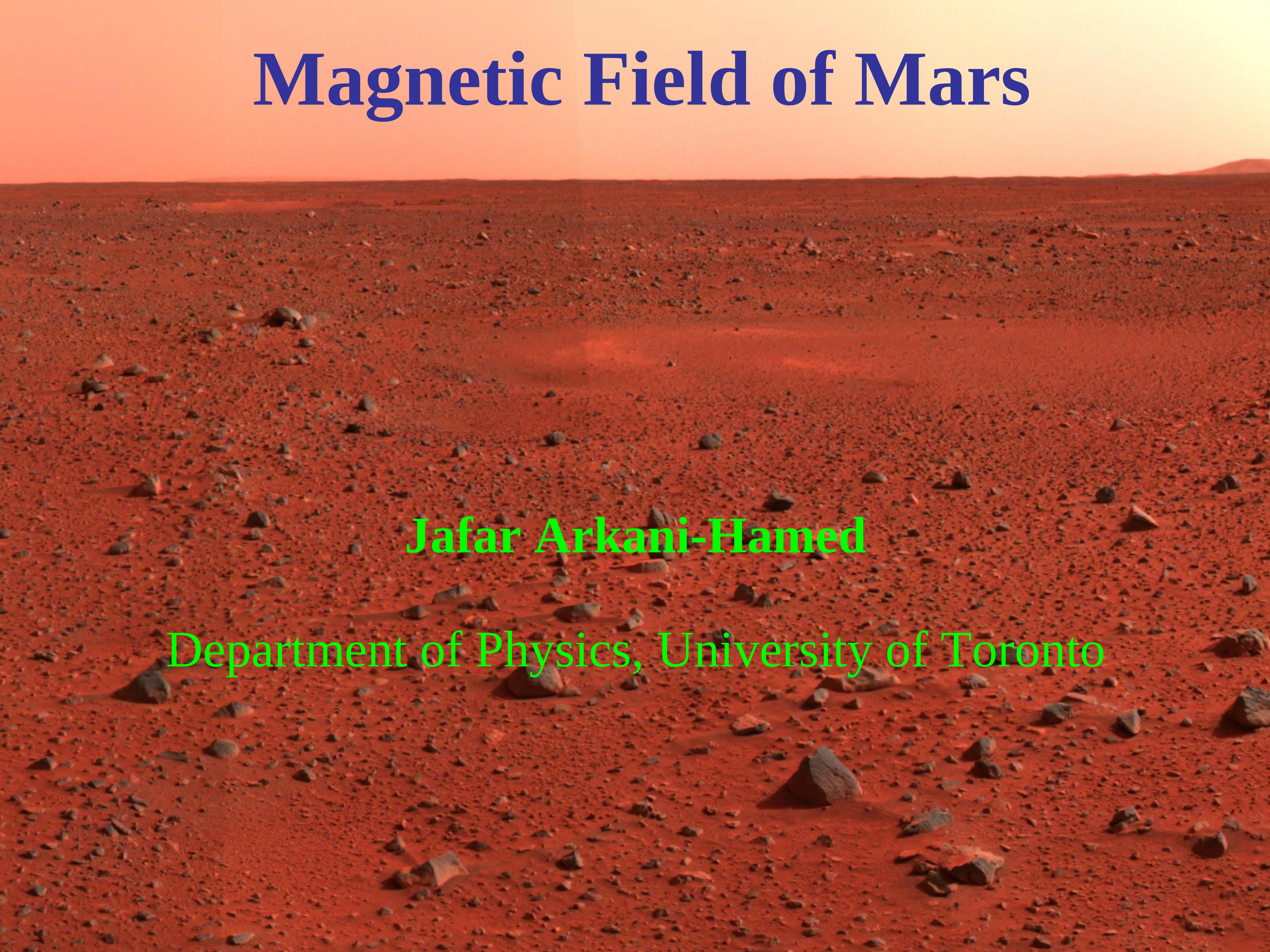


Magnetic Field of Mars

Jafar Arkani-Hamed

Department of Physics, University of Toronto

We have lived here
for 40 000 centuries

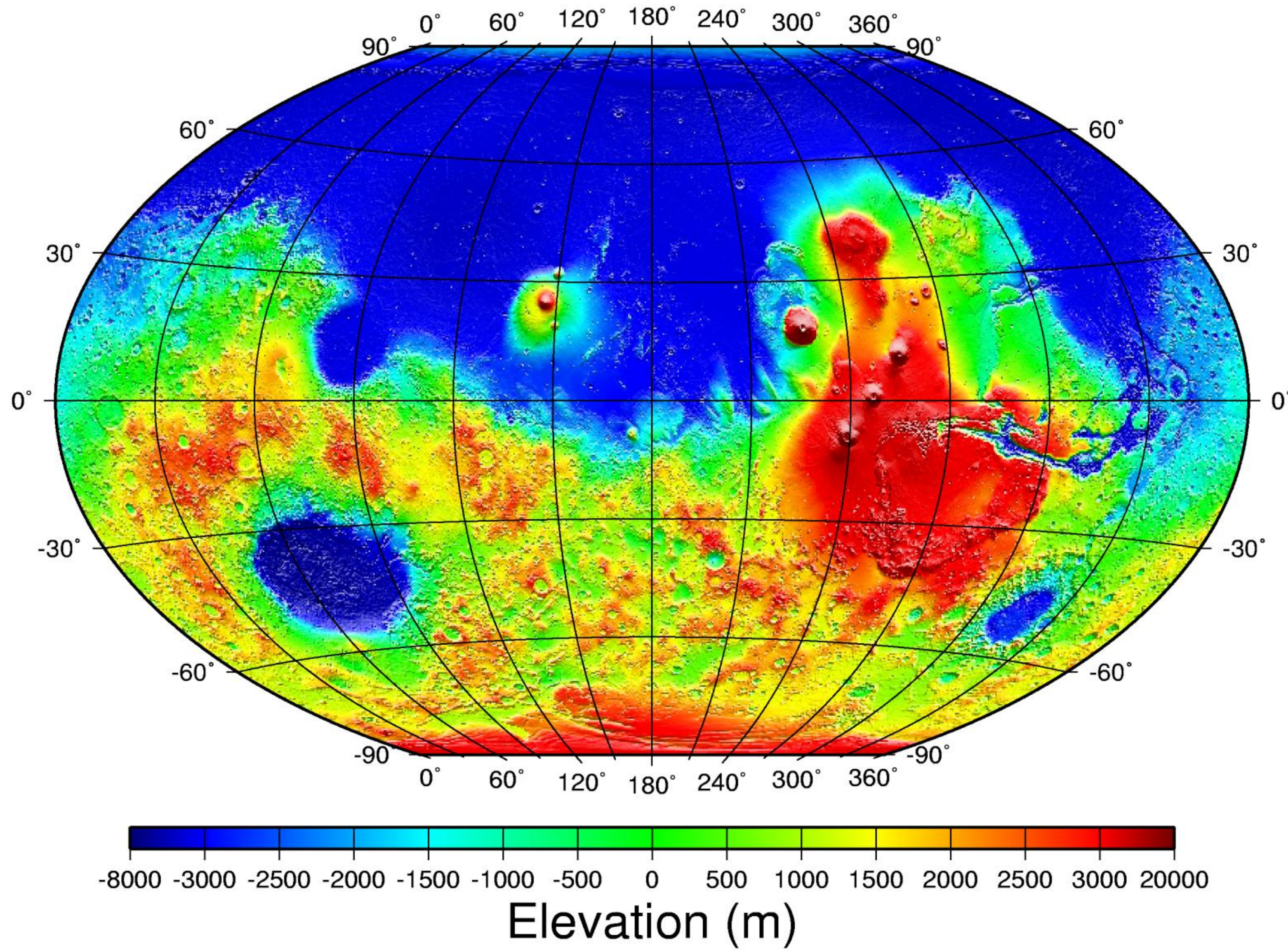
We will live here within
the next two centuries

Missions to Mars: 1960 - 2004

Images from: http://nssdc.gsfc.nasa.gov and http://photojournal.jpl.nasa.gov

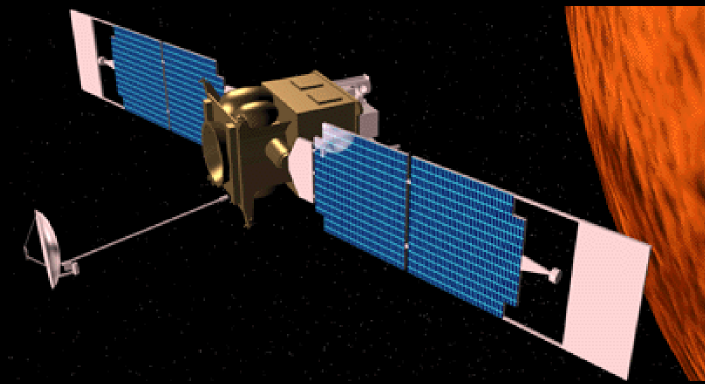

Tim Hortons
COMING SOON

Mars Topography



Mars Global Surveyor

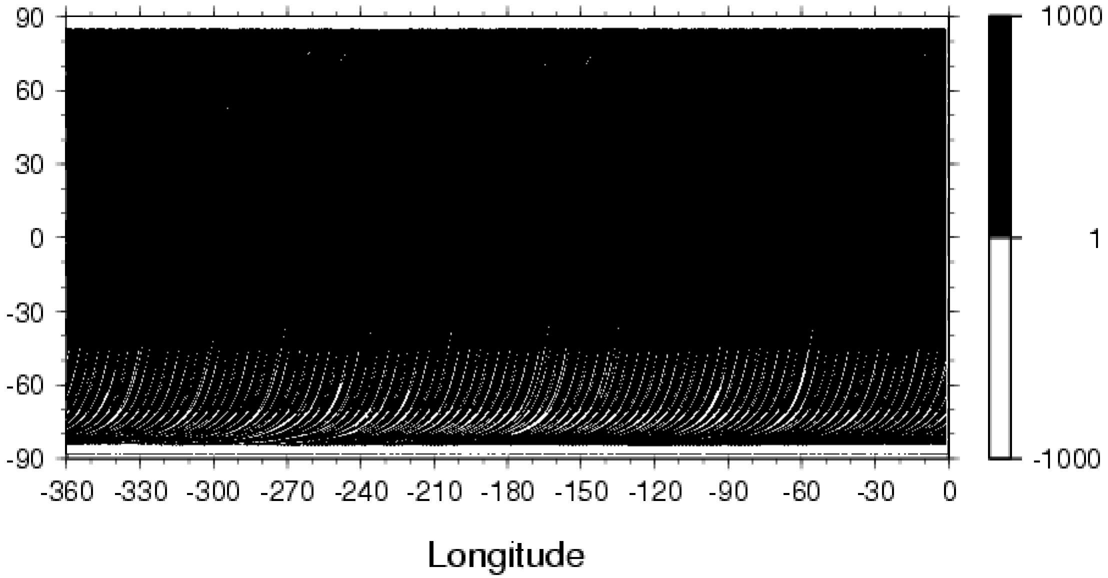
Dry mass: 1030.5 kg
Entered orbit: 12 Sept, 1997



Science Objectives:

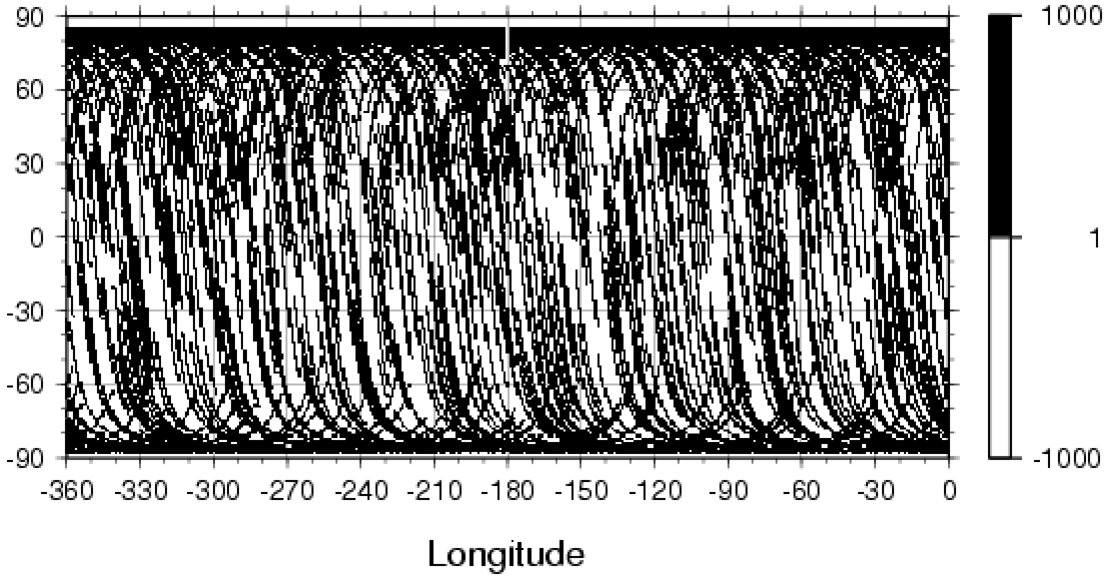
- Studies of the topography and gravity
- The role of water on the surface and in the atmosphere
- High resolution imaging of the surface
- The weather and climate of Mars
- The composition of the surface and atmosphere
- Existence and evolution of the Martian magnetic field

