ESS2222H

Tectonics and Planetary Dynamics
Lecture 7 – Tectonic Evolution of the other Terrestrial Planets

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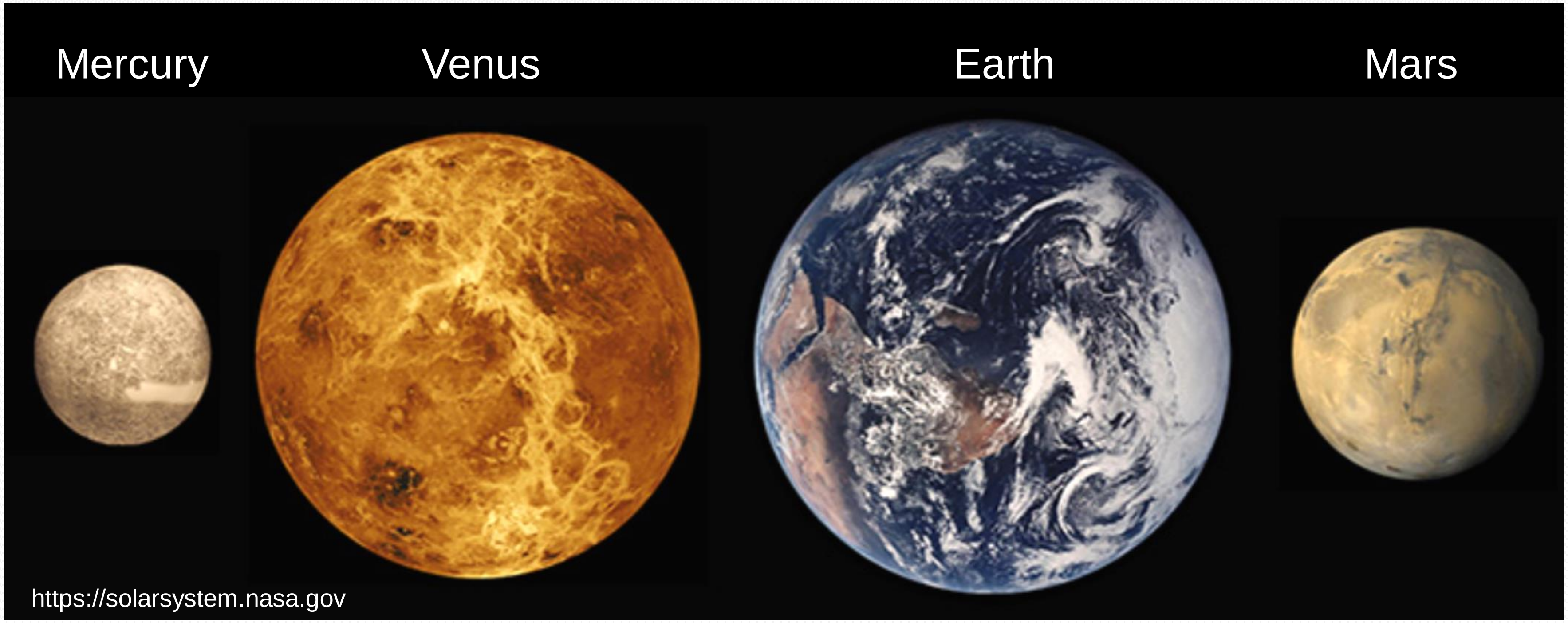
Solar System Planets

a) Terrestrial (Earth-like)
b) Gaseous (Gas Giants, Jovian Planets)

Terrestrial Planets

Terrestrial Planets – Rocky Plants

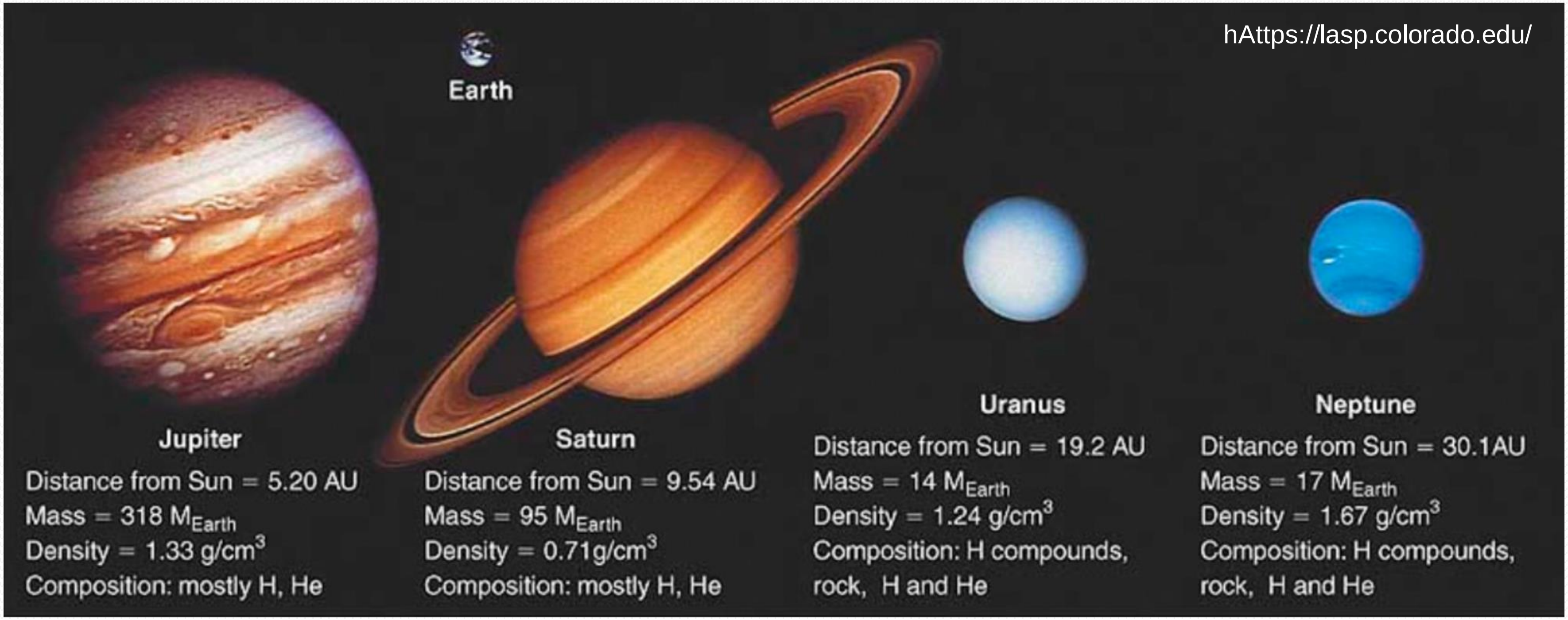
Mercury, Venus, Earth and **Mars** are known as Rocky or terrestrial planets. Unlike the Jovian planets, they have a large **metallic core** sounded by **rocky** (silicate) layers.



Gas Giants - Jovian Planets

Jovian Planets

Jupiter, Saturn, Uranus and **Neptune** are known as Jovian planets. Unlike the rocky Earth, they have a **small core** sounded by **massive layers of gases** in **metallic, liquid and gaseous states**, mainly **hydrogen** and **helium** with **no solid surface.**



Mars

Tectonic Regime of Mars

Atmosphere

The atmosphere of Mars consists of **carbon dioxide** (95%), **Nitrogen (**2.8%), **Argon (**2%), and traces of **Oxygen, Carbon monoxide, Methane, water vapour, hydrogen, noble gases, , dust**, etc. Surface pressure **~610 Pa.**

Dust hanging in the air colors Martian skies **tan** in photos taken from the surface.

Interior

Core: 1794 ± 65 km, **Iron** and **nickel** with about 16–17% **sulphur** (Rivoldini et al, 2011).

Magnetic field

Mars has **no core dynamo**. The source of magnetic field of Mars is the remnants of the magnetic minerals in the southern crust.

Mass: $0.64169 \times 10^{24}\ kg$
g: $3.71\ \ m/s^2$
Distance from Sun: 1.5 AU (meam)
Length of day: 24.65hr
Orbit period: .686 days
Radius (Eq): 3396.2 km
Radius (Pl): 3376.2 km

The Thermal and Tectonic Evolution of the Planets
Mars

Single Plate Planet

Mars is a **one-plate planet** with a lithosphere that has **thickened** with time during the course of its thermal evolution (Solomon, 1978; Schubert et al., 1979). **Stagnant-lid** convection is a **plausible state** for the Martian mantle given that Mars is a one-plate planet with a thick lithosphere (Reese et al.,1998, 1999).

Heat Flux

Based on the Martian thermal history model of Schubert and Spohn (1990) the present **mantle heat flow** in these models is about **30mWm^{-2}**. The **present surface heat flow** is about **40mWm^{-2}**. Because of lithosphere thickening and cooling, surface heat flow is approximately **10mWm^{-2}** larger than the present mantle heat flow.

Tectonic Regime of Mars

Plate Tectonics

Active plate tectonics is **unique** to the **Earth**. Plate tectonics occurred on **Mars early** in its evolution (firs few hundred million years).

Mars is significantly **smaller** than the Earth and Venus and, for this reason, its **tectonic** and **volcanic evolution** would be expected to be **different**. Mars is believed to be largely **tectonically quiescent** (dead planet), because:

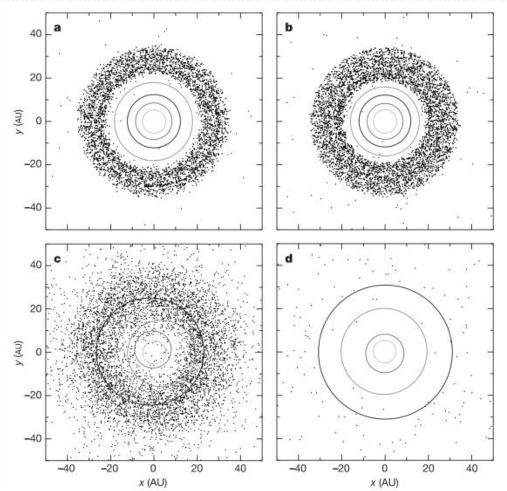
1) Due to **the large surface area to volume ratio** more heat has been lost and the interior has cooled (**no convection**). $(A/V)_{Earth} = 6.03 \times 10^{-7}$, $(A/V)_{Mars} = 1.17 \times 10^{-6}$.
2) **Crustal differentiation** on Mars has been **more efficient** (e.g., Breuer et al., 1993) and a large fraction of the incompatible heat-producing elements are now **near the surface** where heat can be lost by **conduction**.

Martian **activities** in estimated to have **stopped 3.5 billion year ago**, with no volcanic activity and magnetic field since then. Today, It may have **molten outer core** but with **no convection**.

Tectonic Regime of the Terrestrial Planets
Mars

The Late Heavy Bombardment (LHB), or Lunar Cataclysm (nicknamed)
This is a **hypothesized** event thought to have occurred approximately **4.1 to 3.8 billion** years (Ga) ago (corresponding to the Neohadean (4.1-3.9 Ga) and Eoarchean (4-3.6 Ga) eras on Earth) (e.g., Cohen et al., 2000). During this interval, a large number of **asteroids** have collided with the early terrestrial planets (inner planets) in the **Solar System**, including **Mercury, Venus, Earth,** and **Mars and Moon.**

Based on analyses on the lunar meteorite **breccia rocks** MAC 88105, QUE 93069, DaG 262, and DaG 400, ^{40}Ar-^{39}Ar dating suggest **7-9 impact events** ranging from **2.76 and 3.92 billion years ago** (e.g., Cohen et al., 2000).



Gomes et al., 2005

Breccia

Tectonic Regime of the Terrestrial Planets
Mars

Lunar Meteorites

Meteorites originated from the Moon are known as lunar meteorites. These meteorites are launched from the Moon by impacts making lunar craters of a few kilometers in diameter or less to the Earth’s and Sun’s orbits around the Earth or Sun, and eventually, succumb to Earth's gravity and land on the Earth’s surface. Most of these rocks were ejected from the Moon’s surface by the impactors within the past 20 Myr (most within the past 100,000 years) (Head et al., 2002).

Lunar **meteorite** are **random samples,** while samples collected from the central near-side of the Moon lack to have randomness. Therefore meteorite samples provide **more representative sampling** of the lunar surface (including far-side).

