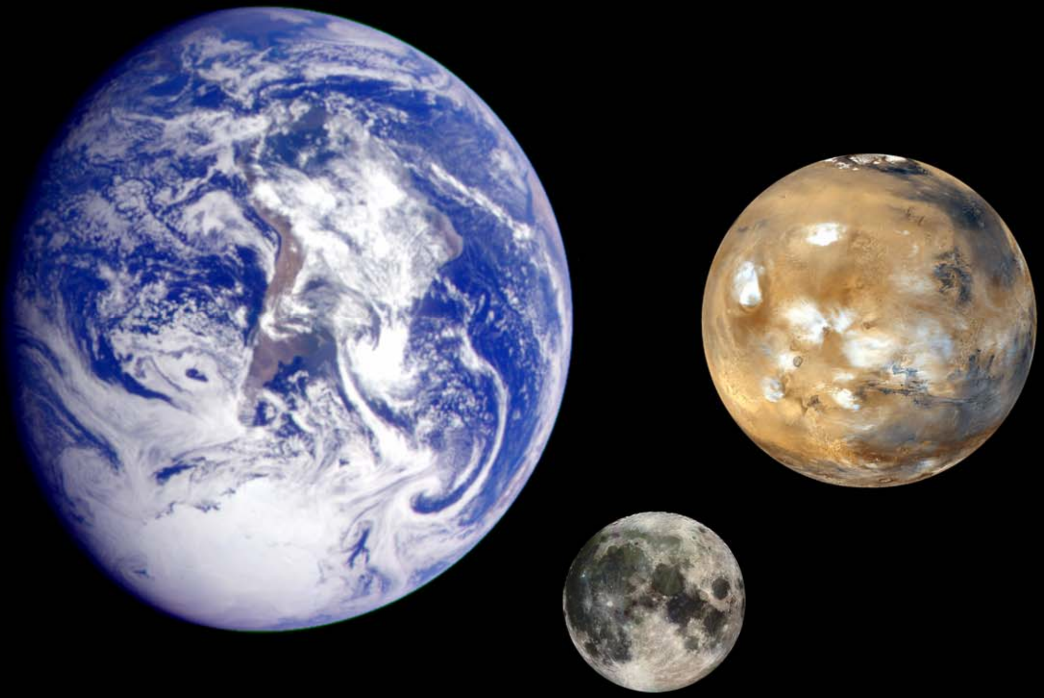
12.001 Introduction to Geology
Spring 2008



The effects of magma ocean depth and initial composition on planetary differentiation

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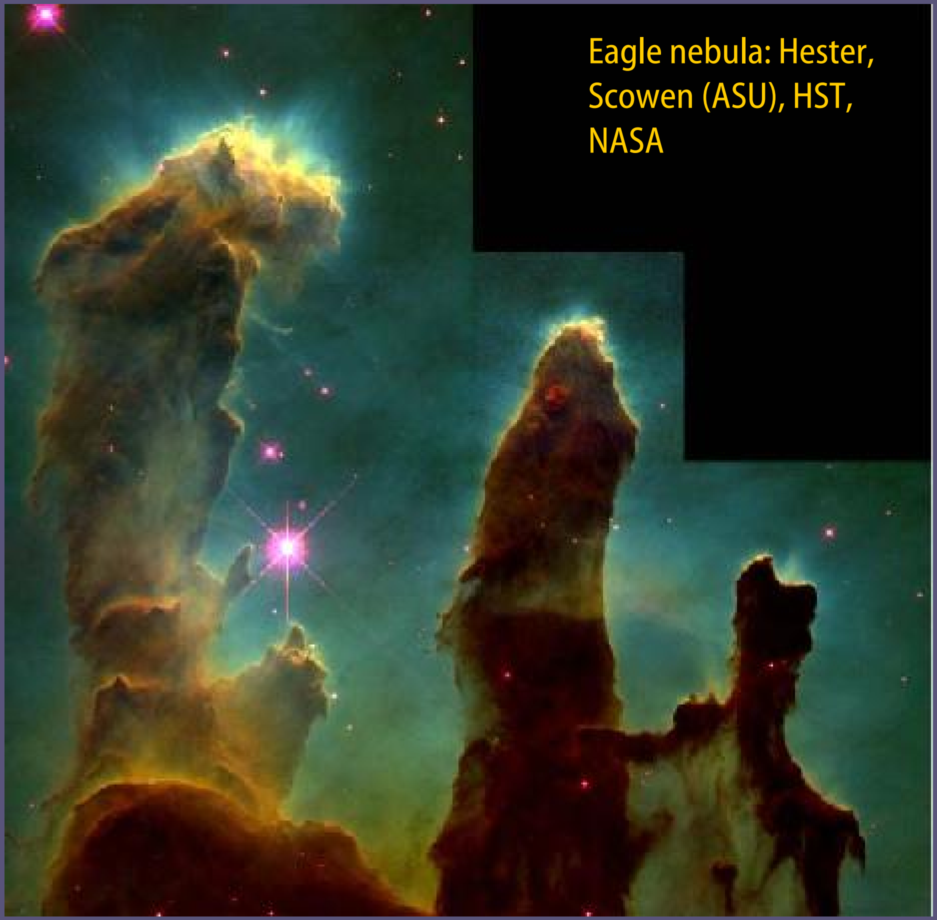
(Image courtesy of NASA/JPL.)

