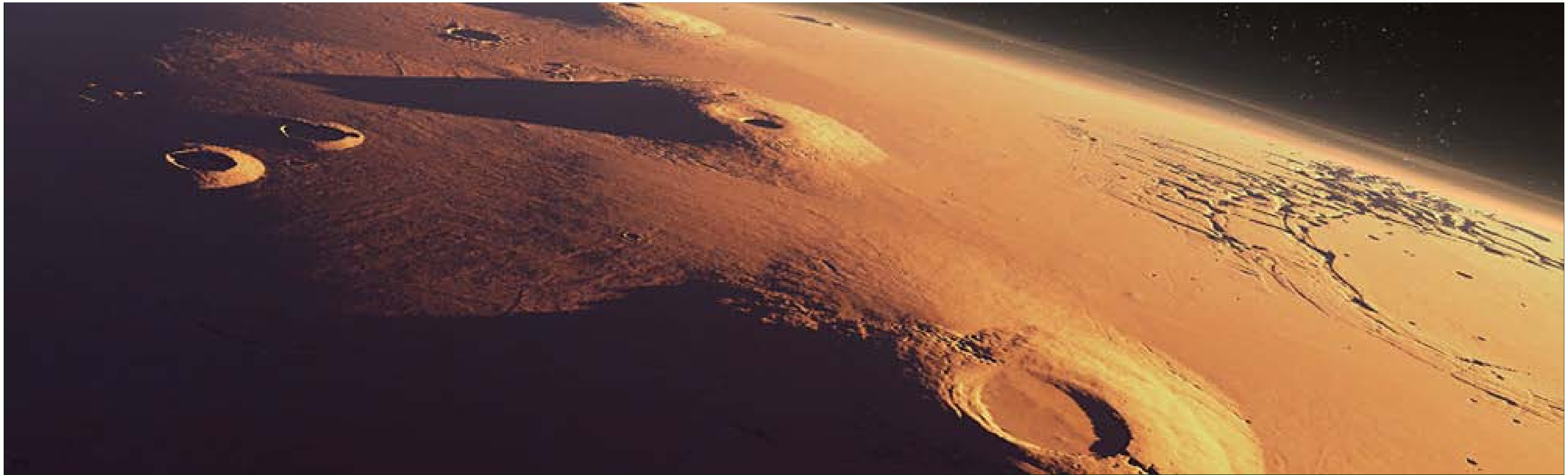


Ana Rita Baptista

Permanence du volcanisme sur Mars; Caractérisation de la Province de Tharsis par imagerie et altimétrie

Longstanding volcanism on Mars; surface and lithosphere studies of the Tharsis region using imagery and altimetry data

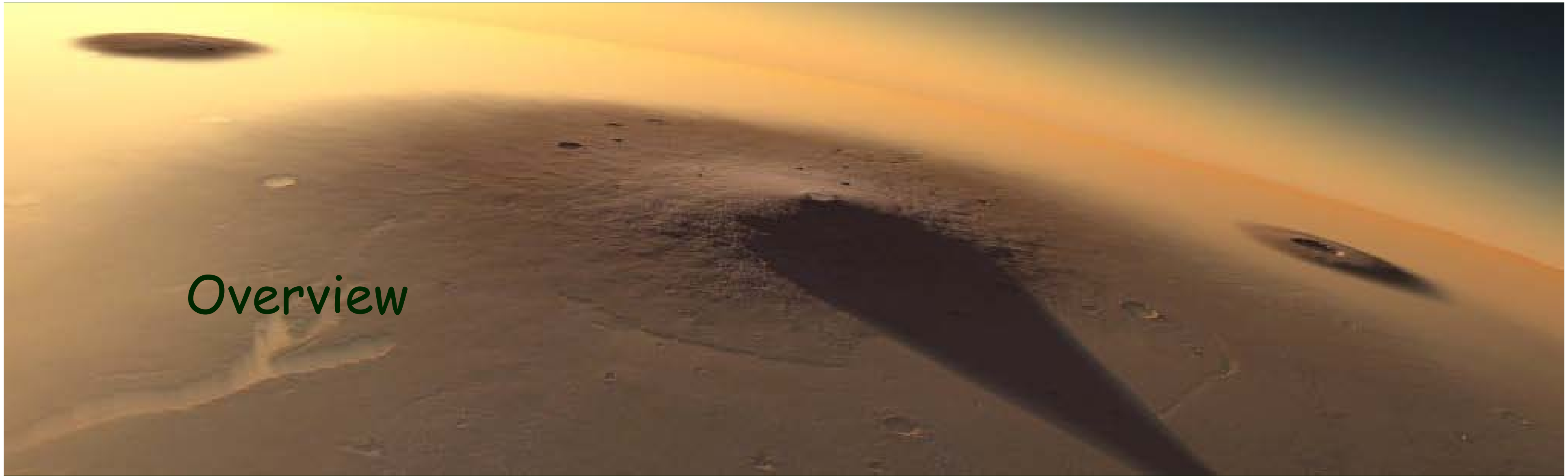
Directeur de Thèse: Philippe Lognonné

Co-Directeur de Thèse: Nicolas Mangold

Fundação para a Ciência e a Tecnologia — Ministério da Ciência, Tecnologia e Ensino Superior, Portugal

08:52

Jeudi, 12 mars 2009



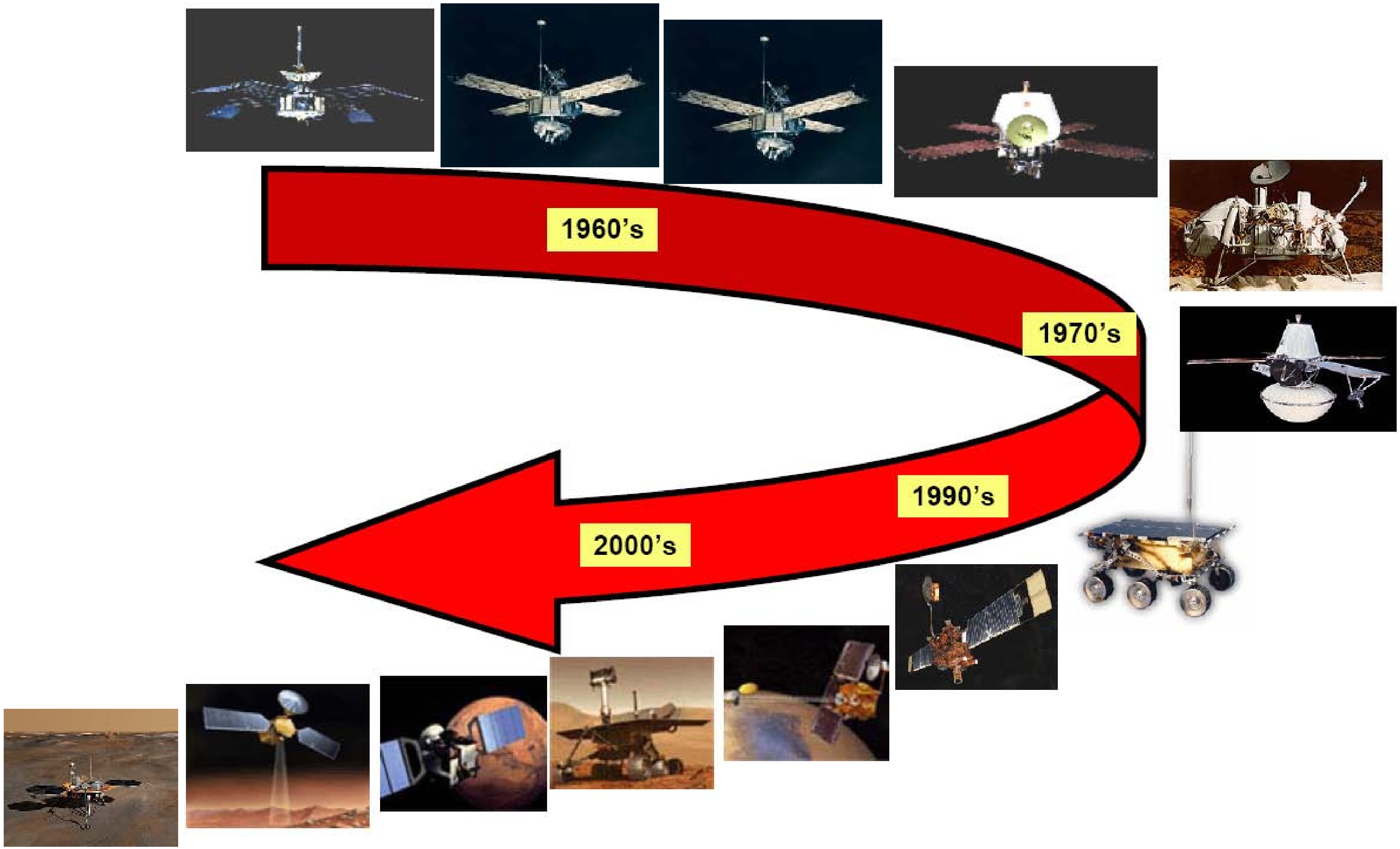
Overview

Mars Volcanism – The Link between Surface and Interior

Mars Lithosphere – Constraining the Interior and Observing the Surface

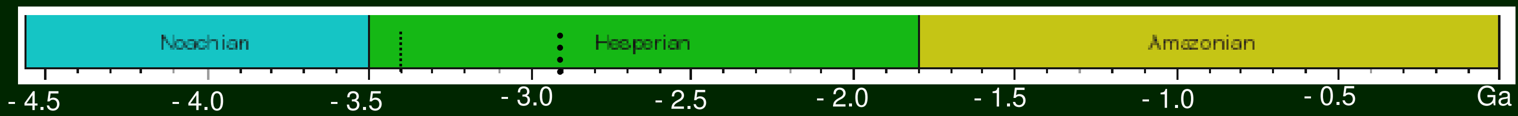
The Use of Terrestrial Analogues in Mars Surface Science – Further Work

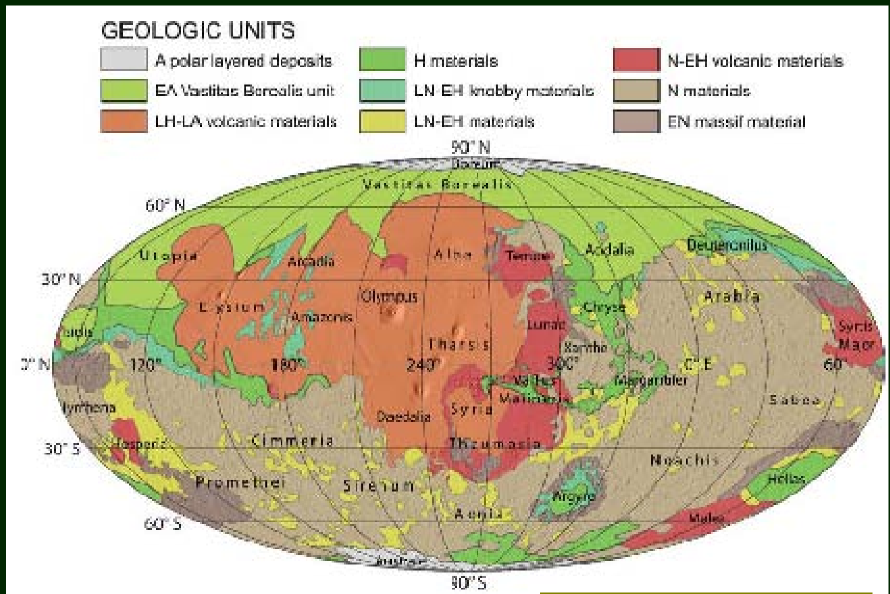
THE SUCCESSFUL MISSIONS TO MARS



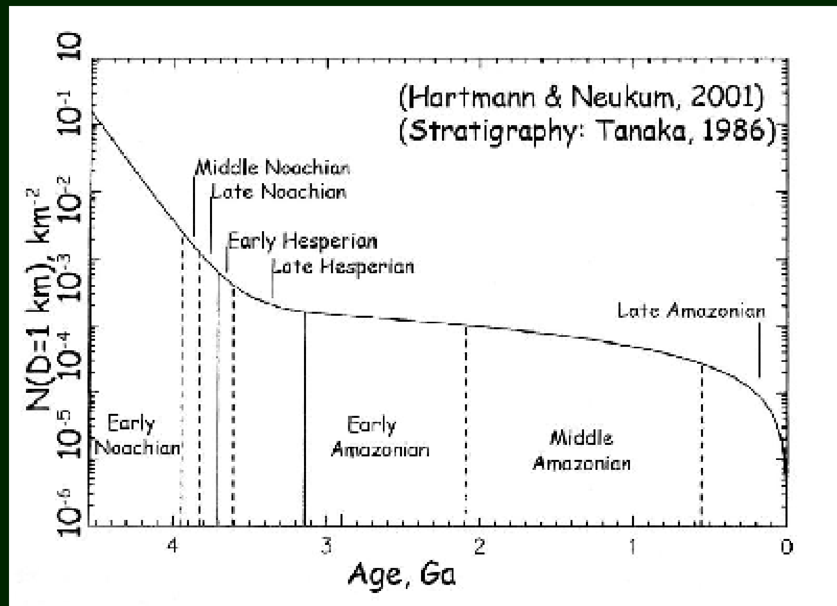
Geological point of vue:

- High hemispheric dichotomy; younger North vs high cratered South
- Crater Density Measurements – Noachian, Hesperian, Amazonian
- Uncertainty in age determination; resurfacing?



