12.007 Geobiology 2013

Description

Parallel evolution of life and the environment. Life processes are influenced by chemical and physical processes in the atmosphere, hydrosphere, cryosphere and the solid earth. In turn, life can influence chemical and physical processes on our planet. This course introduces the concept of life as a geological agent and examines the interaction between biology and the earth system during the roughly 4 billion years since life first appeared.

Grading:

25%	Participation in class discussions
15%	Problem Sets/Assignments
10%	Weekly quizzes
20%	Final Blog Piece
15%	Midterm Exam
15%	Final Exam

12.007 Geobiology 2013

Lecture Schedule

1. Wed 2/6 Overview of course; What is life? Can it be defined? Habitability and the HZ; Alternate forms of life? Abundance of elements. That arsenic paper!!. Geochronology; Time scales of major events in formation of Universe and Solar System; Life as a geological agent. (Summons)

Stanley, Chap. 1 & 2 Kump 187-195

2. Mon 2/11: Planetary accretion and differentiation. Sedimentary environments and processes; Stratigraphy; Plate tectonics; Isostasy; Radiative balance; Greenhouse gases. Faint Young Sun. Brief history of paleontology and geobiology; (Summons)

Stanley pp. 129-151, 177-197

3. Wed 2/13: Prebiotic chemistry, Nucleic acids, Amino Acids and Chirality, Origins of life, Panspermia; Luca and the three domains; Universal tree of life (Summons)

Kump 381-396, Stanley 103-127

What is Life Quiz

Woese paper for Wed 2/23

The Solar System and Earth Accretion & Differentiation

Formation of the Solar System

- Sites and images → Maria Zuber Website

12.004 Introduction to Planetary Science

http://web.mit.edu/12.004/www/sites.html

Text: Earth System History Steven M. Stanley, 1998

Other Readings:

5 papers in Scientific American Oct 1994 Volume 271 from the big bang to pollution Weinberg, Peebles, Kirschner, Allegre and Orgel

Delsemme, 1996, The origin of the atmosphere and of the oceans in *Comets and the Origin and Evolution of Life* (Eds Thomas, P.J., Chyba, C.F., McKay, C.P.)

Chyba and Sagan, 1996, Comets as a source of Prebiotic Organic Molecules for the Early Earth in *Comets and the Origin and Evolution of Life* (Eds Thomas, P.J., Chyba, C.F., McKay, C.P.)

Origin of Solar System: Nebular Hypothesis

- Rotating dust cloud (nebulae)
  - Rotation causes flattening
  - Gravity causes contraction
  - Rotation increases
  - Material accumulates in center--protosun
  - Compression increases T to 106 ° C—fusion begins
  - Great explosion
- Origin of planets
  - Gases condense
  - Gravity causes them to coalesce into planetesimals
  - Planetesimals coalesce & contract into planets
- The planets
  - Terrestrial or inner planets
    - Mercury, Venus, Earth, Mars
    - loss of volatiles (H, He, H_2O) by solar wind
    - made of rock (O,Mg,Si,Fe)
  - Jovian planets (4 of the 5 outer planets)
    - Jupiter, Saturn, Neptune, Uranus
    - mostly volatiles (H, He)
  - Pluto
    - anomalous--rock w/ frozen H_2O &CH_4

Origin of Planetary System from Solar Nebula

- Slowly rotating cloud of gas & dust
- Gravitational contraction
- High P=High T (PV=nRT)
- Rotation rate increases (conserve angular momentum)
- Rings of material condense to form planetesimals, then planets (Accretion)

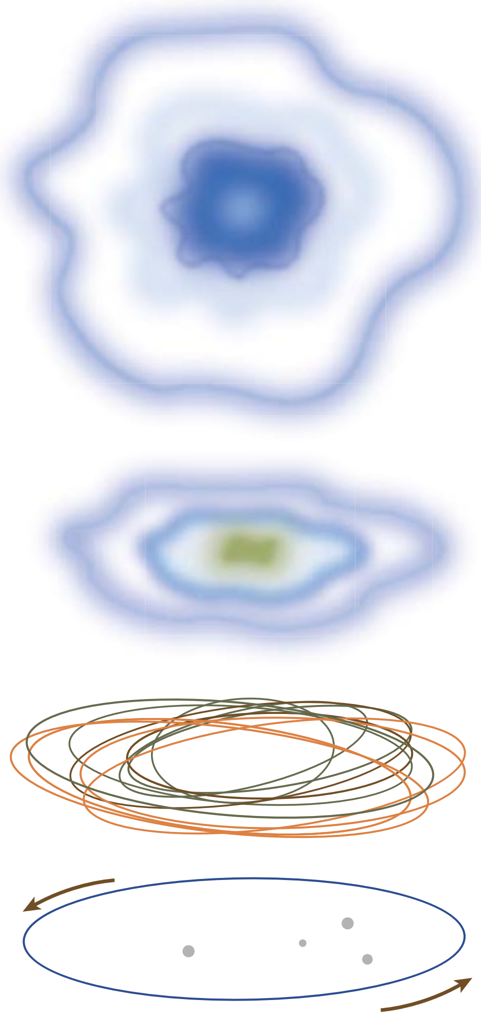
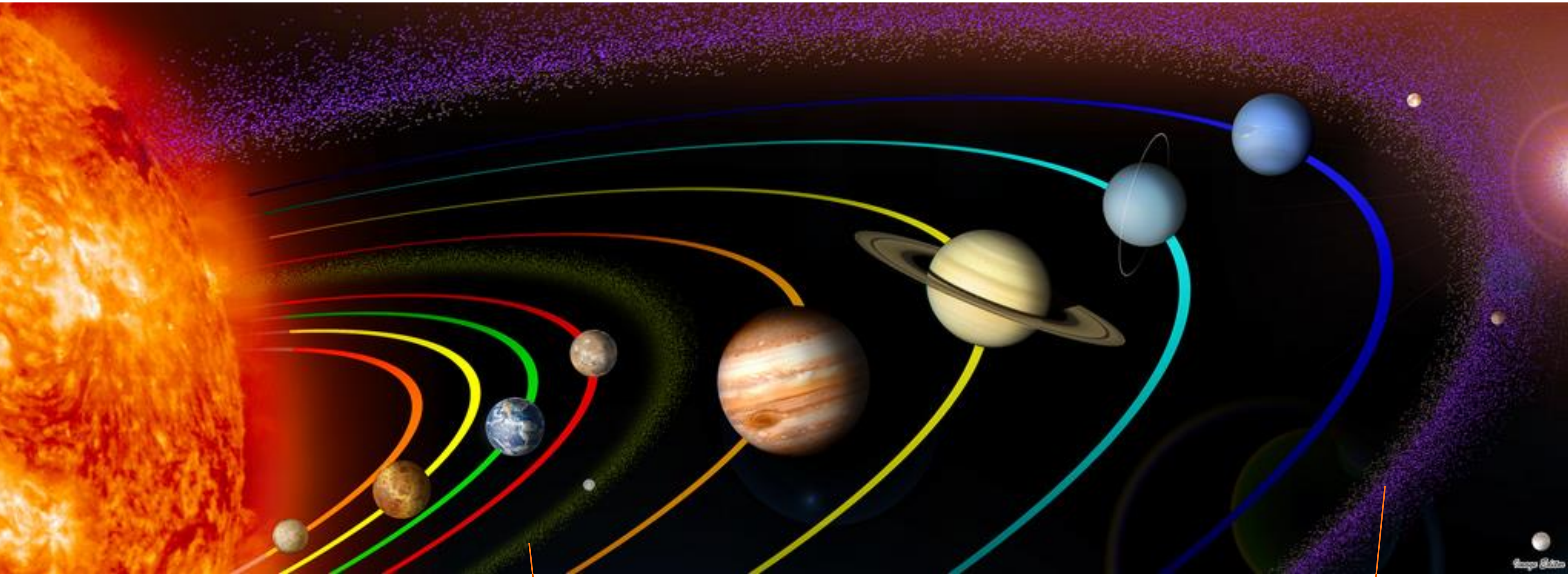