High altitude orbits (360-480 km)



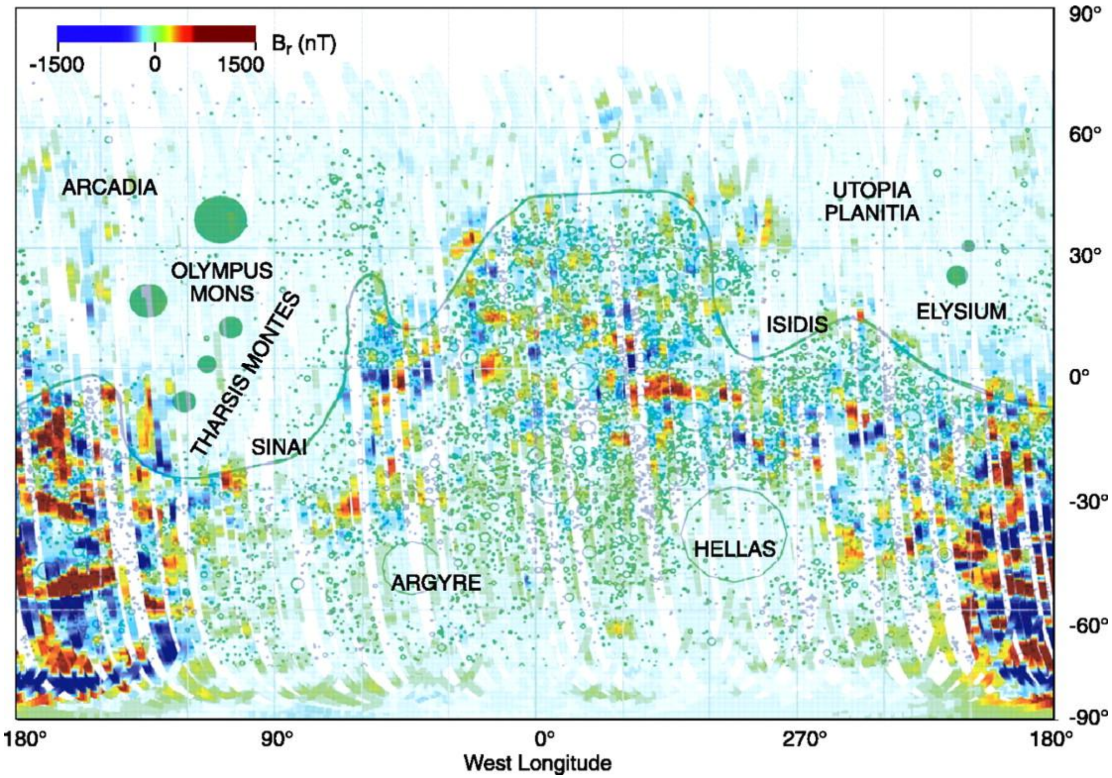
•No data at the poles

Low altitude orbits (100-200 km)



•Large gaps

Radial Component of Magnetic Field



From Acuna et al, Science, v284, 790-793, 1999

- Major anomalies are in the south
- No altitude corrections are made

Presentation outline

- Magnetic Anomalies of Mars
  - Derivation and charateristics
  - Global interpretations

- Source of the Magnetic Anomalies
  1. Strong core field
  2. Thick magnetic crust
  3. High concentration of magnetic minerals
  4. Magnetic minerals with strong NRM

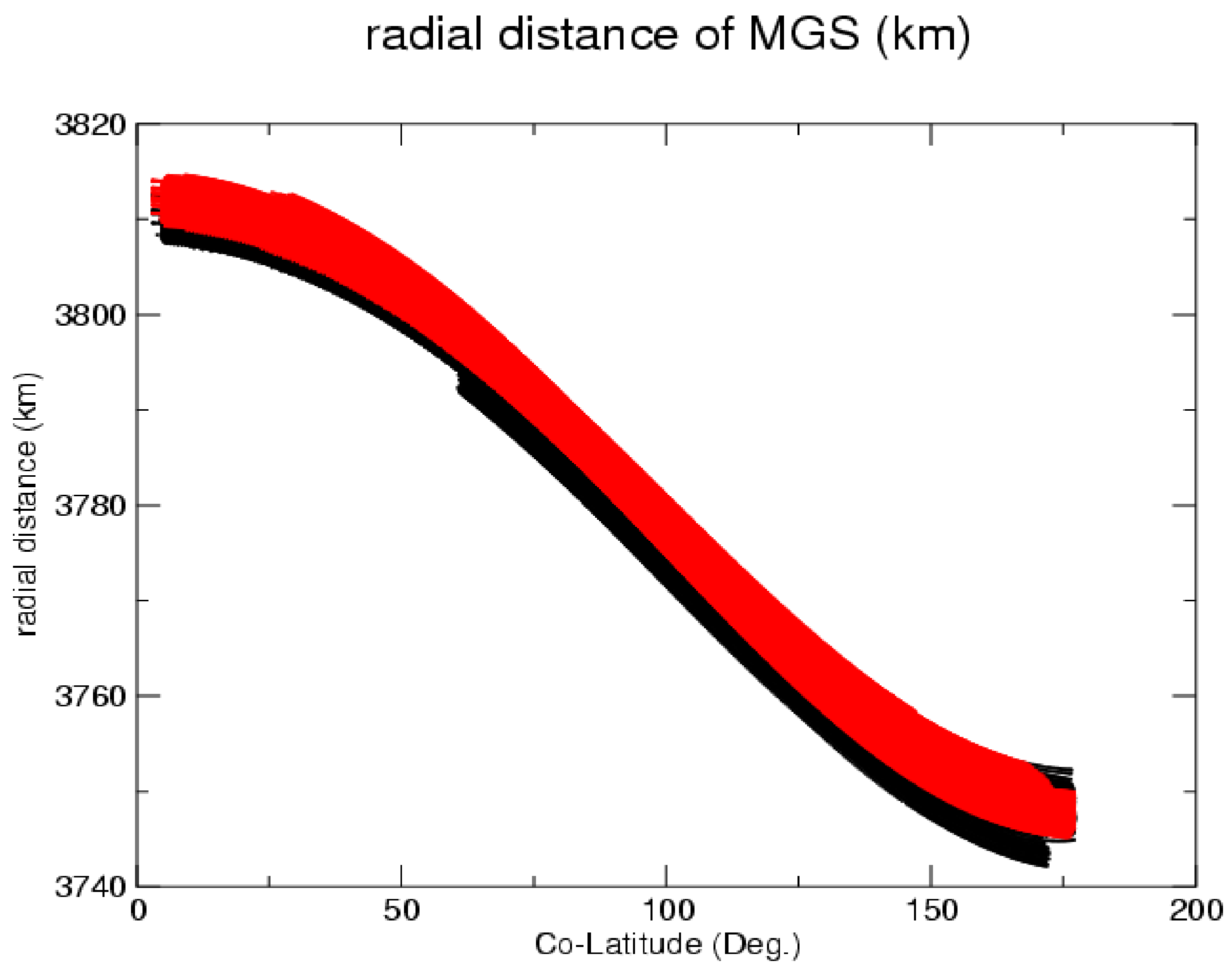
Contributers

- Daniel Boutin
- Alex Lemerle
- Pundit Mohit
- Hosein Shahnas
- Many other investigators (no explicit reference)

High-Altitude Magnetic Data Analysis

- Data acquired 1999-2003
- All three components of the magnetic field
- Divide the data into two almost equal parts
- Analysis each part separately
- Covariance analysis of the two sets of data

- Derive a magnetic anomaly map based on the most repeatable features of the two sets


radial distance of MGS (km)
3820
3800
3780
3760
3740
radial distance (km)
0
50
100
150
200
Co-Latitude (Deg.)

Spherical Harmonic Analysis of Magnetic Data

Magnetic Potential

$$V(r,\theta,\phi) = a \sum_{n=1}^{N} (\frac{a}{r})^{n+1} \sum_{m=0}^{n} V_{nm} Y_{nm}(\theta,\phi)$$

Magnetic Field

$$\mathbf{F} = -\nabla \mathbf{V}$$

Least Squares Fitting

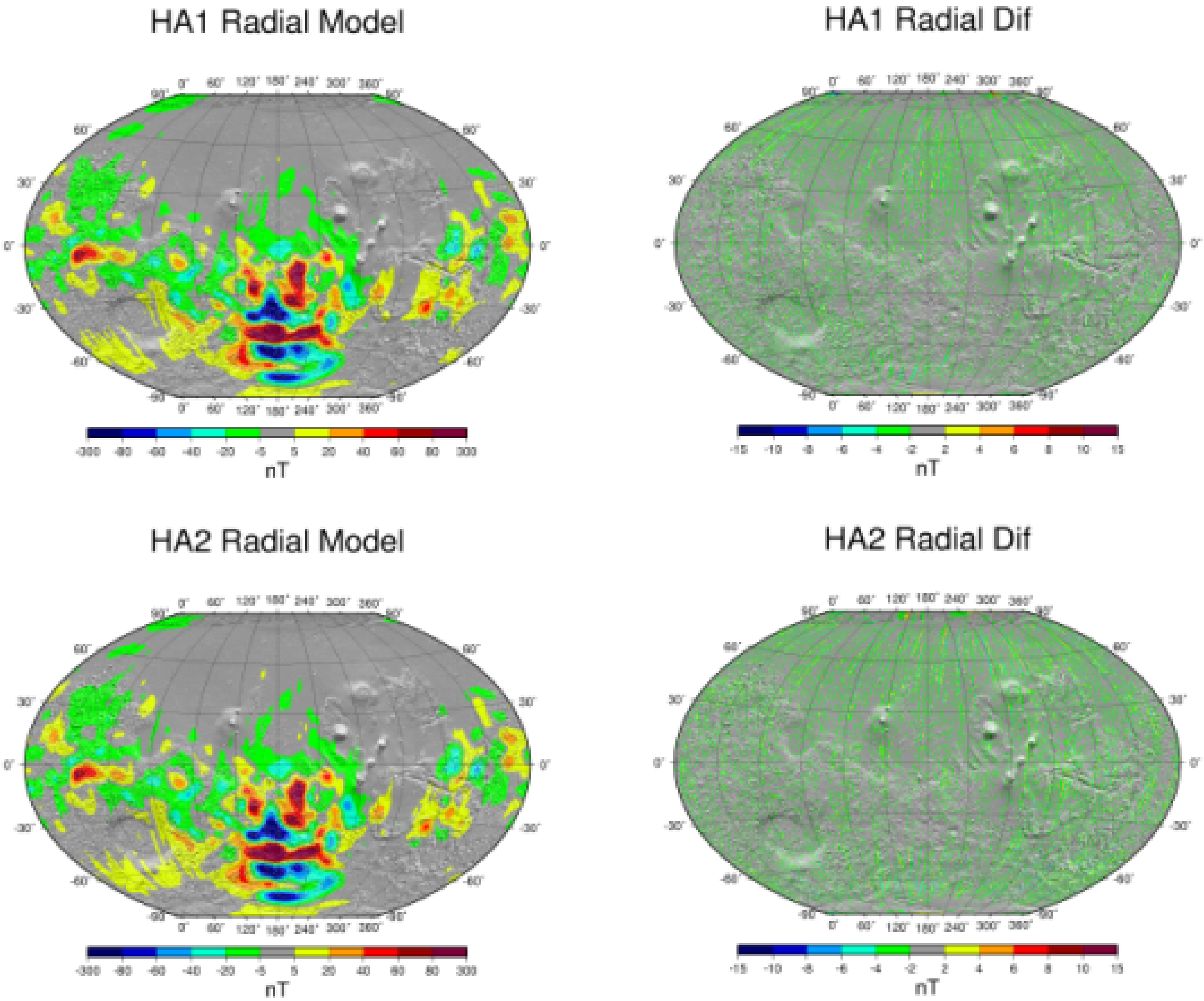
$$\epsilon^2 = \sum_i [(B_r - F_r)_i^2 + \alpha(B_\theta - F_\theta)_i^2 + \beta(B_\phi - F_\phi)_i^2] W_i$$