Martian meteorites

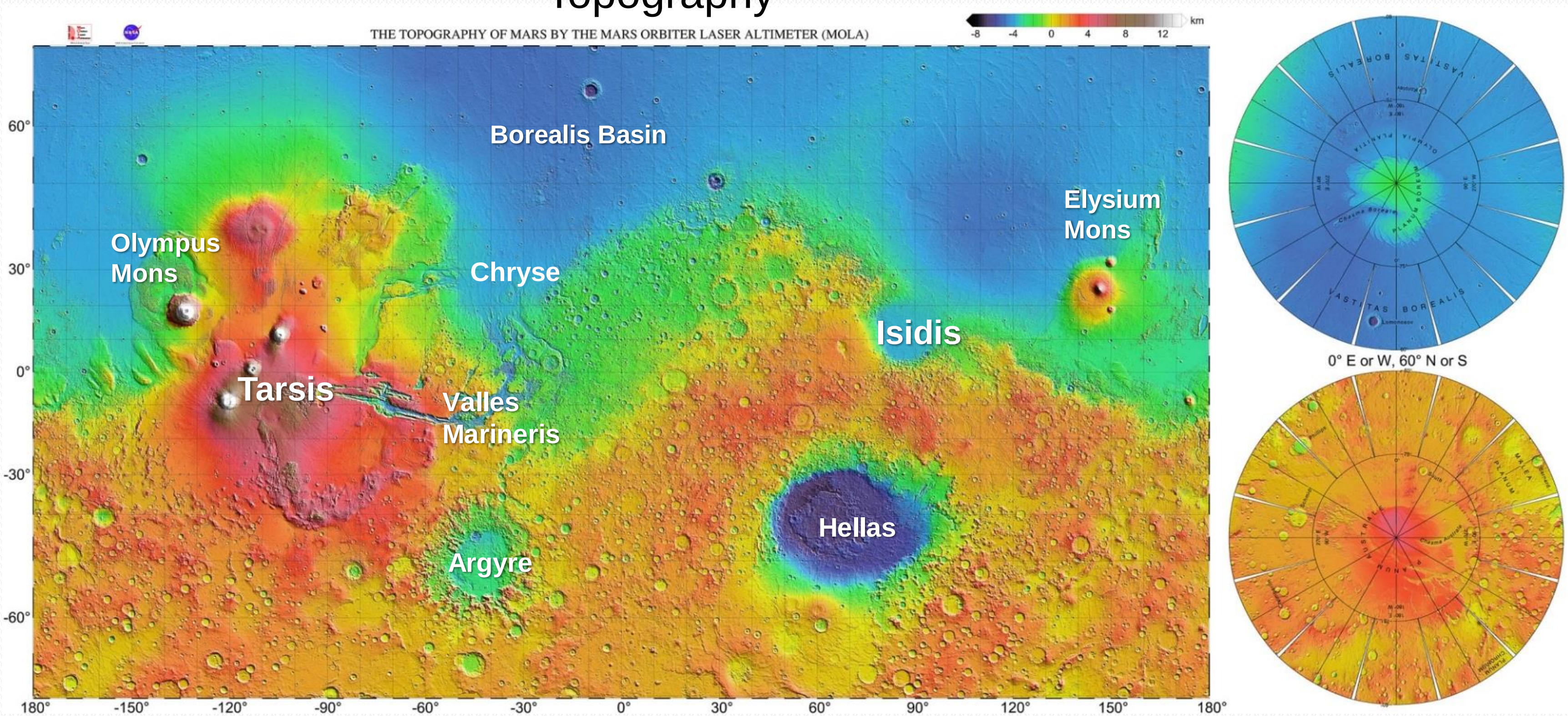
Martian meteorites have also reach the Earth’s surface in similar way (Treimana et al., 200).

Tectonic Regime of the Terrestrial Planets
Mars

Hemispheric Dichotomy

The most striking global feature of the Martian surface is its hemispheric **dichotomy** (Sharp, 1973, Watters & McGovern , 2006). This could be related to the dominance of a **low degree** spherical harmonic pattern of **mantle convection** early in Mars' geologic history or, possibly, with a period of plate tectonics.

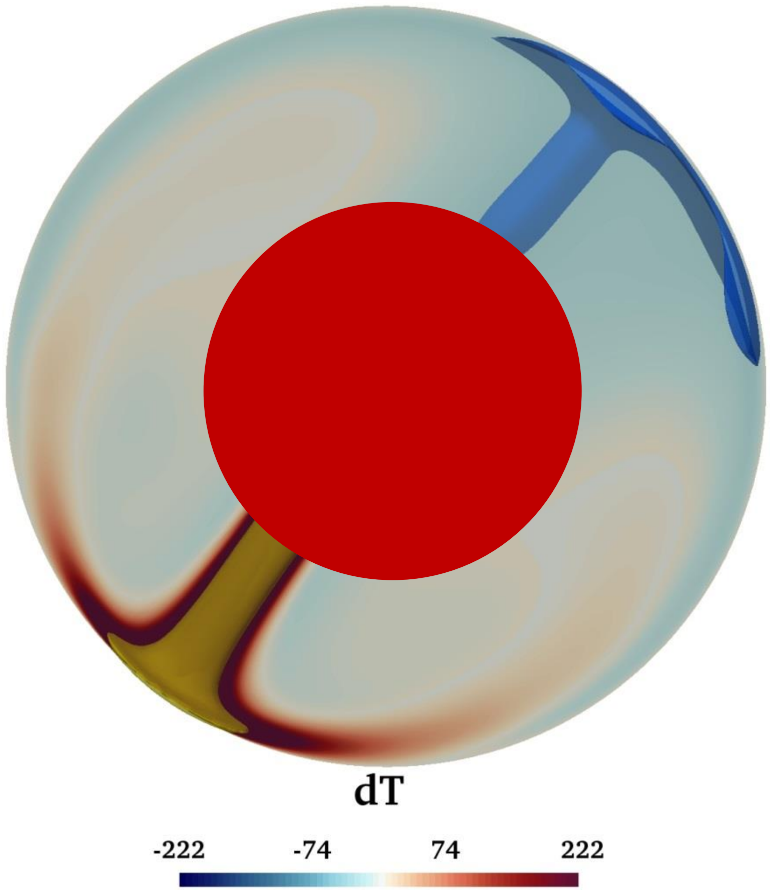
Topography



Tectonic Regime of the Terrestrial Planets
Mars

Possible Mechanism for Martian Dichotomy

Radius: 3,389.5 km
Core radius: ~1800 km



A **low degree** spherical harmonic pattern of **mantle convection**
The **spinel–perovskite** or **olivine–spinel** transformation in the Martian mantle could enforce a convection mode dominated by a **single plume**.

Tectonic Regime of the Terrestrial Planets
Mars

Degree-1 Convection (Roberts & Zhong, 2006)

Model I - An endothermic phase change near the CMB

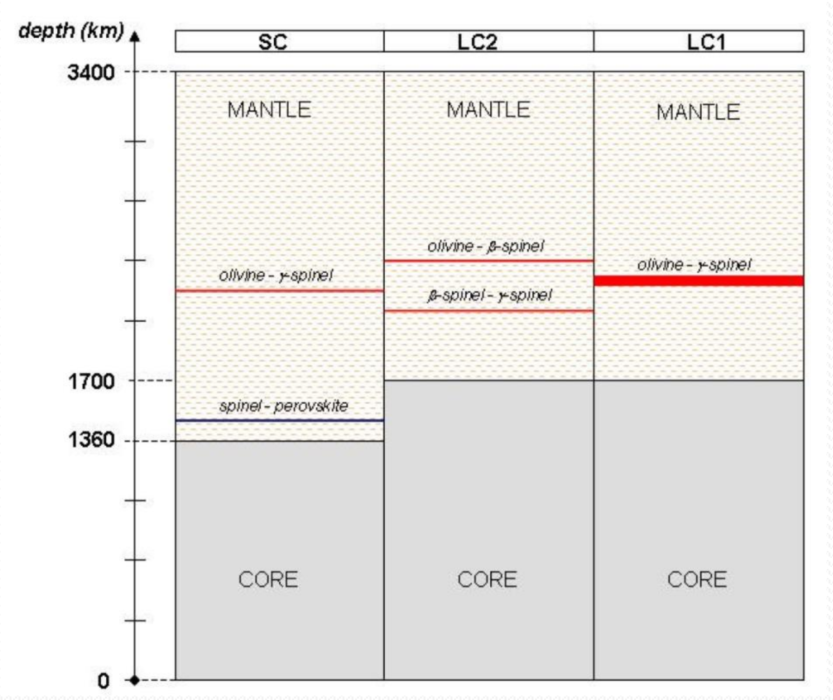
Model II - Viscosity layering in the mid-mantle

Based on 2-D and 3-D spherical model results Roberts & Zhong (2006) **concluded** that degree-1 mantle convection induced by a **layered viscosity structure** may be **responsible** for the formation of the **crustal dichotomy**.

Tectonic Regime of the Terrestrial Planets
Mars

The Influence of Phase Transitions (Michel & Forni, 2010)

Their numerical model included the phase transitions of:
a) Olivine to β-Spinel
b) Olivine to γ-Spinel
c) β-Spinel to β-Spinel
d) Spinel to Perovskite
and different core sizes.



They concluded that it is **less likely** to obtain degree-1 convection **with the endothermic phase transition**.

Tectonic Regime of the Terrestrial Planets
Mars

Surface Ages

The **density of impact craters** can be used to specify **relative ages** of the surface (by **counting the number of visible craters**: a higher number and density of craters indicates older terrain) (Tanaka, 1986, Tanaka et al., 2003).

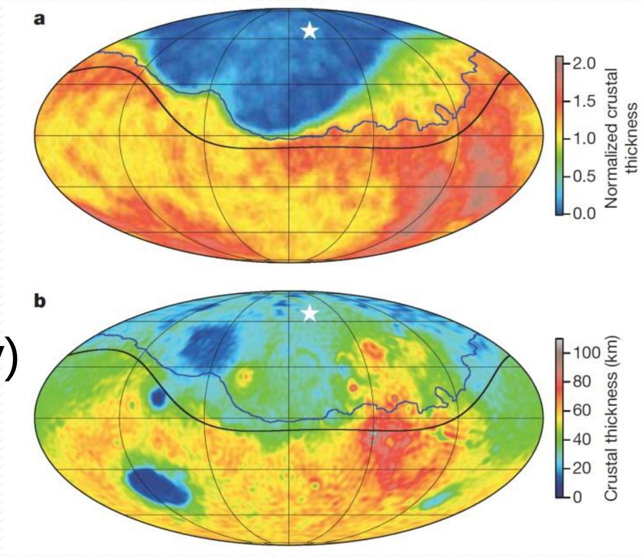
Southern hemisphere (heavily cratered) : **Older** (60% of the surface)
Northern hemisphere (low-lying non-volcanic plains): **Younger** (40% of the surface)

Among the hypothesis a large **impactor** may have created the northern basin (~4.5 Ga).

An impact hypothesis compared with Mars's crustal thickness.

a) Post- to pre-impact simulation crustal thickness ratio
b) Model thicknesses (based on gravity and topography)

(Marinova et al., 2008)



Tectonic Regime of the Terrestrial Planets
Mars

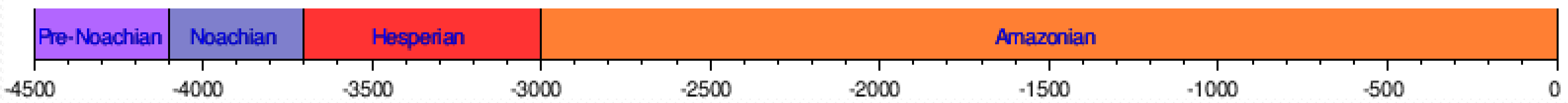
The geologic history of Mars is divided into three broad time periods, or Epochs:

a) **Noachian**: A **geologic system** and **early time period** on Mars characterized by **high rates of meteorite and asteroid impacts** and the **possible** presence of **abundant surface water (**4.1-3.7 Ga, not certain).

b) **Hesperian**: A **geologic system** and **time period** on Mars characterized by **widespread volcanic activity** and **catastrophic flooding** that carved **immense outflow channels** across the surface. The Hesperian is an intermediate and transitional period of Martian history.

c) **Amazonian**: A **geologic system** and **time period** on Mars characterized **by low rates of meteorite** and **asteroid impacts** and by cold, hyperarid (highly dry) conditions broadly similar to those on Mars today.