Formation of new stars and planets

Horsehead nebula: NASA, NOAO, ESA and The Hubble Heritage Team (STScI/AURA)



Eagle nebula: Hester, Scowen (ASU), HST, NASA

protoplanetary nebula = planetary nebula = preplanetary nebula, NEBULAS, not new SOLAR SYSTEMS

protoplanetary disk = proplyd ≈ accretionary disk (this really refers just to the star)

Rotating nebula begins to contract

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Contraction and rotation of protoplanetary disk

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Ca-Al inclusions in carbonaceous chondrites: 4567.2±0.6 million years old

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Accretion simulations

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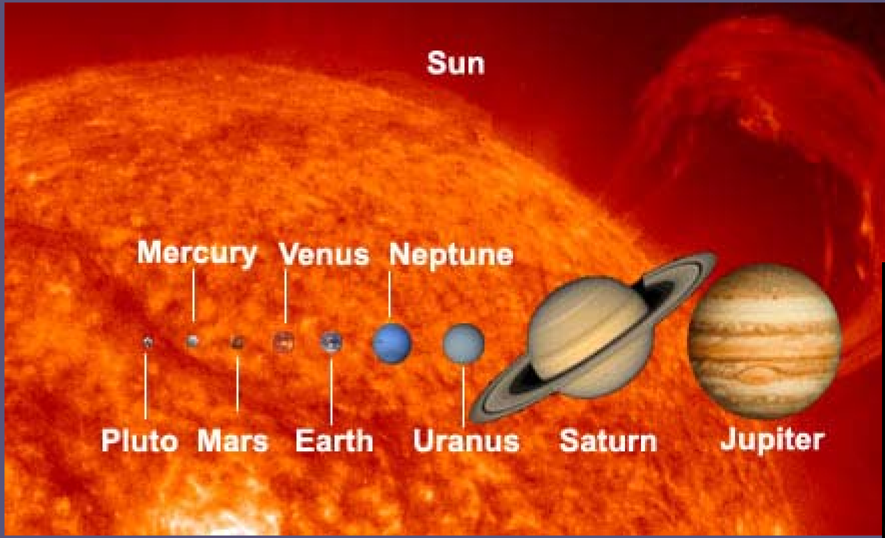
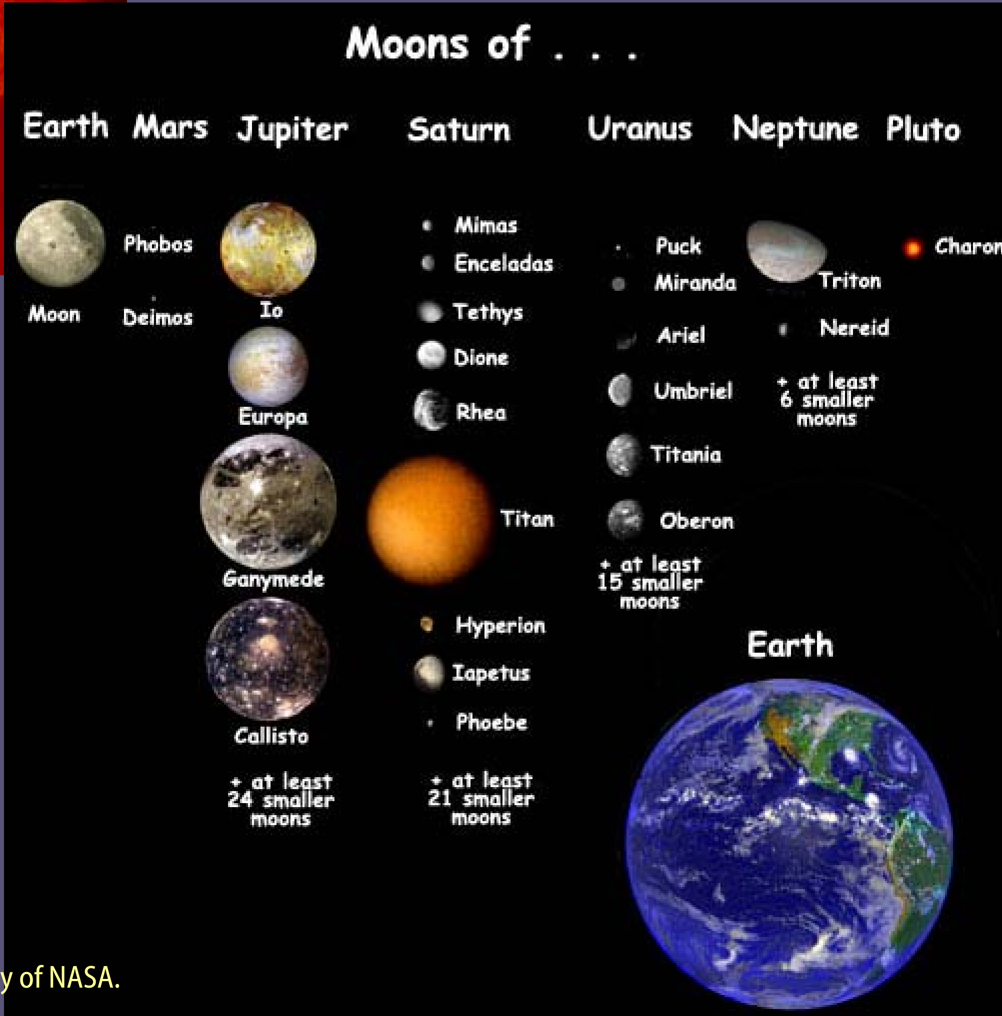
Planetary accretion simulation from Raymond et al. (2006), using 1054 initial planetesimals from 1 to 10 km radius. Earthlike planets are formed, but their orbital eccentricities are too high.

Size of the planets





Images courtesy of NASA.

Young planets are hot

Factors lead to heating and melting early in a terrestrial planet's history

Radioactive decay of elements

Accretion of large bodies (meters [planetesimals] to hundreds of kilometers [embryos])

    Converts kinetic energy to heat

Core formation

    Converts potential energy to heat

Global Chemical Differentiation

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Iron meteorites: The cores of failed planetesimals

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Short-lived radioisotopes

Some short-lived radioactive elements produced enough heat to help melt planetesimals or embryos:

- ^{26}Al (700,000 y) $\longrightarrow$ ^{26}Mg releases 4.8×10^{-13} J/atom; Mars may have had 10^{42} atoms
  Wasserburg: ^{26}Al was present in CAIs, meaning at most a few million years for CAI formation
- ^{60}Fe (1,500,000 y) $\longrightarrow$ ^{60}Co (5.2714 y) $\longrightarrow$ ^{60}Ni