Power Spectrum

$$R_n = (n+1) \sum_{m=0}^{n} V_{nm}^2$$

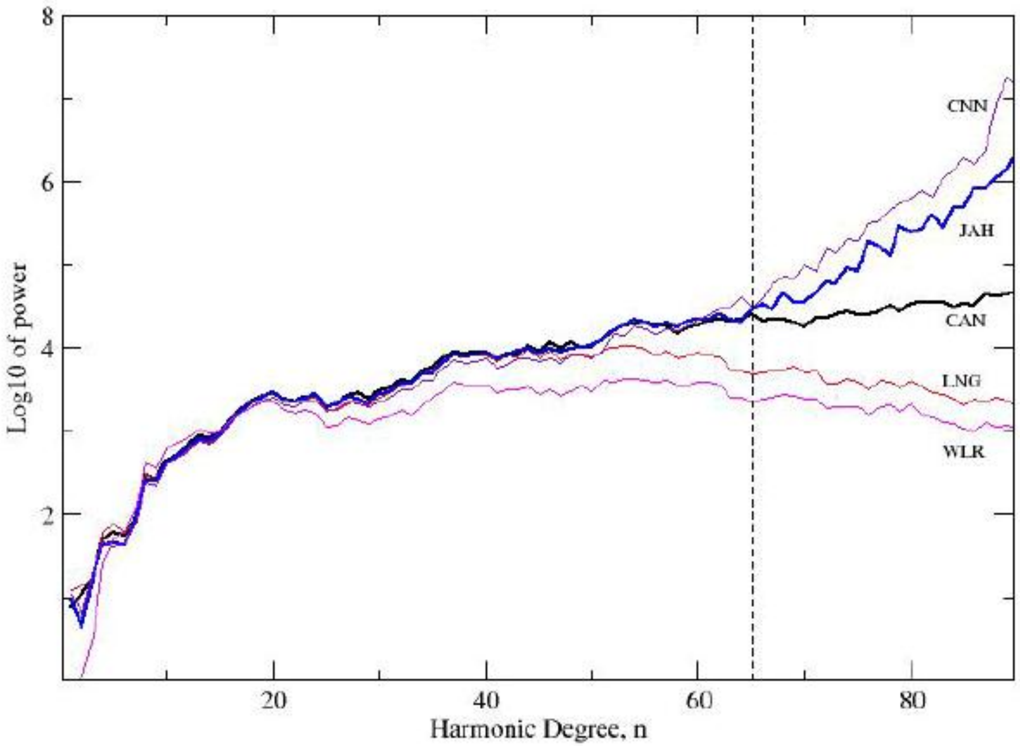
Degree Correlation

$$\eta_n = \frac{\sum_{m=0}^{n} (V_{nm}^* V'_{nm})}{\{[\sum_{m=0}^{n} V_{nm}^2][\sum_{m=0}^{n} V'^2_{nm}]\}^{1/2}}$$

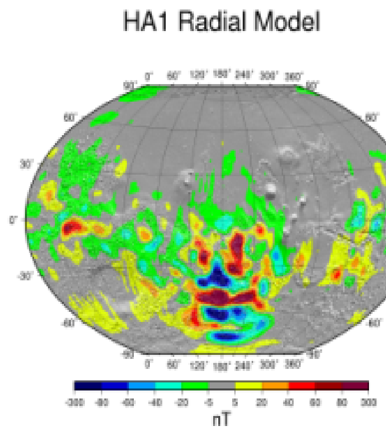

HA1 Radial Model
HA1 Radial Dif
HA2 Radial Model
HA2 Radial Dif
0° 60° 120° 180° 240° 300° 360°
90° 60° 30° 0° -30° -60° -90°
-300 -80 -60 -40 -20 -5 5 20 40 60 80 300
nT
-15 -10 -8 -6 -4 -2 2 4 6 8 10 15
nT

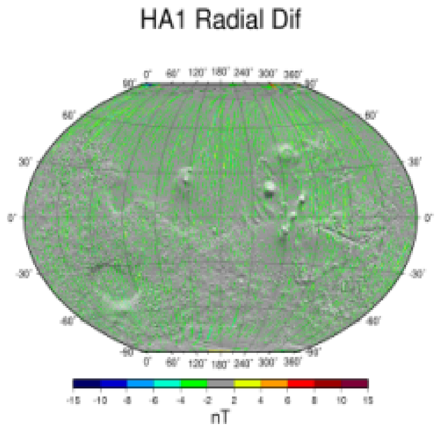
Power Spectra of Recent Spherical Harmonic Models

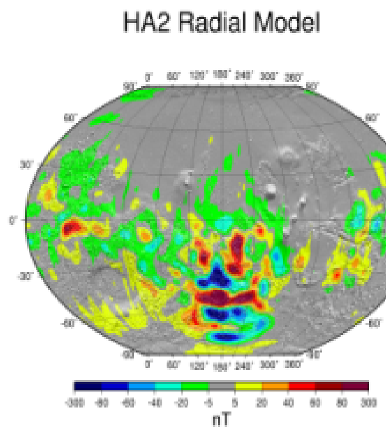
$$R_n = (n+1) \quad {}_{m=-n}^{\;n} V_{nm}^{\;2}$$

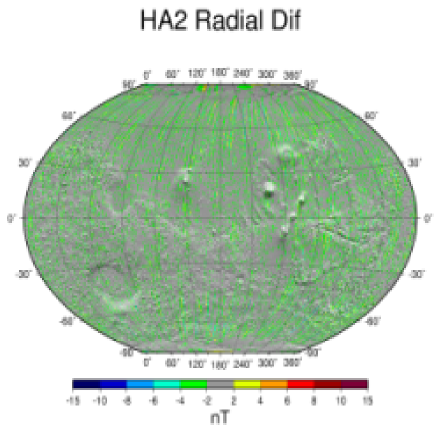


Low Resolution

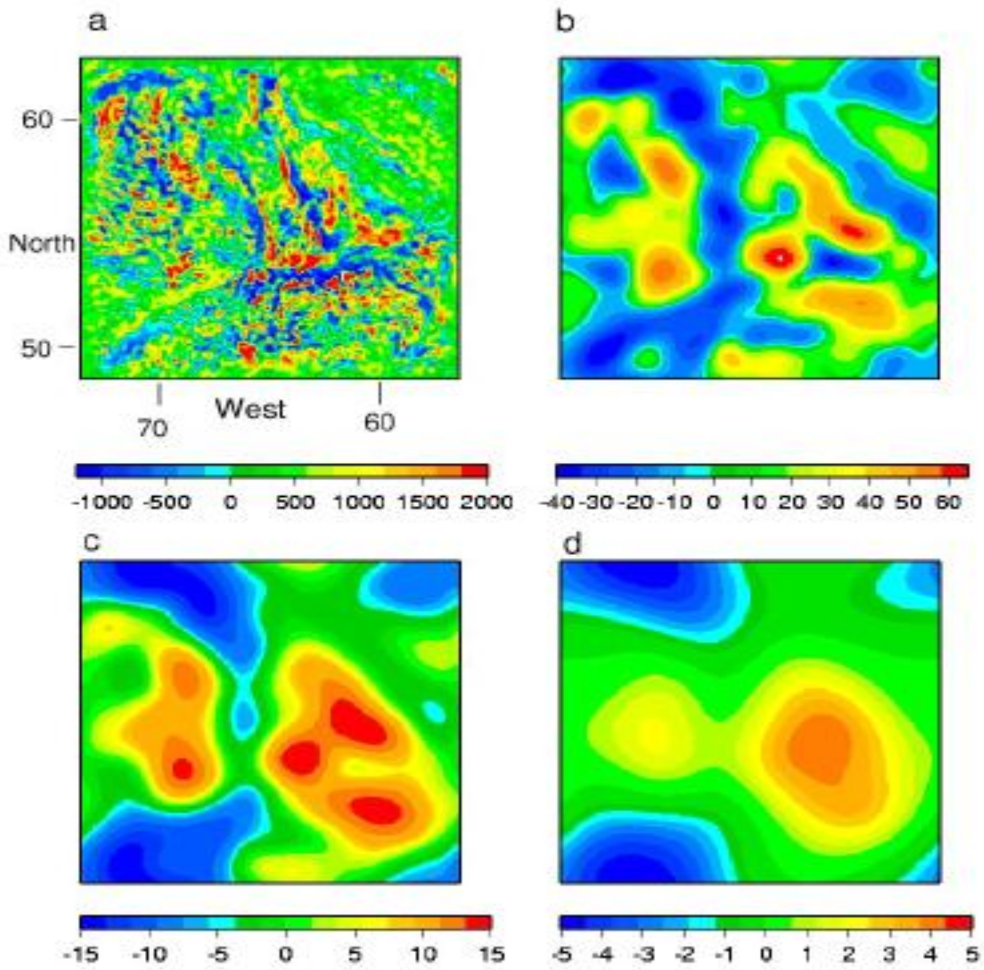




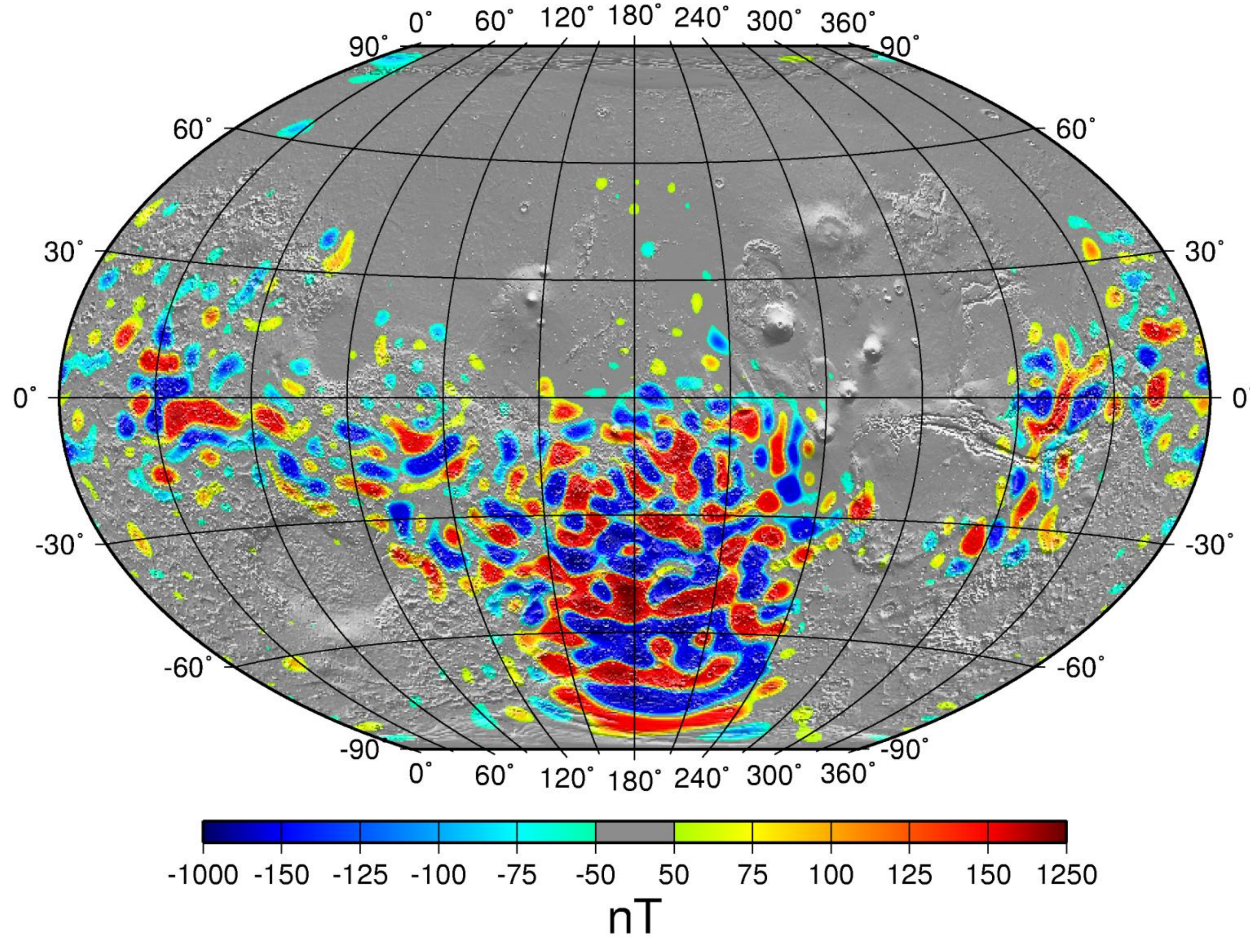




Magnetic Anomalies of Eastern Canada



Radial magnetic field



Timing of the Core Dynamo

Crustal field and tectonics

- Lowlands
- Impact basins
- Shield volcanoes
- Valles Marineris

Martian meteorites

- Young ~ 1.3 – 0.6 Gyr.
- Old (ALH0084) ~ 4 Gyr.