Image by MIT OpenCourseWare.

The Solar System

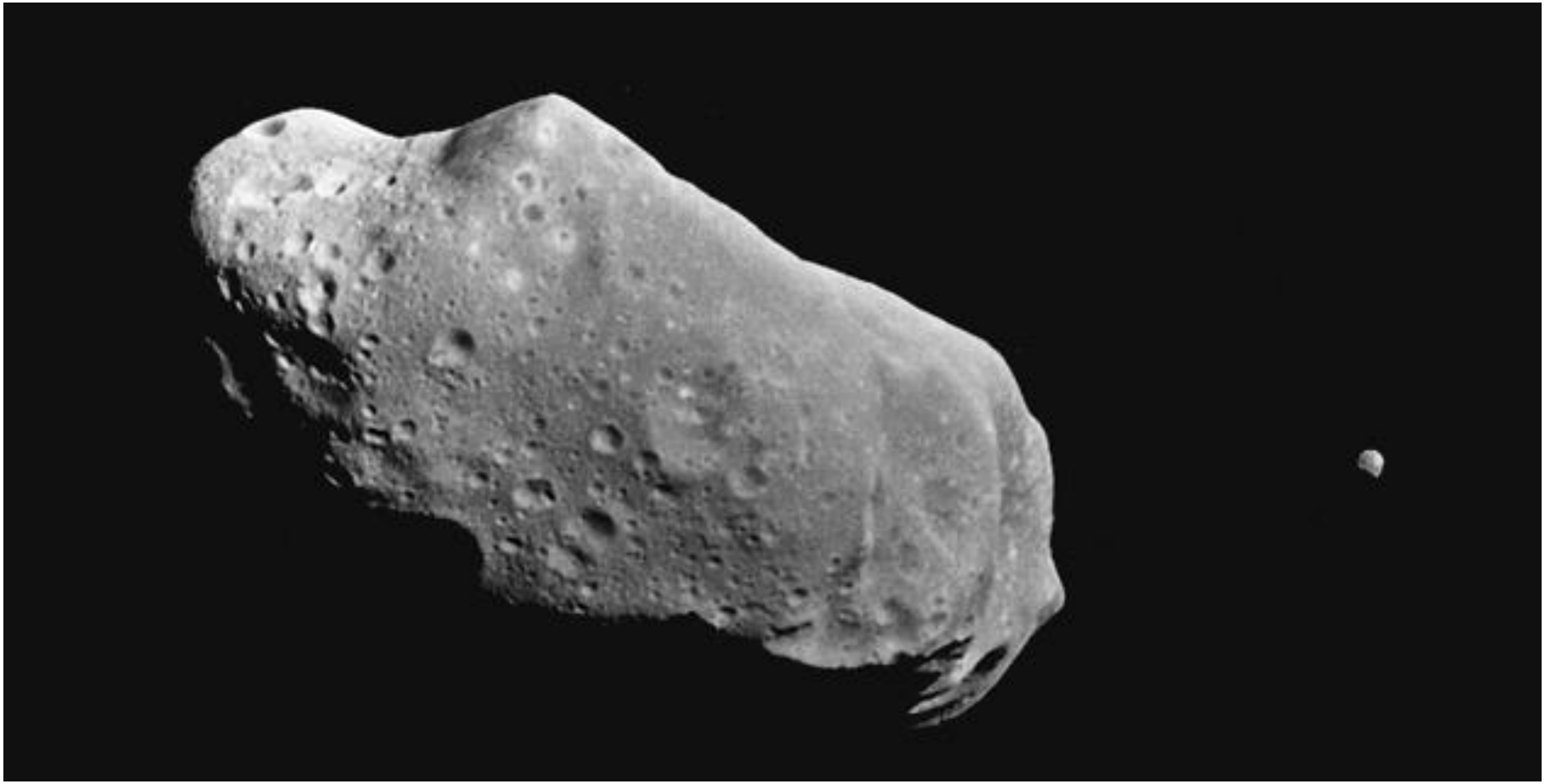


“Failed Planet”

Anomalous Planet

Courtesy of Flickr user Image Editor

Asteroid 243 IDA



- Cratering indicates early origin
- Chemical composition of meteorites collected on Earth indicate undifferentiated primordial material.

Courtesy NASA

Accretion of the Earth

Earth mostly accreted from rocky material in a large, viscous disc of dust around a young star (Laplace, 1796 & now supported by Hubble observations)

Earth accreted from planetesimals in the zone 0.8 to 1.3 au around the young sun where the temperature gradient (1500K to 900K) determined the chemical composition of condensing material and the ultimate composition of the bulk of the planet.

This NASA Hubble Space Telescope image shows a small portion of one of the largest observable star-forming regions in the Galaxy, the Carina Nebula, located 7500 light-years away in the southern constellation Carina. It captures the chaotic activity atop a three-light-year-tall pillar of gas and dust that is being eaten away by the UV light from nearby massive stars.. The image celebrates the 20th anniversary of Hubble's launch and deployment into an orbit around Earth. Image courtesy NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team(STScI)

Accretion of the Earth 2

Coagulation of grains to 1m -1km sized objects x10^3 yrs; larger ‘embryos’ during ‘runaway growth 10^4-10^6 yrs formed objects lunar to martian mass

Simulations predict an accretion time of roughly 50 million years for an Earth analogue to reach >90% of its final mass (review by Halliday et al. 2000)

Accretion of the Earth 3

- Chrondrites provide much of the evidence for planetary formation - ‘planets that never formed’. Chondrites = primitive objects, stony meteorites from the asteroid belt with elemental abundance ratios = those of the sun. Very heterogeneous rocks formed by accretion of grains (chondrules) with a variety of origins. Roughly ten times too much D/H to have delivered Earth’s water otherwise have solar elemental abundances

