class D).

  Magnetic cleanliness is important but often relatively easy (e.g. a boom)

Future Exploration



(1) Resource Exploration:

Magnetic fields as proxy for subsurface variations →
Association with Iron bearing minerals

Identification and Characterization of building materials

(2) Ions are a radiation hazard:

- Come from the sun and deep space.
- Deflected by magnetic fields
- >~100 MeV reach the surface.
- >~10 MeV can penetrate spacesuits.

- Depend strongly on crustal field geometry and angular/energy distribution of particles.
- Need to be modeled at high resolution with better crustal magnetic field maps.

→ Realistic high resolution modeling needed.

MEPAG Goals and magnetic fields

(1) Dynamo (2) Magnetic Carrier (3) Acquisition (4) Exploration Effort

GOAL III: UNDERSTAND THE ORIGIN AND EVOLUTION OF MARS AS A GEOLOGICAL SYSTEM

Objective A: Document the **geologic record preserved in the crust** and investigate the processes that have **created and modified** that record.

→ NRM records the time at which a dynamo was present (2)

→ NRM is dependent on surface conditions (3)

Objective B: Determine the structure, composition, and dynamics of the **interior** and how it has evolved.

→ Dynamo cessation (1)

High Resolution!

GOAL II: UNDERSTAND THE PROCESSES AND HISTORY OF CLIMATE ON MARS

Objective C: Characterize Mars' ancient **climate** and underlying processes.

→ NRM is dependent on surface conditions / climate (1, 3)

GOAL IV: PREPARE FOR HUMAN EXPLORATION

Objective A: Obtain knowledge of Mars sufficient to design and implement **human landing** at the designated human landing site with acceptable cost, risk and performance.

→ Geophysical exploration – iron bearing minerals (4)

→ Small scale crustal fields as radiation shields? (4)

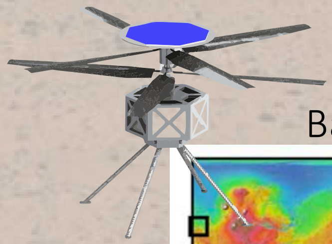
High Resolution!

Broad Interest in Mars' Magnetic Field

- Support from 11 co-authors and 33 signatories from 28 institutions
- Involvement in 2 further Decadal whitepapers

THANK YOU!

Rapin et al.: "*Critical knowledge gaps in the Martian geological record: A rationale for regional-scale in situ exploration by rotorcraft mid-air deployment*")



Bapst et al.: "*Mars Science Helicopter*"

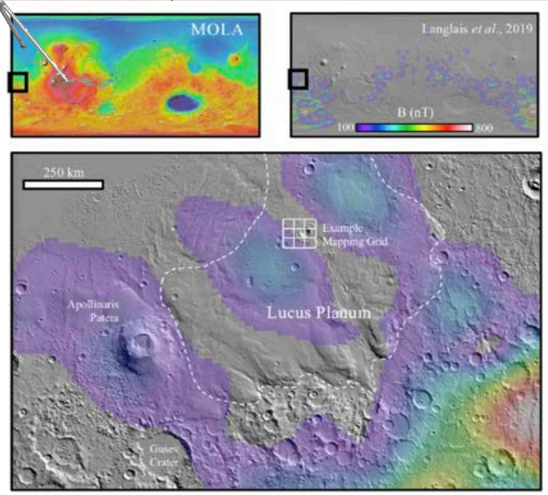
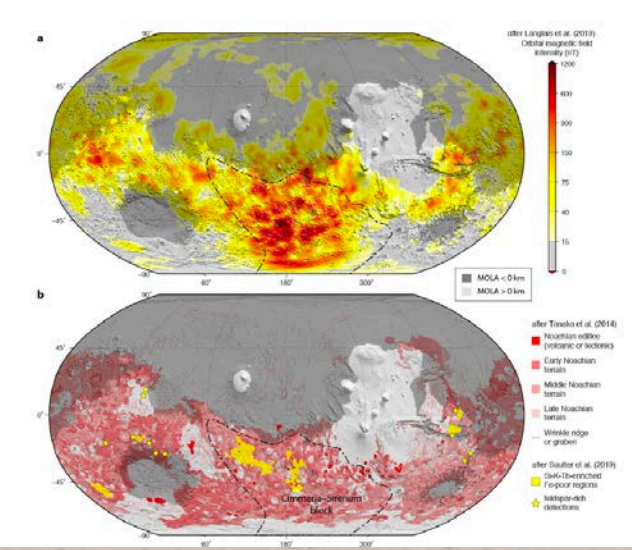
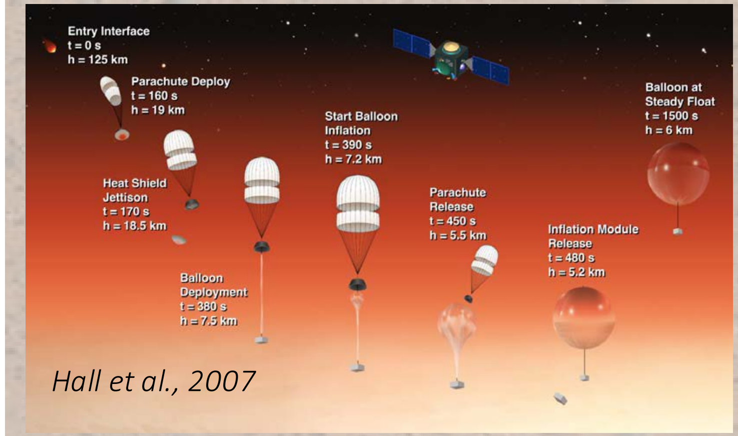