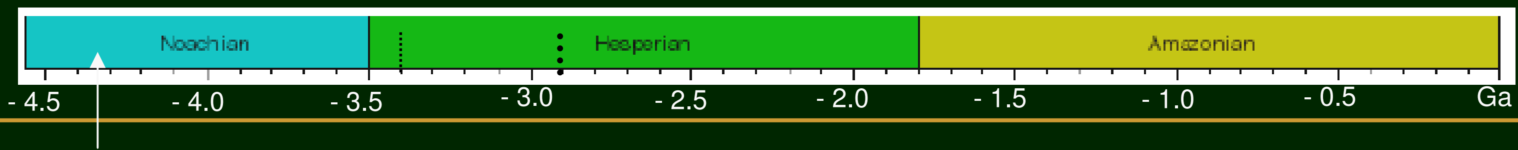


Nimmo and Tanaka, 2005



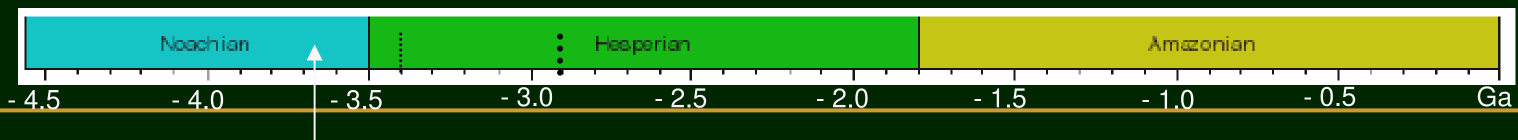
The Early Mars

- Mars forms
  - Accretion and core formation in about 20-30 Ma (Halliday et al., 2001)
  - Crust forms from magma ocean in the first 0.5 Ga (e.g. Elkins and Parmentier, 2004)
  - ALH84001 crystallizes at ~4.5 Ga (Kring and Gleason, 1997)
- Crust develops asymmetry
  - Perhaps due to degree-1 mantle convection (Zhong and Zuber, 2001)
- Core-Dynamo switches off
  - Magnetic remnants frozen in to crustal rocks (Connerney et al., 1999)



Early Mars *(cont.)*

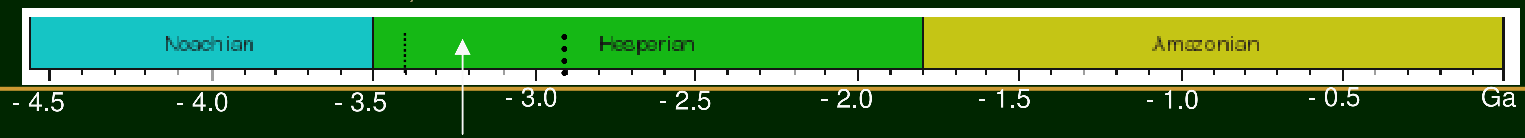
- Major impact basins form (heavy bombardement dominates)
  - Both hemispheres are heavily cratered
  - Remnant magnetism erased over large basins (Langlais et al., 2004)
- Tharsis rise is constructed
  - Vigorous volcanism outgasses significant atmosphere
  - Polar wander (Arkani-Hamed 2001)
- Valley networks form
  - Orientation controlled by pole-to-pole slope and Tharsis bulge (Phillips et al., 2001)
  - Erosion rates orders of magnitude higher than Hesperian or Amazonian epochs (Golombek et al., 2007)
  - Strong greenhouse needed to offset faint young sun (Kasting et al., 2006)
  - Lack of carbonates from greenhouse atmosphere still unsolved



Middle Mars

A time of transition from fluvial activity to cold/dry conditions

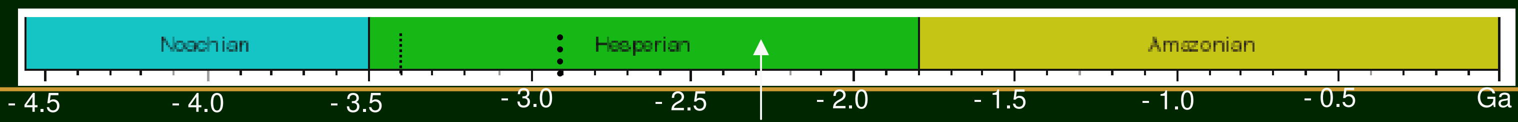
- Change in alteration chemistry
  - Phillosilicates → Sulfates → Anhydrous ferrous chemistry (Bibring, 2005)
- Erosion rates drastically reduced
  - Reduction in atmospheric greenhouse → less available water
- Liquid water turning solid
  - First evidence of polar ice caps
  - Thickening cryosphere
- Water appears in flood outbursts rather than being permanently present (Hoffman and Tanaka, 2002)



Middle Mars *(cont)*

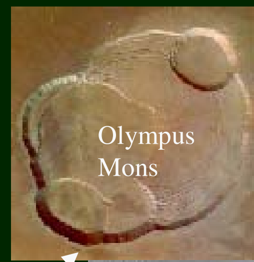
Massive volcanic resurfacing and tectonic activity

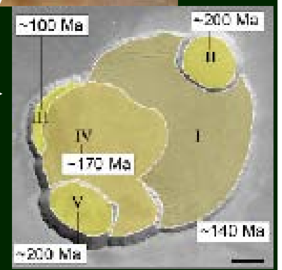
- Plains volcanism resurfaces large areas
  - Presence of SO2 may change chemical alteration of the surface (Craddock and Greeley, 1994)
- Paterae volcanoes
  - Vigorous volcanism outgases significant atmosphere (Halevy et al., 2007)
- Wrinkle ridge formation (Parmentier, 2004)
- Circum-Tharsis extension
  - Opening of Valles Marineris (Andrews-Hanna, 2009)
- Late Hesperian-Early Amazonian – building of the big Tharsis shield volcanoes (Hauber and Neukum, 2004)

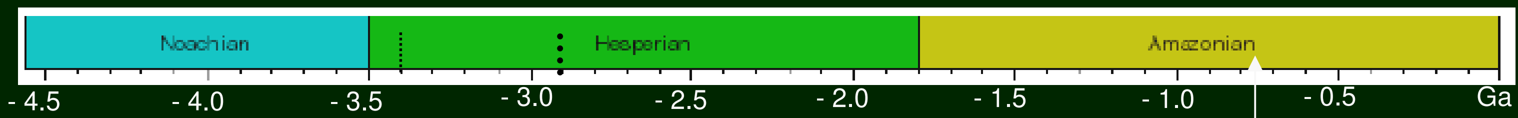


Current Mars

- Cratering continues at a steady (and slow) pace
  - Small crater production during the MGS mission (Hartmann et al., 2002)
- Volcanic activity in the recent past (Ma?)
  - Volcanic resurfacing low in comparison to previous rates
  - Apparent activity in 100 and 200 Ma (Neukum et al., 2004)
- Martian methane
  - Constantly renewed in the atmosphere (Encrenaz, 2006)
  - Post hydrothermal decomposition or biologic source?







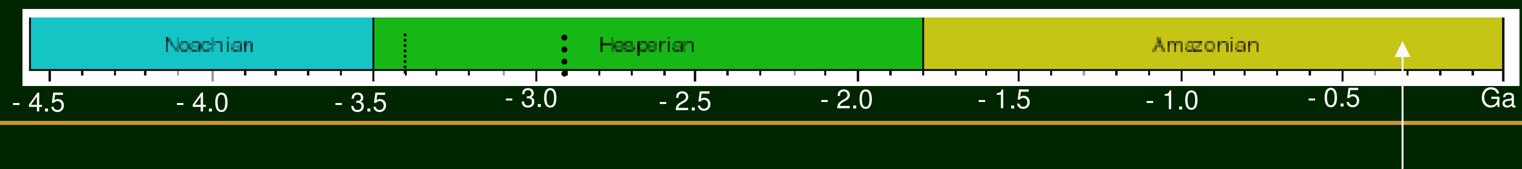
Current Mars *(cont)*

Mid-latitude Deposits

- Transport of material from pole to mid-latitudes
  - Gullies (Heldmann at al., 2005)
  - Flow features (Milliken et al. 2003)
  - Ground ice (Hartmann et al., 2009)

Polar Deposits

- Climatic record of 10^{ths} Myr (Cutts and Pollack, 2002)
- Annual changes in ice caps
  - No climate change implied (Smith and Zuber, 2003)



MARS VOLCANISM
THE LINK BETWEEN SURFACE AND INTERIOR

✓ Volcanic activity is the surface expression of interior processes
✓ Data more precise – better constraints to build thermal evolution models

Key questions at global scale (Objectives):

✓ 1st: What was the sequence, intensity and spatial distribution of Volcanic-tectonic Tharsis-related events?

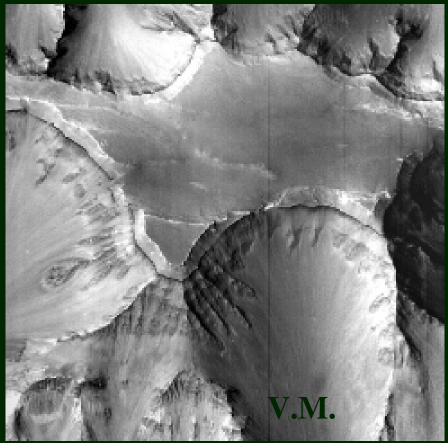
✓ **2nd:** How is this related to the surface structure and the thermal evolution of Syria Planum?

✓ What are the similarities and dissimilarities in terms of sources and style between these Martian and terrestrial analogues?

THARSIS PROVINCE, MARS
GEOLOGICAL & GEOPHYSICAL OBSERVATIONS

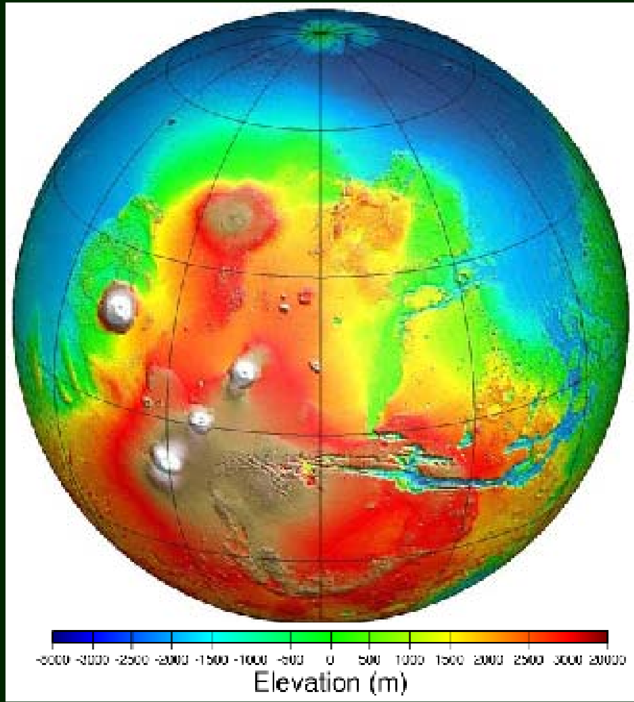
- Tharsis- **Broad topographic rise & centre of large scale magmatism**
  - Shield volcanoes: Tharsis Montes, Olympus Mons
  - Layered volcanics in Valles Marineris [McEwen et al., 1999]

Olympus Mons



V.M.

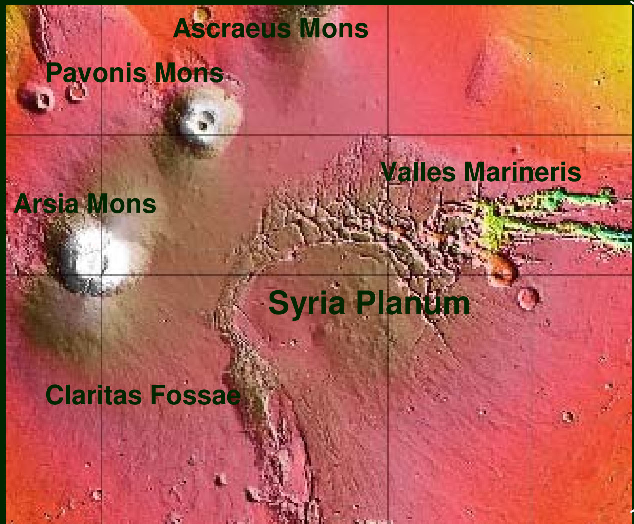
MOLA

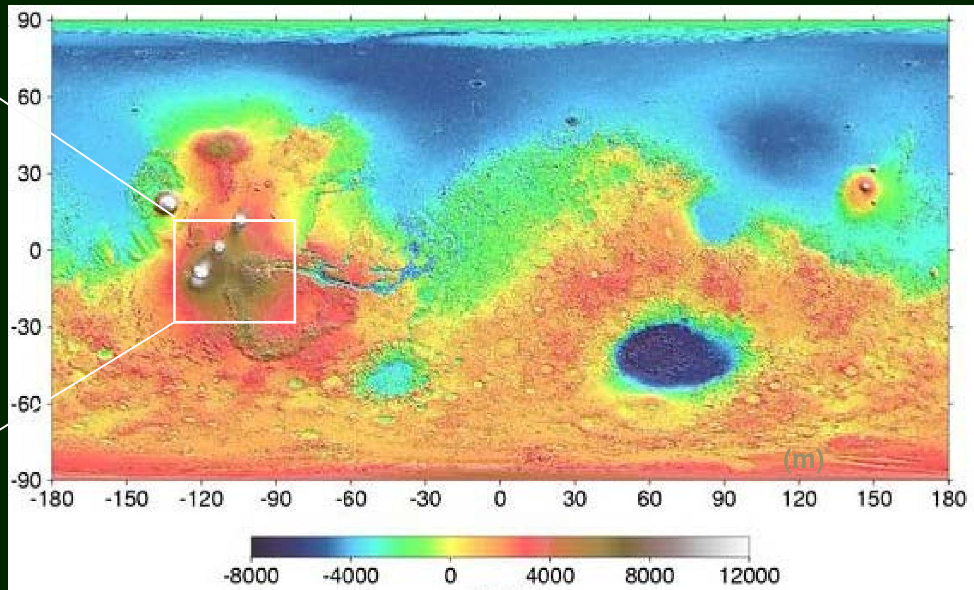


- **Geoid-Topography Ratio consistent with surface loading & flexure of lithosphere** [Zhong & Roberts, 2003]
  - Thick complex crust [Zuber, 2001]

A UNIQUE VOLCANIC TYPE – SYRIA PLANUM, MARS

✓ Placed on the surrounding of Tharsis

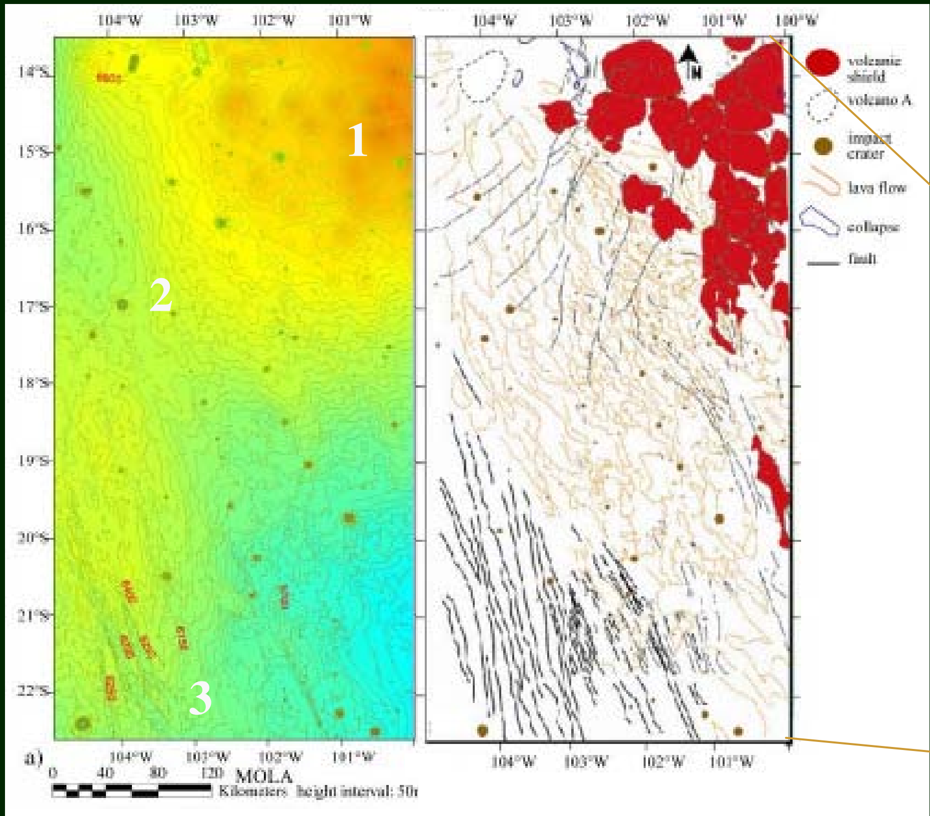


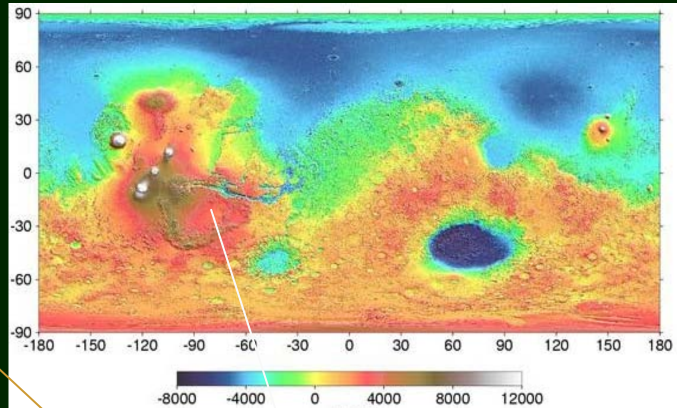


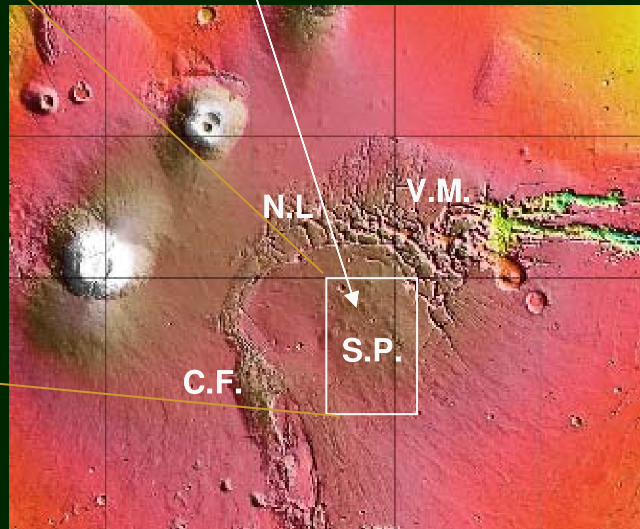
Key questions at local scale:

- ✓ What are the volcanic occurrences on Syria Planum? What type of volcanoes do we find? How were they formed?
- ✓ What are the time-frames for the lavas eruption?
- ✓ During what period of the Tharsis growth did Syria Planum form ?
- ✓ Is Syria Planum related to the Tharsis main Formation?

PLAINS STYLE VOLCANISM – volcano growth?





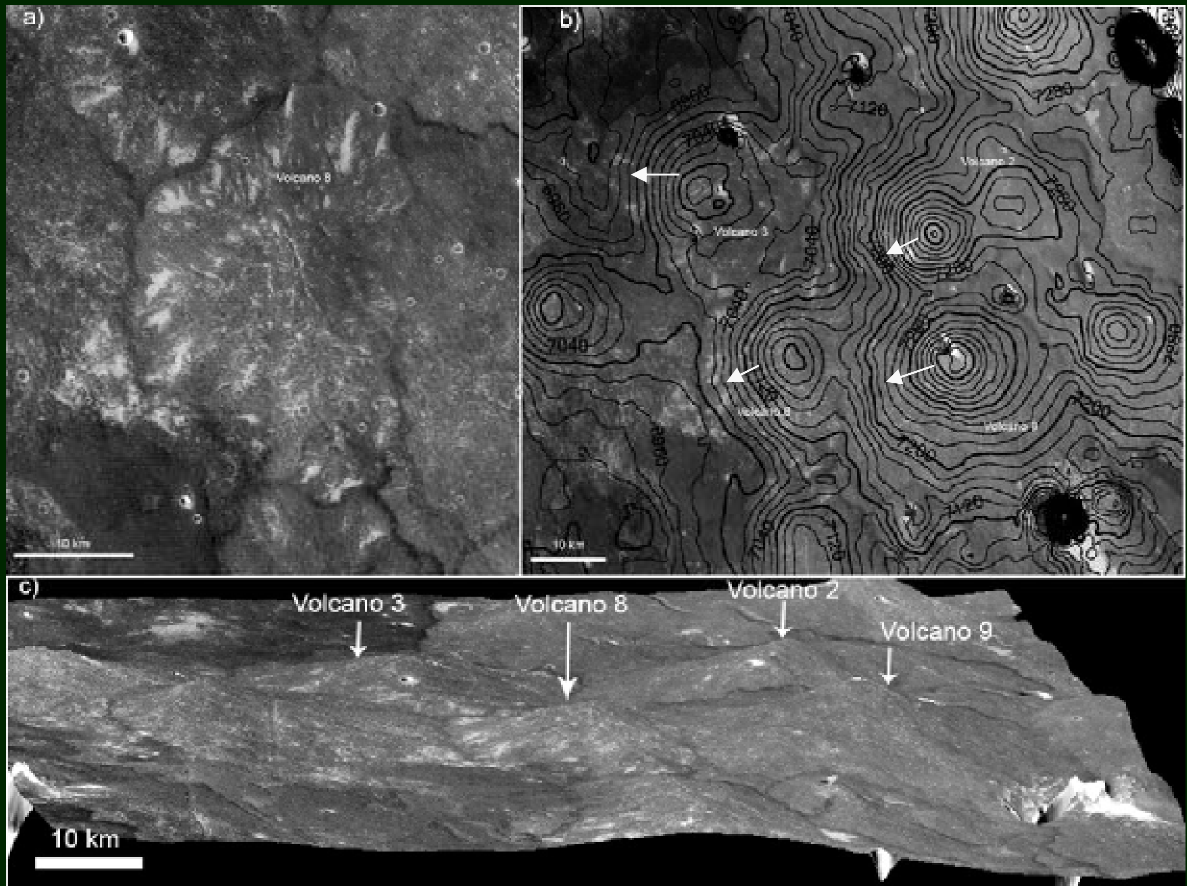


[Baptista et al., *JGR*, 2008]

1) Small Shields
2) Lava Flows
3) Fractured Lava Terrains

- 450 km – 700 km wide Plateau
- Placed at ~6000 – 7000 m high, forming a dome

1) COALESCED SMALL SHIELD VOLCANOES ON SYRIA PLANUM



[Baptista et al., *JGR*, 2008]

HRSC

Scaled pixel width:
~15 meters

• Small shield volcano: small constructional feature formed by the eruption of lava from a central vent

• Usually have conical shape:
Eccentricity : 0.4 (N) - 0.9 (S)

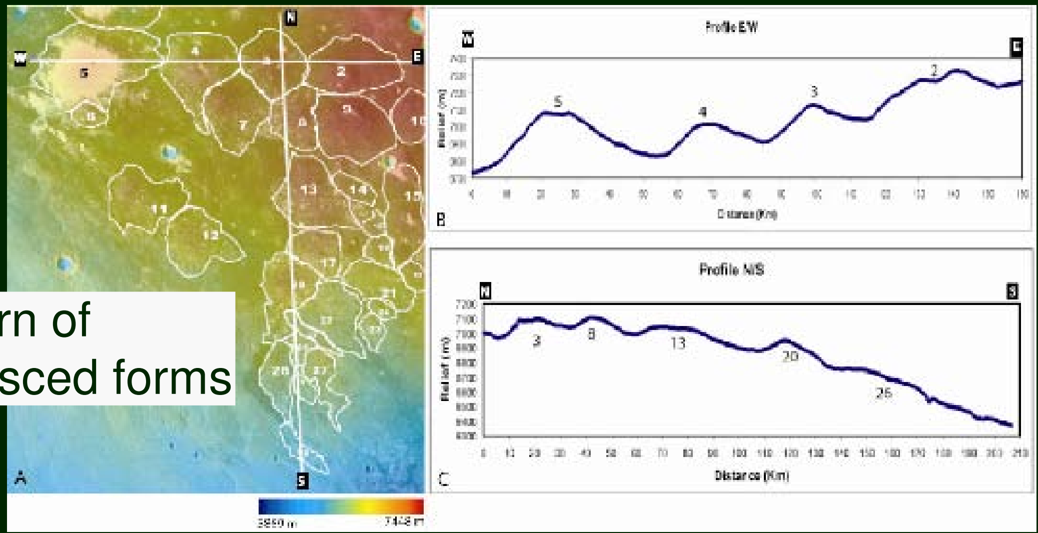
MOC

Longitude of image center:
100.31°W

Latitude of image center:
16.22°S

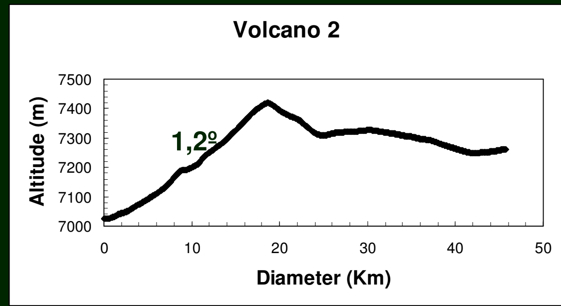
Scaled pixel width:
236.82 meters

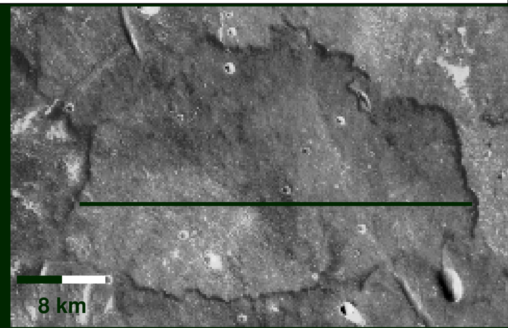
SMALL SHIELDS MORPHOLOGY - Shape

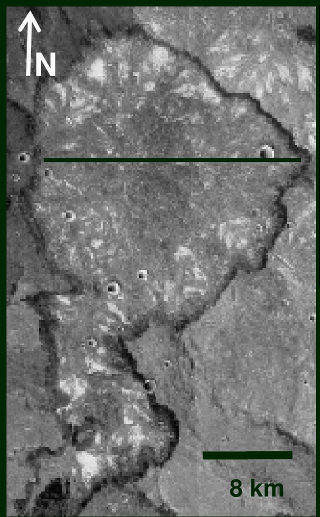


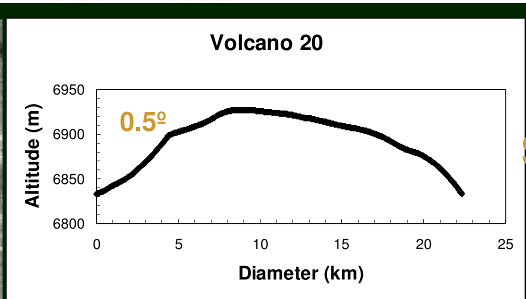
Pattern of coalesced forms

[Baptista et al., *JGR*, 2008]

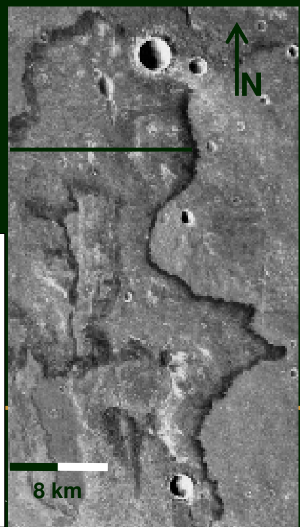


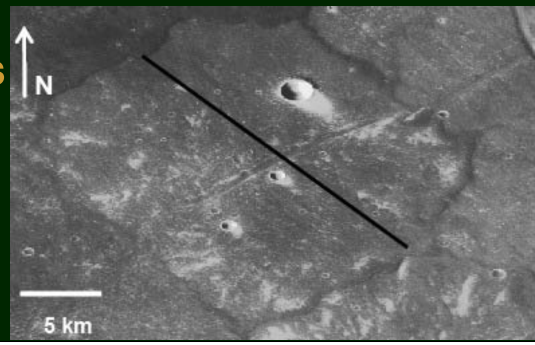


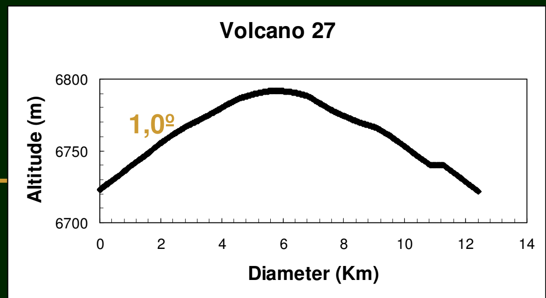


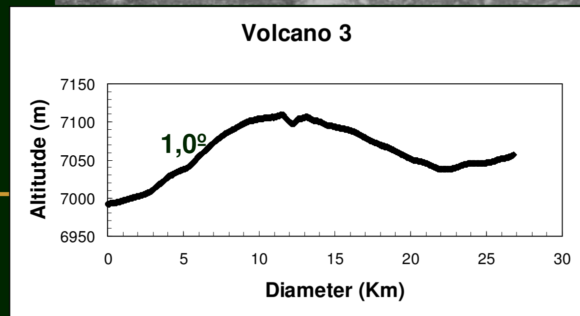


Small Volcanic features

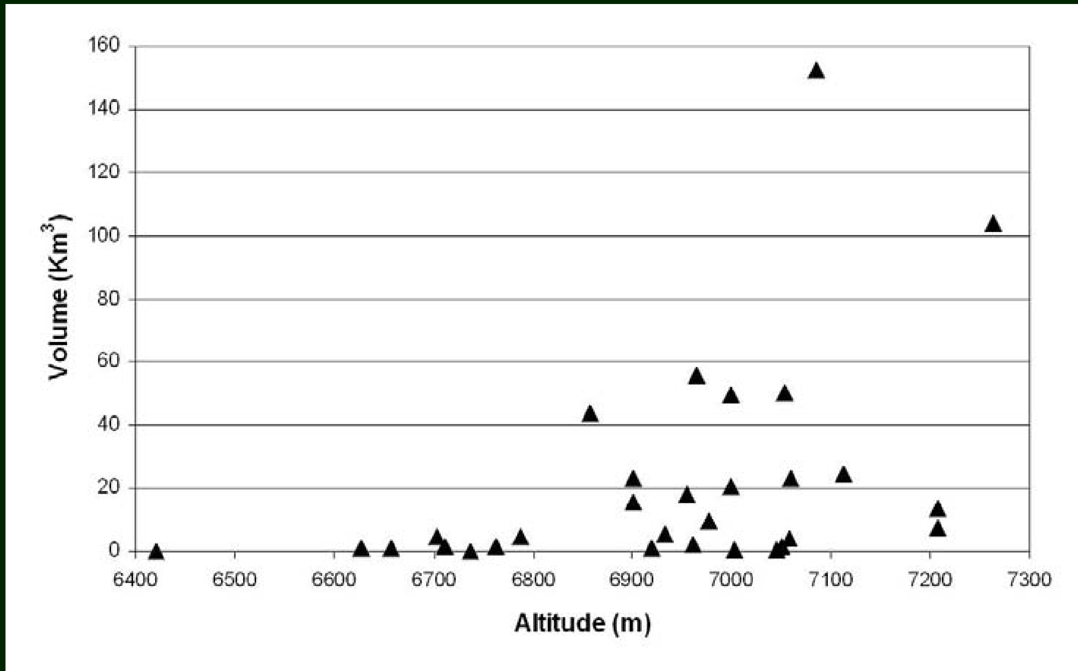








Distribution of Syria Planum small shield volcanoes' volumes according to their summit altitudes.