No strong core dynamo has existed for the last 4 Gyr

Strong Magnetization of Martian Crust

- Requires a vertically integrated Remanent magnetization of (6-10) x 10^5 A,

  more than 10 times that of the Earth

- Has been resulted from some combination of

  1. a strong magnetizing core field,
  2. a thick magnetic layer,
  3. a high concentration of magnetic minerals,
  4. magnetic minerals with strong remanent magnetization.

1. Strength of the Core Field

Two methods to estimate the core field intensity

- The energy balance method (the gravitational energy released by the cooling of the core is balanced by the Ohmic energy dissipated). Depends on highly unconstrained thermal evolution estimates.

- The magnetostrophic balance method (the Coriolis force is balanced by the Lorentz force).

$$B = (2\,\Omega\,\rho\,\mu_o\,U\,L)^{1/2}$$

Ω = rotation rate, ρ = density, μ_o = magnetic permeability, U = the characteristic velocity in the core, and L = the characteristic dimension of the core.

Mars / Earth

$$B / B' = [\Omega \rho U L / (\Omega' \rho' U' L']^{1/2}$$

$$\sim 0.5$$

The field decreases from the core, Rc, to the surface, Rs

$$\beta_n = Bs / Bc = (Rc/Rs)^{\mathbf{(n+2)}}$$

$\beta_1 / \beta'_1 \sim 0.5$ for dipole field

The dipole core field at the surface of Mars that magnetized the crust was weaker than the present core field at the surface of the Earth.

2. Thickness of the Magnetic Crust

- Thermal state of the Martian crust when the core dynamo was active

- Magnetic blocking temperatures of the major magnetic carriers of the crust
  - Magnetite (T_c = 580 C)
  - Hematite (T_c = 670 C)
  - Pyrrhotite (T_c = 230 C)

Convection Regime in the Mantle

- Early plate tectonics
  - Thinner magnetic layer

- Stagnant-lid convection
  - Thicker magnetic layer

We seek an upper limit for the thickness of the magnetic crust

Thermal Evolution of Mars: Stagnant Lid, Parameterized Convection

Energy balance in the core

Energy balance in the convecting part of the mantle

Heat conduction in the upper and lower thermal boundary layers, and in the growing stagnant lid

Temperature- and pressure-dependent viscosity

Time-dependent temperature at the base of the stagnant lid

Pressure-dependent thermal expansion coefficient

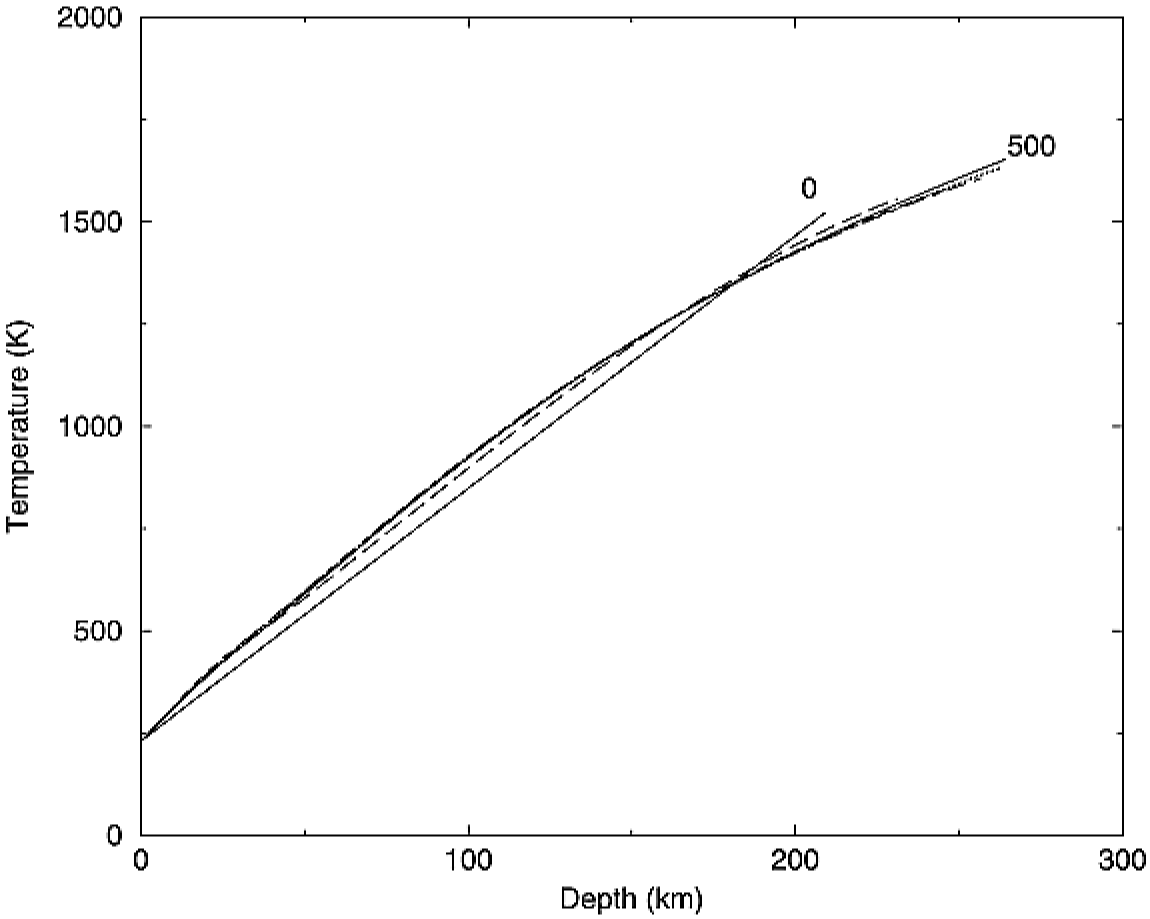
Temperature-dependent thermal conductivity

Time- and space-dependent heat generation

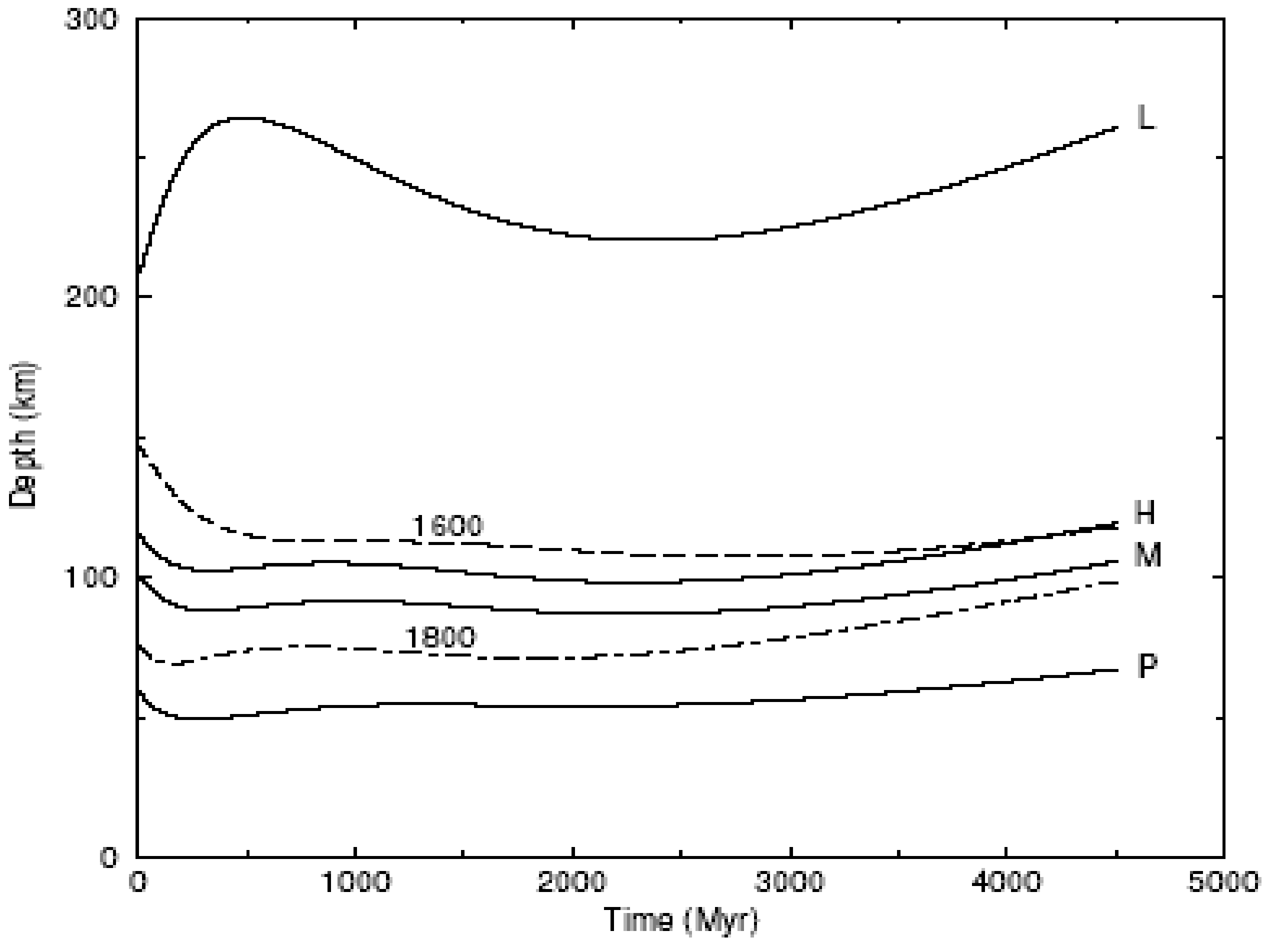
Thermal Evolution Models

- A total of 23 thermal Evolution Models are calculated
- The parameters examined:
  - Thickness of initial crust
  - Total heat generation and its concentration in the crust
  - Initial temperature of the mantle
  - Viscosity of the mantel
  - Thermal expansion coefficient of the mantle
  - Super heated core
  - Heat generation in the core

Temperature in the Martian Lithosphere

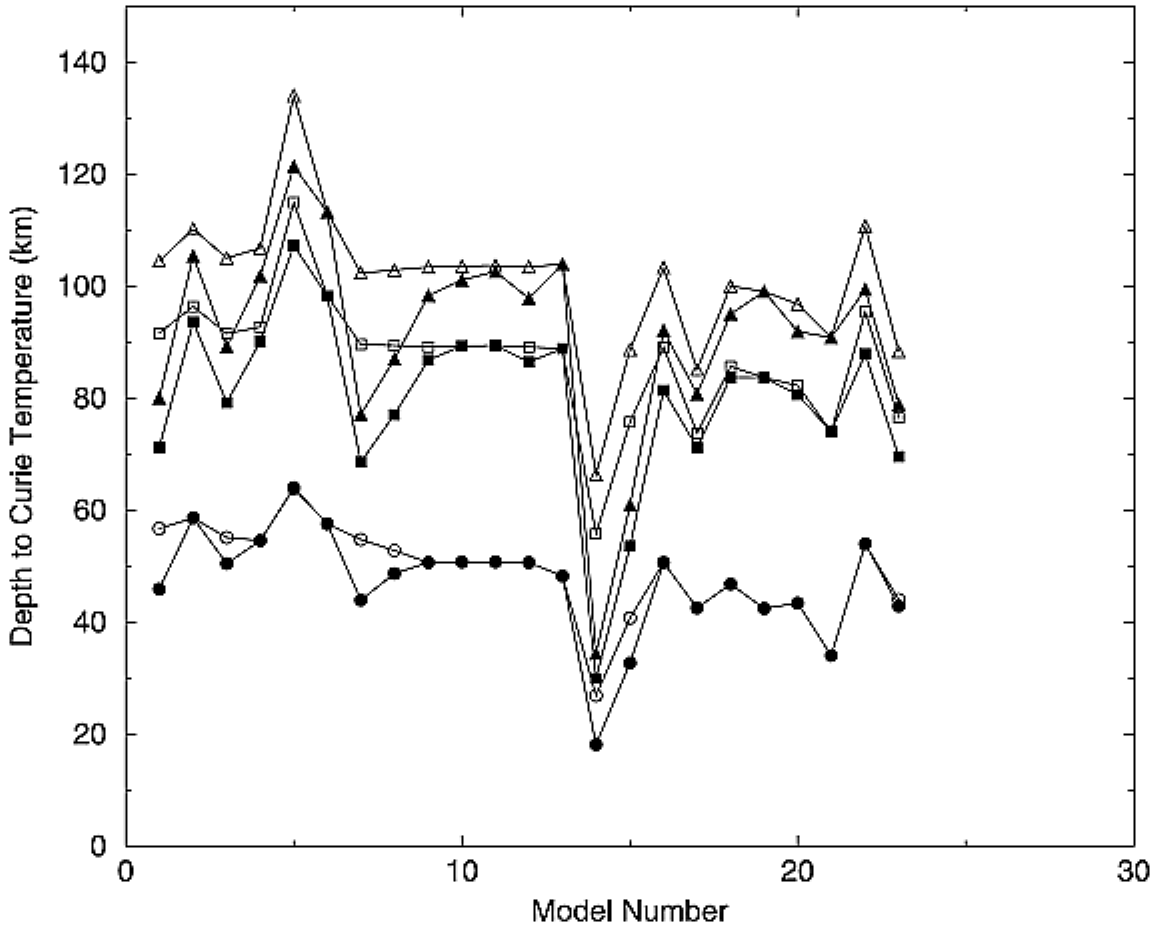


Time Variations of Magnetic Layer Thickness, and the Stagnant Lid



Depth to Curie Temperatures of Hematite, Magnetite and Pyrrhotite

(at 4 Gyr ago, and the minimum achieved)