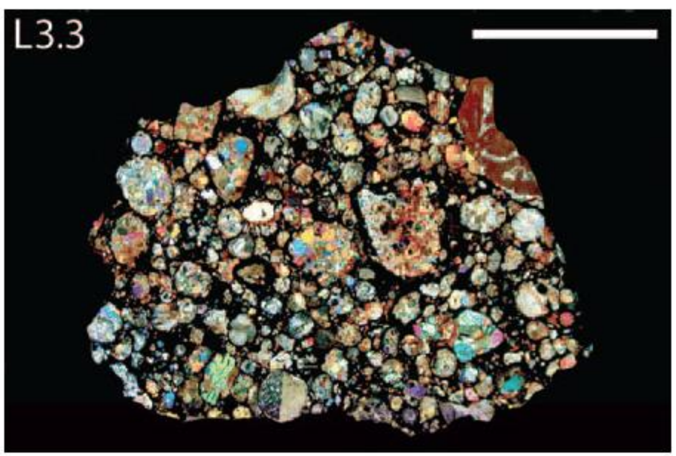
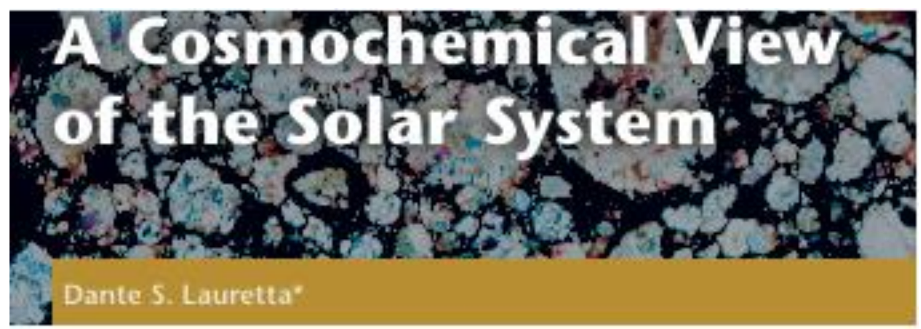


FIGURE 4 A primitive type-3 ordinary chondrite (L3) illustrates the diversity of chondrule textures and morphologies. Scale bar = 0.5 cm. PHOTO FROM LAURETTA AND KILLGORE 2005

Figure 4 from Dante S. Lauretta. "Cosmochemistry: A Cosmochemical View of the Solar System." *Elements* 7, 2011, no. 1 (2011): 11-6. Used with permission.

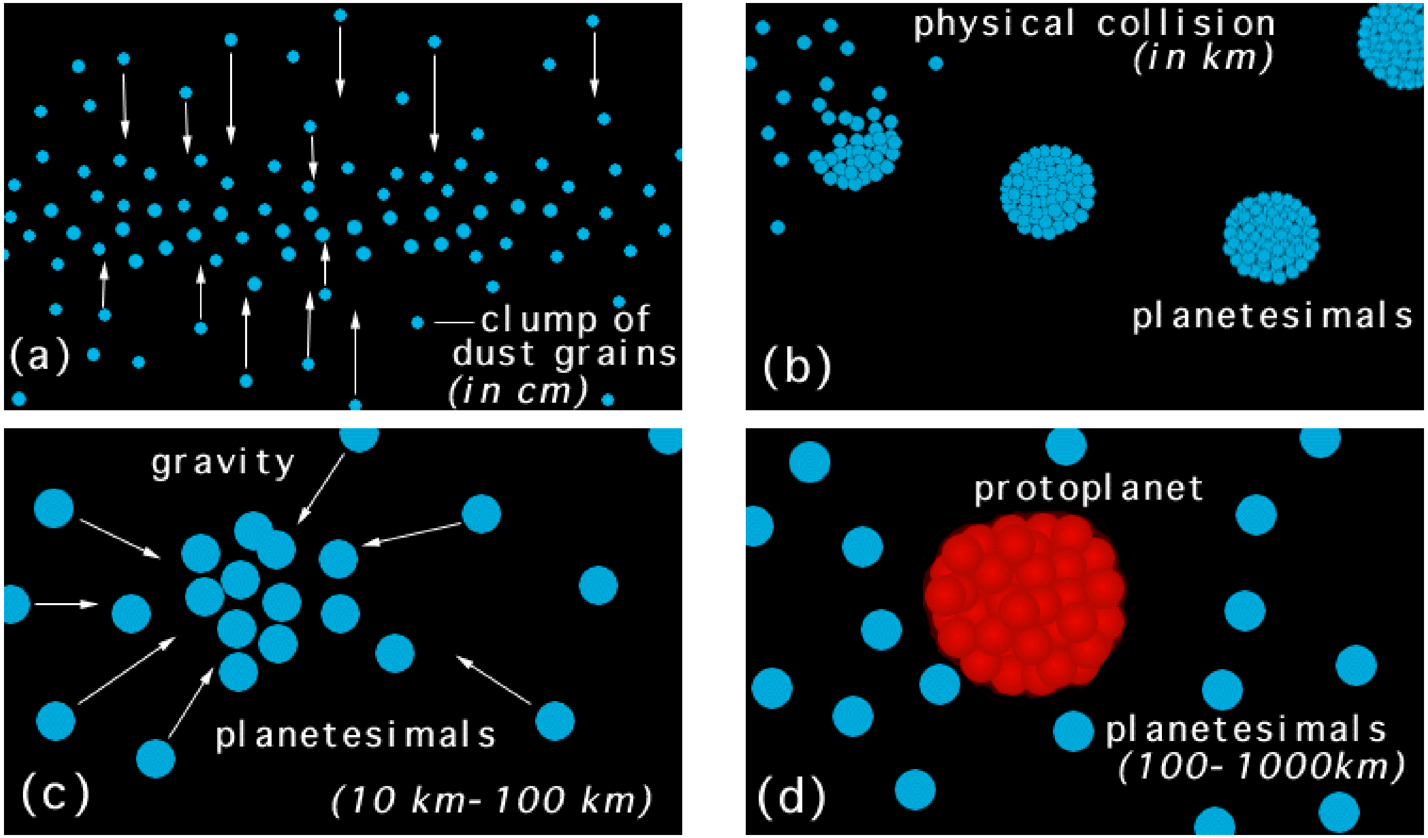


Header image from Dante S. Lauretta. "Cosmochemistry: A Cosmochemical View of the Solar System." *Elements* 7, no. 1 (2011): 11-6. Used with permission.