Figure 6. (top-left) MOLA elevation and (top-right) global crustal magnetic field magnitude at 130 km altitude[28]. Note the coarse scale of the crustal field. (bottom) Zoomed in map showing Lucus Planum where finer-scale fields along the dichotomy boundary would provide updated age constraints on the dynamo[29]. Additionally, the Medusa Fossae Formation, an extremely large deposit of putative pyroclastic material and enigmatic in origin, is extensive throughout this region, which is additional incentive to choose this site as a science destination.





Hall et al., 2007

Backup

Mars Crustal Magnetism: Puzzles

1) Dynamo

1) Timing, mechanism, strength, polarity change, ...

2) TRM dominant? CRM a viable alternative? Surface conditions / type of environment during dynamo?

3) magnetic properties of the carriers? Distribution? What is the global pattern of Mars' crustal magnetic fields (~km)? How does it correlate with characteristics such as topography, gravity, morphology and stratigraphy?

2) Acquisition Mechanism

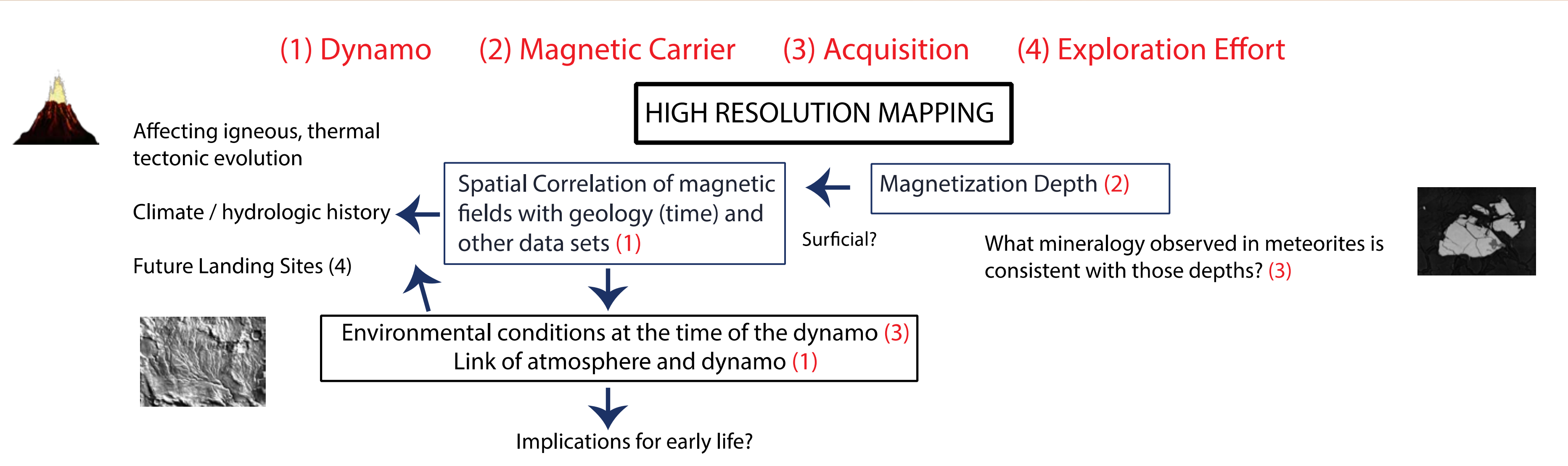
3) Magnetic Carrier

4) Future Exploration Efforts

(4) Radiation, astrobiology implications, resource identification, ...

MEPAG Goals and magnetic fields

What could we learn?
Some examples



GOAL III: UNDERSTAND THE ORIGIN AND EVOLUTION OF MARS AS A GEOLOGICAL SYSTEM

(3) (2) Objective A: Document the geologic record preserved in the crust and investigate the processes that have created and modified that record.

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Objective A: Obtain knowledge of Mars sufficient to design and implement human landing at the designated human landing site with acceptable cost, risk and performance.

Different data sets

Scales	Data and Studies so far	Optimal Measurement Platform
Global; resolution of ~150 km	MGS and MAVEN	Satellites
~100s-1000s km	Missing	Airplanes, Balloons
~1 km	Missing	Drone
~meters	Missing	Field Surveys, Rovers
in-situ spot measurement	InSight	Lander
μm-mm	(1) To some degree via meteorites (2) Returned sample	Laboratory studies