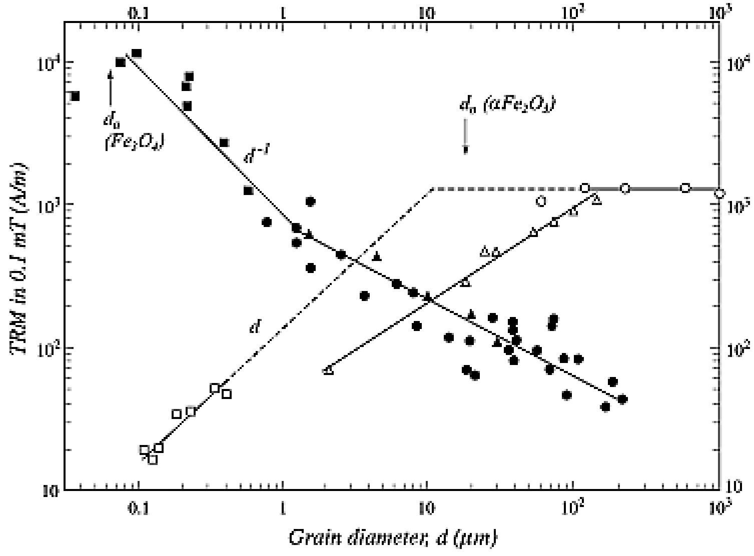
3. Concentration of Magnetic Minerals

- Martian crust is more iron rich than Earth's
- No information is available about the state of oxidation of iron in the Martian crust

An Open Question !!

4. Magnetic Minerals with Strong Remanent Magnetization

(Magnetite, Hematite, Pyrrhotite)



SD/PSD Magnetite Particles

- SD/PSD magnetite particles can be produced during the initial rapid cooling of lava
  - Oxyexsolusion of titanomagnetite to intergrown magnetically single-domain magnetite [Dunlop and Ozdemir [1997].
  - Oxidation of olivine basalt and exsolution of magnetite in a single domain state, that might have acquired strong magnetization in the presence of the core field [Gunnlaugsson et al., [2006]

Mars a One-Plate Planet

- Mantle differentiation and core formation within 20-30 My. (Halliday et al., 2001)
- Martian crust has likely formed gradually in the first 500 My. (Norman, 2002).
- The entire Martian crust has probably a basaltic composition (McSween et al., 2003)
- Crustal thickening is largely by volcanism in a one-plate planet (Tharsis bulge with an about 20 km thick basaltic layer is possibly the last major crust forming volcanism)

Cooling of a Lava Flow

- We consider an initially hot lithosphere of 100 km thickness, with or without an initial crust.
- The lithosphere cools for a while before a layer of lava is added on it.
- The lava cools for a period before being covered by the next lava flow.
- The 1-D heat conduction equation is solved

$$C \rho \partial T / \partial t = \partial / \partial z (K \partial T / \partial z) + Q$$

  - C (1200 J/kg/K) and ρ (3000 kg/m^3) are constant
  - K is temperature dependent (Shatz and Simmons, 1972)
  - Q is space and time dependent, at present U = 16 ppb; Th/U =3.5; K/U =19,062 (Wanke and Drebius, 1994)

Cooling of a Lava Flow

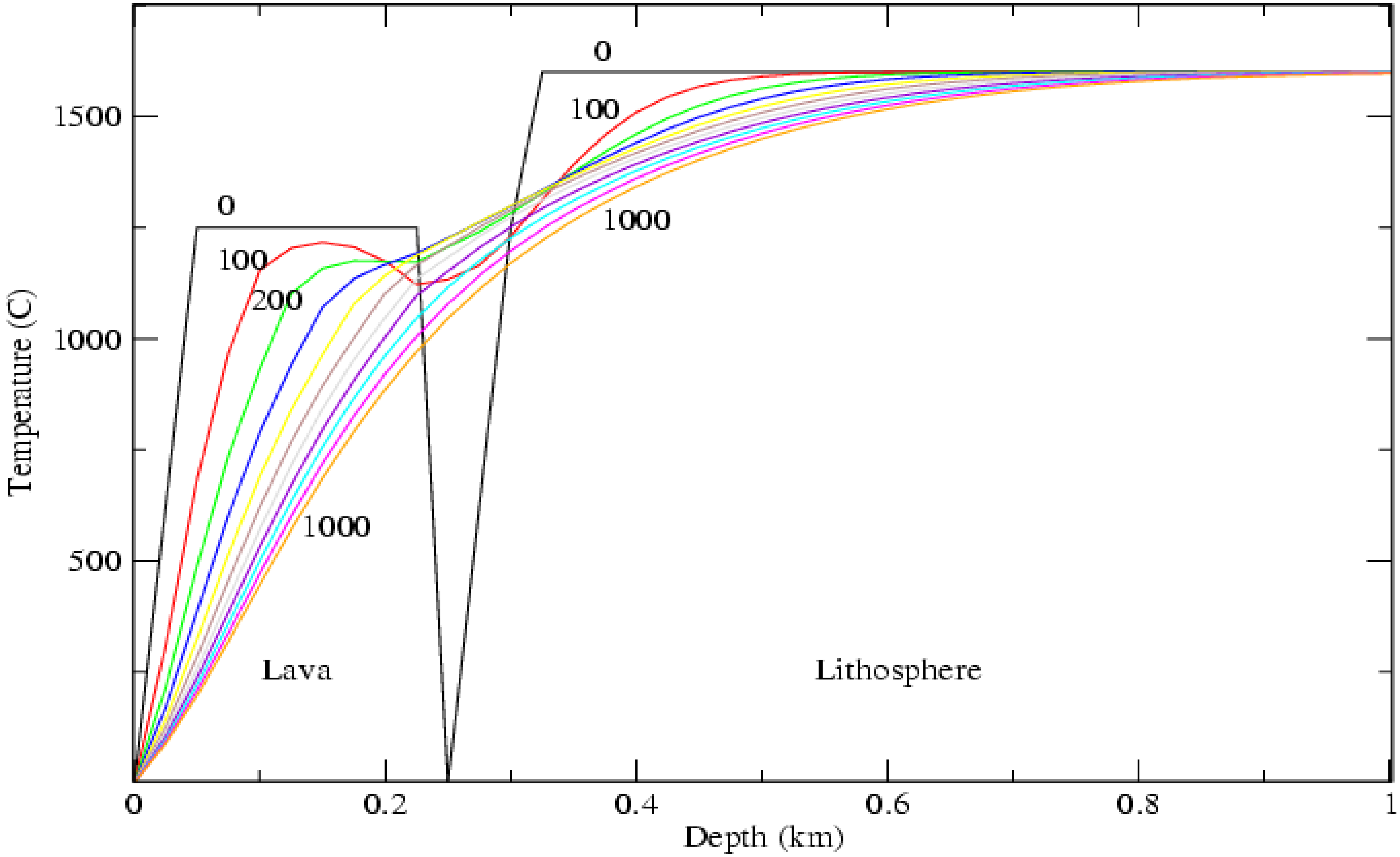
- The temperature is zero at the surface and fixed at the base of the lithosphere
- The initial temperature of the lithosphere is the solidus of dry peridotite (1600 C)
- For the lithosphere with an initial crust, the initial temperature increases linearly in the crust.
- The lava is assumed completely molten and at the liquidus of dry basalt (1250 C)
- The thickness of the lava layers (d) is constant and the time interval Δt for lava flows is determined by

$$\Delta t = \{[\exp(-t_o/\tau) - \exp(-t_f/\tau)] . \tau . d . \exp(-t/\tau)\} / (\delta_f - \delta_o)$$

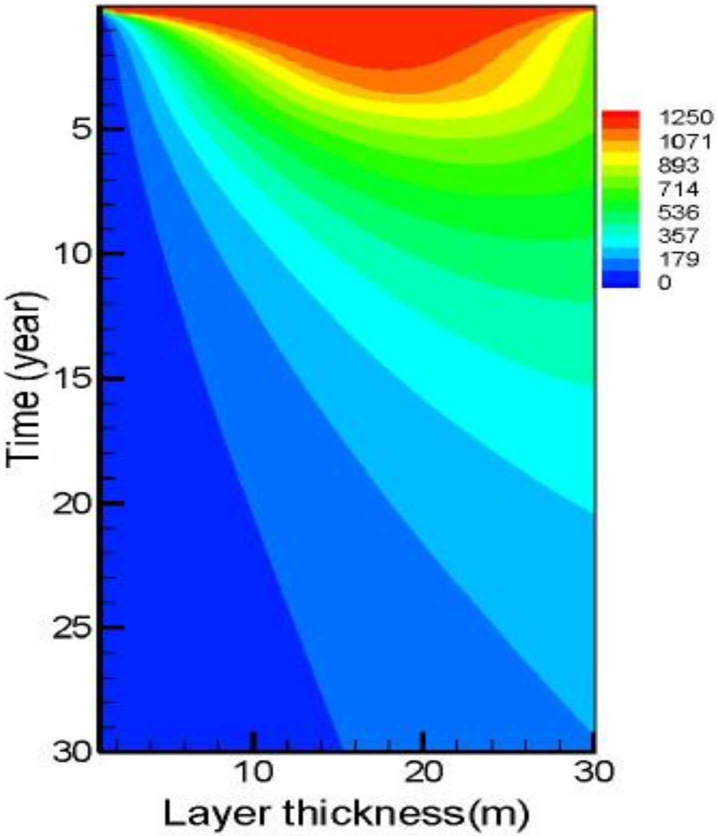
where δ_o and δ_f denote the initial and final thicknesses of the crust, t_o and t_f are the starting and ending times of volcanism, and τ is the characteristic time of the exponential growth of the crust.