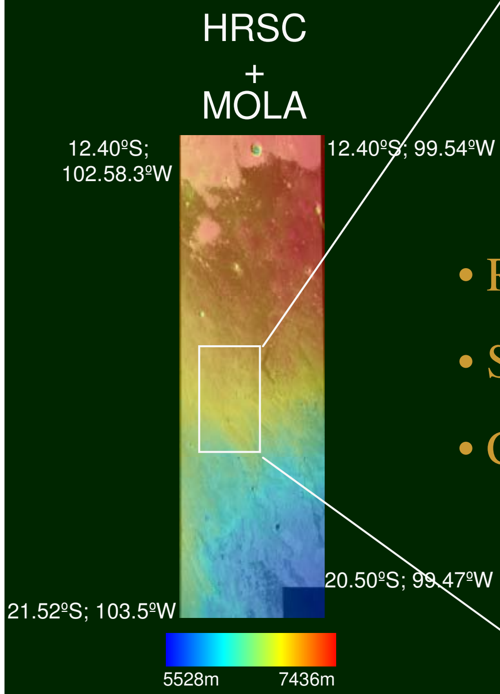


- The Volume (V) was calculated, assuming a conical shape, using: average relief (h) and W–E basal width (2r):

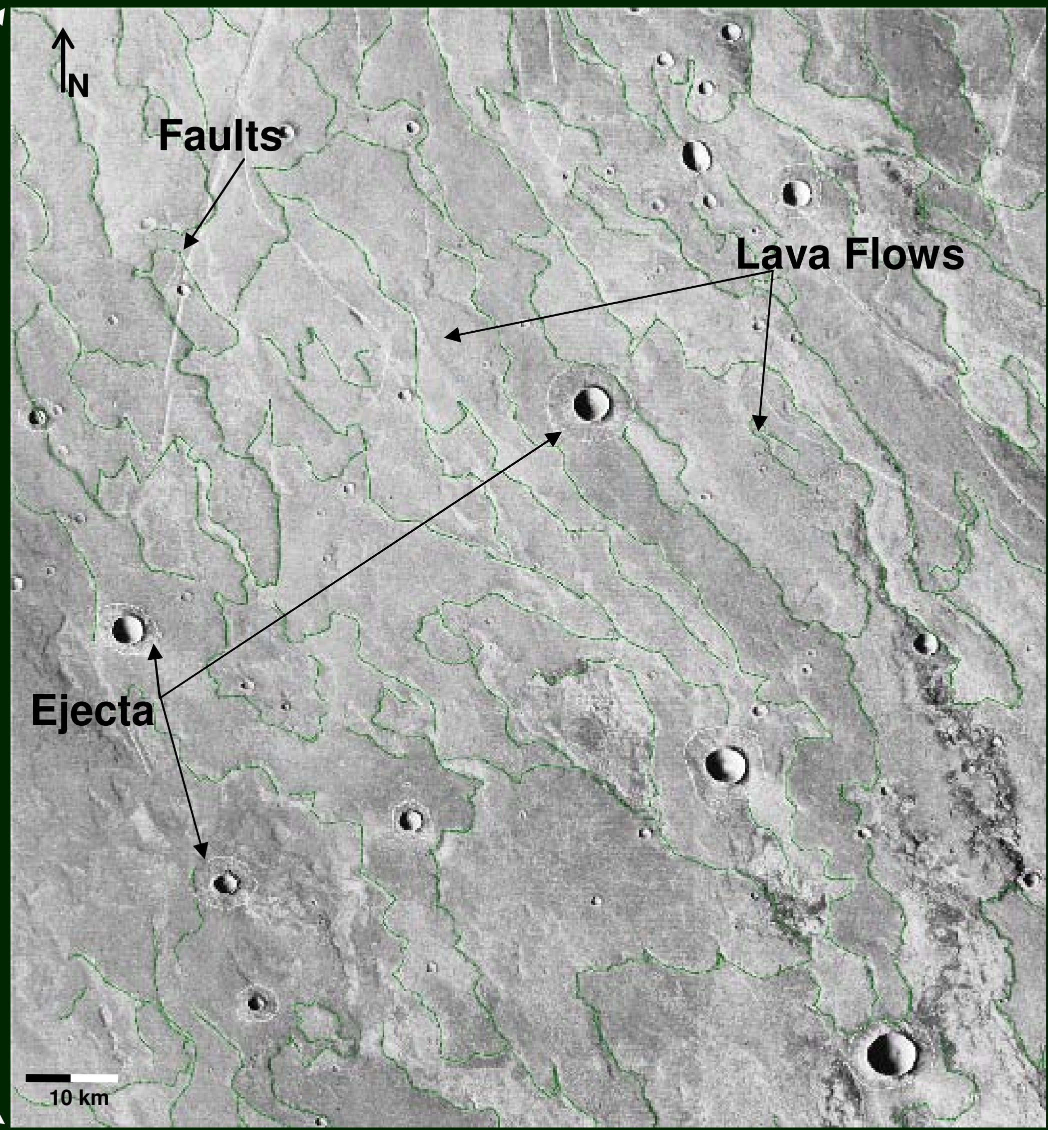
$V = 1/3\ \pi\ r^2\ h.$

- It is observed a general tendency for the volcanoes with higher volumes of lava to concentrate at higher altitudes, on the North.
- The volume of volcanic edifices ranges from 0.2 to 152.7 km^3

2) LONG LAVA FLOWS ON SYRIA PLANUM



- Rheology
- Shape
- Contacts



Initial Newtonian viscous spreading till Bingham behavior

$$Q = \frac{G_z k x w}{b}$$

Effusion rate → **Emplacement time:**

140 days in average, with a maximum of 700 days

= Arsia Mons [Warner and Gregg, 2003]

Ascraeus Mons - 18-60 m^3s^{-1} and a mean value of 35 m^3s^{-1}, from Zimbelman [1985]

Olympus Mons 400 m3s-1, from Zimbelman [1985]

Hawaii Shields: 10^{ths} m^3s^{-1} Hulme [1976]

$$\frac{Q}{w} = \frac{b^3 \rho g' \sin(\theta)}{3\mu}$$

Viscosity

Basalts on Earth : $10^2 - 10^7$ Pa.s

$$\sigma_s = \rho g b^2 / w$$

$$\sigma_s = \rho g b \sin\theta$$

Yield stress

Similar to Basaltic to Andesitic lava flows on Earth

Q = Volume flow rate (effusion rate)

Gz = Graetz dimensionless number

k = thermal diffusivity (m^2s^{-1})

x = flow length (m)

b= thickness of the flow (m)

w = width of the flow (m)

g = gravity for Mars

θ = slope (º)

ρ = density (kg m^{-3})

Table 2. Geometric and Rheologic Parameters Measured From Topographic Data From Profiles on 10 Lava Flows

	Length (m)	Thickness (m)	Width (m)	Slope (°)	Effusion Rate (m^3 s^{-1})	Viscosity (Pa s)	Yield Stress (Pa)
Minimum	45×10^3	15	5×10^3	0.15	990	6.89×10^5	–
Maximum	200×10^3	70	15×10^3	1	6,075	4.23×10^6	–
Mean	150×10^3	34.5	9.4×10^3	0.2	3,300	–	1.2×10^{3}[a]

[a]Lengths between 100 and 200 km and thicknesses between 15 and 70 m were used. The mean value for the smaller size lavas is 7.9×10^2 and 1.7×10^7 for the larger ones.

[Baptista et al., *JGR*, 2008]

Relatively High Ψ
(resistance of lava flow against cooling)

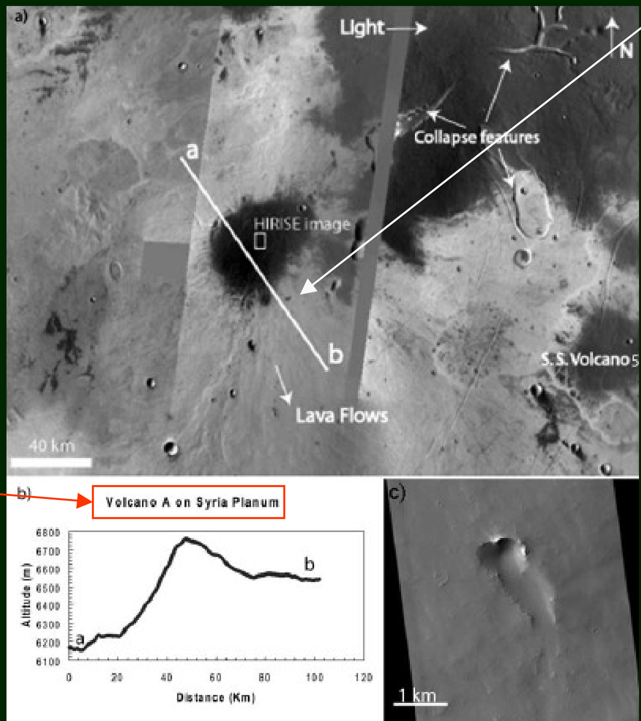
↓

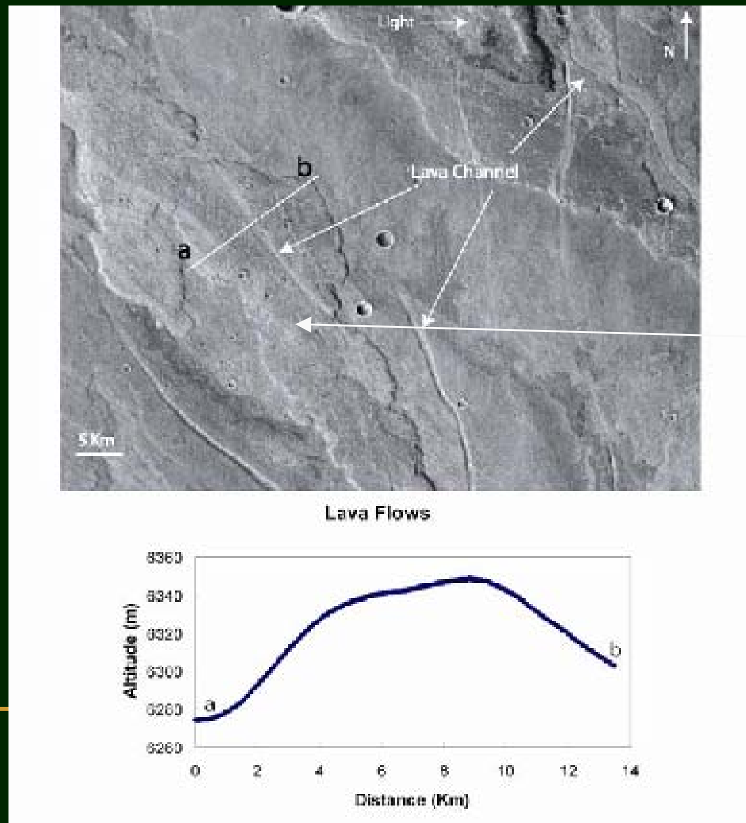
Levees upstream + flatter downstream

↓

High effusion rate and low viscosity

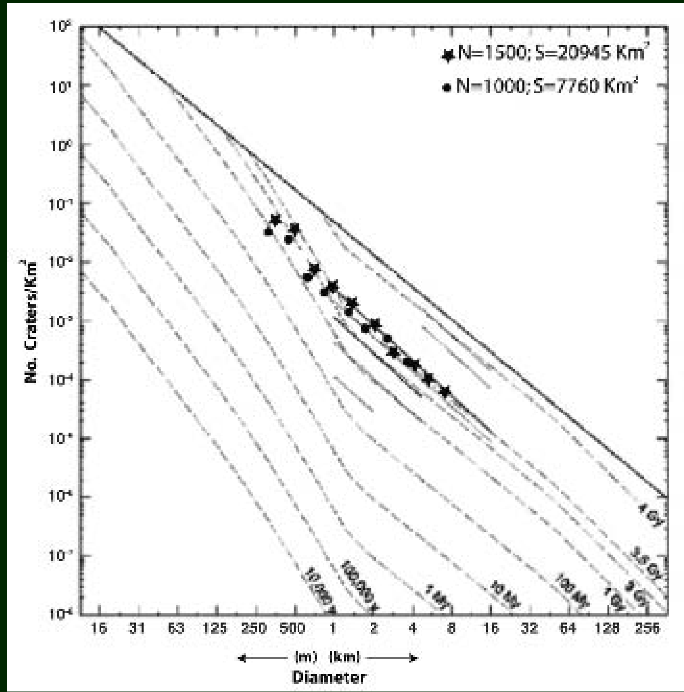
Upstream





Downstream

[Baptista et al., 2009a, in prep.]



Size-frequency distribution of craters = relative ages

↓

Craters density + cratering rate = absolute ages

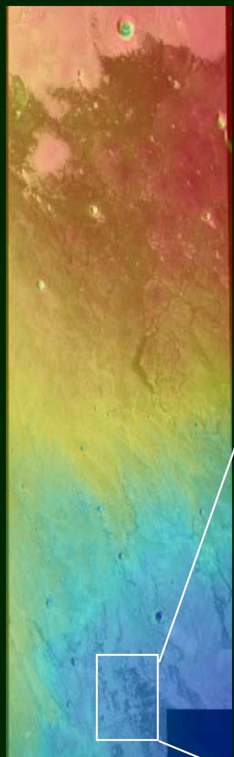
3.6 Ga – Lava Flows

3.5 Ga – S.S.V.

- Crater distribution over the studied Syria Planum lava flows and shield volcanoes.
- Isochrones are plotted according to Hartmann et al. (2000).
- Craters >250m diameter
- Ages associated with the isochrones are given by the lunar rates modulated by a ratio of R=1.6 corresponding to the ratio between the crater production function on Mars and the same rate on the Moon. These could all correspond to Hesperian ages.
- Dots correspond to volcanoes ages, associated with a surface of 7760 km^2.