Elements Magazine July 2011

Formation of the Earth by Accretion

- Step 1: **accretion of cm sized particles**
- Step 2: **Physical Collision on km scale**
- Step 3: **Gravitational accretion on 10-100 km scale**
- Step 4: **Molten protoplanet from the heat of accretion**



Accretion 4

Asteroids orbit roughly 2-4 Au (between Mars and Jupiter) around the Sun but delivered slowly to the inner solar system. Different families identified by their spectral characteristics and the variable nature of meteorites. Some are undifferentiated – too small/cold to gravitationally separate into a core and mantle

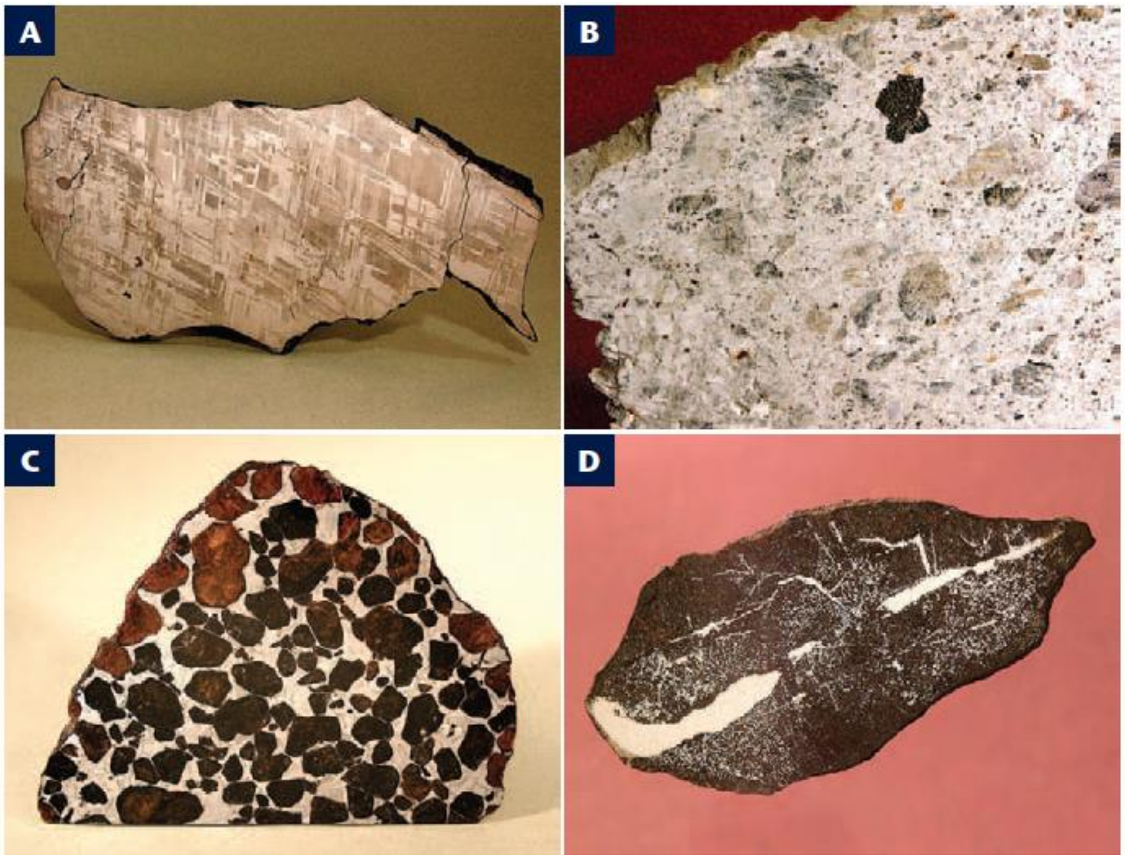


FIGURE 2 Four kinds of differentiated meteorites from asteroids that melted. (**A**) A slice of the San Angelo IIIAB iron etched to show the Widmanstätten pattern of oriented kamacite crystals (body-centered cubic Fe–Ni), which exsolved from a single crystal of taenite (face-centered cubic Fe–Ni). (**B**) A slice of the Peña Blanca Spring aubrite—an achondritic breccia composed largely of enstatite fragments. (**C**) A polished and etched slice of the Ahumada pallasite showing olivine fragments enclosed by Fe–Ni metal. (**D**) Monument Draw is a so-called "primitive achondrite" containing rare chondrules and metallic veins; it formed in an asteroid that was hot enough to melt Fe–Ni metal and iron sulfide. Long dimensions of samples: (A) 20 cm, (B) 9 cm, (C) 17 cm, (D) 6 cm. ALL PHOTOS BY GEOFFREY NOTKIN©, OSCAR E. MONNIG METEORITE COLLECTION, TEXAS CHRISTIAN UNIVERSITY

Figure 2 from Edward R. D. Scott. "Cosmochemistry: Meteorites: An Overview." *Elements* 7, no. 1 (2011): 47-8. Used with permission.

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Accretion of the Earth: 5

Chrondrites provide much of the evidence for origins of nebula components and for planetary formation - ‘planets that never formed’.

Many chondrites have roughly ten times too much D/H (the deuterium excess) to have delivered Earth’s water otherwise have solar elemental abundances

Presence of ‘extinct isotopes’ eg Al^{26} now present as Mg^{26}. Half-life of Al^{26} is low and all would be dissipated in 2 million years. Therefore Al^{26} must have been trapped in the solar nebula very early after it was formed in a supernova.

TABLE 1 IMPORTANT CHRONOMETERS OF THE EARLY SOLAR SYSTEM

Parent	Daughter	Half-life (My)	Application
^{26}Al	^{26}Mg	0.73	Relative ages of CAIs and chondrules
^{53}Mn	^{53}Cr	3.7	Relative ages of meteorites and their components
^{182}Hf	^{182}W	8.9	Core formation in planetesimals and terrestrial planets
^{146}Sm	^{142}Nd	103	Mantle differentiation in terrestrial planets
^{235}U	^{207}Pb	703	Absolute age of CAIs; core formation in the Earth
^{238}U	^{206}Pb	4468	

Table 1 from Kleine, Thorsten, and John F. Rudge. "Cosmochemistry: Chronometry of Meteorites and the Formation of the Earth and Moon." *Elements* 7, no. 1 (2011): 41-6. Used with permission.

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Accretion of the Earth: 6

Carbonaceous chondrites contain the most volatile elements and typically about 6% organic carbon. Delivered significant amounts of organic matter to the early Earth

Comets are nomadic bodies of ice, rock and organic and inorganic volatile compounds left over from the formation of our solar system. Comets come from the Kuiper belt located beyond Neptune, and from the Oort Cloud >200Au, which marks the outside edge of the solar system. Main belt comets are a recent discovery.

	Abundances (ppm)	
Compounds	**Murchison**	**Tagish Lake**
Carboxylic acids (monocarboxylic)	332	40
Sulfonic acids	67	≥20
Amino acids	60	<6
Dicarboximides	>50	5.5
Dicarboxylic acids	>30	17.5
Ketones	17	n.d.
Hydrocarbons (aromatic)	15–28	≥1
Hydroxycarboxylic acids	15	b.d.
Hydrocarbons (aliphatic)	12–35	5
Alcohols	11	n.d.
Aldehydes	11	n.d.
Amines	8	<0.1
Pyridine carboxylic acid	>7	7.5
Phosphonic acid	1.5	n.d.
Purines	1.2	n.d.
Diamino acids	0.4	n.d.
Benzothiophenes	0.3	n.d.
Pyrimidines	0.06	n.d.
Basic N-heterocycles	0.05–0.5	n.d.

b.d. – below the detection limit; n.d. – not determined

Adapted from Pizzarello et al. 2001, Botta and Bada 2002, Sephton 2002, and Glavin et al. 2010

Table 1 from Zita Martins. "Cosmochemistry: Organic Chemistry of Carbonaceous Meteorites." *Elements* 7, no. 1 (2011): 35-40. Used with permission.