Chronological unit: Period
Stratigraphic unit: System



Tectonic Regime of the Terrestrial Planets
Mars

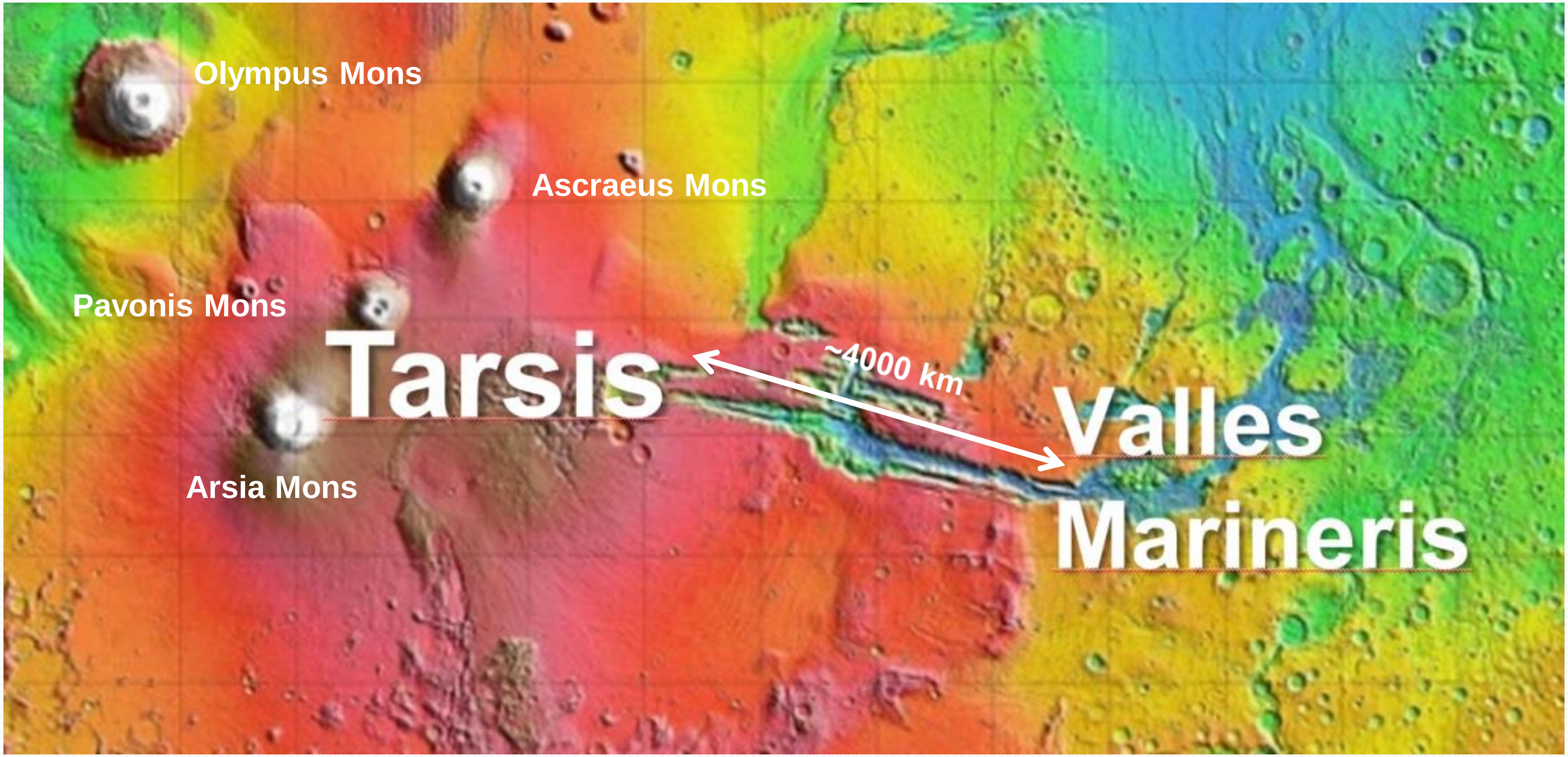
Martian Epochs and Absolute-age Ranges Based on **Hartmann–Tanaka (HT)** and **Neukum–Wise (NW)** Ages, Which Represent the Two Different Time Scale Models (Tanaka et al., 1992; Hartmann & Neukum, 2001).

There are uncertainties about transitions from one epoch to another.

Epoch	**Absolute-age Range (Gyr)**	
	HT	**NW**
Late Amazonian	0.25–0.00	0.70–0.00
Middle Amazonian	0.70–0.25	2.50–0.70
Early Amazonian	1.80–0.70	3.55–2.50
Late Hesperian	3.10–1.80	3.70–3.55
Early Hesperian	3.50–3.10	3.80–3.70
Late Noachian	3.85–3.50	4.30–3.80
Middle Noachian	3.92–3.85	4.50–4.30
Early Noachian	4.60–3.92	4.60–4.50

Tectonic Regime of the Terrestrial Planets
Mars

Tarsis Bulge and Valles Marineris



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Mars

Tarsis Bulge

The Tharsis uplift **(volcanic province)** and the associated great **shield volcanoes** on Mars can be attributed to **pressure-release melting** in a **single large plume** in the mantle of Mars.

The **largest volcanoes** in the **Solar System**, including the three enormous shield volcanoes **Arsia Mons, Pavonis Mons**, and **Ascraeus Mons (Tharsis Montes)** are located in this area near the equator. The tallest volcano (~25 km), **Olympus Mons**, is often associated with the Tharsis region (Williams et al., 2008).

Elevation

Arsia Mons	~17.78 km
Pavonis Mons	~14.31 km
Ascraeus Mons	~18 km

Tectonic Regime of the Terrestrial Planets
Mars

Valles Marineris

The formation of **Valles Marineris canyon** system (Mariner Valley) is point of the debate.

a) It has been suggested that Valles Marineris is a large **tectonic "crack"** in the Martian crust as the planet cooled (formed by the **crust thickening**), affected by the **rising crust** in the Tharsis region to the west, and subsequently **widened** by **erosional forces.**

b) Rifting

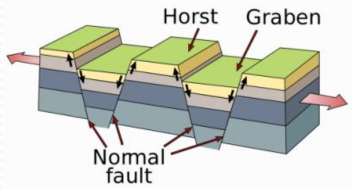
c) strike-slip faulting (e.g., An Yin, 2012)

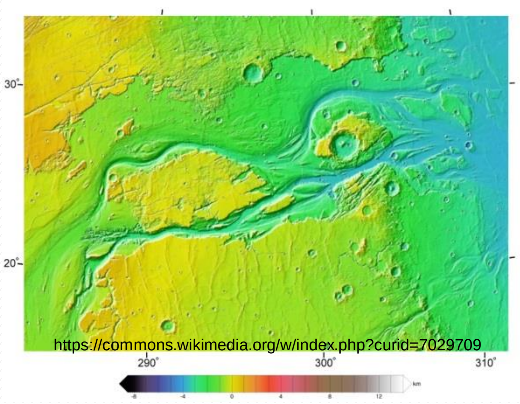
d) Subsurface mass removal

e) The role of water or carbon dioxide rivers in the past.

f) An impact may have initiated the crack

g) Stresses by the Tharsis load





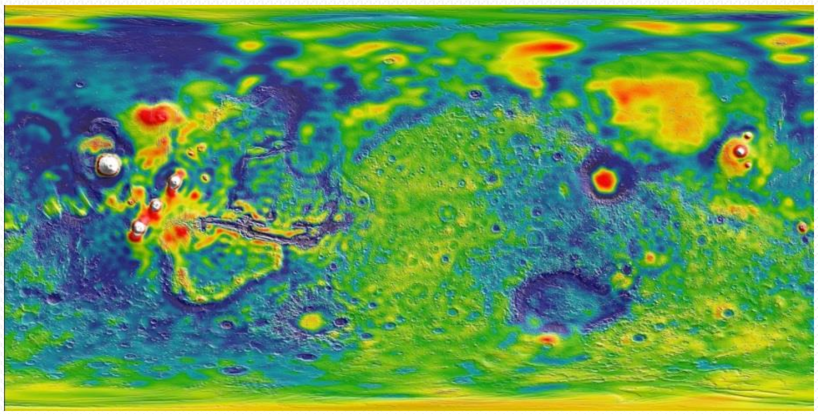
Outflow channels

The **graben** systems in and near the Tharsis region are likely the result of **stresses** generated by the Tharsis load. The system is **~ 4000 km long** and reaches **~7 km in depth**. The canyon system and associated outflow channels (by flooding) developed mainly during the **Hesperian Period**.

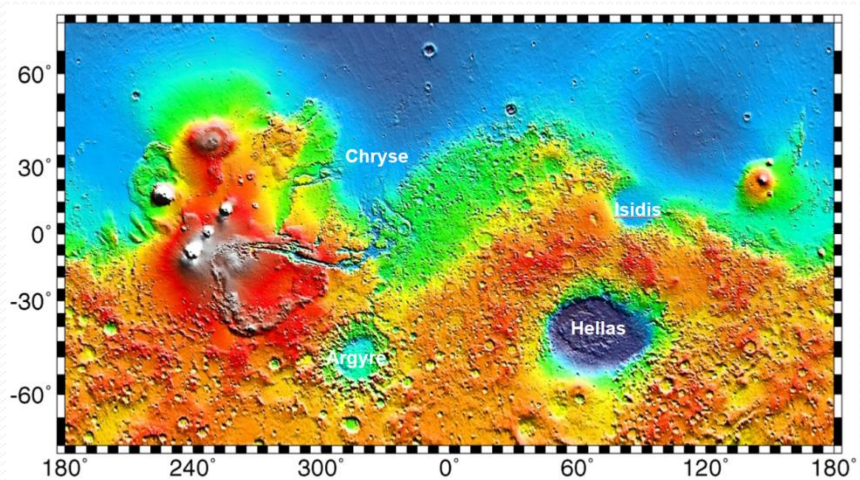
Tectonic Regime of the Terrestrial Planets
Mars

Isostatic Balance

The **older** regions on Mars are **isostatically compensated**. The younger region are usually only partially compensated.



Mars free-air gravity map (Red: gravity high; Blue: gravity low)

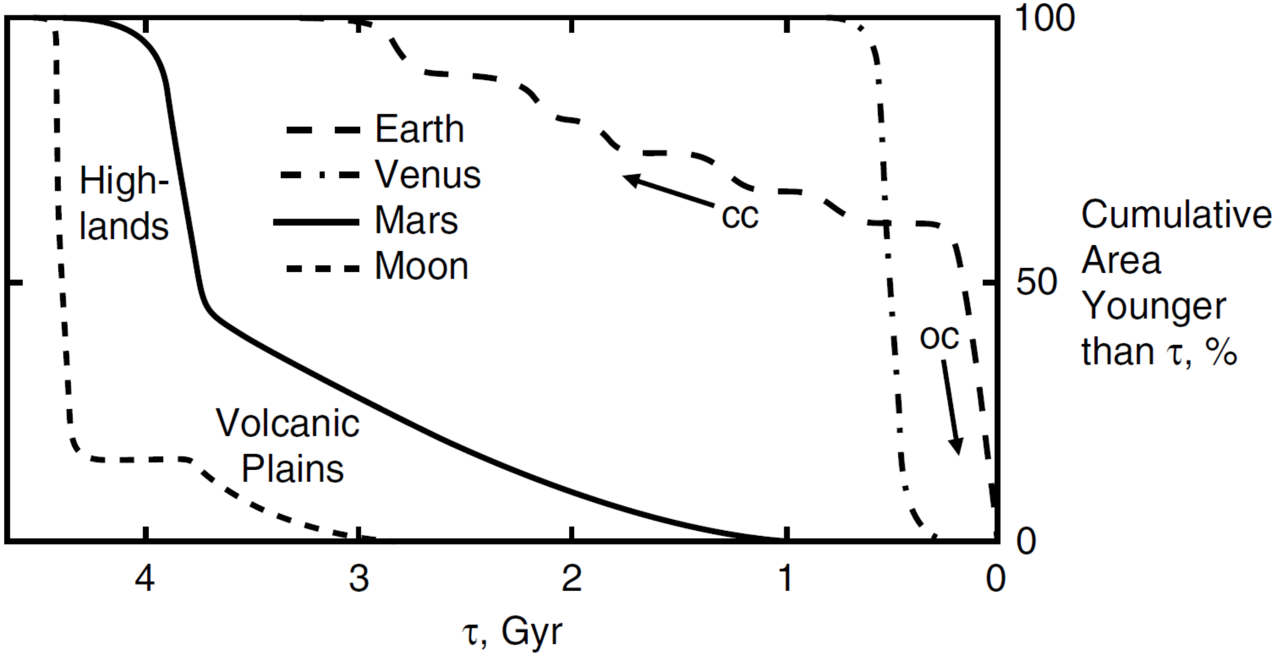


The topography model MEDGRs

Tectonic Regime of the Terrestrial Planets
Mars

Cumulative surface area, in percent, younger than τ as a function of the age τ

For the Earth, crustal ages younger than 125 Myr are principally oceanic (oc), whereas older crust is entirely continental (cc). For Mars and the Moon the older highlands are distinguished from the younger, lower-lying volcanic plains. For Venus and Mars the ages are based solely on crater counts, so that relative ages are reasonably accurate but absolute ages are subject to considerable error (Schubert, Turcotte & Olson).



Tectonic Regime of the Terrestrial Planets
Mars

Early Differentiation

The major evidence for an **initially hot and differentiated Mars** is the acceptance of Mars as the **parent body** of the SNC meteorites ((Shergotty (India), Nakhla (Egypt), and Chassigny (France) meteorites; the locations where these meteorites were found) (Becker and Pepin, 1984; Bogard et al., 1984; McSween, 1985).

The old age **(≥4 Gyr)** of the southern hemisphere highlands suggests **early crustal differentiation**, and the magnetization of this ancient southern hemisphere crust (Acuna et al., 1998, 1999).

Crustal Differentiation

Reese et al. (1999) find that hot early Mars models undergo substantial **crustal differentiation** within a **few hundred million years** at the onset of evolution and substantially deplete their **interiors of radiogenic** heat sources. The rest of the evolution subsequent to crustal formation involves a **steady decline of mantle temperature** and a thickening of the lithosphere to present values of around **500 km**.

Tectonic Regime of the Terrestrial Planets
Mars

Thermal Evolution Models (Breuer et al., 1993)

Model I - Homogeneous Differentiation Model

Assumption: A **basaltic crust** has grown steadily in **4.5 Ga** as a consequence of **pressure-release partial melting** of mantle rock.