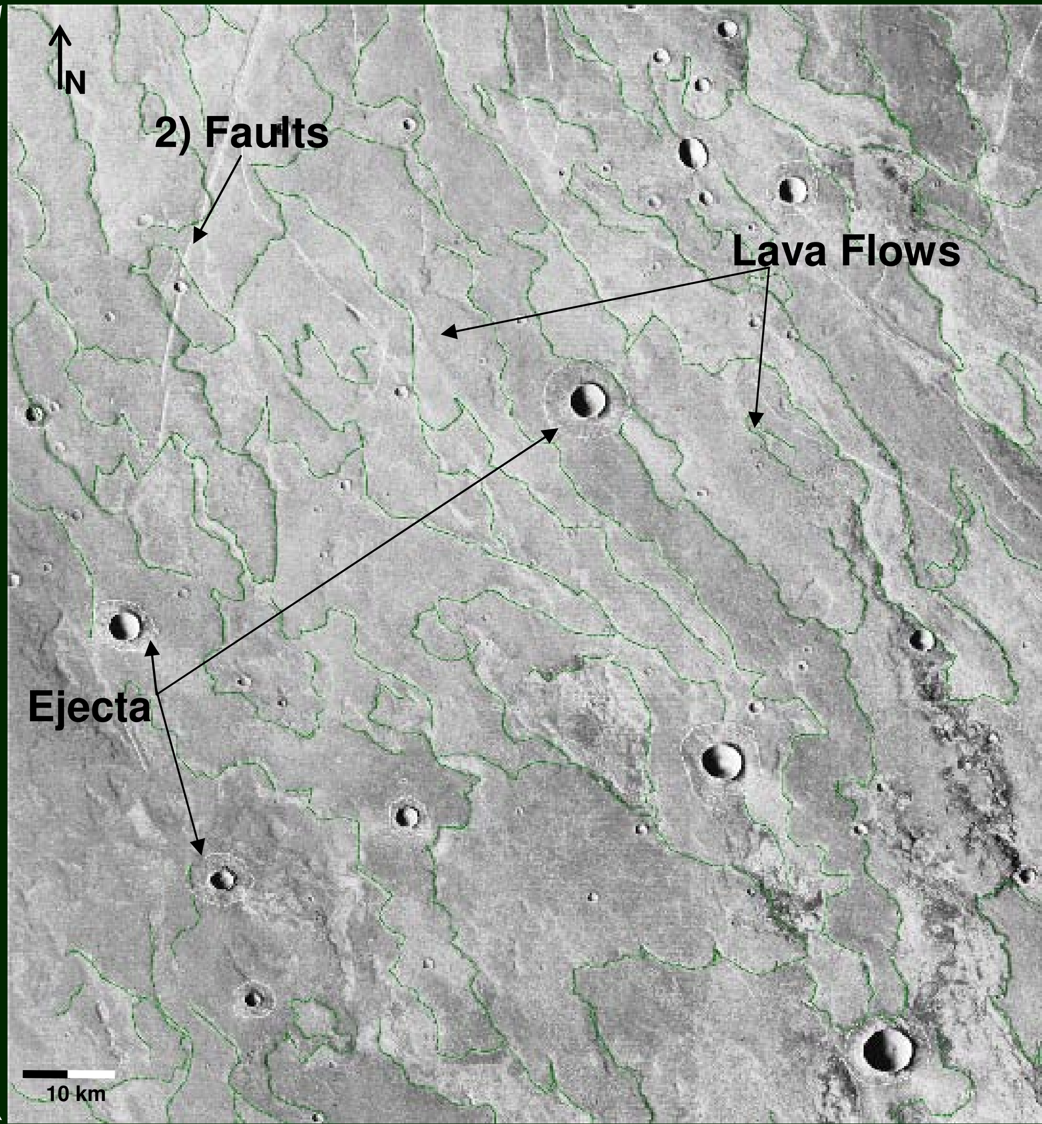
3) Grabens and Fissures on Syria Planum

1) Radial grabens NW/SE
2) Faults NE/SW
3) Fissures NW/SE



1) Radial grabens NW/SE
2) Faults NE/SW
3) Fissures NW/SE

HRSC
+
MOLA

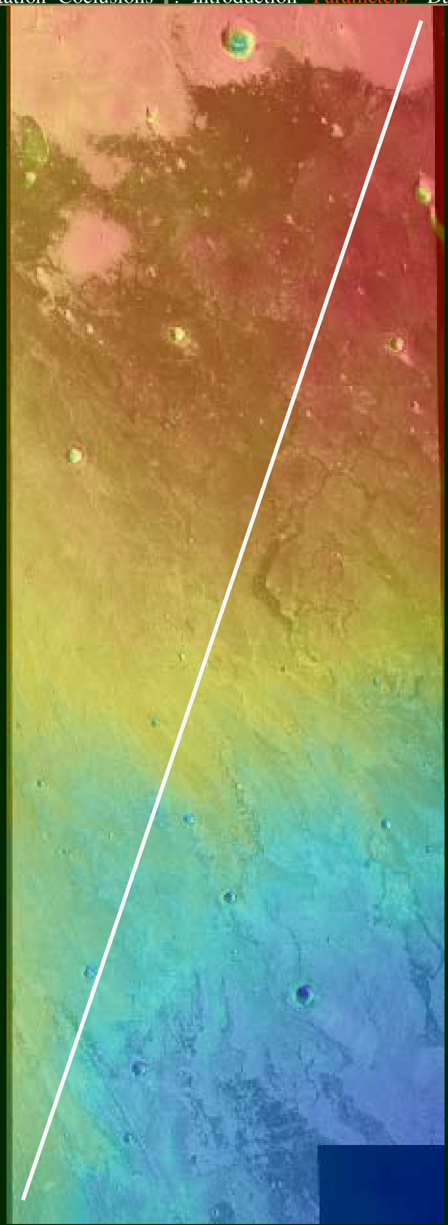


Syria Planum

HRSC

+

MOLA



Profile NE/SW

MOLA

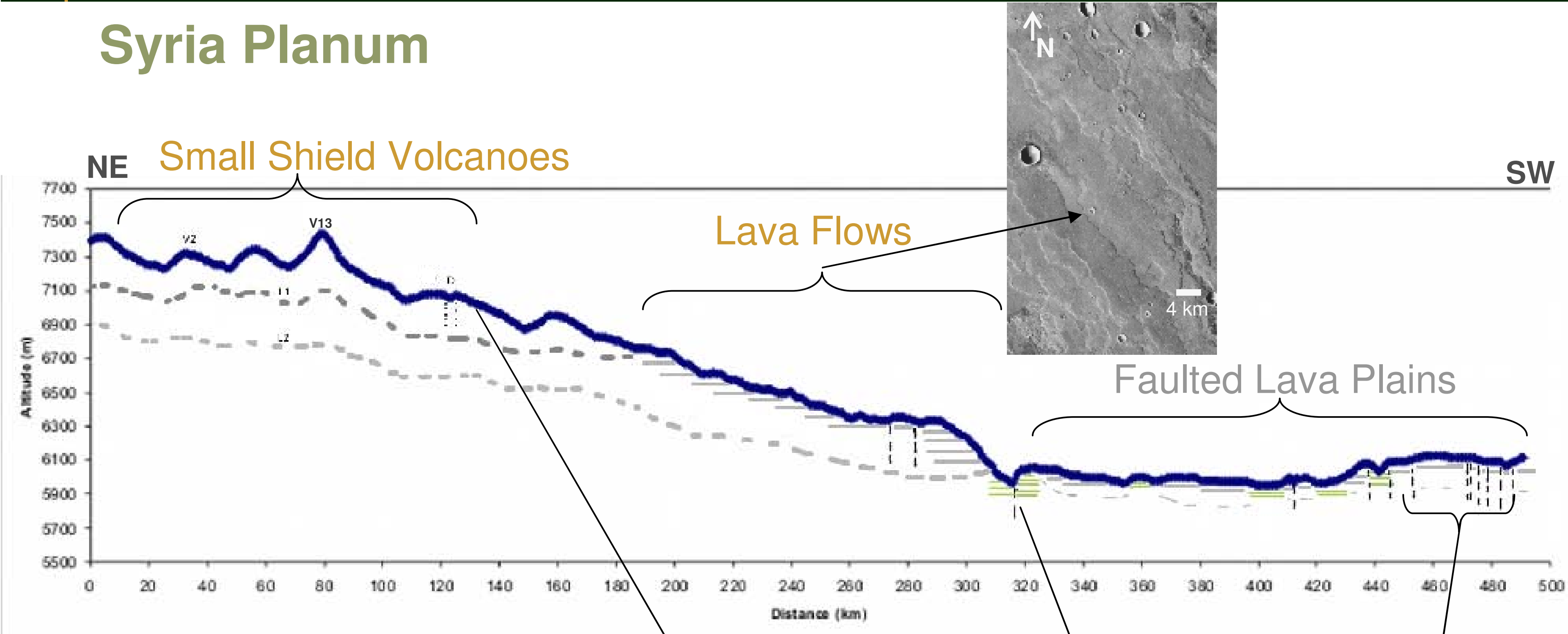
~400 m/pixel

5528m 7436m

HRSC

15 m/pixel

Syria Planum



Legend:

V2: Small Shield Volcano 2

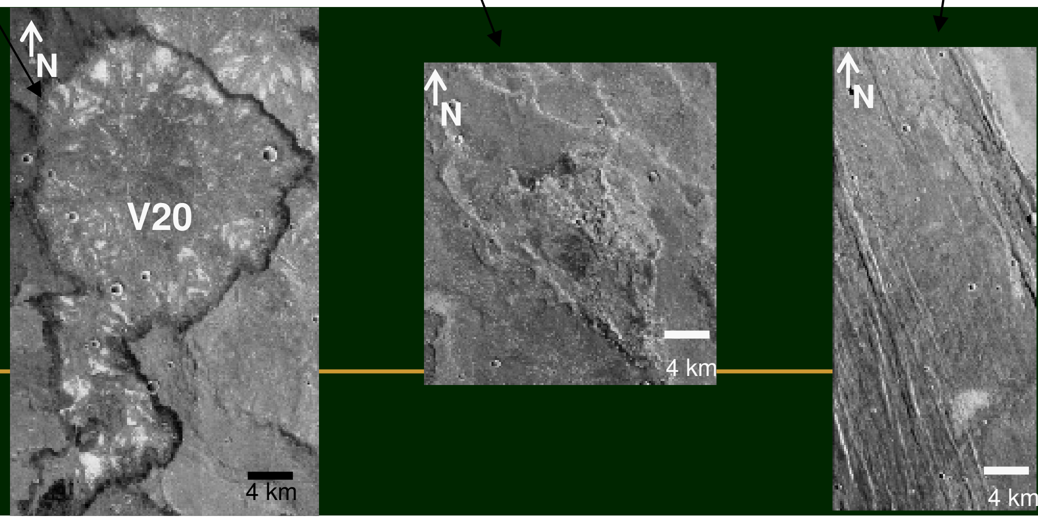
VJ: Small Shield Volcano 13

V9: Small Shield Volcano 20

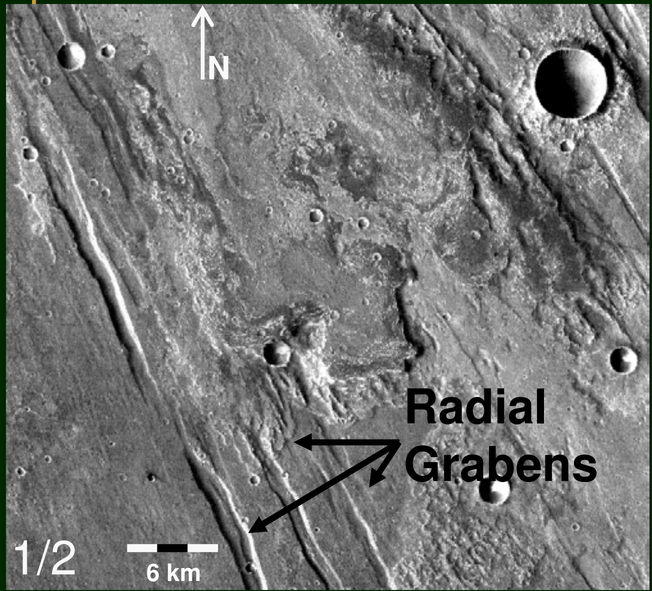
D: Dike

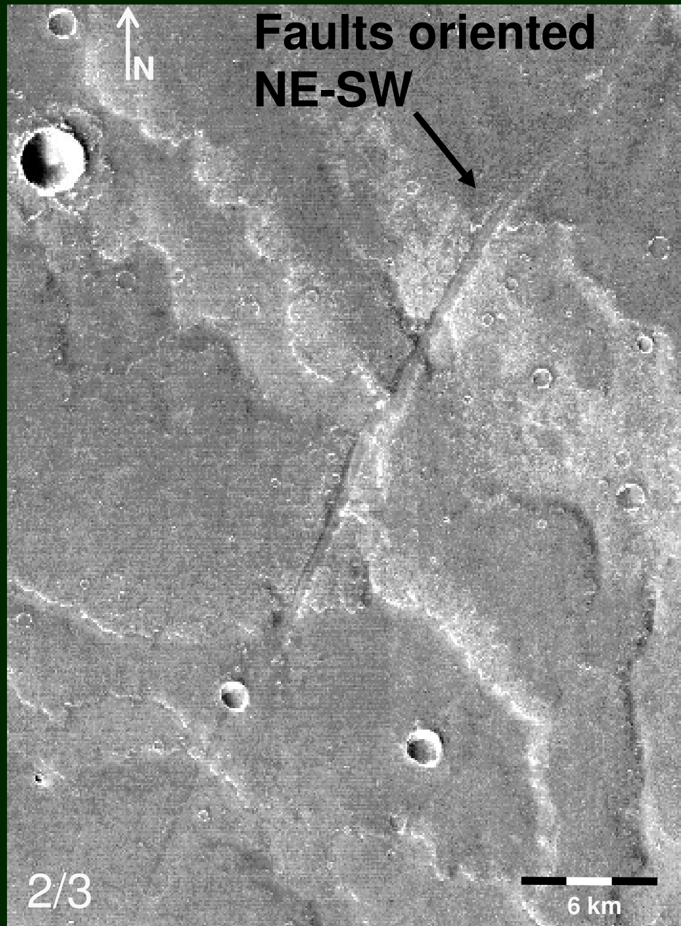
L1: Possible inferior limit for the shield volcanoes

L2: Possible inferior limit for the lava flows

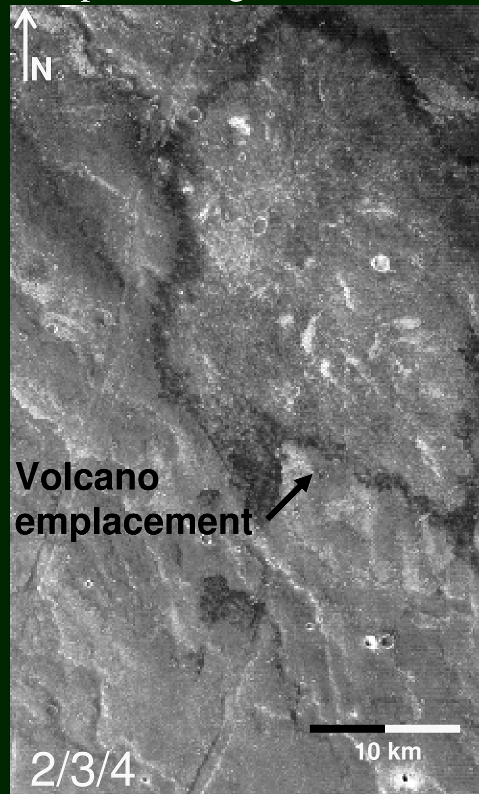


[Baptista et al., *JGR*, 2008]





4) New episodes of volcanic activity, the coalesced small shields that bury preexisting faults



We may constrain the formation of the Syria Planum due to successive magmatic and tectonic events, from the Early to the Late Hesperian period:

1) Opening of a graben swarm.

2) Volcano A erupted and the lavas are spread over Syria Planum.

3) Tectonic deformation of the emplaced lava flows by the formation of several fractured patterns such as NW/SE en-echelon faults, troughs and adjacent grabens.