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Formation of the Earth by Accretion

- Tremendous heat generated in the final accretion process resulted in initially molten objects.
- Any molten object of size greater than about 500 km has sufficient gravity to cause gravitational separation of light and heavy elements thus producing a *differentiated* body.
- The accretion process is inefficient, there is lots of left over debris.
- In the inner part of the solar system, leftover rocky debris cratered the surfaces of the newly formed planets *(Heavy Bombardment*, 4.6-3.8 Ga).
- In the outer part of the solar system, the same 4 step process of accretion occurred but it was accretion of ices (cometisemals) instead of grains.

http://zebu.uoregon.edu/disted/ph121/l7.html

Moon-Forming Impact

Canup R & AspaugE:Eos Trans. AGU, 82(47), Fall Meet. Suppl., Abstract U51A-02, 2001

http://www.swri.edu/9what/releases/canupmoon.htm

Hypothesis for lunar origin - Moon forms from debris ejected as a result of the collision of a roughly Mars-sized impactor with early Earth

- **Geophysical simulations use a method known as smooth particle hydrodynamics, or SPH and can achieve resolutions sufficient to study the production of orbit-bound debris necessary to yield the Moon**
- **Off-center, low-velocity collisions yield material in bound orbit from which a satellite may then accumulate.**
- **Simulations must account for mass, angular momentum and compositions of the earth-Moon system.**
- **Must yield an Earth that retains an iron-rich core and a moon that is appropriately iron-depleted and the right density.**
- **SPH results suggest:**
  - **The object had 10-12% of Earth's mass**
  - **Produces a satellite with <3% Fe by mass. Out of reach & unable to be captured subsequently**
  - **Happened when Earth near its current ie final mass & near the very end of the accretion history**

Formation of the Moon
model of Robin Canup SWRI

Image removed due to copyright restriction.
Source: Figure 2D in Canup, Robin M. "Simulations of a late lunar-forming impact." *Icarus* 168, no. 2 (2004): 433-456.

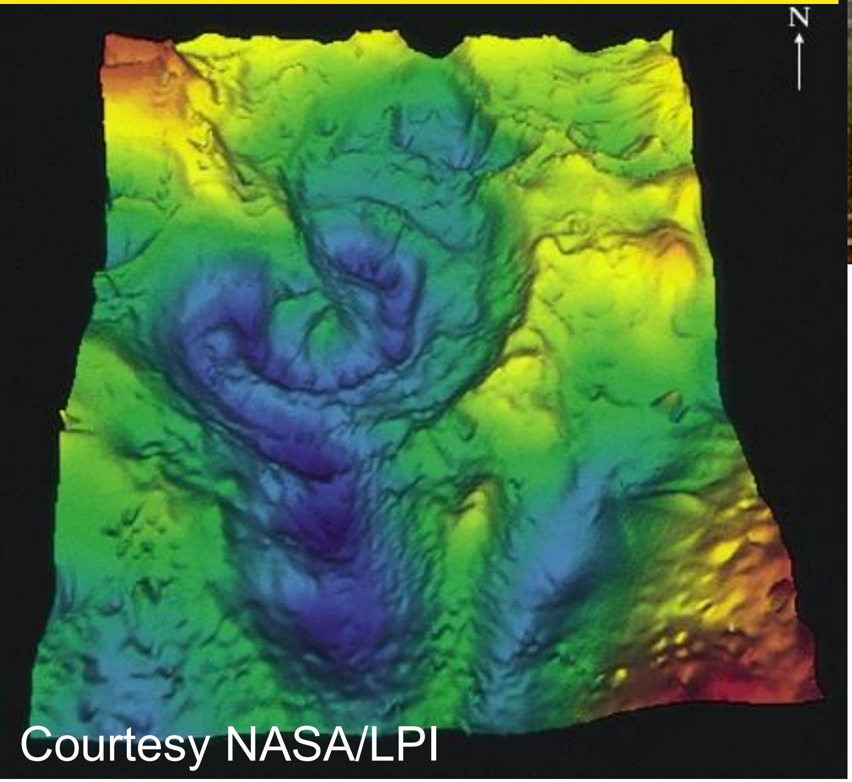
http://www.boulder.swri.edu/~robin/moonimpact/canup2012/Canup_MoonImpact.mov

http://www.youtube.com/watch?v=2sr-MriOCzw

Accretion continues…

<u>Chicxulub Crater, Gulf of Mexico</u>

- 200 km crater
- 10-km impactor
- 65 Myr BP
- Extinction of 75% of all species!



<u>Meteor (Barringer) Crater, Arizona</u>

- 1 km diam. Crater
- 40-m diam Fe-meteorite
- 50 kyr BP
- 300,000 Mton
- 15 km/s

Differentiation of the Earth:1

VM Goldschmidt 1922 published landmark paper ‘Differentiation of the Earth’

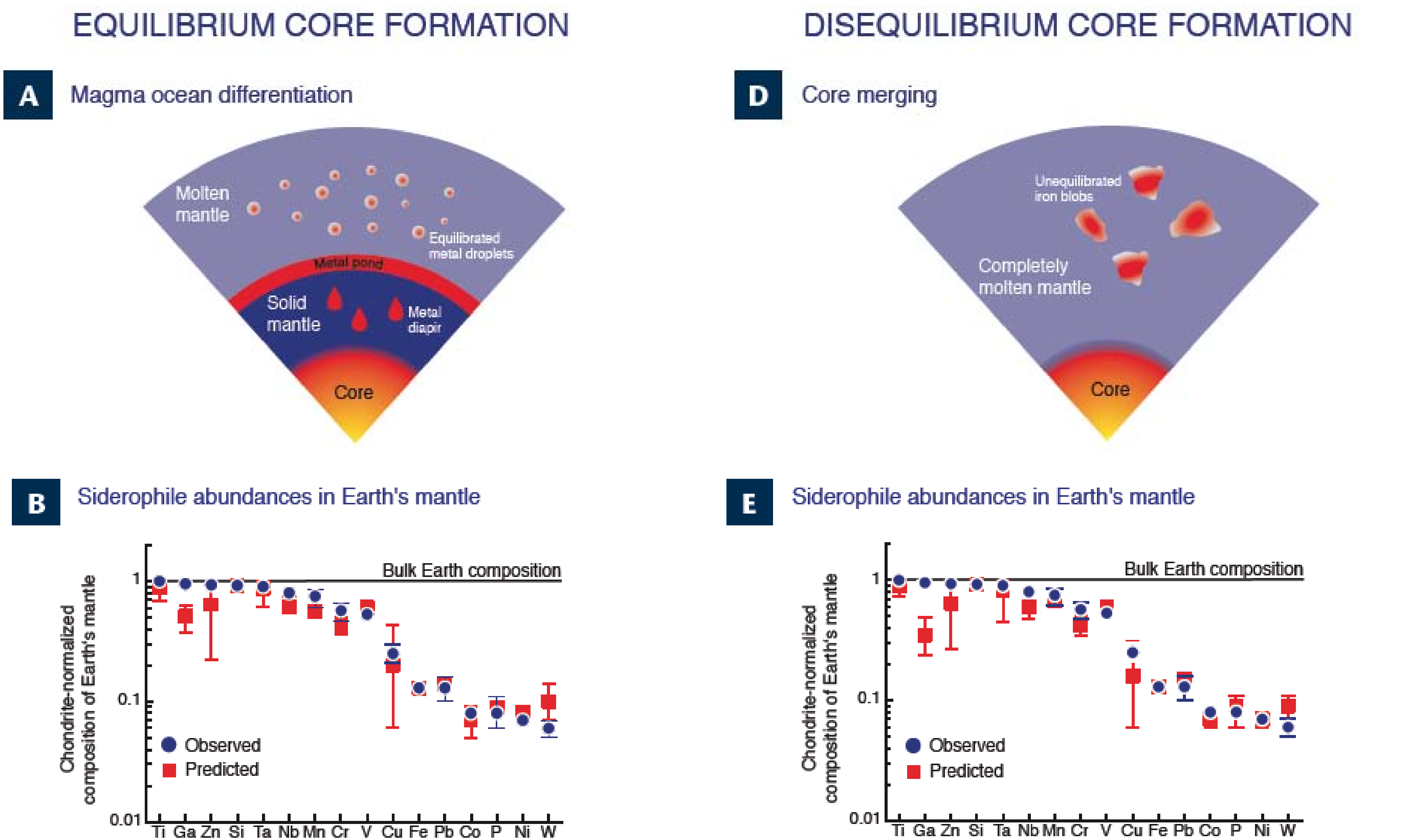
‘Father of Geochemistry’ because of the realization that Earth has a chondritic (meteoritic) elemental composition. Surface rocks are not chemically representative of solar abundances therefore must be differentiated