Model II - Early Differentiation Model

Assumption: a) **Mantle depleted of radioactive elements** and a primordial enriched southern highland crust formed, b) The primordial crust acts as an efficient thermal blanket on the **southern** hemisphere mantle, c) In a second stage of differentiation, a **secondary basaltic crust** in the **northern** hemisphere is produced by pressure-release partial mantle melting.

They conclude that **Model I is not consistent** with SNC-meteorites data analysis.

Tectonic Regime of the Terrestrial Planets
Mars

Early Core Formation

Early Mars was similar to the larger terrestrial planets Venus and Earth, whose cores formed early as a consequence of high accretional temperatures.

The **U/Pb** isotopic composition of SNC meteorites requires **core formation at about 4.6 Gyr ago** (Chen and Wasserburg, 1986).

Early core formation in a hot Mars is further supported by the discovery of **remnant magnetization** in the ancient crust of the southern hemisphere Highlands (Acuna et al., 1999; Connerney et al., 1999).

Mantle Convection

The **persistence** of mantle convection in Mars to the present depends on the extent to which the interior has been depleted of radiogenic heat sources by **crustal differentiation**.

Crustal formation is an important influence on planetary **thermal history** because the process of forming the crust by **magmatism** and **volcanism** removes heat-producing radiogenic elements from the mantle and **concentrates them in the crust**.

Tectonic Regime of the Terrestrial Planets
Mars

Early vigorous Convection

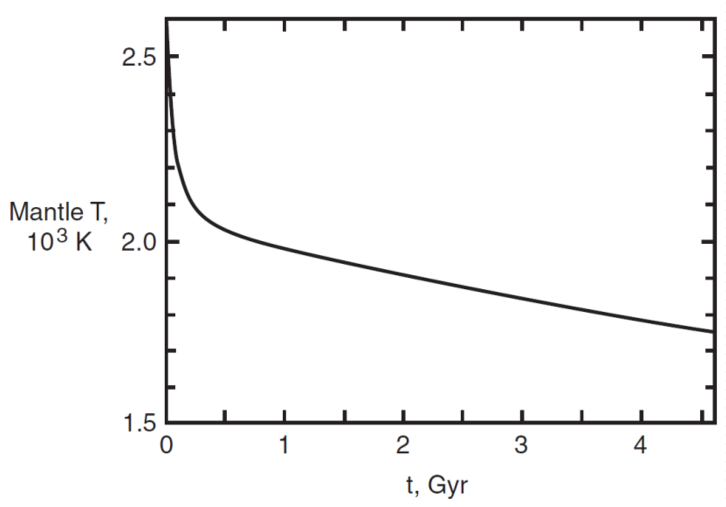
As a result of **accretional** heating and **core formation** essentially **contemporaneous** with planetary formation, the early history of Mars was characterized by **high internal temperatures**, a **vigorously convecting mantle**, and **high surface fluxes of heat and magma.**

Outgassing contributed to an early atmosphere, and widespread magmatism may have helped trigger the **release of subsurface water** and **large scale floods**.

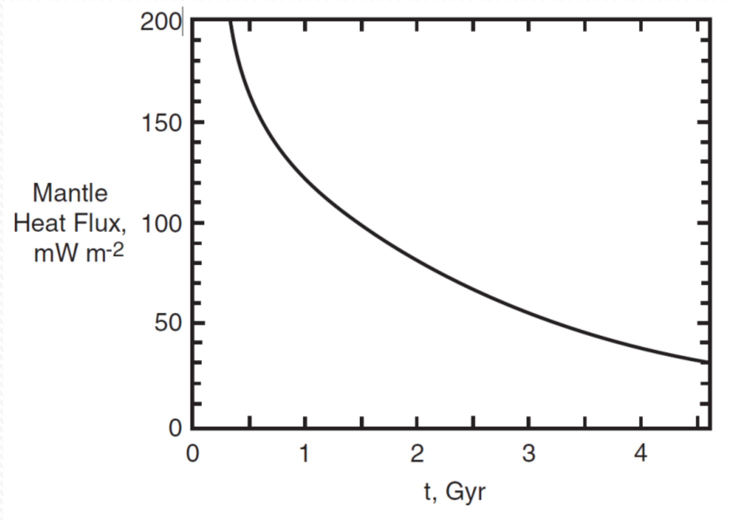
Fast Cooling

Parameterized convection models indicate, however, that on a time scale of **only a few 100Myr** the mantle convective engine slowed, as primordial interior heat was lost and as radioactive heat production decayed or was **concentrated into the shallow crust**. **Rapid interior cooling** led to a globally **thick lithosphere** and was accompanied by global contraction, recorded in the pervasive formation of **wrinkle ridges** now preserved on ancient geologic units. The last **3.5 Gyr** of Martian history was marked, in contrast, by **slow cooling** and by the concentration of volcanic and tectonic activity in ever more limited regions.

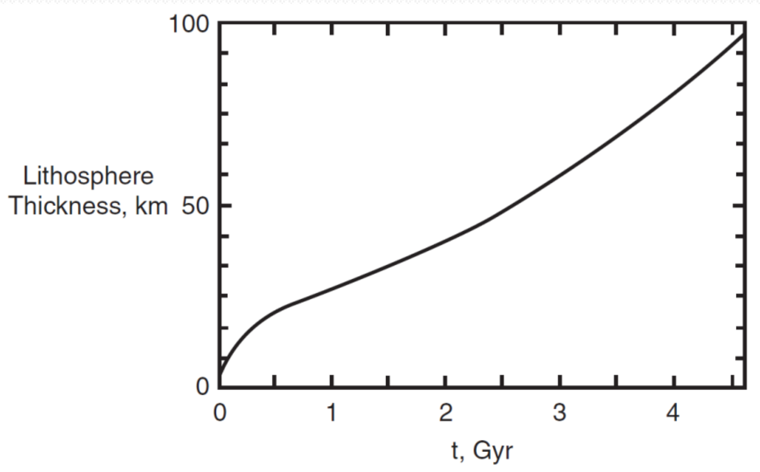
Tectonic Regime of the Terrestrial Planets
Mars



Mantle temperature versus time from the Martian thermal history model of Schubert and Spohn (1990).



Heat flux from the mantle as a function of time for a model Martian thermal history (after Schubert and Spohn, 1990).



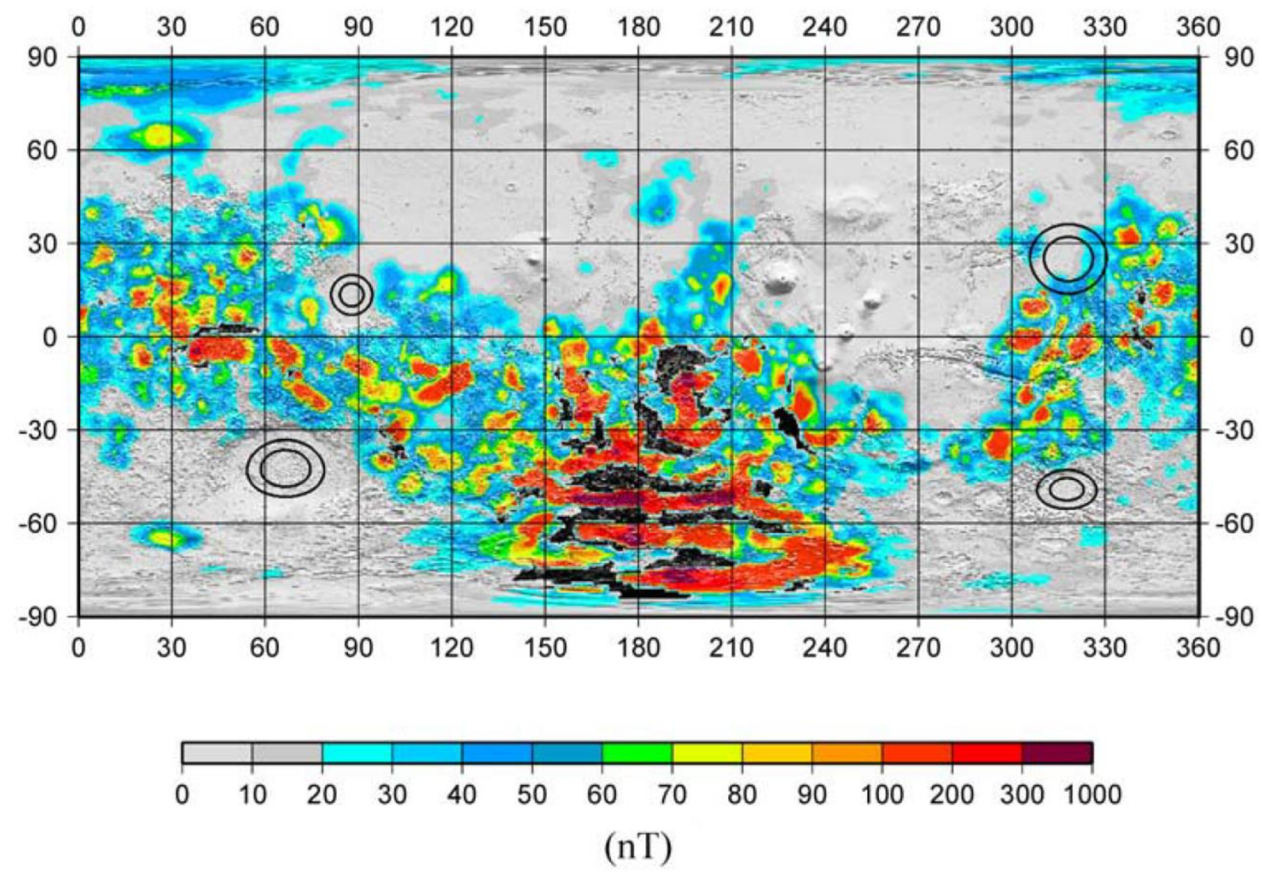
Thickening of the lithosphere with time during the model thermal evolution of Mars (after Schubert and Spohn, 1990).

Tectonic Regime of the Terrestrial Planets
Mars

Core Dynamo

Mars does not have a magnetic field at present (Acuna et al., 1998, 1999). The **southern hemisphere crust** must have been magnetized in a magnetic field generated by a dynamo in the molten metallic core of Mars during **the first several hundred million years** of Martian evolution (Acuña et al., 1999; Connerney et al., 1999). A **core dynamo** existed for perhaps the first **500 Myr** of Martian history. The **absence** of crustal magnetism **near large impact basins** such as **Hellas** and **Argyre** implies that the early Martian dynamo ceased to operate about **4 Gyr** ago (Acuna et al., 1999; Shahnas & Arkani-Hamed, 2007).

Tectonic Regime of the Terrestrial Planets
Mars



The magnetic intensity map at 170 km derived from the Electron Reflectometer data by Mitchell et al. (2001). The magnetic intensity is shaded using the surface topography for better illustration of the giant impact basins. The impact-demagnetized pressure boundaries, 2 GPa, of the large basins **Isidis**, **Chryse**, **Hellas**, and **Argyre**, calculated using the H-S-H scaling (outer curves) and Pi scaling (inner curves), are superimposed over the map.

Tectonic Regime of the Terrestrial Planets
Mars

Viscous and impact demagnetization of Martian crust

Magnetization of Martian crust has been modified by:

1- **Impact-induced shock waves**
2- **Viscous decay** since the **cessation** of the **core dynamo** of Mars at around **4 Gyr ago**.

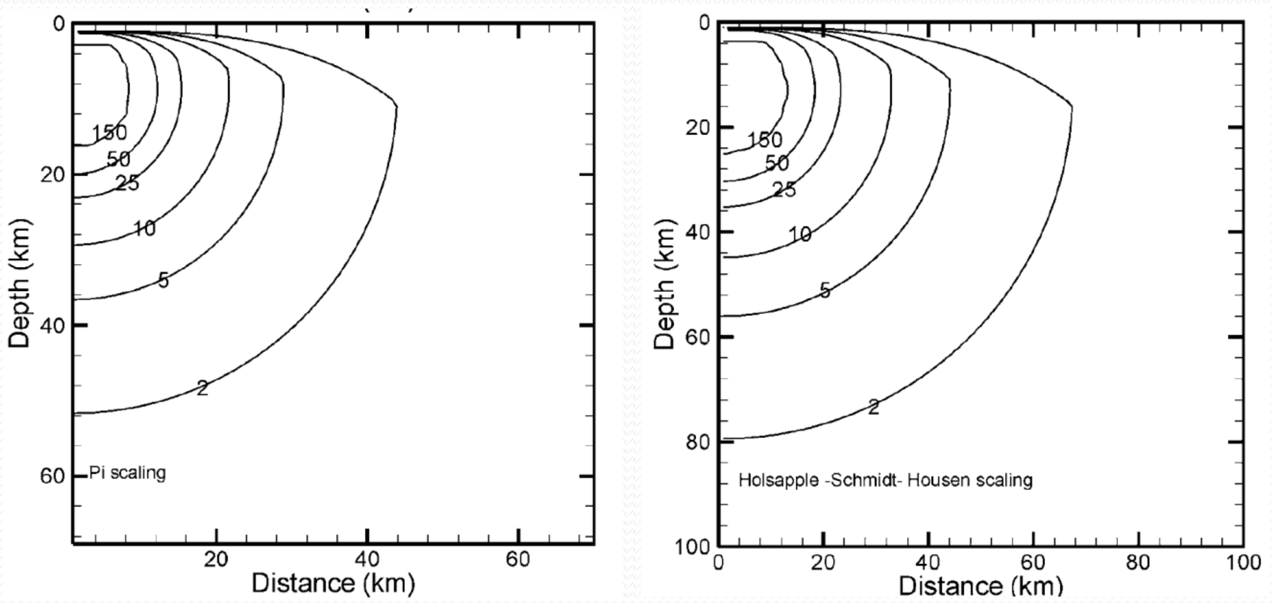
Estimations from the Numerical Models

a) Thermal evolution models of Mars suggest that the potentially **magnetic layer** was about **85 km thick** during the **active period of the core dynamo**, **assuming magnetite as the major magnetic carrier**. The lower boundary of the magnetic layer has gradually **decreased, by a total of about 30 km**, through **viscous decay of magnetization**.

b) The **large impacts** that created the giant basins **Hellas**, **Argyre**, and **Isidis** have **almost completely demagnetized** the crust beneath the basins.