Syria Conclusions

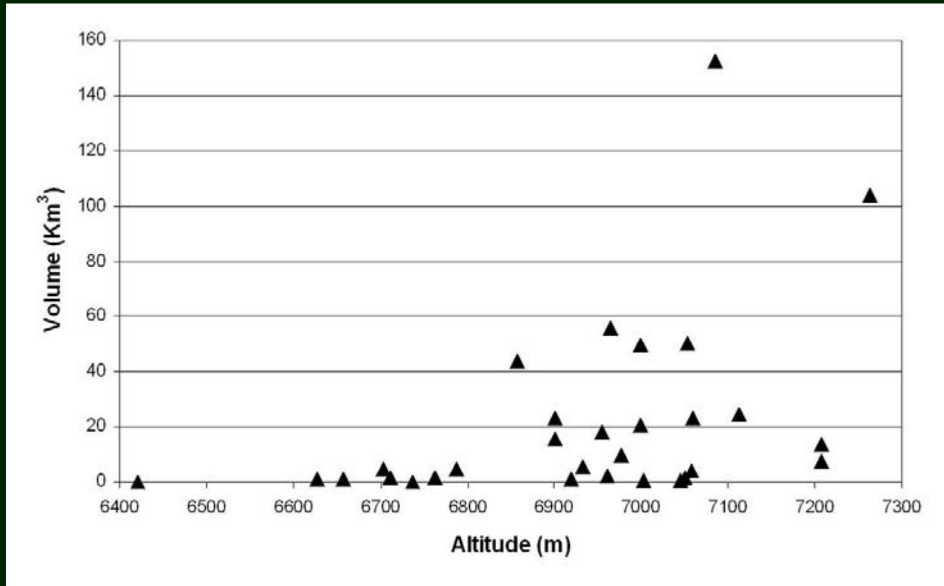
- Syria Planum shield volcanoes played an important role in the primordial Tharsis Province volcanism and that their activity ceased in the Hesperian, early in the geologic history of this region

- The progressive cessation of activity might be due to the enhanced crustal thickness in the magmatic processes of this region.

- The highest crustal thickness beneath Syria Planum led us to focus on its principal role in the origin, but also the decline, of volcanism in this area and its continuation on the northwestern side of Tharsis, leading to the formation of the present Tharsis Montes.

- The influence of this thick crust on the stall of a giant volcano on Syria, and on the volcanism continuation beneath the Tharsis Montes and Olympus Mons, are analyzed in the next section.

MARS LITHOSPHERE



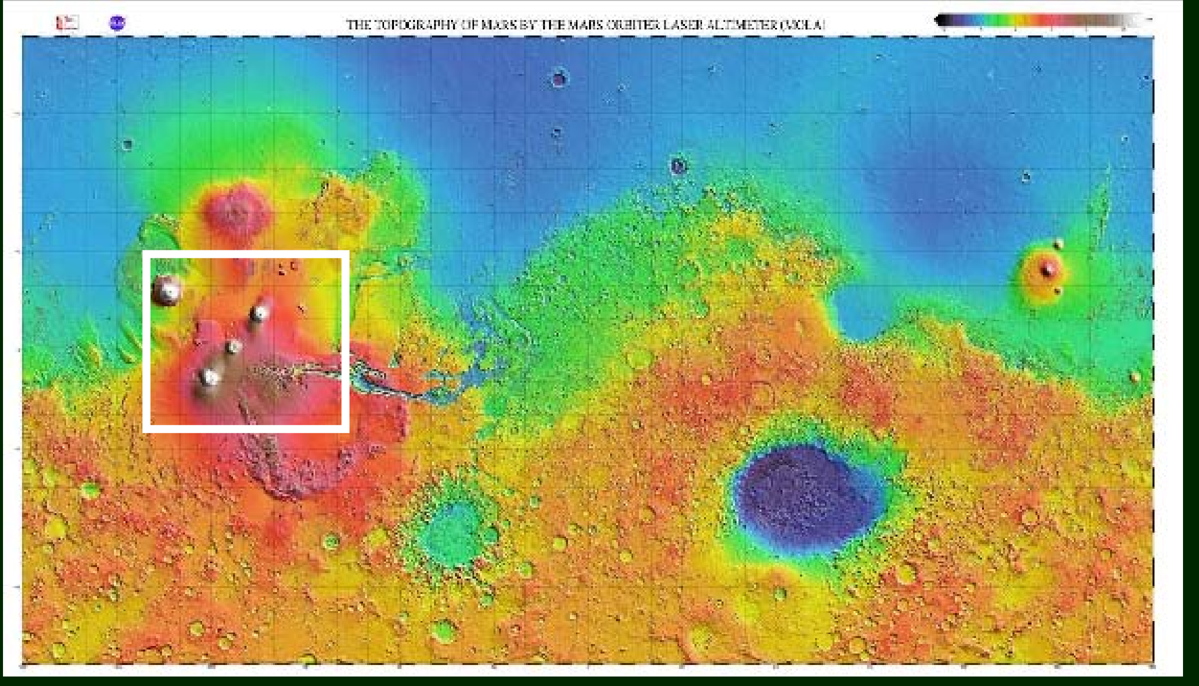
- Key: High crustal thickness

Key questions:

- ✓ What is the role of the crustal thickness on the volcanism duration?
- ✓ What is the influence of the topography on the thermal conditions in the present-state evolution of Mars ?
- ✓ What is the present heat flux on Tharsis ? What is the present volcanic and tectonic activity
- ✓ The Tharsis topography may it explain Syria's ?

➢ To understand the volcanism duration, a 3D heat flow modeling was applied to the conductive part of the lithosphere.

➢ 3-D heat equation with a finite elements code for the temperature distribution in the lithosphere for present-day Tharsis conditions.



Temperature distribution in the crust and Martian lithosphere

The Fourier's Law of Heat – Temperatures calculation in the thermal planetary lithosphere :

The mathematical model of finite element analysis for heat transfer by conduction is the heat equation:

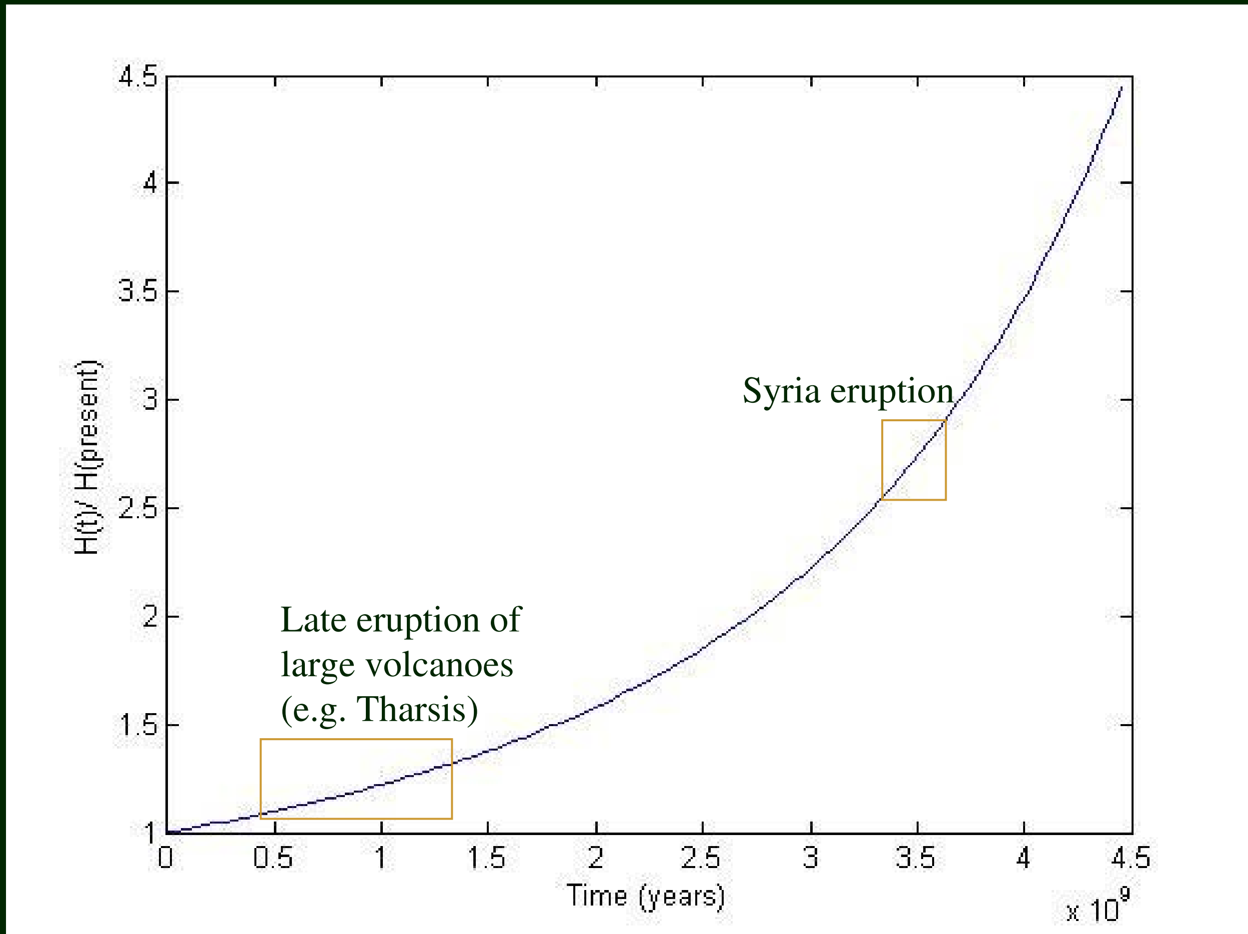
$$\rho C \frac{\partial T}{\partial t} - \vec{\nabla}.(k\vec{\nabla}T) = Q$$

- **Where**
  - T is the temperature,
  - ρ is the density,
  - C is the heat capacity per mass unit (at constant pressure),
  - k is thermal conductivity,
  - Q is the volumetric heat source.

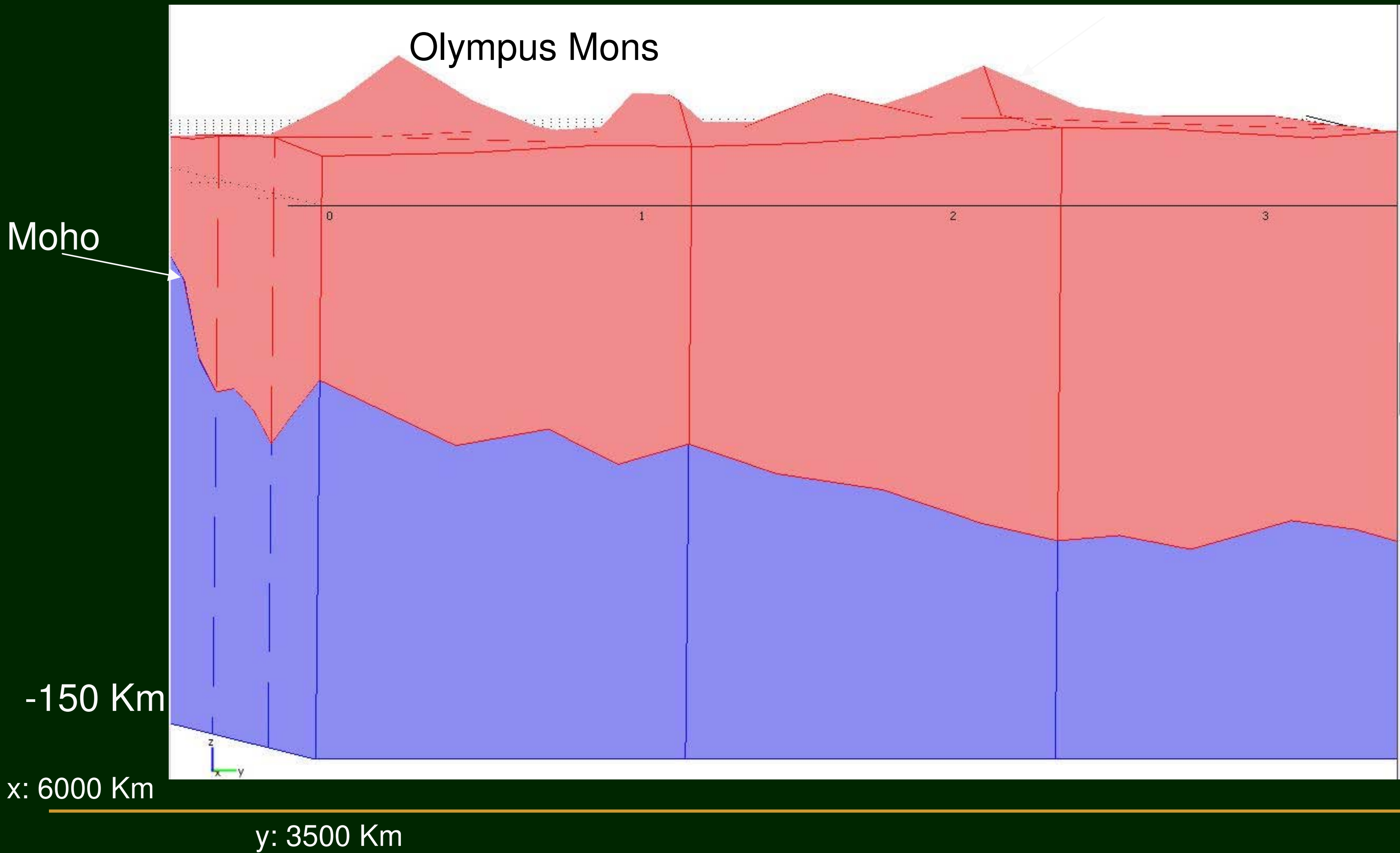
For a steady-state model, temperature does not change with time, and the first term containing ρ and C vanishes.

- Mean total Martian mantle heat production rate due to the decay of the radioactive isotopes of U, Th and K as function of time, from the present till 4.5 Gy, based on Shergotites' composition.

- Heat transport from the interior of the planet



3D Martian Elastic lithosphere – Present



- The Parameters :
  - Heat capacity
  - Thermal conductivity
  - Constant temperatures
  - Density
  - Roots effect related to density
  - General Heat source
  - Heat flux

- The models of conductive heat transfer were calculated using the parameters described and then their variations were explored:

- The effect of the temperature at the base of the elastic lithosphere
- The different thermal conductivity values on the crust and mantle
- The general heat (affected by the radiogenic decaying) and
- The presence of a stagnant lid on the temperatures variation.

For each model, we obtained temperature profiles for the surface and along the crustal depth. Then it was determined the associated heat flux variations (models M1-M7 and MSL).