Temperature Profiles in a Lava Layer

(The numbers on the curves are times in years)

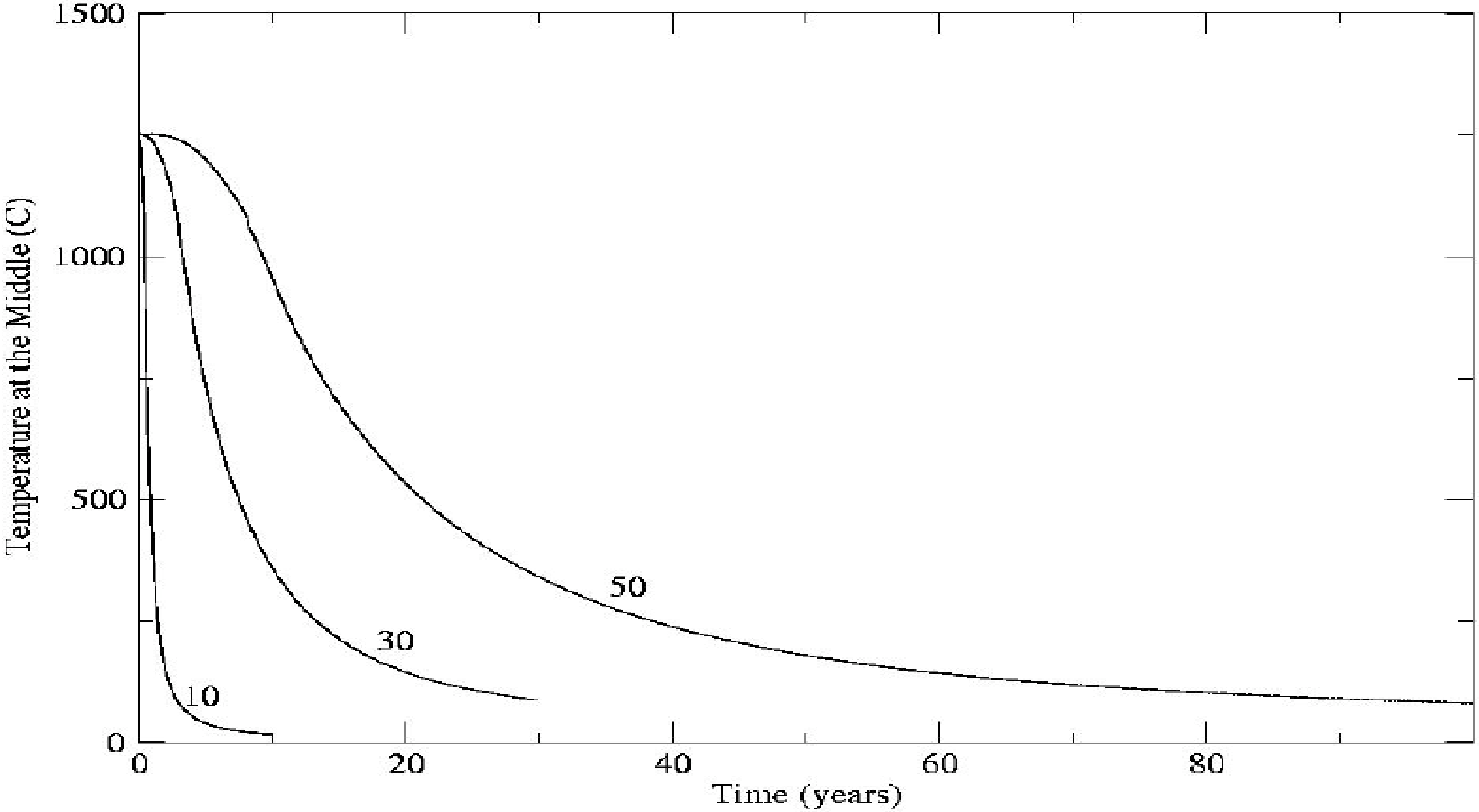


Thermal Evolution of a 30 m thick Lava Flow



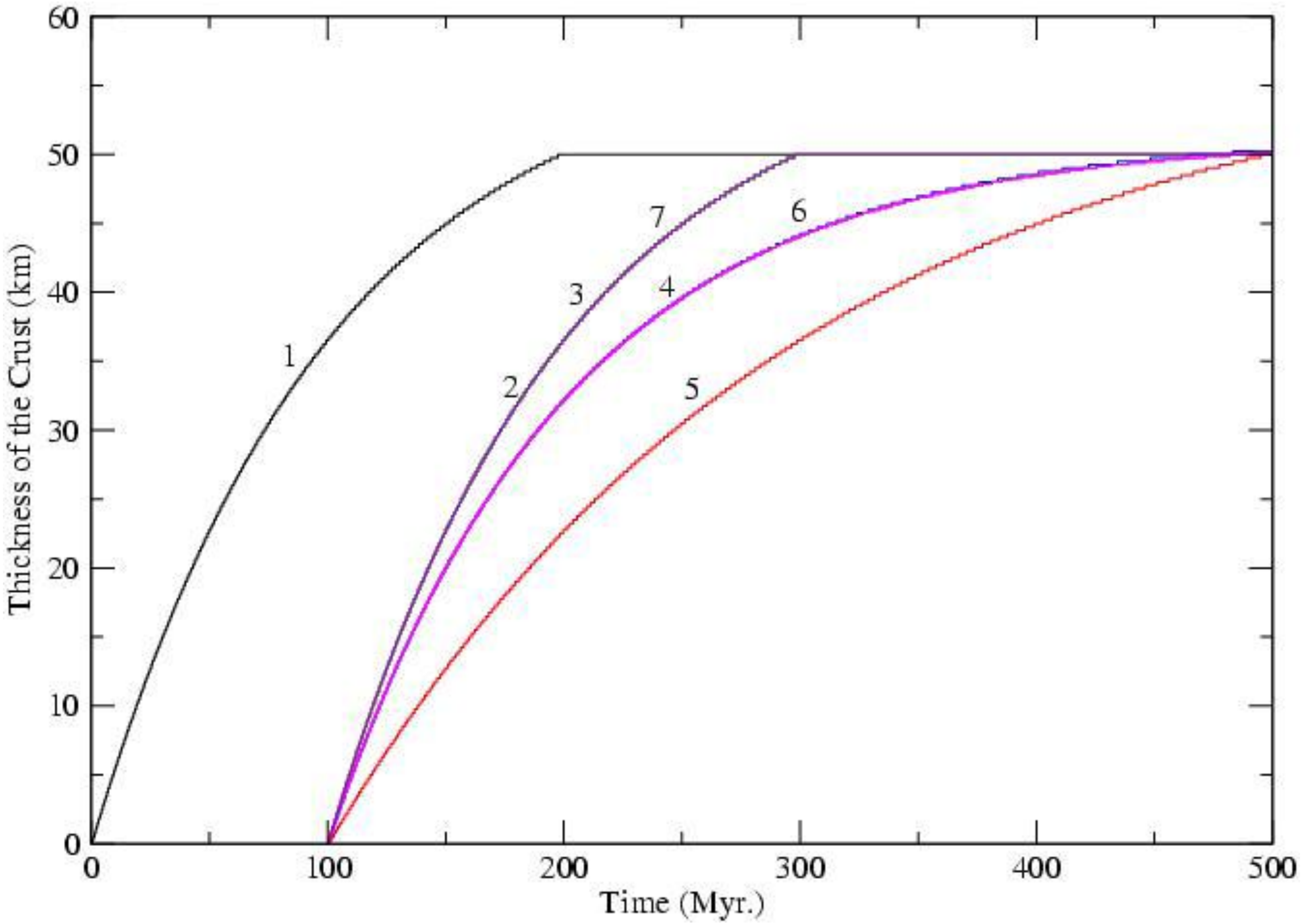
Temperature at the Middle of a Lava Flow

(10, 30, and 50 m thick lava)



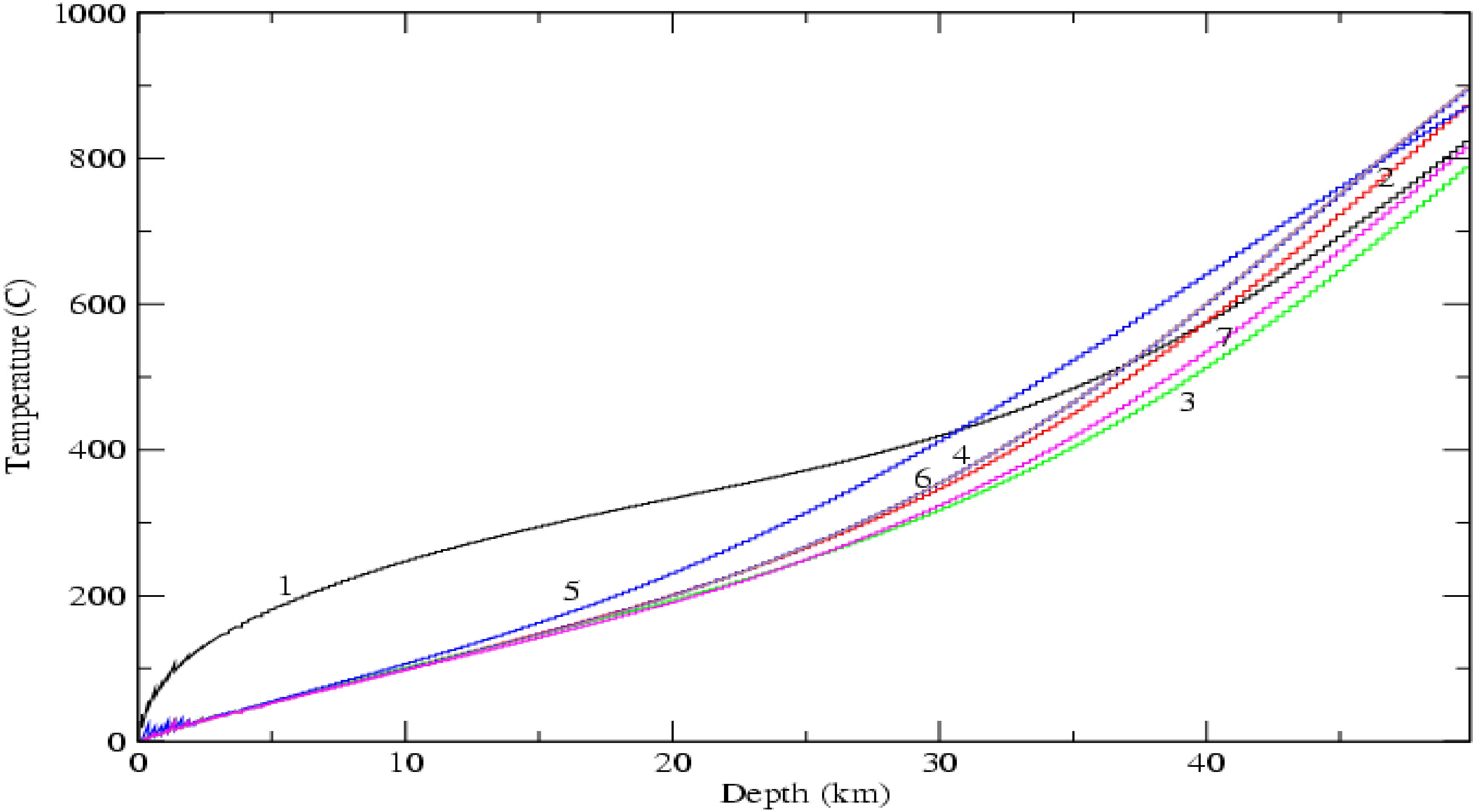
Growth of Volcanic Crust

(The numbers on the curves denote models)



Temperature at the Center of the First Lava Layer Versus Depth of the Layer

(The numbers on the curves denote models)