Other short-lived radioisotopes date differentiation events:

- ^{182}Hf (9,000,000y) $\longrightarrow$ ^{182}Ta (114.43 days) $\longrightarrow$ ^{182}W
  Core formation constraint (W into core, Hf into silicate mantle)
- ^{146}Sm (103,000,000 y) $\longrightarrow$ ^{142}Nd
  Silicate differentiation constraint (Sm slightly more into minerals, Nd into melt)

Formation of the Moon

(about 15 – 20 million years after CAIs)

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Clearing out the inner solar system

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Far side of the Moon

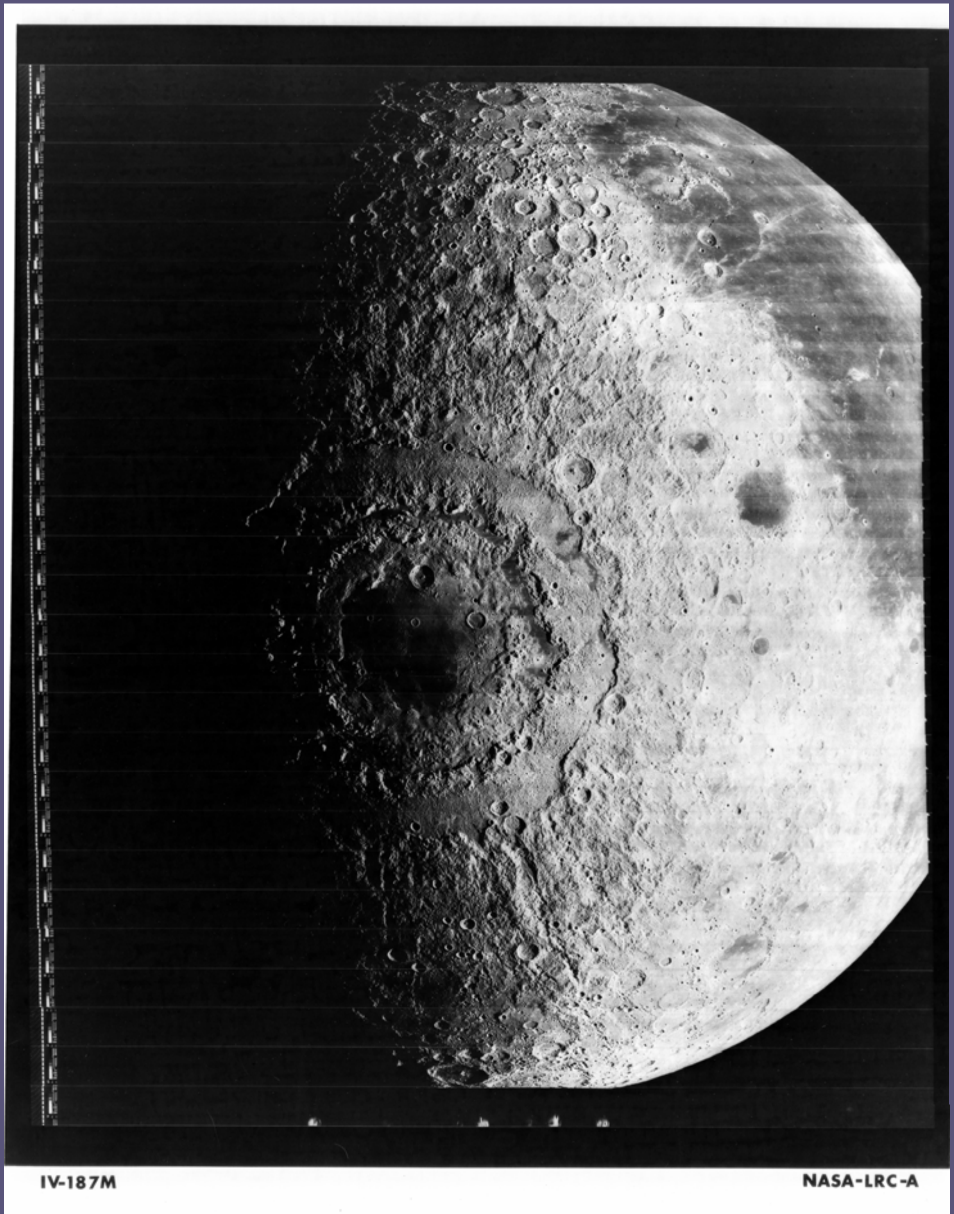

Image courtesy of NASA.