M1 – Control Model

PARAMETER	DESCRIPTION	VALUE
C_p	Heat capacity ($JKg^{-1}K^{-1}$)	1000
k	Thermal conductivity ($Wm^{-1}K^{-1}$)	$k_c=3$*
		$K_m=3$*
Q_H	General Heat source (Wm^{-3})	$1.378e^{-8}$
T	Temperature at -150 km (K)	1073
T_0	Temperature at the surface (K)	220

M2 – Present Crustal Enrichment

M3 – Crustal Enrichment and Radiogenic Heating correspondent to ~550 Ma ago

M5 – Reduced crustal conductivity in relation to the mantle

M6 – Assembles all effects for ~550 Ma ago

M7 – Assembles all effects + thicker crust (density varying and roots effect)

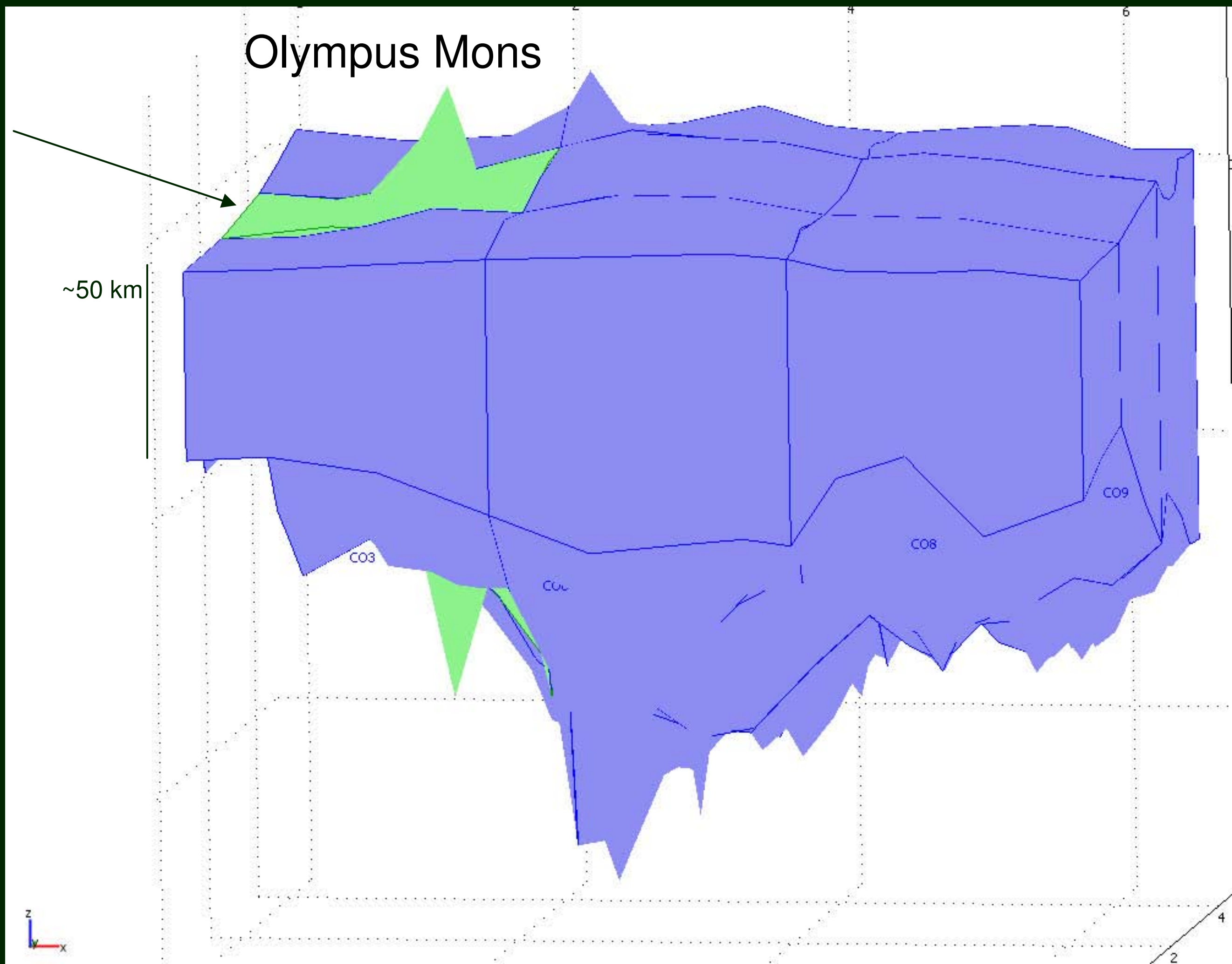
MSL – With Stagnant lid at constant heat flux at the base

Data Analysis

- Crustal Thickness Variations
- Moho Depth Variations
- Temperature Variations
- Heat Flow Variations

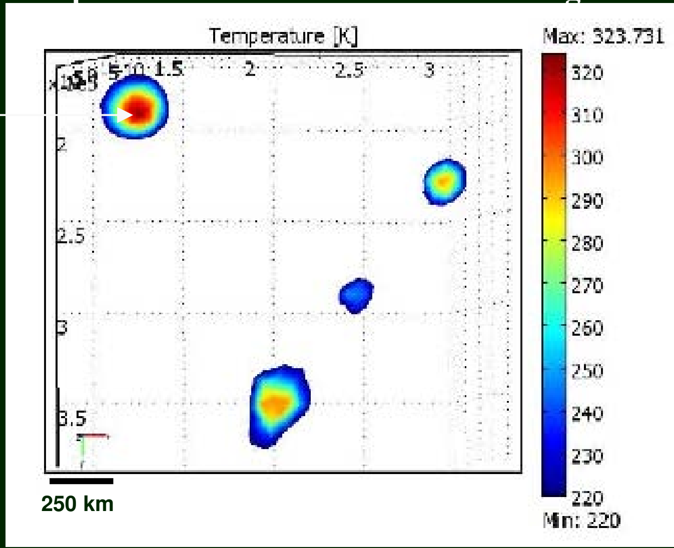
- Crustal Thickness Variations
- Moho Depth Variations

Crustal Dicothomy

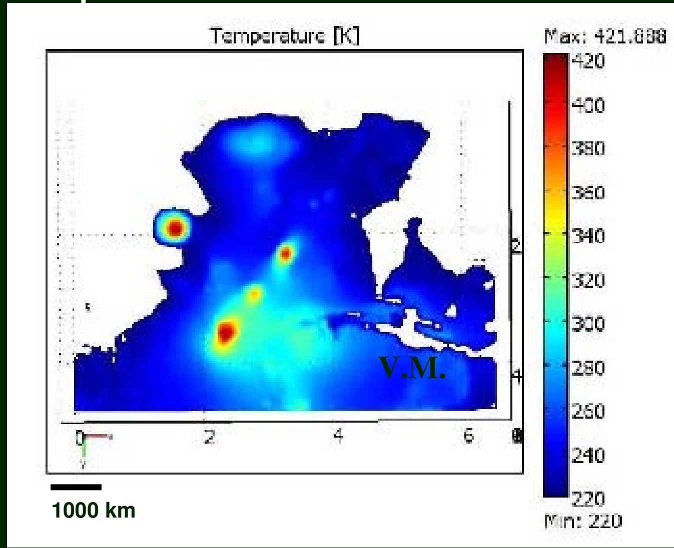


50ºN – 40ºS; 50ºW – 140ºW

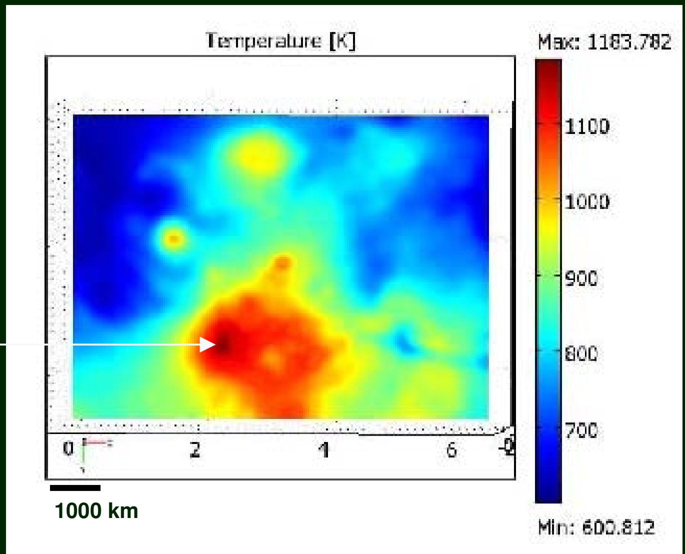
Temperatures are calculated at 10 km high

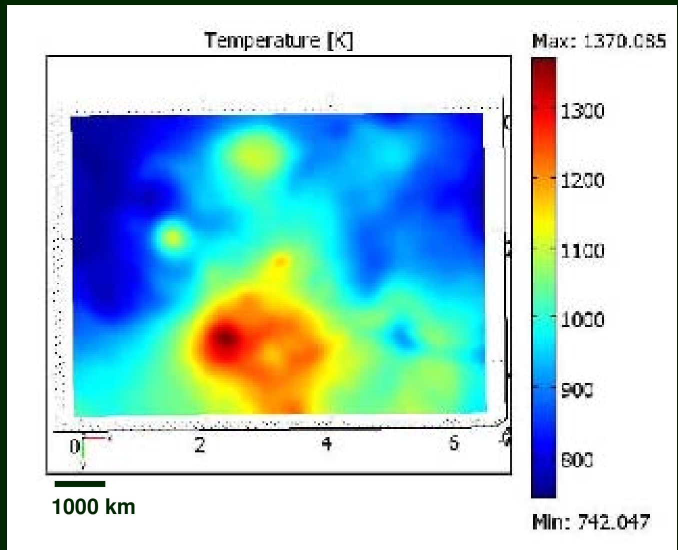


Temperatures are calculated at z=0 km



M6





Temperatures are calculated at z=-80 km

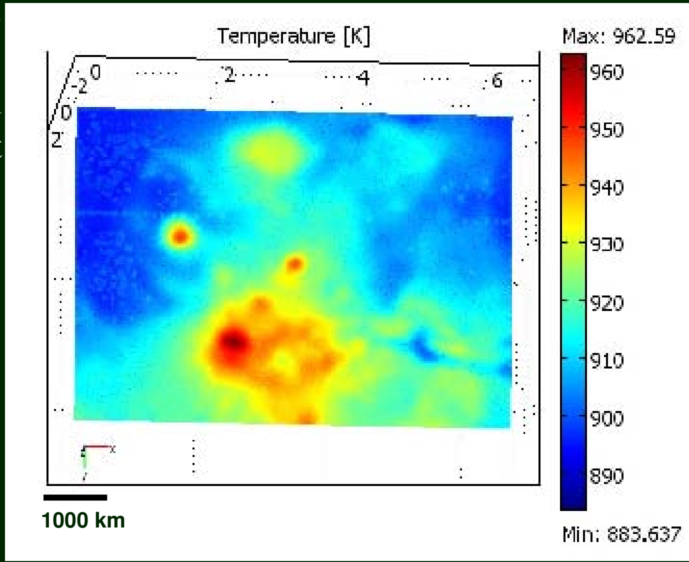
Temperatures are calculated at -120 km

[Baptista et al., 2009b, in prep]

Temperatures are calculated at z=-120 km

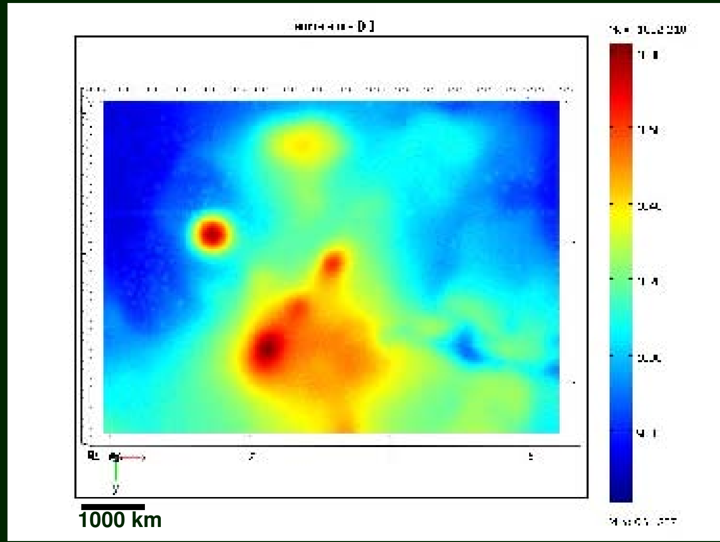
M2

Crustal enrichment



M5

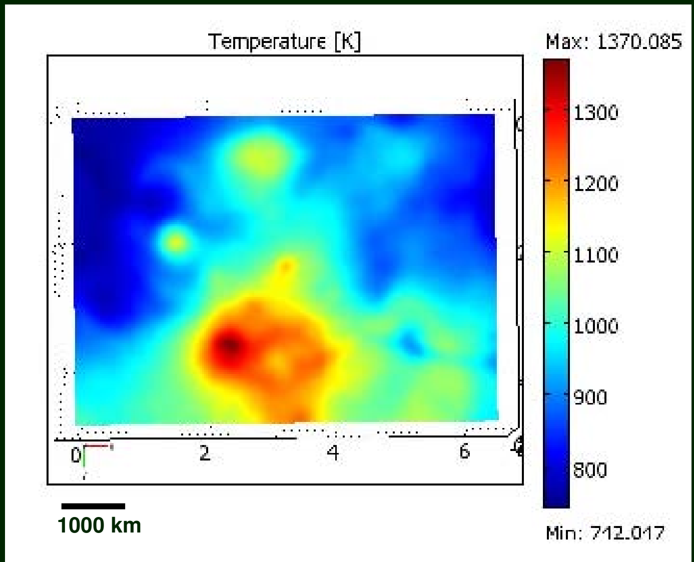
Less conductive crust



M6

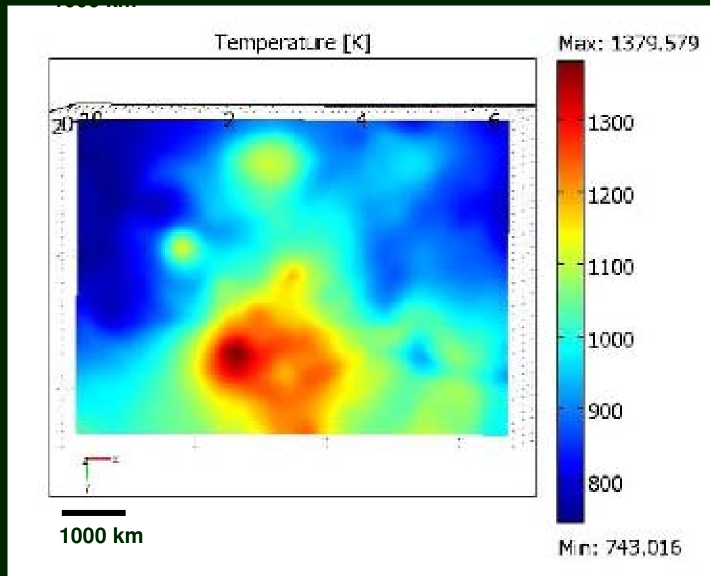
All effects

For 550 Myr



M7

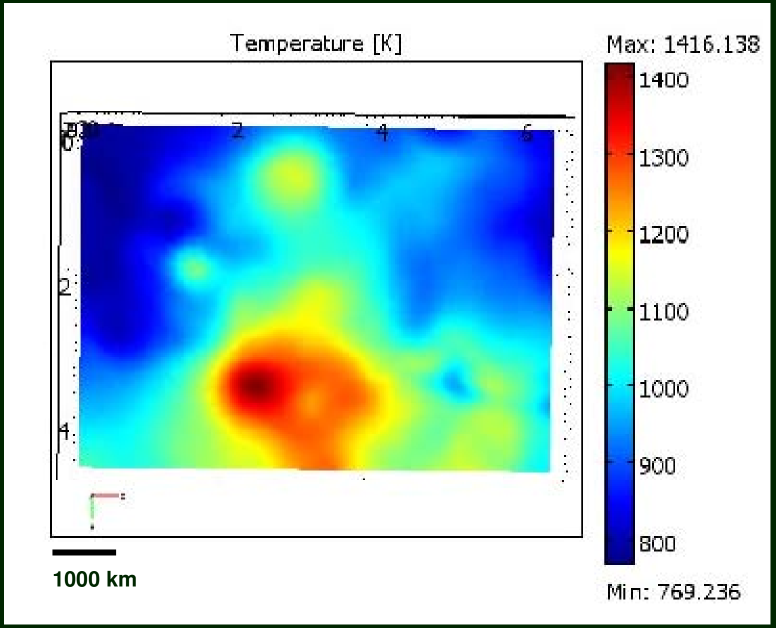
All effects + thicker crust



[Baptista et al., 2009b, in prep]