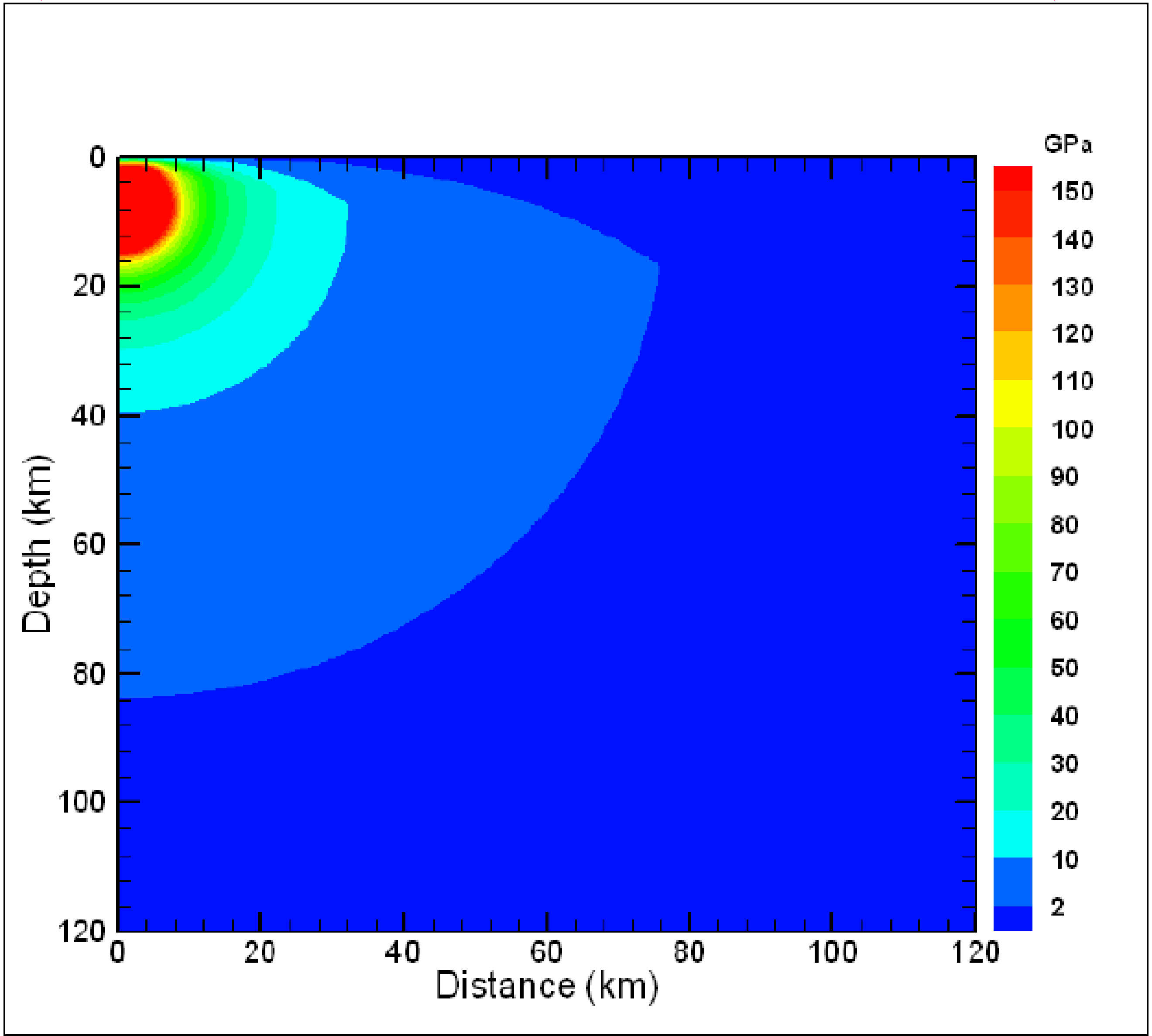


Changes in the Magnetization of the Crust

Factors that have affected the crustal Magnetization

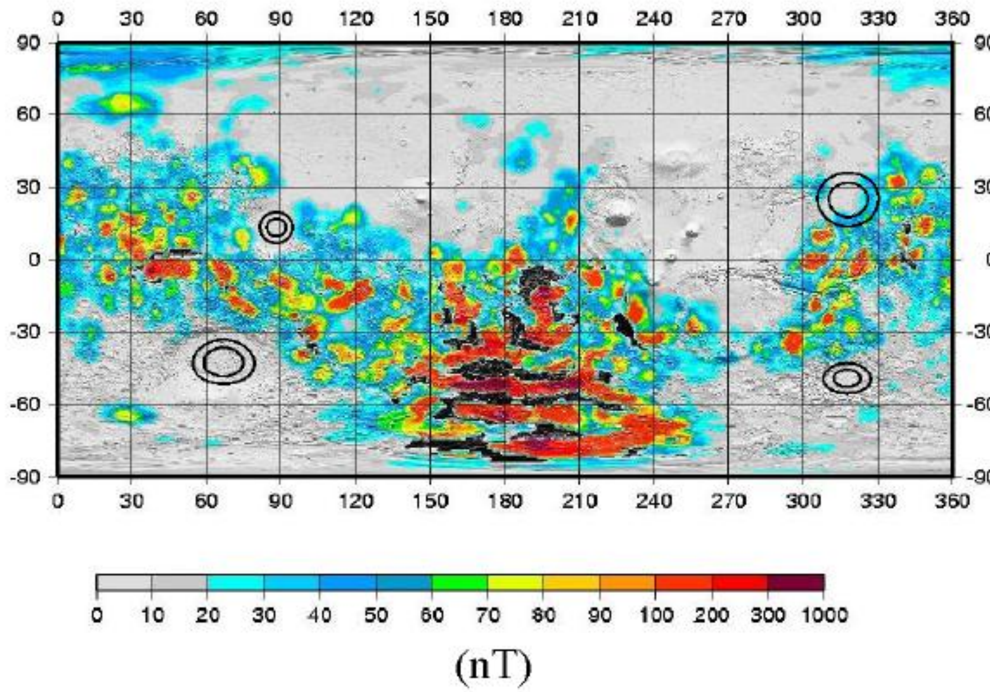
- Hydrothermal magnetization / demagnetization
- Impact demagnetization
- Secondary magnetization
- Viscous decay of magnetization

Impact-Induced Shock Pressure
(a basin with 200 km radius)



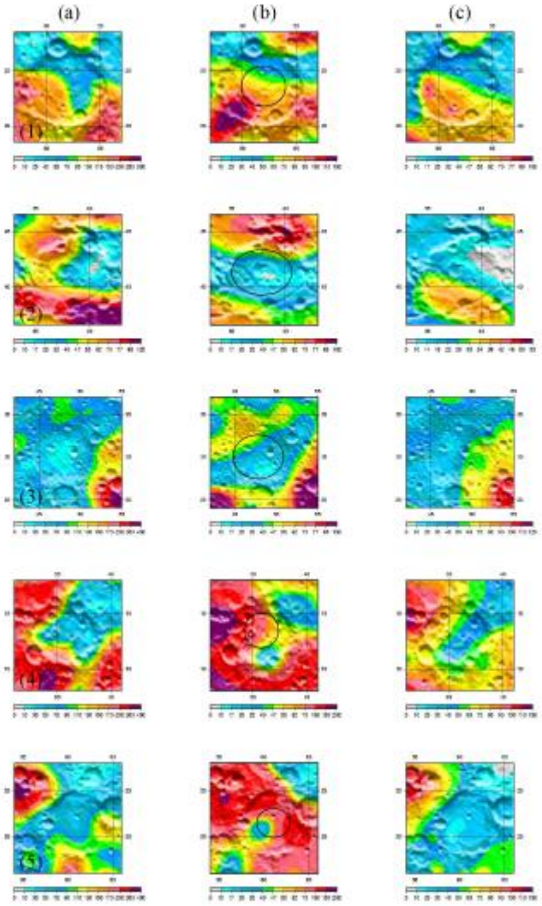
Intensity of the Magnetic Field at 100 km Altitude

(Inner Circle = Pi scaling; outer circle = Holsapple-Schmidt scaling)



Intermediate Size Craters

Cain   JAH Mitchell



Secondary Magnetization

- Upper crust is magnetized by the core field
- Lower crust is magnetized by the magnetic field of the upper crust, in the absence of the core dynamo
- Lower crust is divided into 5 equal thickness layers.
- Magnetization of each layer is assumed depth-independent

Thermo-remanent Magnetization of the Lower Crust

Magnetic potential at $\mathbf{r}$ due to magnetization at $\mathbf{r_o}$

$$V(\mathbf{r}) = \iiint \mathbf{M}(\mathbf{r_o}) \bullet \Delta_{\mathbf{o}} (1 / |\mathbf{r} - \mathbf{r_o}|)\, dv_o$$

Corresponding magnetic field $\mathbf{r}$

$$\mathbf{B}(\mathbf{r}) = -\Delta V$$

Magnetization acquired at r

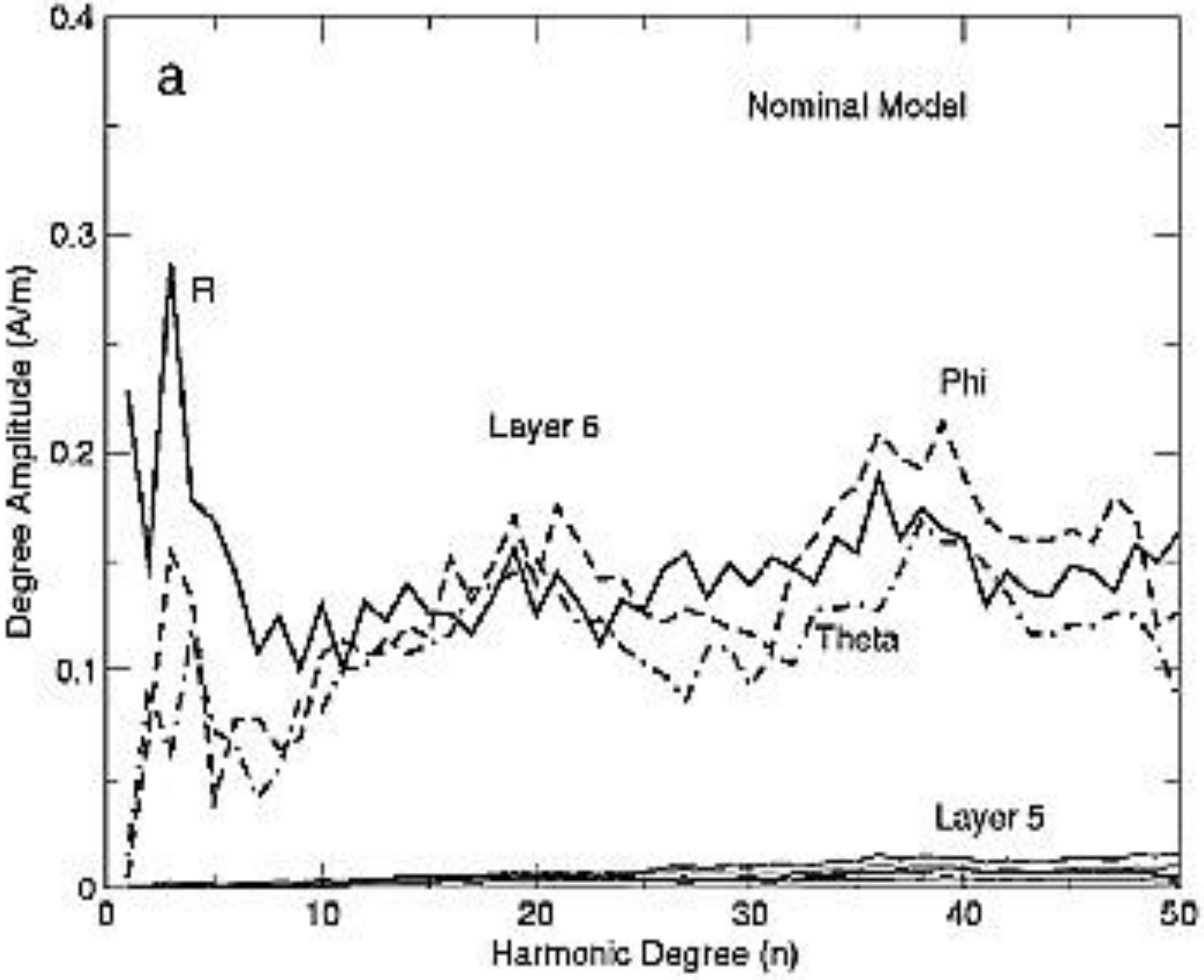
$$\mathbf{m}(\mathbf{r}) = \sigma\ \mathbf{B}(\mathbf{r})$$

Criteria

- The magnetic field of the entire crust at satellite altitude must equal to the observed field
- The lower crust is basaltic with magnetic properties equal to those of oceanic extrusive basalts