Tectonic Regime of the Terrestrial Planets
Mars

Comparison of magnetic anomalies over areas surrounding the giant basins **Hellas**, **Isidis**, and **Argyre** and the calculated distribution of shock pressures shows that the crust is almost completely demagnetized at pressures 2–3 GPa (Shahnas & Arkani-Hamed,2007; Mohit and Arkani-Hamed, 2004).



The shock wave pressure distribution due to an impact that creates a crater of 300 km diameter, determined using the two scaling laws. The numbers on the curves denote pressure in Gpa (Shahnas & Arkani-Hamed,2007).

Tectonic Regime of the Terrestrial Planets
Mars

The shock wave pressure produced by impacts that created craters of diameters **300–1000 km** is **expected to significantly demagnetize** the crust beneath the craters. **However,** except for a few craters, there is **no signature of appreciable demagnetization.**

a) Either the magnetic carriers have high **coercivity** and have resisted demagnetization

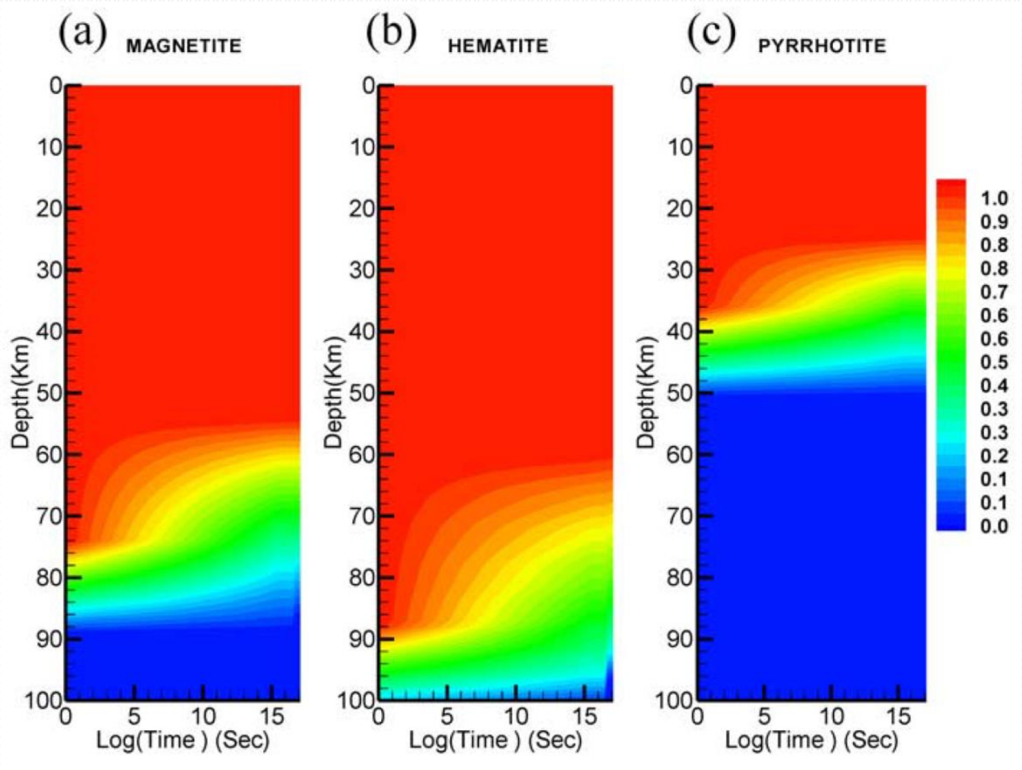
b) Or **magnetic source bodies** are **deep seated**

c) Or they have **acquired magnetization after the intensive impact cratering period.**

Tectonic Regime of the Terrestrial Planets
Mars

Viscous magnetic decay for Mars with stagnant-lid lithosphere model

Curie Temperatures
Magnetite: 580C
Hematite: 670C
Pyrrhotite: 320C

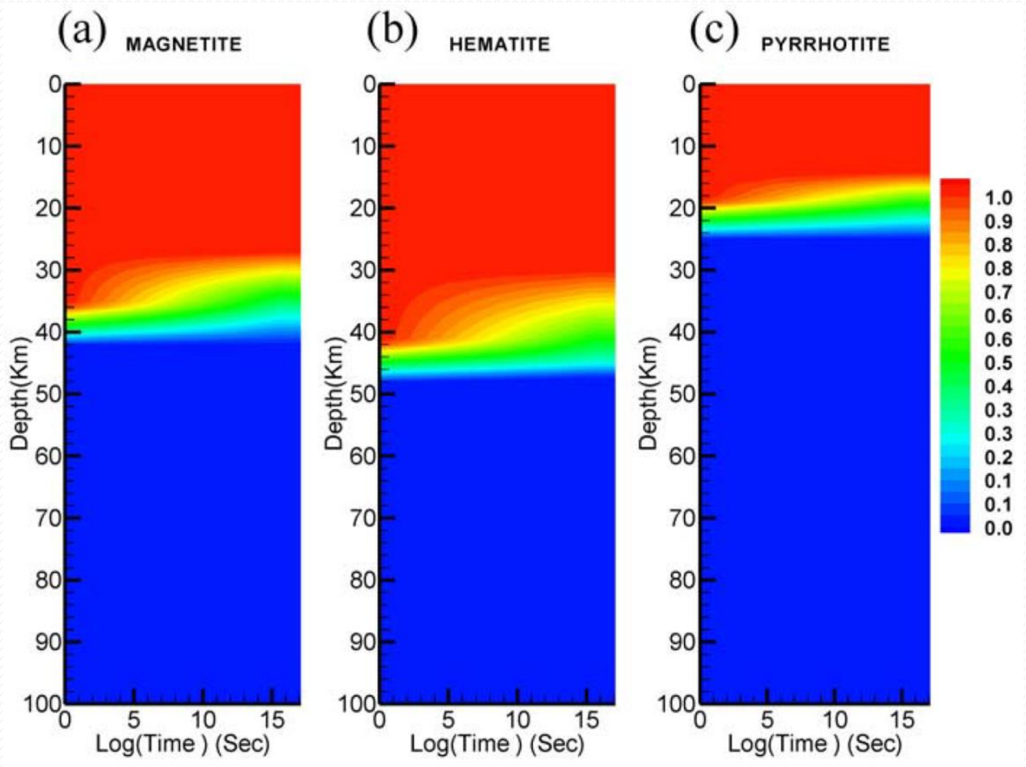


The normalized magnetization (normalized to 1 at 4 Gyr ago) of the magnetic layer as a function of time, for (a) **magnetite**, (b) **hematite**, and (c) **pyrrhotite** (Shahnas & Arkani-Hamed, 2007)

Tectonic Regime of the Terrestrial Planets
Mars

Viscous magnetic decay for Mars with 500 Myr plate tectonic operating model

Curie Temperatures
Magnetite: 580C
Hematite: 670C
Pyrrhotite: 320C



The normalized magnetization (normalized to 1 at 4 Gyr ago) of the magnetic layer as a function of time, for (a) **magnetite**, (b) **hematite**, and (c) **pyrrhotite** (Shahnas & Arkani-Hamed, 2007)

Appendix

Age Determination of Rocks

The age of rocks can be determined by radiometric dating. **Zircon** is one of the nature's best clocks for dating, and geochronology.

U/Pb dating

The method is usually applied to **zircon** ($ZrSiO_4$). This mineral incorporates **uranium** and **thorium** atoms into its crystal structure, but strongly **rejects lead** when forming (melt phase). As a result, newly-formed zircon deposits will contain no lead, meaning that any lead found in the mineral is radiogenic. Zircons are both **ubiquitous** in the Earth's crust and are able to **survive processes of erosion**, **transport**, and even **high-grade metamorphism**, they provide exquisite records of tectonophysical processes.

Venus

Tectonic Regime of the Terrestrial Planets
Venus

Similarities with Earth

Venus is **similar** to Earth in:

a) Size
b) Mass
c) Density
d) **All the Solar System planets** orbit the Sun in an **anticlockwise** direction (viewed from above Earth's north pole) and so does Venus.

Differences

a) **Venus** orbits the **Sun** every 224.7 Earth solar days
b) Most planets also **rotate on their axes** in an **anti-clockwise direction**, but **Venus rotates clockwise in retrograde rotation.**
c) Venus has a **synodic** day length of **117** Earth days and a **sidereal** rotation period of **243** Earth days.
d) Because its rotation is so slow, Venus is very close to **spherical shape.**

Tectonic Regime of the Terrestrial Planets
Venus

Synodic day

The period of time that the **same face** of a planet points to its **host star after** rotating along its ration axis.

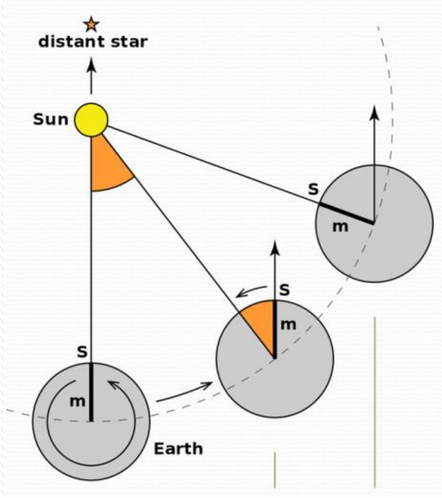
Sidereal day

The period of time that the **same face** of a planet points to a **distant star** after rotating along its ration axis.

Because a synodic day is slightly more than one full Earth's rotation, a sidereal day is slightly shorter than 24 hours. The difference of a sidereal day and a synodic day for Earth sum up to a single day in a year.

Synodic day for Earth: 24:00:00
Sidereal day for Earth: 23:56:04

Sidereal day for Venus is longer than the synodic day because of its retrograde rotation.



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Tectonic Regime of the Terrestrial Planets
Venus

Possible Mechanisms for Slow Rotation

a) Tidal locking to the Sun's gravitation (dissipation of rotational energy by tidal effects) (Dumoulin et al., 2016).
b) Dissipation of energy due to the tidal effects in the Venus thick atmosphere (Correiaa & Laskar, 2003).

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Expected Hypothesis:

The tectonics of Venus **would be similar** to the tectonics of the Earth and that there would be plate tectonics on Venus.

But

We know that **this is not the case** and that **mantle convection** on Venus must be **substantially different** from mantle convection on the Earth. Indeed two planets are **quiet different.**

Missing Features

a) **Oceanic rift system**
b) **Ocean trenches**

These surface manifestations of plate tectonics are **missing** on Venus.

→ Active plate tectonics **is not occurring** on that planet (Kaula and Phillips, 1981).

Tectonism and volcanism on Venus requires an **understanding of mechanism for heat transfer.**

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How essentially Venus is different from the Earth?

a) Venus has a thick **Carbon dioxide** (with very high green house effects) atmosphere, much denser than the Earth's, and is composed of **96.5% carbon dioxide, 3.5% nitrogen,** and traces of other gases, most notably sulphur dioxide.

b) The surface temperature and pressure are **~740 K** (~**475 K** higher than **Earth**) and 93 bar (9.3 MPa), respectively (Seiff, 1983).

c) Covered by sulphuric **acid clouds** and droplets and **lightning** (associated with clouds of sulphuric acid), **storms**

d) Some **Venus models** predict **thin lithosphere** (~40 km), **hot and weak**, **without the capability of supporting high topography** or large gravity anomalies. The **relaxation** of **large impact craters** would be expected **faster** in this model

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e) **However**, Topography and gravity data obtained by **Pioneer** Venus show serious **inconsistencies** with these expectations (thin lithosphere).

f) Although the **mean surface roughness** (height to wavelength ratio) on **Venus** is a factor of **3 or 4 less** than on the **Earth**, the **maximum elevations** are **nearly equal** (Pettengill et al., 1980; Bills and Kobrick, 1985; Turcotte, 1987; Ford and Pettengill, 1992).

g) Some models assume a thickness of **200-400 km** for the lithosphere.