OUTLINE: Solidification of a magma ocean

1. Theory and calculations
2. Planetary radius and a heterogeneous mantle
3. Depth of initial magma ocean and resulting crustal compositions
4. Production of a magnetic field
5. Volatiles and plagioclase flotation

Linked solidification and cooling processes

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Volatiles partition among three reservoirs

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Heat flux through atmosphere allows calculation of cooling rates

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Structure and thermal evolution of an evolving magma ocean

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Mineralogy and solidus based on data from Longhi *et al*. (1992)

Settling or entrainment: Calculation of liquid/crystal density inversion

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Elkins-Tanton et al. (2003)

Stolper *et al*. (1981) and Walker and Agee (1988): olivine buoyancy inversion between 7.5 and 9 GPa.

Lunar magma ocean

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Idealized overturn

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OUTLINE

1. Theory and calculations
    - Magma oceans would solidify from the bottom up
    - Volatiles partition between cumulates and atmosphere
    - Garnet may sink into a near-monominerallic layer
    - Shallowest cumulates are denser than deeper cumulates

2. Planetary radius and a heterogeneous mantle
3. Depth of initial magma ocean and resulting crustal compositions
4. Production of a magnetic field
5. Volatiles and plagioclase flotation

Gravitational overturn: Nonmonotonic density gradients

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Gravitational overturn: Numerical models in spherical coordinates

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Monotonic density gradient

Nonmonotonic density gradient

Overturn creates a laterally-heterogeneous mantle

Before overturn

After overturn

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Axisymmetic models show: The majority of overturn complete in <2 Myr; small-scale heterogeneities last a long time

Depths of origin of lunar volcanic rocks

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OUTLINE

1. Theory and calculations
2. Planetary radius and a heterogeneous mantle

   Cumulate overturn is fast and efficient

   Following early differentiation there will be no simple composition-depth relationships

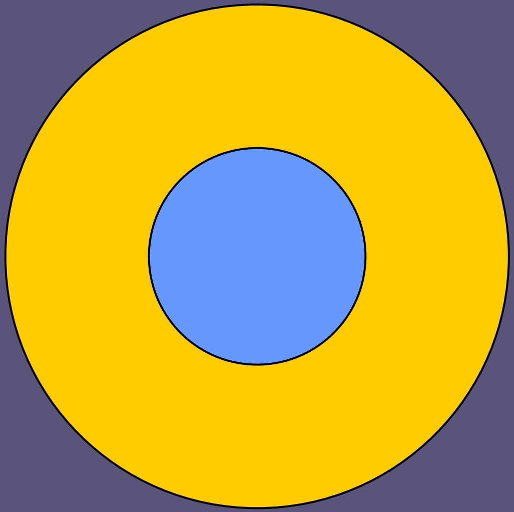
   Following early differentiation the mantle will have a stable density stratification

3. Depth of initial magma ocean and resulting crustal compositions
4. Production of a magnetic field
5. Volatiles and plagioclase flotation

Volatile content considerations

- The Moon likely accreted dry, while Mars and the Earth had non-zero volatile contents
- Volatiles form an insulating atmosphere and partition into nominally anhydrous mantle cumulates
- No mafic quench crust is likely to form on a magma ocean, because of density and temperature considerations
- Water in the silicate liquid inhibits the formation of plagioclase
- If plagioclase forms and floats, it may significantly slow planetary cooling

Volatile contents of possible planetary building blocks



If planet up to ~1,300 km radius retains volatiles (Safronov), bulk Mars-size planet contains:

	C	H_2O	CO_2	H_2O
C1 (CI)	3.5%	20%	0.06%	1.2%
C2 (CM)	2.5	13		
CR	1.5	6	0.03	0.36
C3 (CV, CO)	0.5	1	0.01	0.06
OC (Type 3)	0.5	1		

John A. Wood (2005) The chondrite types and their origins.