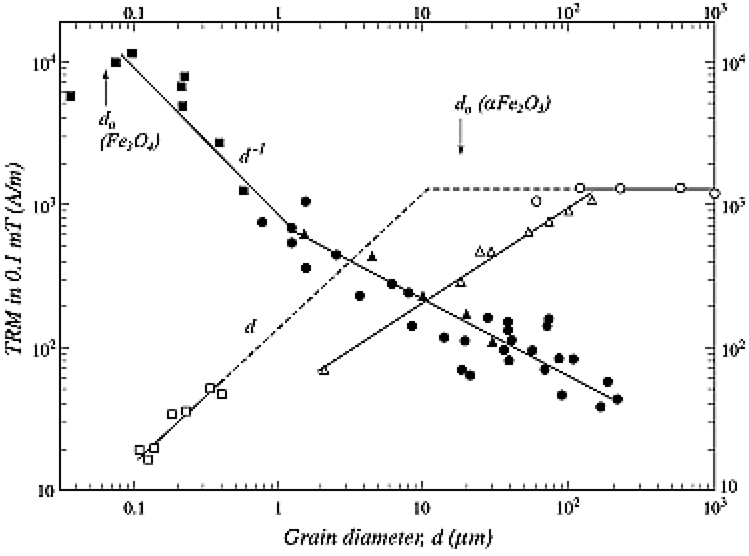
Solve in the spherical harmonic domain

Magnetization Acquired by the Lower Crust

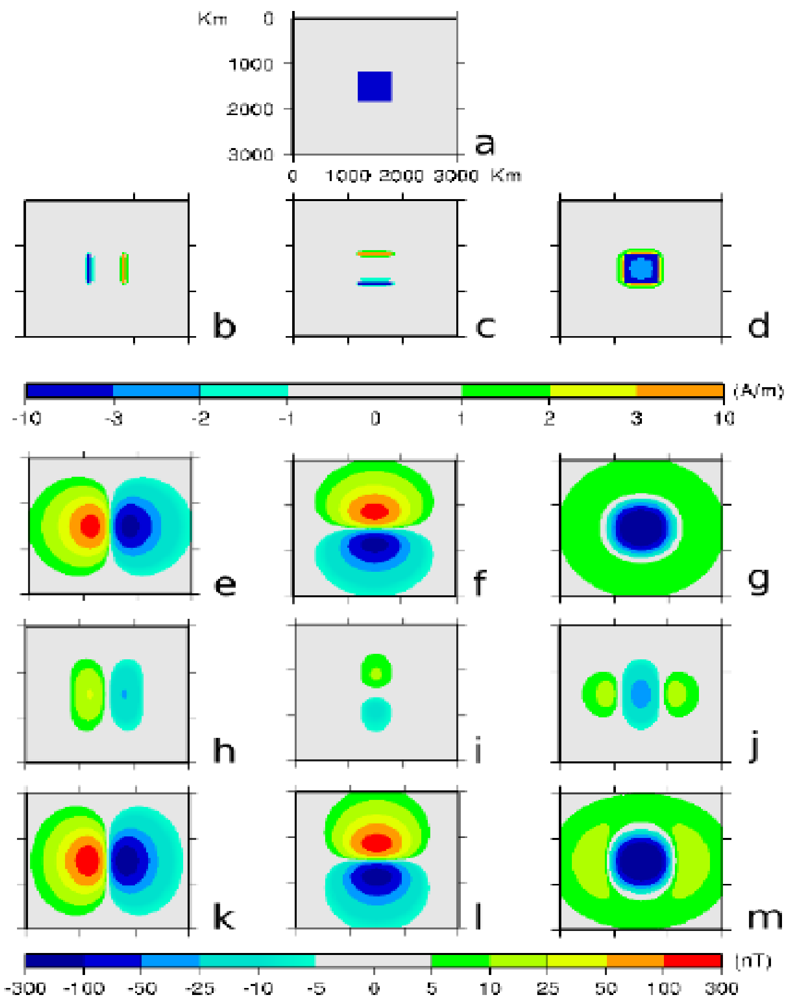


Magnetization Versus Grain Size

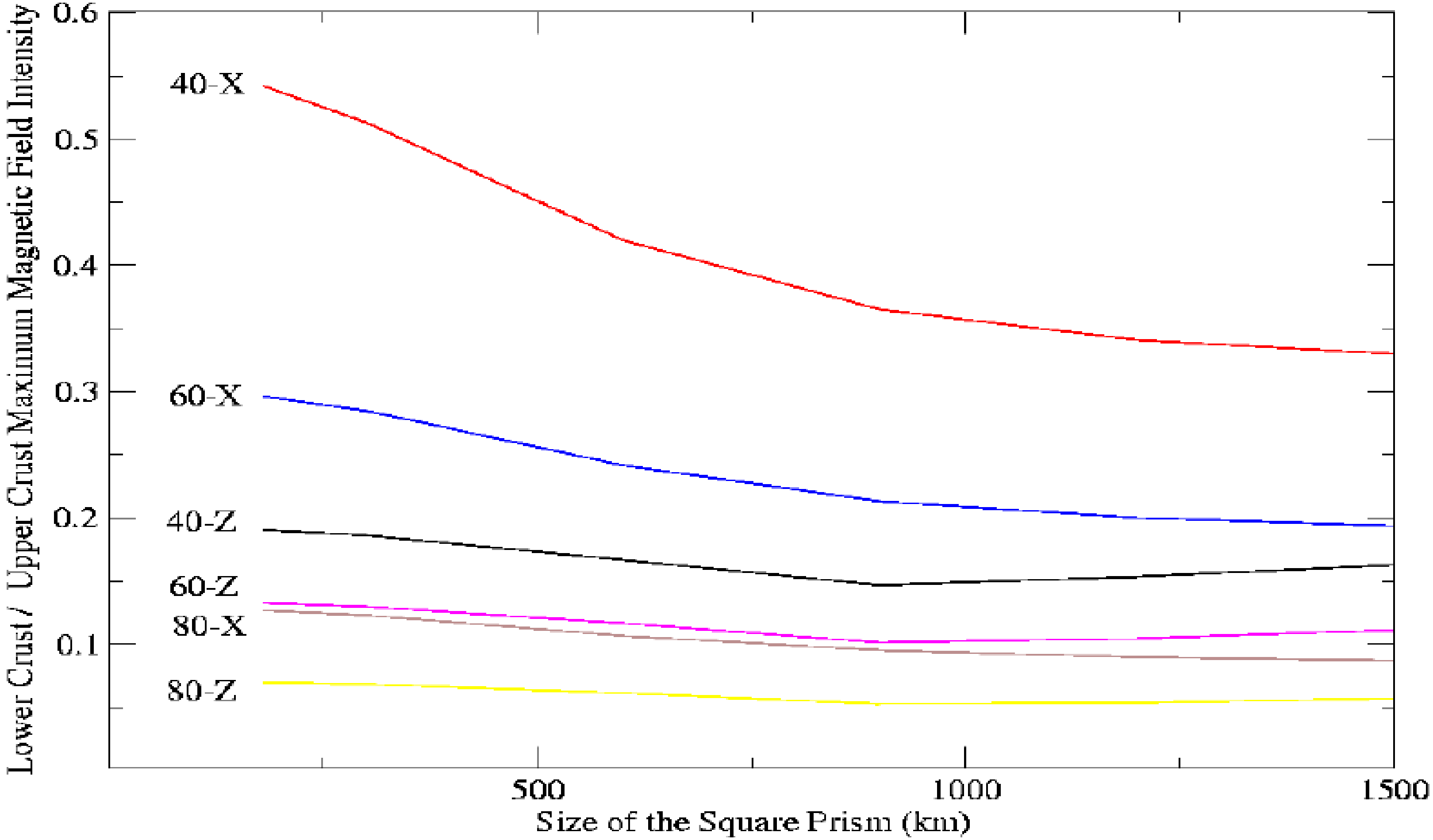
(Magnetite, Hematite, Pyrrhotite)



Magnetization of the Lower Crust by a Magnetic Prism of 50 x 600 x 600 km Located in the Upper Crust, Containing 20% Coarse Grain Hematite and Vertically Magnetized in 50,000 nT Field

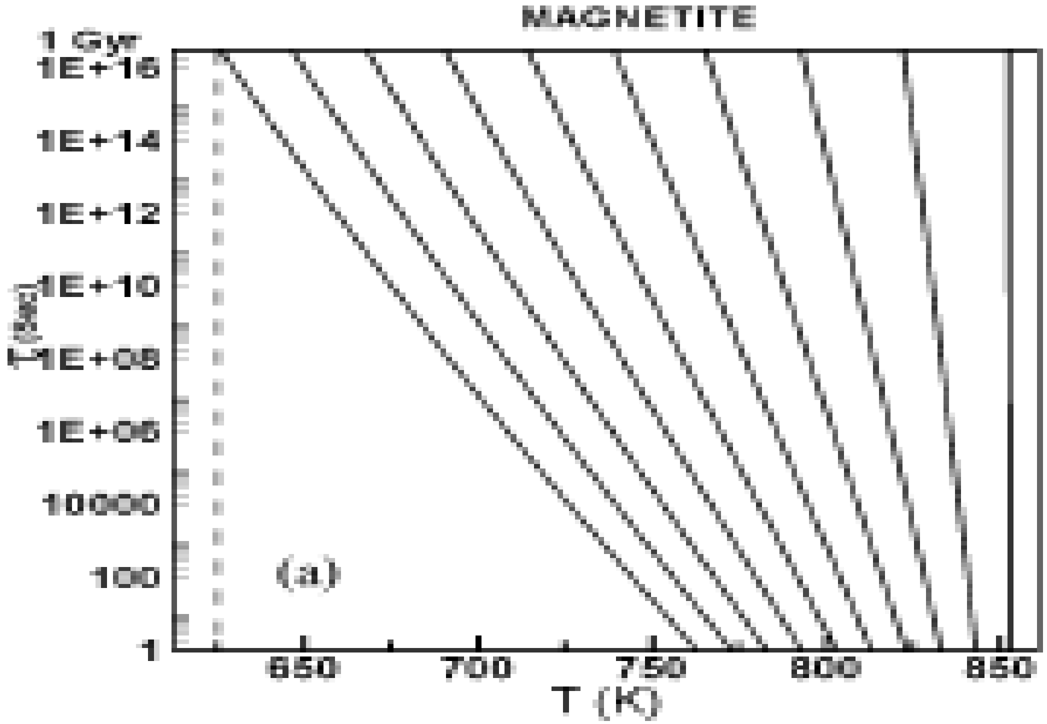


Contribution of the Lower Crust to the Observed Magnetic Field

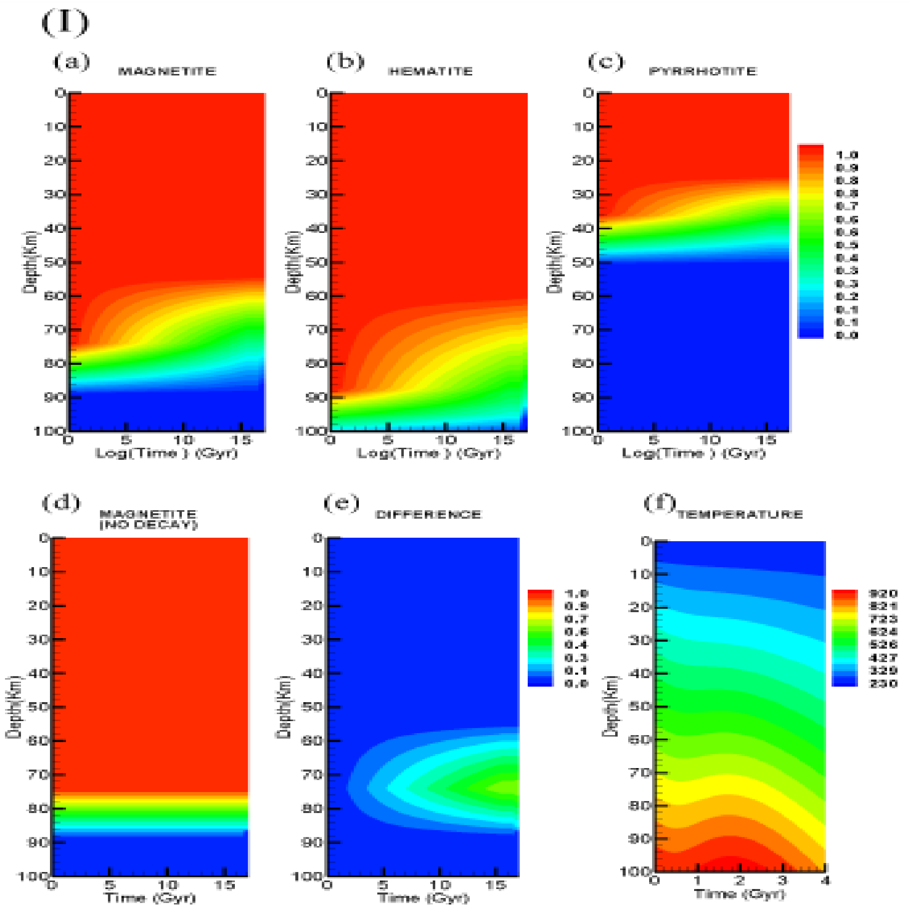


Viscous Decay of Magnetization

Magnetite Particles



Viscous Decay of the Magnetization of the Crust in the Last 4 Gyr



Conclusions - 1

- The core dynamo ceased some times before ~4 Gyr ago
- The core field of Mars that magnetized the Martian crust was likely weaker than the present core field of the Earth.
- The potentially magnetic crust of Mars ranges in thickness from 30 to 80 km, depending on the major magnetic carriers.
- Low-temperature hydration, secondary magnetization, and viscous decay have minor effects on the bulk crustal magnetization.
- Impact demagnetization is important only within the large impact basins

Conclusions - 2

Thermal evolution of a basaltic lava flow suggests:

- If SD/PSD magnetite particles formed during the initial rapid cooling of lava they might have acquired strong magnetization in the presence of the core field

- The subsequent burial heating of the lava layer does not enhance its temperature beyond the magnetic blocking temperatures of magnetite, 480-580C, until the layer reaches a depth of 30-45 km.

An olivine basaltic crust of 30 km thickness with ~1% SD/PSD magnetite grains magnetized in a 20,000 nT magnetic field is capable of explaining the strong magnetic anomalies of Mars.