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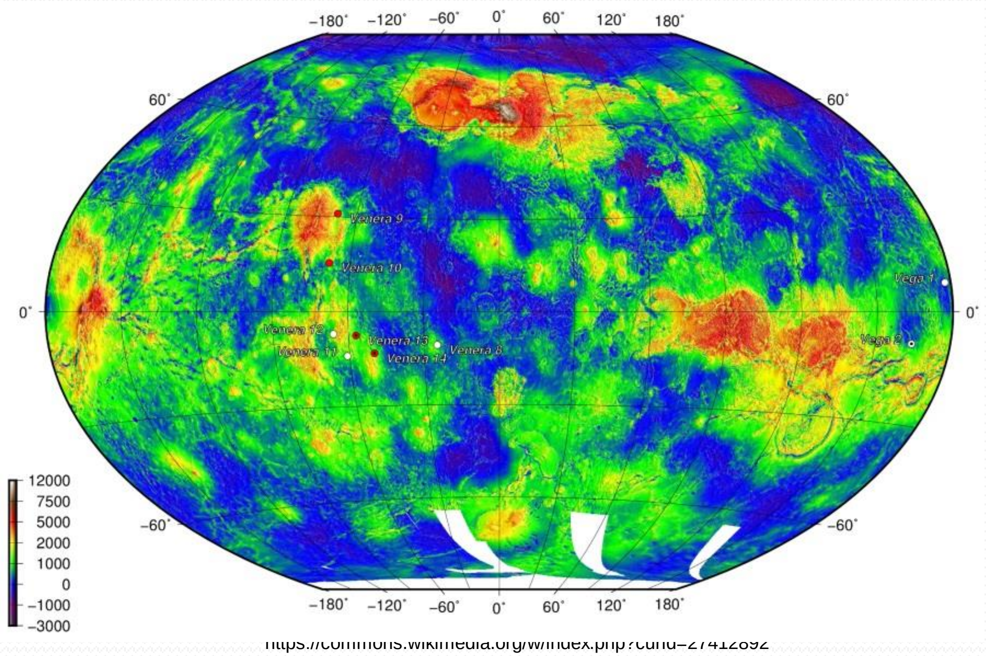
Venus Topography

As a **one-plate planet**. **Tectonic features** are present to a **limited extent**, including **deformation belts** composed of **folds and faults** (Fernández, 2014; Farnk & Head, 1990). These may be caused by mantle convection and volcanism.

Deformation belts are complex tectonic units including **ridges**, **extensional fractures (graben)**, and **strike-slip fractures.**



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Volcanic Rises:

Volcanic rises are more like islands than a continents. They are formed by plumes, in a similar fashion to island formation on Earth. Hot magma deep beneath these rises supports mountains at the surface. **Three types** of volcanic rises are:

a) Volcano-Type Rises

Volcano dominated rises such as the **Bell Regio** (Rogers & Zuber, 1998). They contain large shield volcanoes. **Tepev** Mons is a prominent **volcanic shield** within Bell Regio.

b) Rift-Type Rises

These are rises that contain two or more deep rift valleys. **Rift dominated rises,** uplifts by **rifting** and thinning of the lithosphere such as the **Beta Regio** and the overlying **Theia Mons. Beta Regio volcanic rise** has many of the features of a continental **rift** on Earth**. Alta, Eistla, and Bell Regiones** have similar rift zone characteristics (Grimm and Phillips, 1992; Senske et al., 1992).

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c) Corona-Type Rises

They **don't have large rift** valleys **or** many **shield volcanoes**, but have many coronae. **Corona dominated** an uplift features are caused by the gravitational collapse and extension of a magma chamber, and include the **Themis Regio** (Stofana et al., 2016).

The rises associated with **high-density anomalies**, indicate a **source from** mantle **plumes beneath** the crust that warp and uplift the region.

Alpha Regio is a **Plateau Highland** of Venus. The **only volcano** known to be found on **Alpha Regio** is **Eve Mons**.

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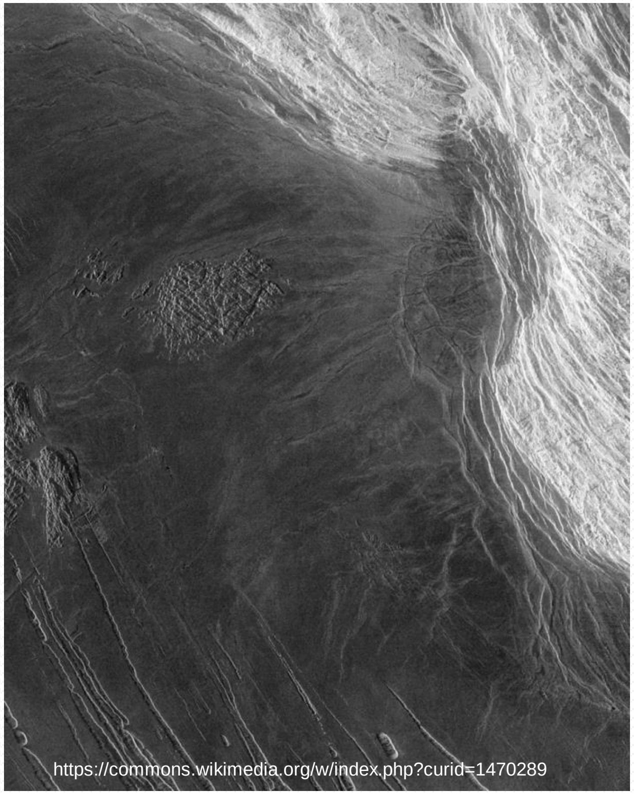
Tessera

A tessera (plural tesserae) is a region of heavily **deformed terrain** on Venus.

Tessera terrain in the **Maxwell Montes** (located in **Aphrodite Terra**) seen in white on the right of the image.



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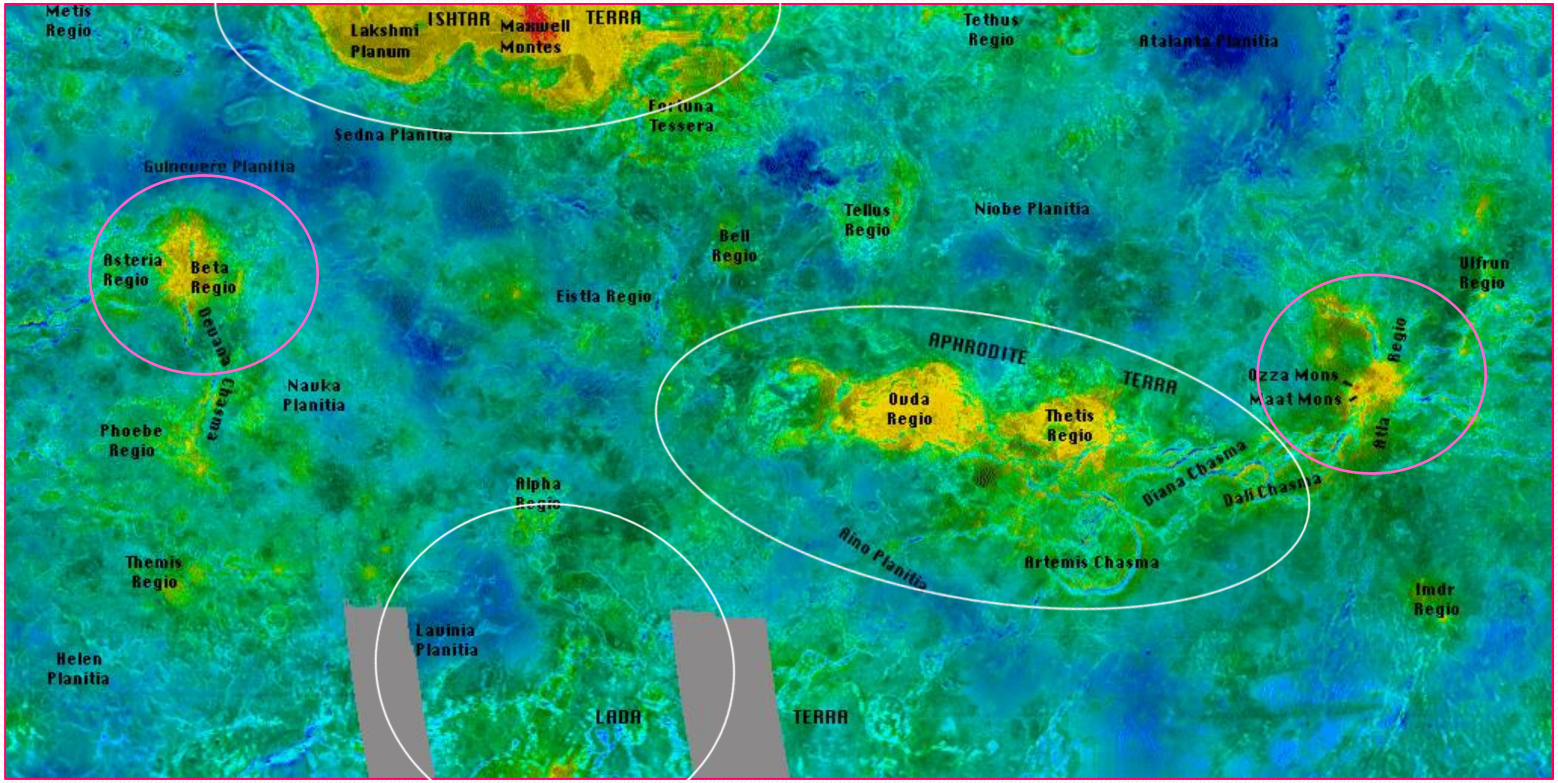
Venus Continents

Venus has three continental regions (land masses):

a) **Ishtar Terra** (the size of the United States, the second largest terra).
b) **Aphrodite Terra** (the size of half the continent of Africa, the largest terra).
c) **Lada Terra.**

The other highlands of Venus include **Alpha Regio, Beta Regio, etc**.



http://www.tsgc.utexas.edu/images/planets/venus/topo1.html

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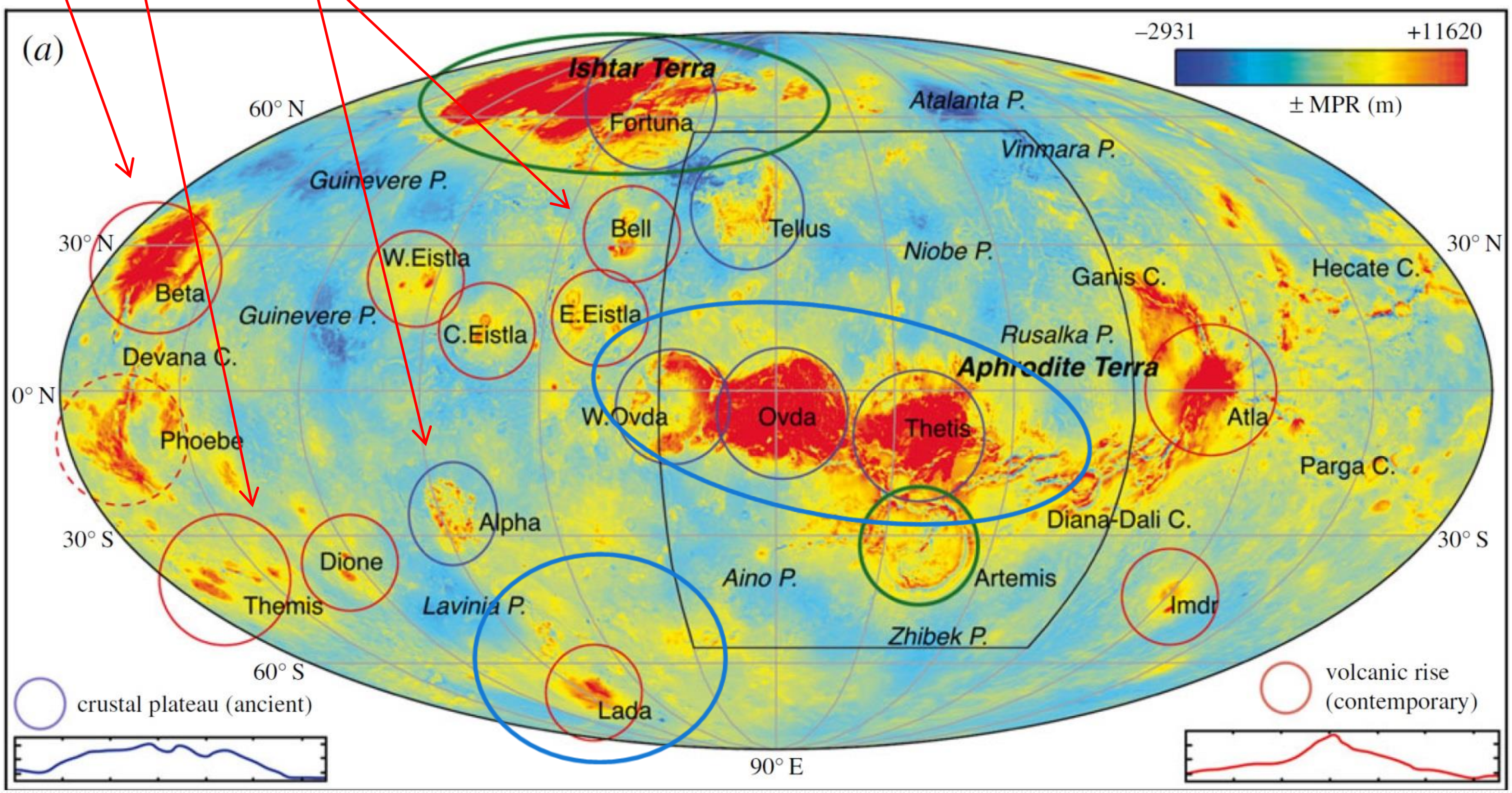
Beta Themis Alpha