Proto-planet differentiated early into an iron-rich core surrounded by a metal sulfide-rich shell and a silicate-rich magma ocean

Cooling of the magma caused segregation of dense silicate minerals – pyroxenes and olivines. Less dense minerals feldspars and quartz floated to surface to form crust.

Less abundant elements segregate according to affinities for Fe = siderophile, sulfide = chalcophile and silicate = lithophile

Differentiation of Earth



Kleine, Thorsten, and John F. Rudge. "Chronometry of Meteorites and the Formation of the Earth and Moon." *Elements* 7, no. 1 (2011): 41-6.

Differentiation of the Earth:2

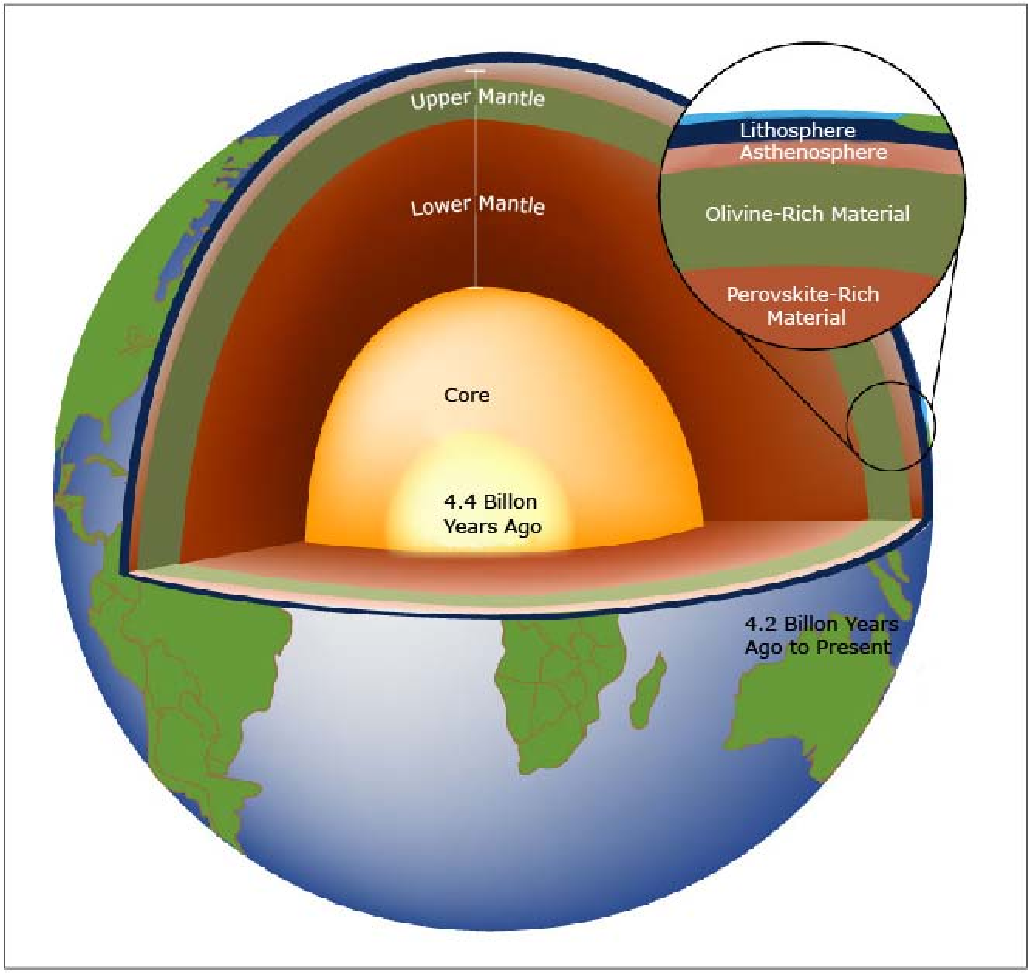


Image by MIT OpenCourseWare.

Differentiation of the Earth:3

Proof of the differentiated planet comes from

- Slightly –flattened shape of the Earth
- Seismology – reflection and refraction of sound waves by materials of different densities and elasticities.

Continuous partial melting of mantle and the rising of less-dense components in ‘plumes’ , and the sinking or more dense ones drives tectonic cycles.

Tectonism essential for the continuity of life

Differentiation of Earth, Continents, Ocean & Atmosphere

- **Differentiation of Earth**
  - Homogenous planetesimal
  - Earth heats up
    - Accretion and compression (T~1000° C)
    - Radioactive decay (T~2000° C)
  - Iron melts--migrates to center
    - Frictional heating as iron migrates
  - Light materials float--crust
  - Intermediate materials remain--mantle

- **Differentiation of Continents, Oceans, and Atmosphere**
  - Continental crust forms from differentiation of primal crust
  - Oceans and atmosphere
  - Two hypotheses
    - internal: degassing of Earth's interior (volcanic gases)
    - external: comet impacts add H_2O CO_2, and other gases
  - Early atmosphere rich in H_2, H_2O, N_2, CO_2; deficient in O_2