Atmospheric growth and planetary solidification

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Brain and Jakosky (1998): 95 to 99% of atmospheric has been lost
Catling (2004): 99% of surface water has been lost

Varying volatile mix in initial magma ocean

Mars-sized planet: Decreasing water, increasing carbon dioxide

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Initial: 0.4 wt% H_2O, 0.1 wt% CO_2

0.3 wt% H_2O, 0.2 wt% CO_2

0.2 wt% H_2O, 0.3 wt% CO_2

Depth of first plagioclase crystallization

PLANETARY SURFACE

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Without a plagioclase flotation crust, planetary solidification is very fast:

90 vol% in less than 50,000 years

The Hadean Earth: Old Version

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Dynamic effects of volatiles in cumulates

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- **Even small amounts of water have a large effect on solid-state creep rates**
- **Volatiles are available for later degassing**

Constraints on planetary formation from isotopic systems

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Liquid water

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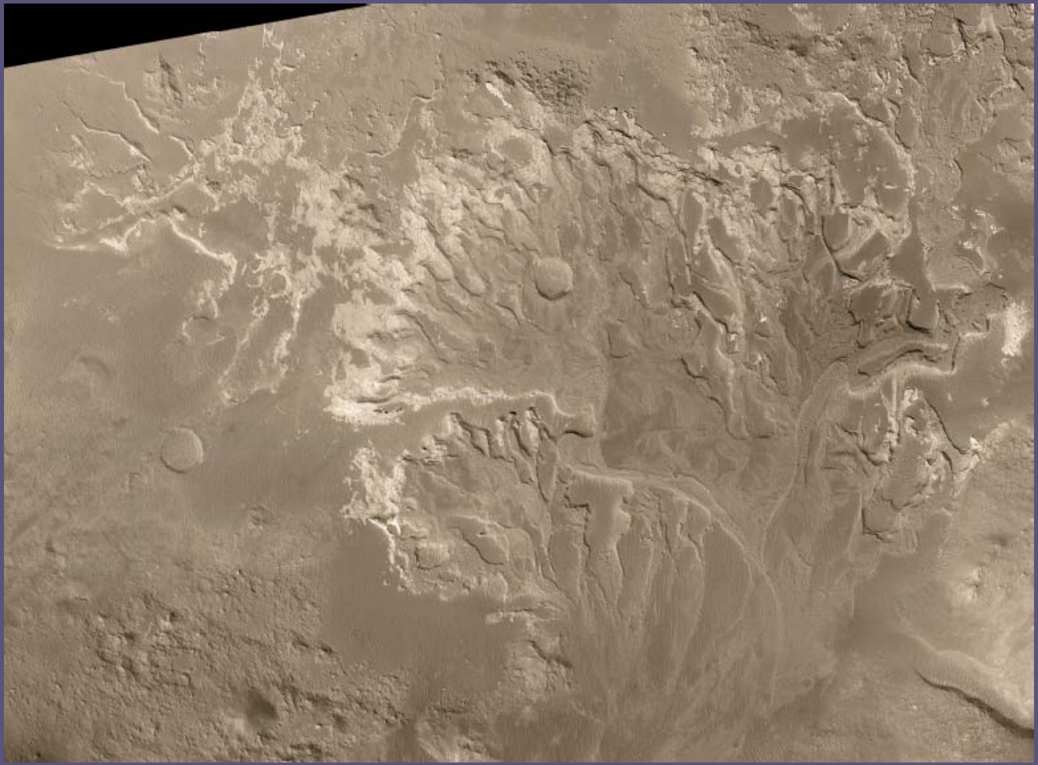
Martian distributary channels



Courtesy of NASA.

Liquid water may be stable on the surface within a few million years