Cooling Effect (Mc)

Mc



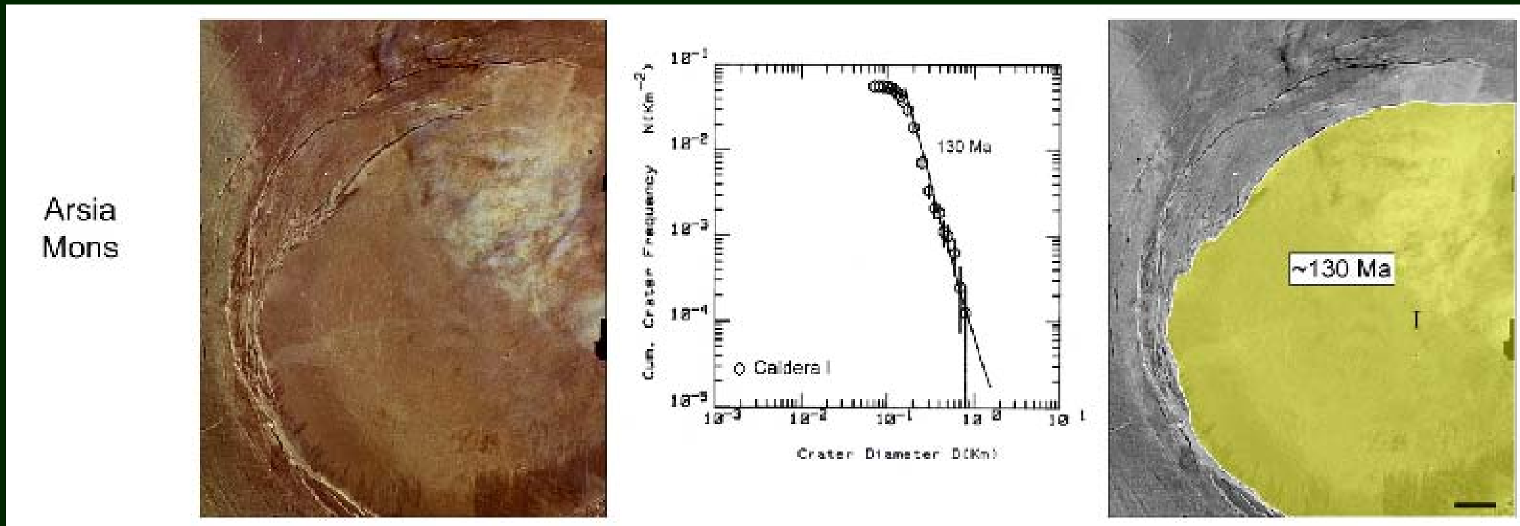
Cooling effect contribution

Steady-state regime

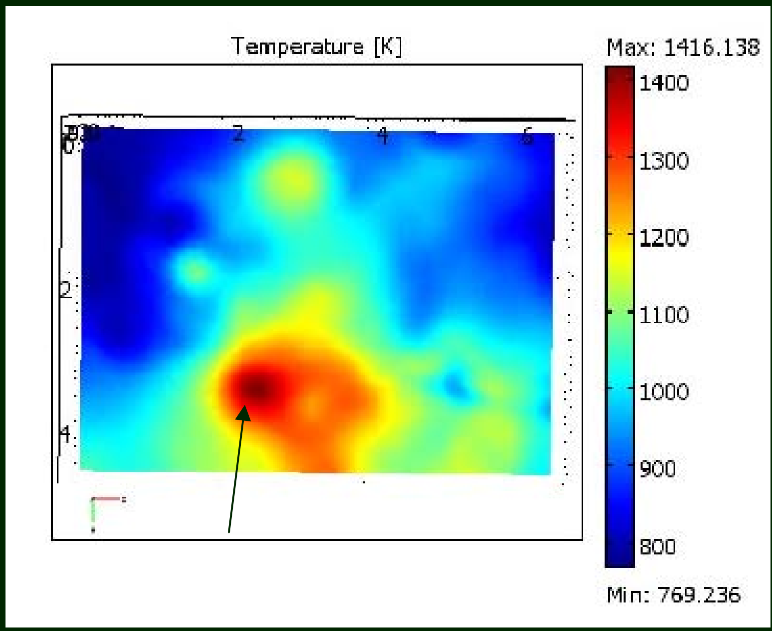
$$\rho C \frac{\partial T}{\partial t} - \vec{\nabla}.(k\vec{\nabla}T) = Q$$

- Results show that the heat due to the radioactive decay is ~34% of the general heat, for this period of time.
- Temperatures increase (comparing to Model M7 without cooling effect) of ~ 40 K.
- Temperatures Convergence for Arsia Mons on the last 1000 Ma ($T_{n+1} - T_n$ is less than 5 K) verify this situation.

1st Conclusions



[Neukum et al., 2004]



• Model Mc Reveals evidences for recent Volcanic Flows on Arsia Mons

[Baptista et al., 2009b, in prep]

2nd Conclusions

1 – The most significant factors for temperatures increase

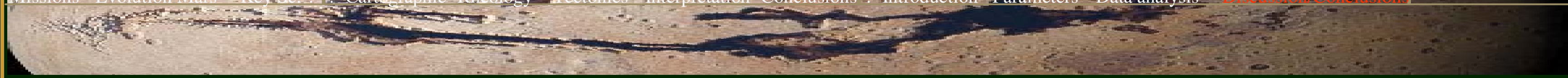
- A topographic high – Olympus Mons
- Existence of a crustal root – Arsia deepest root and highest temperature at -80 km; Syria deep but thick root doesn't verify higher temperature.

- Lower thermal conductivity on the crust in comparison to the mantle
- … accresced with a crustal enrichment in radiogenic sources (M6)

favours the highest temperatures at the lithosphere of Tharsis

- Topographic depression. An isolated high interferes more in the heat increase than several coupled highs.

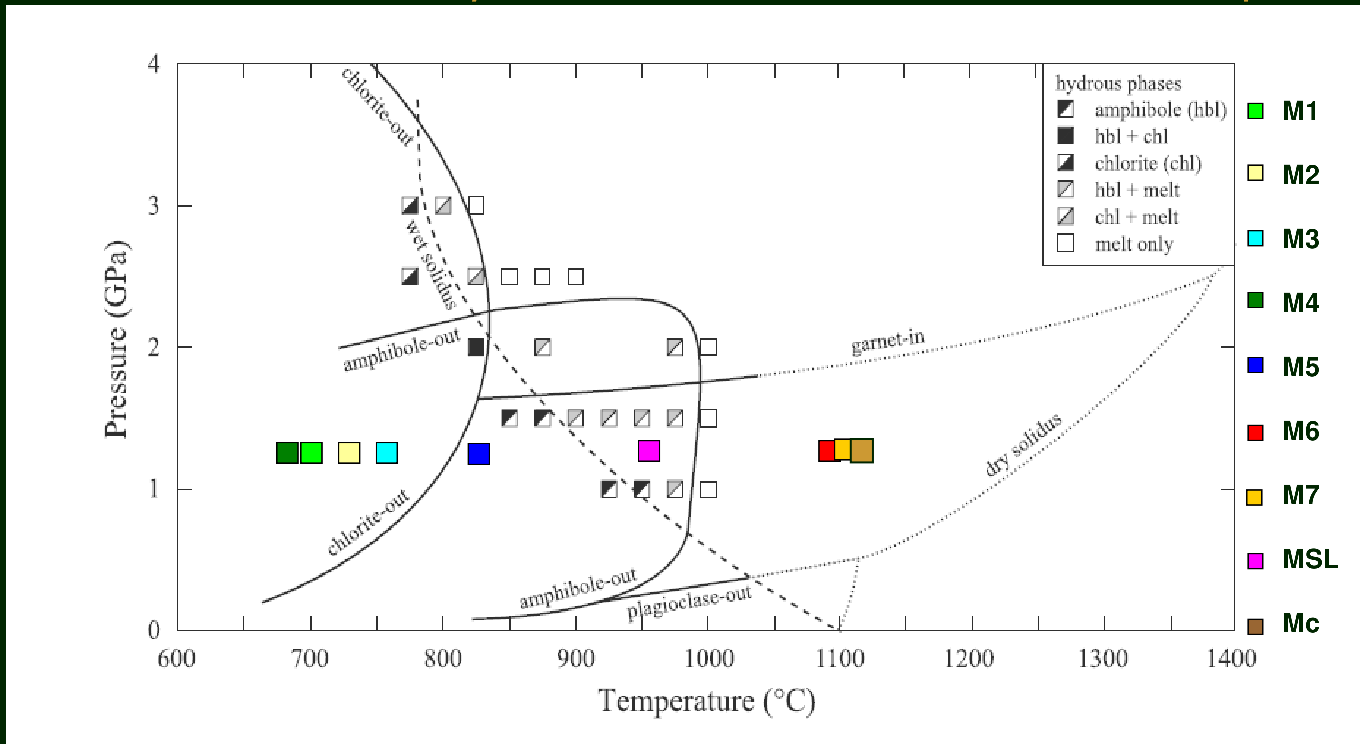
  - Is this enough to generate partial melt ?



Discussions

- Partial Melt Generation

Experimental water-phase relation for a primitive mantle + crust Martian composition



Adap. from Medard and Grove [2006]

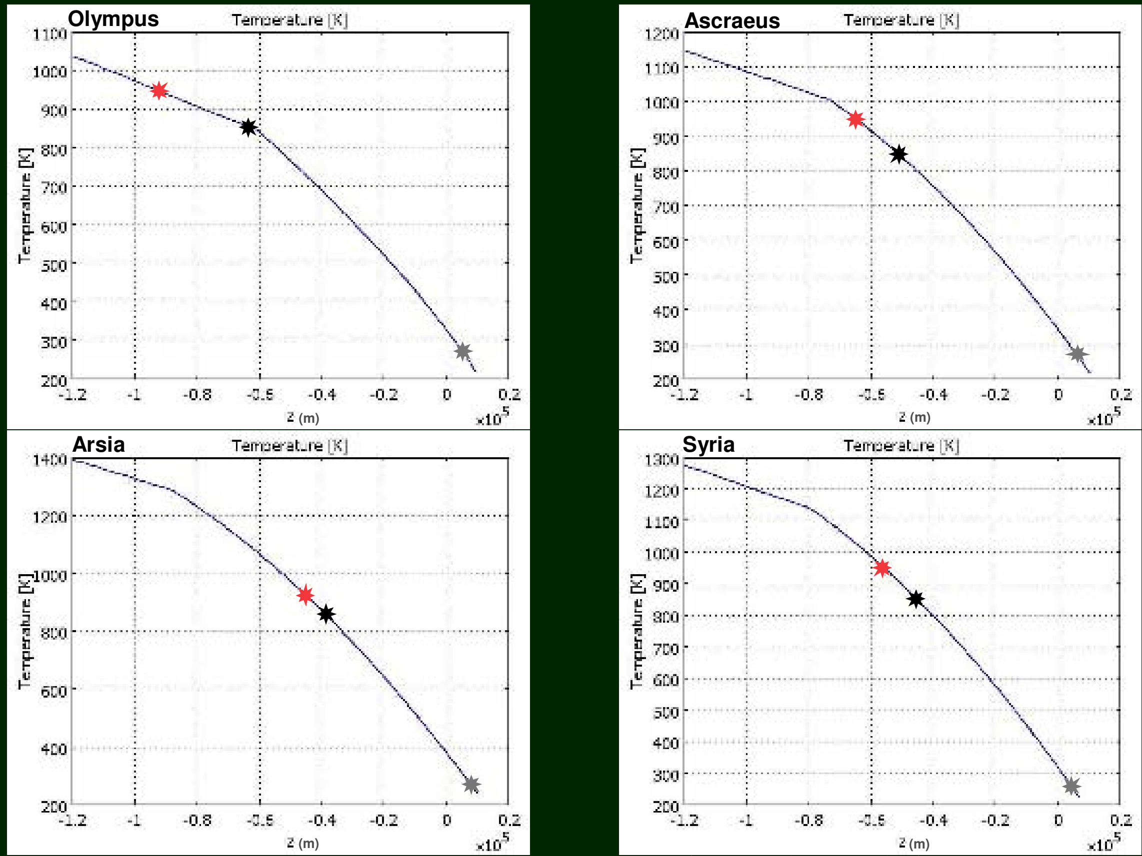
The solidus is reached, at -120 km (~ 1.3 GPa), for
- **Present-day conditions (MSL)**
- **At ~550 Ma ago considering models M6 and M7**
- **Present-day considering the cooling effect (Mc)**

[Baptista et al., 2009b, in prep]

Vertical Temperature profile along the Tharsis Volcanoes and Olympus Crustal roots.

Legend:

- ✱ **Hematite Curie Temperature**
- ✱ **Magnetite Curie Temperature**
- ✱ **Water/Ice transition**



[Baptista et al., 2009b, in prep]

- **The emplacement of surface lava flows heats the underlying crust till a certain depth, which can be determined by the Curie temperatures of the magnetic minerals**

- **Gives the flow thickness formed after the dynamo cessation**

- **The Curie temperatures correspond to a single-domain magnetite (853 K) and to the hematite (943 K).**

- **In grey it's shown the depth for the transition ice-water. The brake in the profiles seems to correspond to the depth where there's the passage between a thicker crust and a crustal root.**

Final Conclusions

- On Syria Planum, there were detected several assembled volcanic features, such as coalesced shield volcanoes in contact with long lobate shape lava flows.
- These volcanic eruptions may have stopped in the early Hesperian. From then on, on the surface of Syria Planum, there are no evidences for other secondary volcanic manifestations or for surface features related to local heat-increasing, such as those found on Olympus or Tharsis Montes
- Olympus Mons and the Tharsis Montes are big topographic highs compensated by deep crustal roots. Under the also high volcanic Syria Planum the crust is therefore largely thick.
- It's at the present northwestern flank of Olympus Mons, where there's a passage from a crustal root to a thin crust (with the consequent surface proximity of the mantle), that higher temperatures are observed.
- The thick less conductive crust under Syria may have conditioned the stall of volcanism in that zone, avoiding the ascension of magma.
- The zones where there are conditions to form a melt are in a lithosphere where the contact between a more conductive mantle and the crust is more extended (in the presence of a crustal root). On Mars, these places are in the surroundings of the Tharsis Montes and Olympus Mons.