Early Earth History

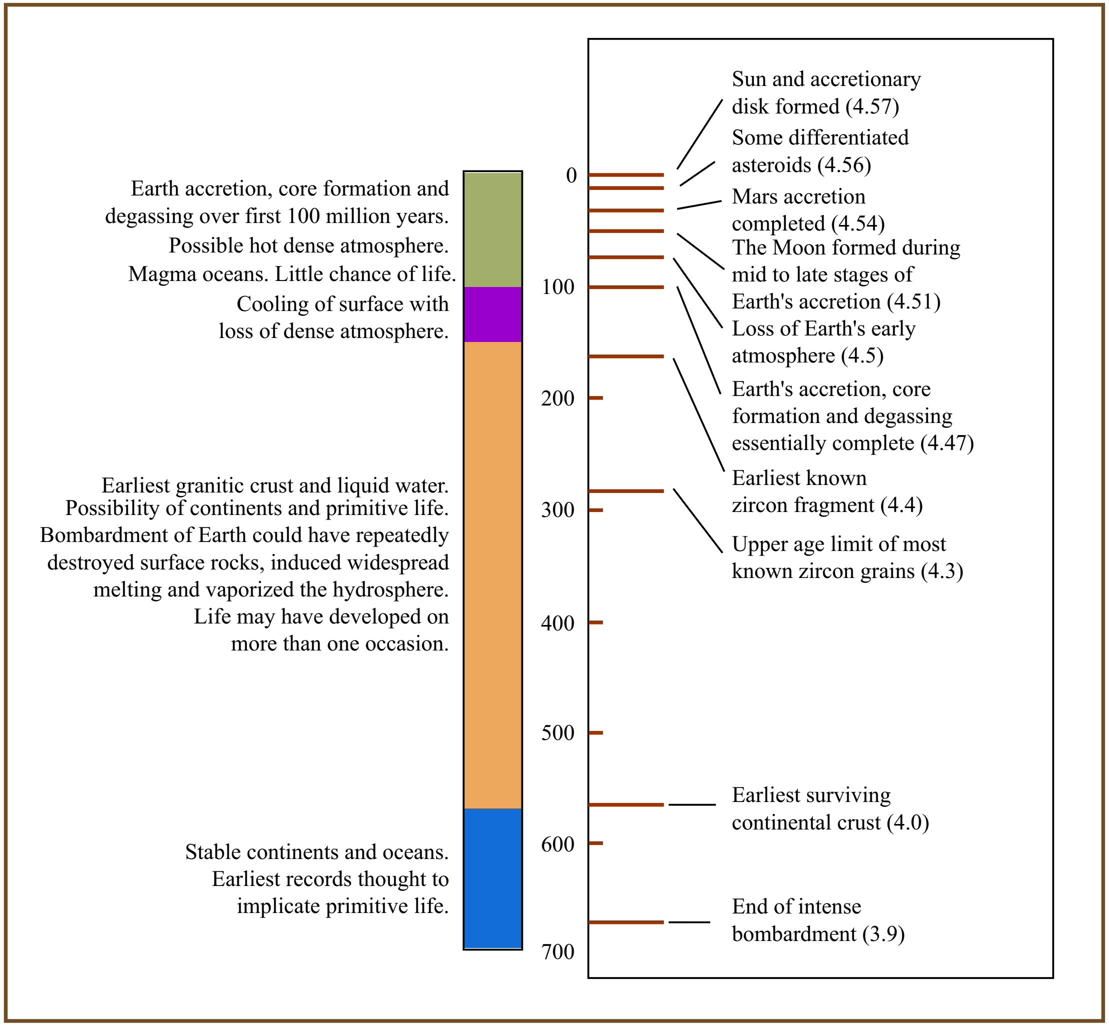


Image by MIT OpenCourseWare.

Timescale in myr

Origin of Earth's Volatile Components Atmosphere, Oceans & Carbon

- Arrived with the planetesimals, partly survived the accretion process and outgassed during volcanic activity (Hogbom 1894, Rubey 1951-5). Volcanic gases vary in composition; not primordial and may have been recycled many times. No record of the time and conclusive answers about this scenario (Turekian, 1972; Delsemme, 1997).
- Arrived with comets during the late bombardment - late veneer hypothesis (Delsemme, 1997)
- Arrived with one or more hydrated planetesimals from the outer asteroid belt (Morbidelli, 2001)
- Arrived with comets and mixed with accreted water

Arrived with comets and mixed with accreted water

U51A-05 Origin of Earth's Volatiles: The Case for a Cometary Contribution : Owen, T C

D/H show comets could not have delivered all the Earth's water.

84Kr/132Xe and the isotopic composition of Xe show that chondrites did not deliver the atmospheric noble gases.

The Martian atmosphere reveals krypton and xenon relative abundances and isotope ratios remarkably similar to Earth's,

An external source seems necessary to satisfy both martian and terrestrial data with the D/H result pointing toward comets.

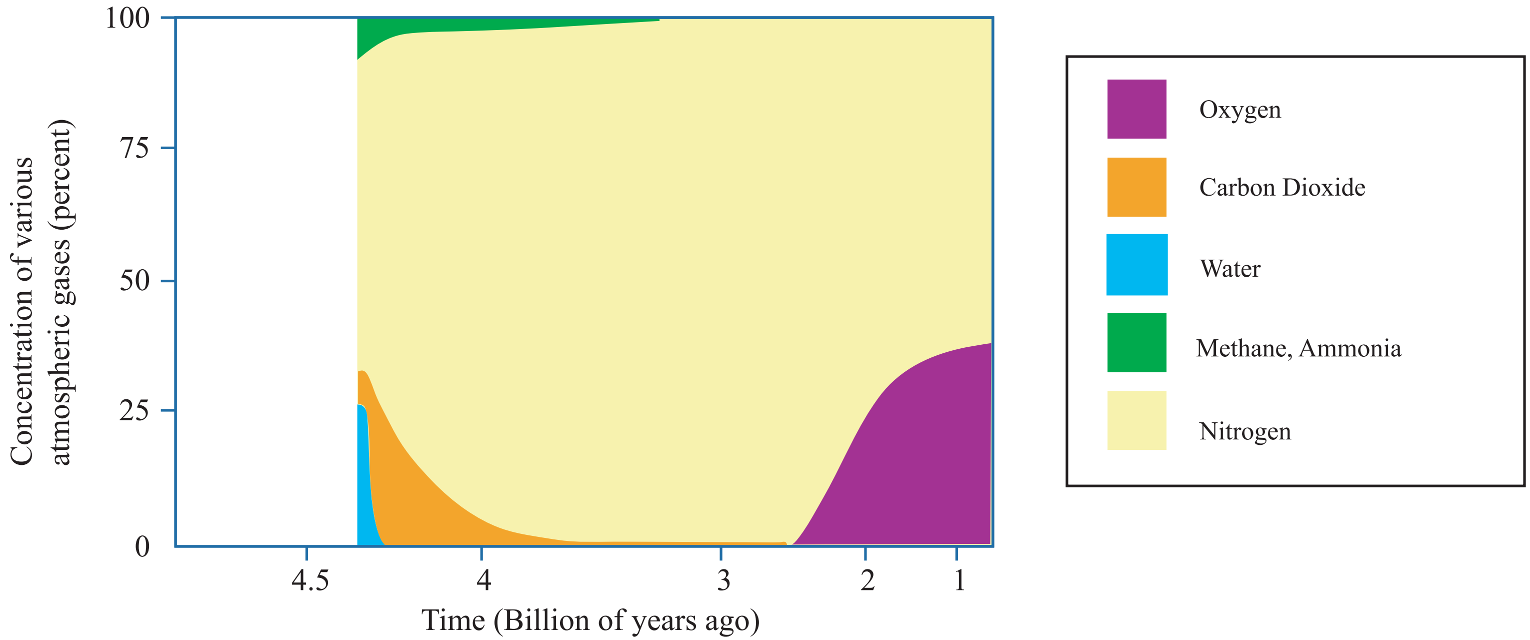
This requires that Earth formed with its own water, to mix with the cometary component. The ratios of 15N/14N on Mars and Earth (in the atmosphere and rocks) are also consistent with cometary delivery of nitrogen in the form of N-compounds.