Bell Ishtar Aphrodite Lada



Hansen, 2018

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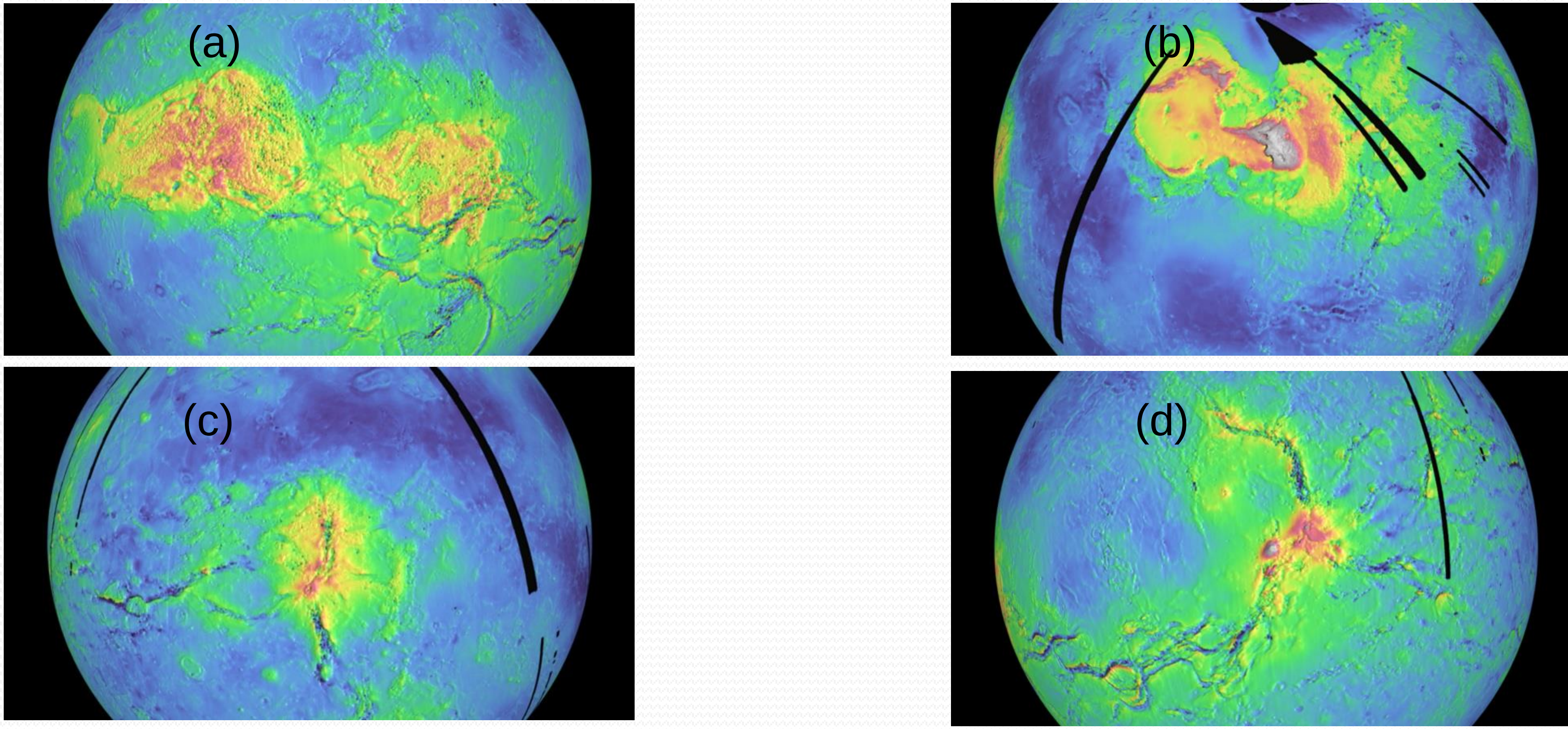

a) Aphrodite Terra is the largest highland on Venus, ~10000 m in diameter and1-5 km in elevation; **b)** Second largest is the highland named Ishtar Terra, ~5600 km in diameter and ~11 km in elevation; **c)** Beta Regio volcanic rise, 2000x25000 km wide and ~3.9 km in elevation (Basilevsky & Head, 2007); **d)** Volcano Maat Mons, ~390 km wide and ~8 km tall (might be active).

https://svs.gsfc.nasa.gov/10904

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f) **Aphrodite Terra,** with a length of some 1,500 km, is reminiscent of major continental collision zones on the Earth (compression). **Ishtar Terra** is a region of elevated topography with a horizontal scale of 2,000–3,000 km.

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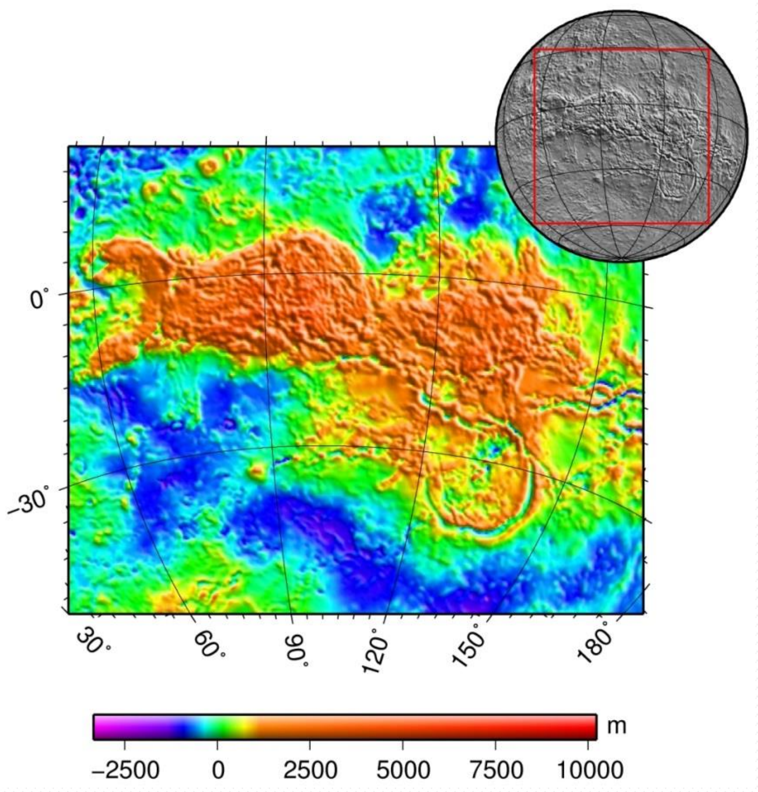
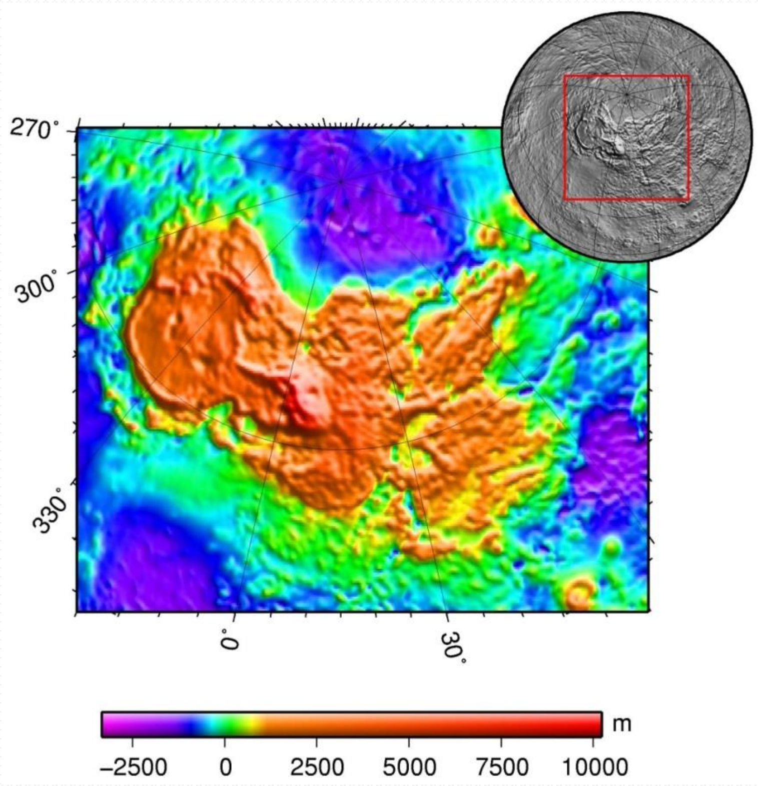


Aphrodite Terra



Ishtar Terra

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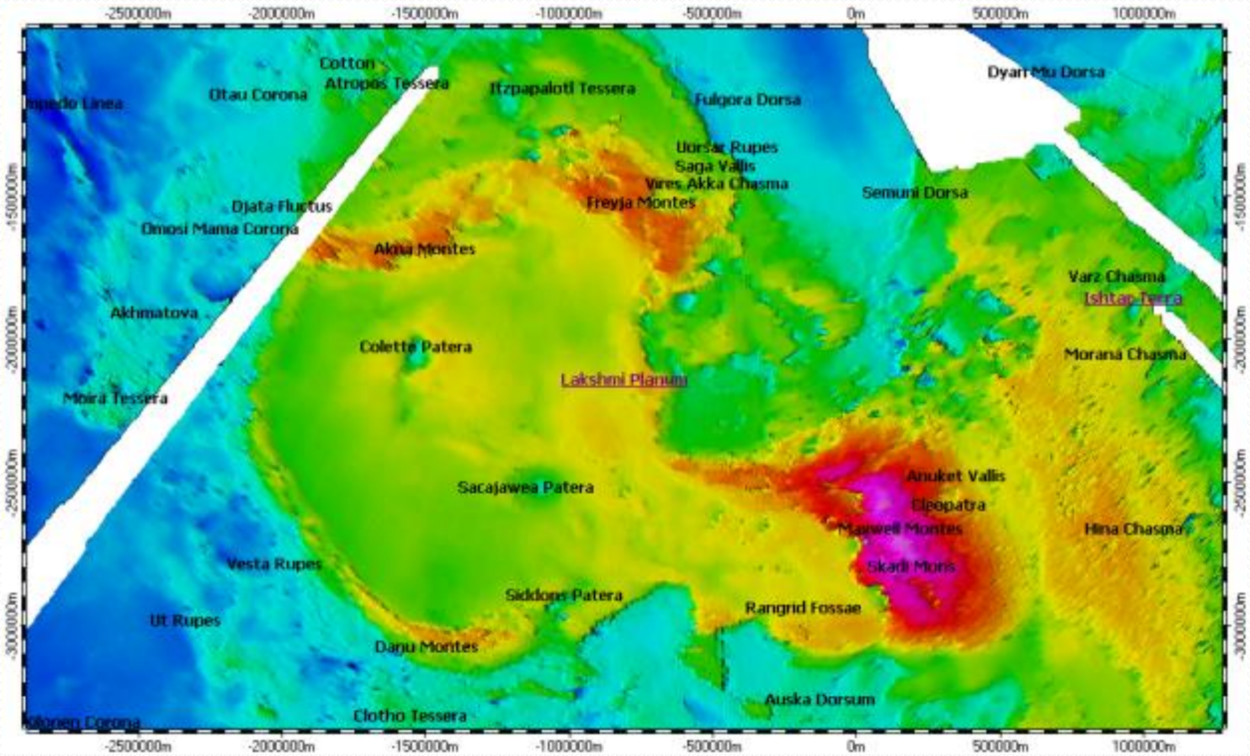
g) A major feature is **Lakshmi Planum**, which is an elevated plateau similar to **Tibet** with a mean elevation of about 4 km

h) The highest mountain chain on Venus, **Maxwell Montes** in Ishtar Terra is 11 km high. It was formed by processes of **compression**, **expansion**, and **lateral movement**



http://www.runspect.com/examples/Lakshmi_Planum_Venus.htm

Lakshmi Planum

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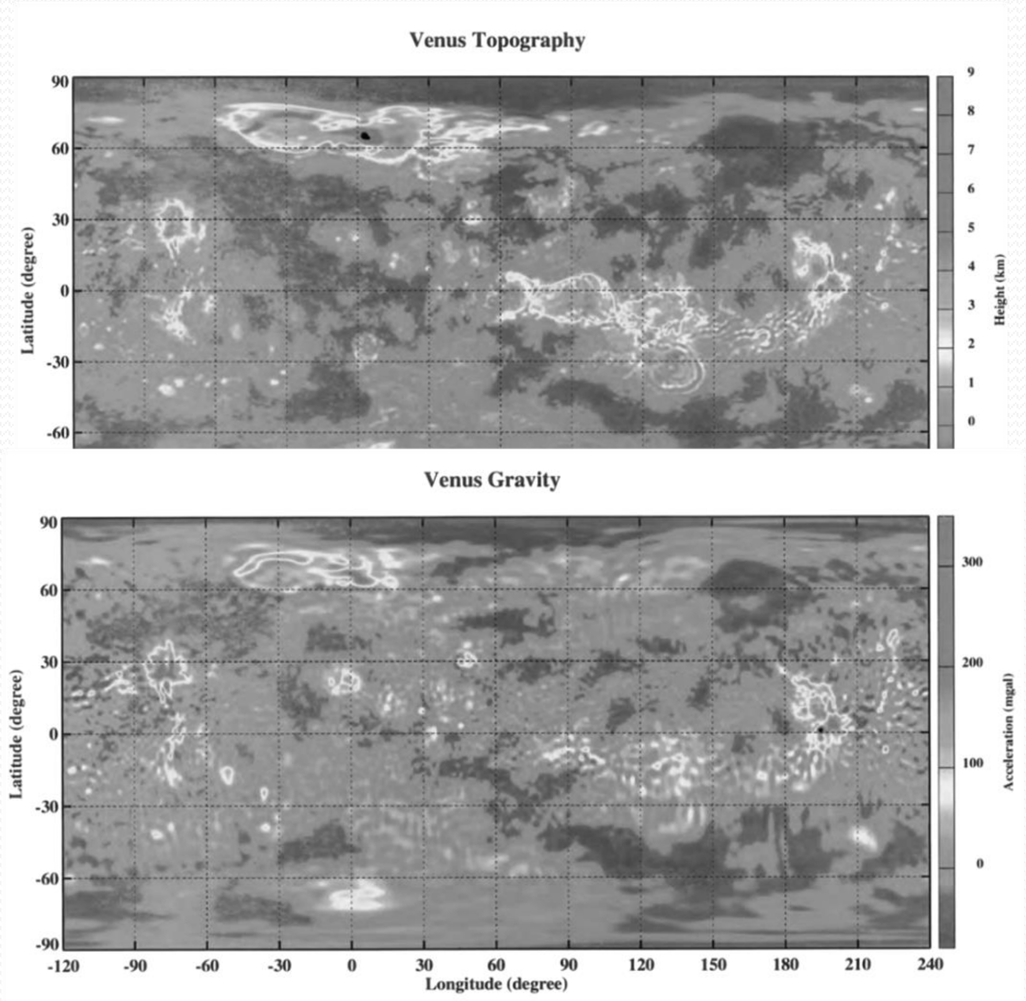
Topography and Gravity Anomaly Correlation

In most regions topography and gravity anomaly are correlated.



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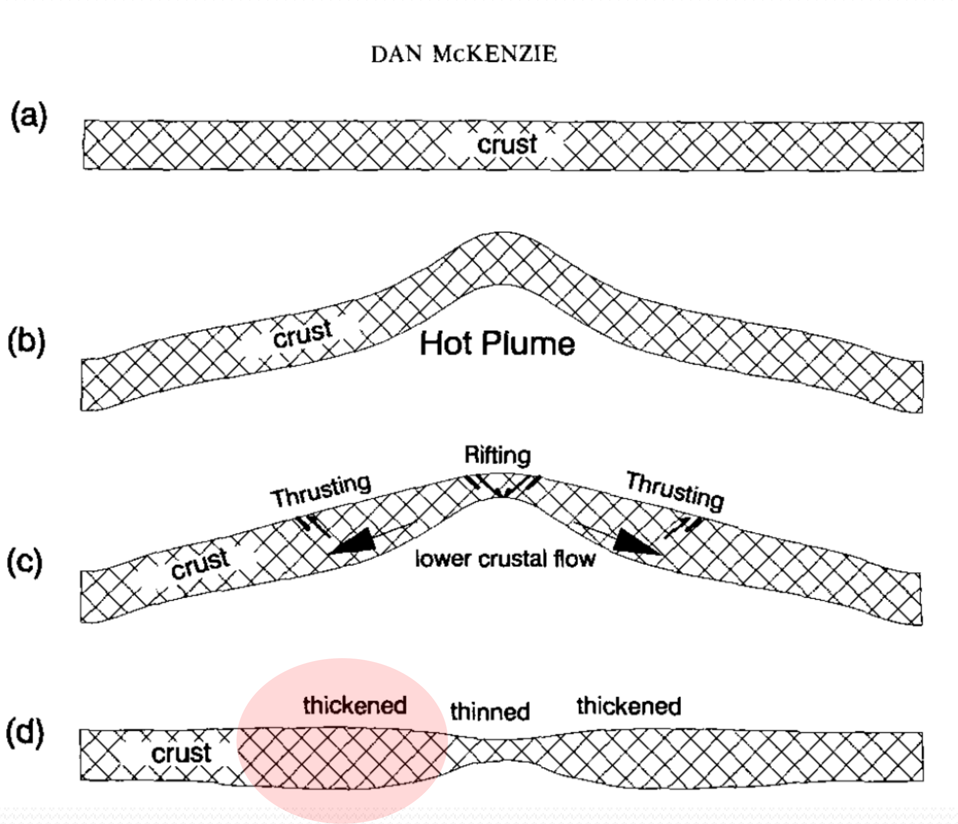
Crustal model deformation associated with Beta Rigio



A region with constant crustal thickness, b) uplifted crust by the influence of a plume, c) the curst flows away from the uplift due to the viscosity reduction (by heat). Such flow generates rifting on the top of dome and thrusting where the crust is thickened. d) The dome subsides after the plume decays leaving a thinned crust. The lower crust cools before it can flow back into the depression (McKenzie, 1994).

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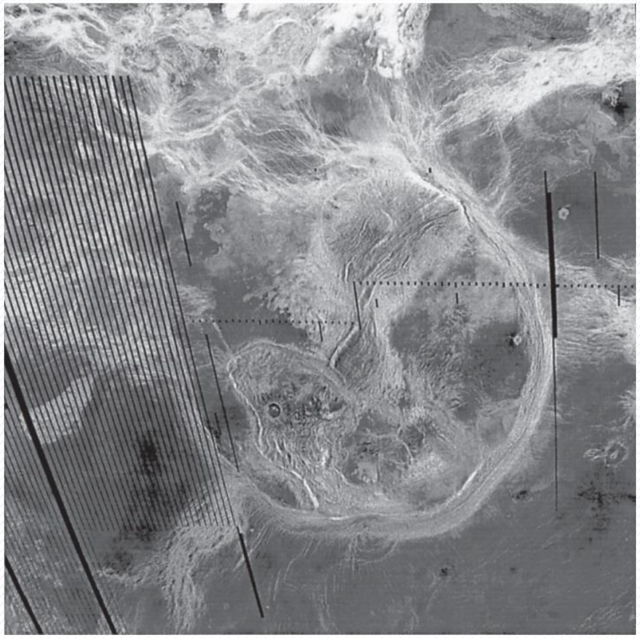
Corona Formation

Coronae are formed when plumes of rising hot material in the mantle push the crust upwards into a dome shape, which then **collapses** in the centre as the **molten magma cools** and **leaks out at the sides**, leaving a crown-like structure: the corona.

The near circular trough of the **Artemis chasma** has a diameter of 2100 km. The concentric features outside the chasma (a deep, steep-sided depression) are attributed to **normal faulting** associated with **lithospheric flexure** similar to that occurring seaward of subduction zones on the Earth.



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Resurfacing

Venus is a single plate planet. Using statistical methods and **counting the number of impact craters** the age of Venus is estimated to be **~ 500 Myr,** postulating that a global resurfacing event occurred on Venus about **500Ma** (Schaber et al., 1992).

More recent studies of cratering on Venus that account for **atmospheric deceleration** and flattening of impactors place the resurfacing somewhat further back in time at about **750 Ma** (McKinnon et al., 1997).

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Convection

Certainly mantle convection occurs in **Venus**. So why the global tectonics is absent in Venus?

The **absence of global tectonics** is possibly related to its **hot and dry** conditions. In the case of Earth water content of the lithosphere play an important role in plate tectonics.

Heat Transfer

How the internal heat generated by radiogenic isotopes is lost to the surface of Venus?

a) Conduction
b) Volcanism
c) Periodic (500-750 Myr) lithosphere overturn

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In the absence of plate tectonics heat is transferred by conduction and volcanism. There are evidences for recent volcanic activities at hot spots, indicating that there are active mantle plumes in the mantle of Venus (Smrekar et al., 2018).

Lithosphere Overturn

Numerical models suggest the possibility of lithosphere overturn with periods of **700 Myr.** Due to the core and radiogenic heating the interior of Venus warms up and the lithosphere becomes unstable and a huge amount of heat is transferred to the surface by the lithosphere overturn mechanism. After this catastrophic subduction event (lithosphere overturn), the lithosphere gradually thickens until its gravitational instability drives another global subduction event (Schubert et al., 2004).

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Basalt Barrier Mechanism

In the basalt barrier mechanism (Ringwood &Irifune, 1988, 1991; Ogawa, 2003, 2007) subducted basaltic crust becomes **positively buoyant** between the mantle depths of **660 km and 750 km**, and **negatively buoyant** at **other depths.**
This can cause mantle layering by accumulation of basalt at ~750 km depth and **episodic mantle overturns** (Geoffrey & Davies, 2012).
Venus contains different volcanic structures with dominant rock type of basalt, a type of volcanic rock observed on the Earth's surface (e.g., in lava flows in Hawaii, the ocean seafloor, and Iceland).

Model results of Davies (2008) show that this mechanism (positive buoyancy of the oceanic basalt) generated episodically layered mantle convection early in **Earth** history before evolving into present day convection style (**whole mantle** and **partially layered** due to the influence of the **endothermic** phase transition at 660 km depth). In the case of Earth numerical models suggest that the termination of layering and overturns occurred during 1.5–2 Ga due to the increasing **negative thermal buoyancy of subducted lithosphere** as the mantle cools and slows due to the viscosity increase (Davies (2008).

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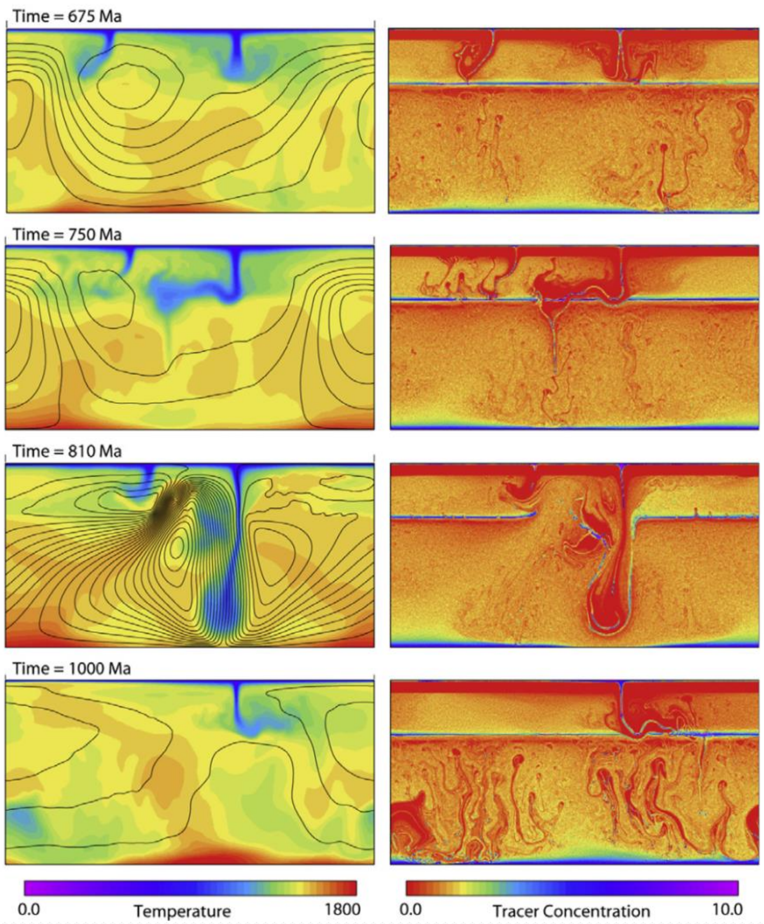

Episodic behaviour of Venus model, showing strong mantle layering at 675 Ma, followed by a break of the basalt barrier at 750 Ma, the mantle overturns at 810 Ma and layering is re-established again at 1000 Ma (Geoffrey & Davies, 2012).

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The Absence of Magnetic Field

Venus may have a molten core, but because it spins very slowly (once every 243 Earth days) it does not generate a magnetic field.

Three requisites for a dynamo to operate:

1) Electrically conductive fluid medium
2) Kinetic energy provided by planetary rotation
3) A convective motions within the fluid