Composition of Comet Halley Volatiles (modeled)

78.5 % H_2O	**2.6% N_2**	**1.5% C_2H_4**	**0.1% H_2S**
4.0% H_2CO	**0.8% NH3**	**0.5% CH_4**	**0.05% S2**
4.5% HCO-OH	**1.0% HCN**	**0.2% C_3H_2**	**0.05% CS_2**
1.5% CO	**0.8% N_2H_4**		
	0.4% $C_4H_4N_2$		
92% with O	**5.6% with N**	**2.6% H/C**	**0.2% S**

Launched on 2 July 1985 by Ariane 1, Giotto was ESA's first deep-space mission, part of an ambitious international effort to solve the mysteries surrounding Comet Halley.
Photo: ESA

Early Composition of the Atmosphere



Atmospheric composition, shown by the relative concentration of various gases, has been greatly influenced by life on the earth. The early atmosphere had fairly high concentrations of water and carbon dioxide and, some experts believe, methane, ammonia, and nitrogen. After the emergence of living organisms, the oxygen that is so vital to our survival became more plentiful. Today carbon dioxide, methane and water exists only in trace amounts in the atmosphere.

Figure by MIT OpenCourseWare. After figure on page 74 of Allegre, Claude J.,and Stephen H. Schneider. "The Evolution of the Earth." *Scientific American* 271 (1994): 66-75.

Why the big deal with water?

http://www.esa.int/Our_Activities/Space_Science/Rosetta

At the end of February 2004, the European Space Agency (ESA) probe set off on its journey to meet Comet Churyumov-Gerasimenko.

The long-planned get-together will not however take place until the middle of 2014.

A few months after arriving at the comet, Rosetta will release a small lander onto its surface. Then, for almost two years it will investigate Churyumov-Gerasimenko from close up.

Why the big deal with water?

http//www.esa.int/rosetta

The comet explorer carries ten scientific instruments to draw out the secrets of the comet's chemical and physical composition and reveal its magnetic and electrical properties. The lander will take pictures in the macro and micro ranges and send all the data thus acquired back to Earth, via Rosetta.

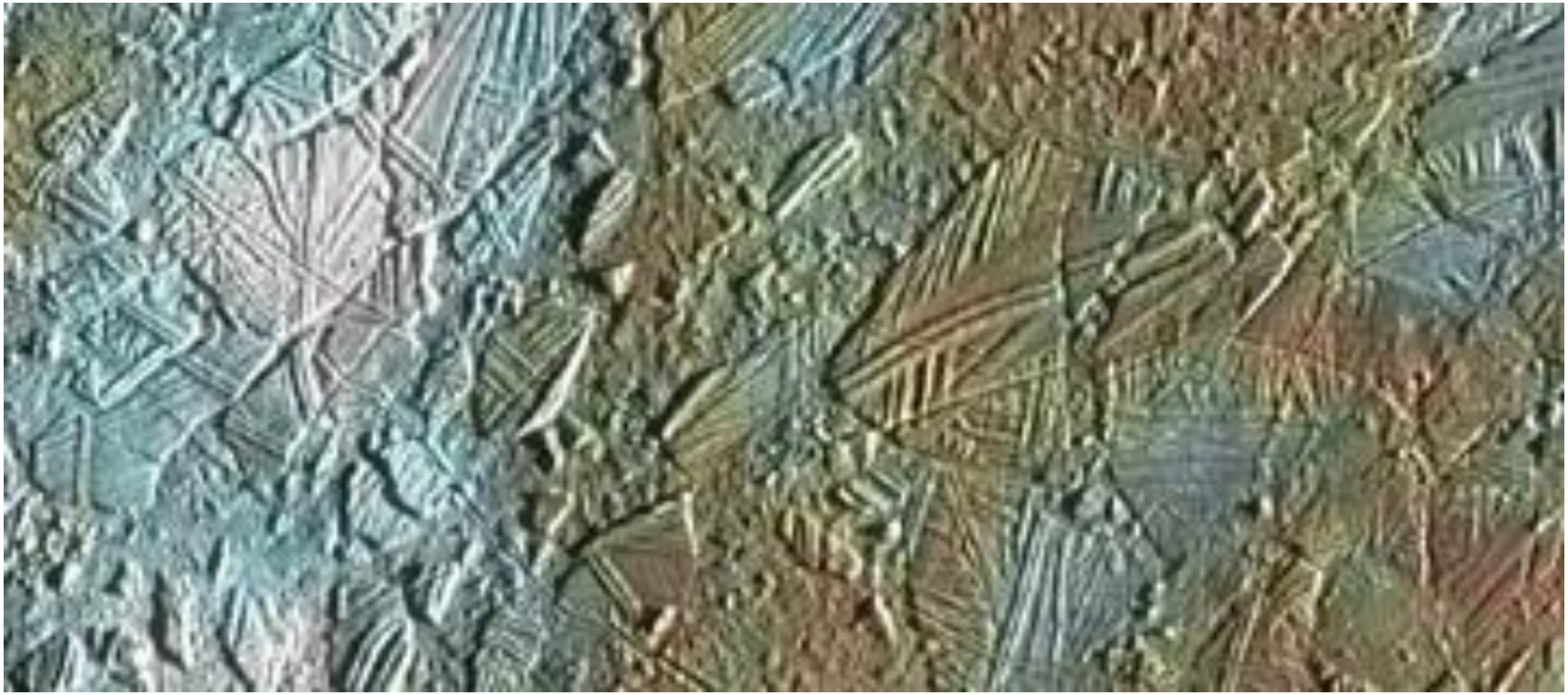
"This will be our first ever chance to be there, at first hand, so to speak, as a comet comes to life,"

When Churyumov-Gerasimenko gets to within about 500 million kilometres of the Sun, the frozen gases that envelop it will evaporate and a trail of dust will be blown back over hundreds of thousands of kilometres. When illuminated by the Sun, this characteristic comet tail then becomes visible from Earth. In the course of the mission, the processes at work within the cometary nucleus will be studied and measured more precisely than has ever before been possible, for earlier probes simply flew past their targets.

Characteristics of the Habitable Zone: known requirements of life?

- Liquid water
- Sources of carbon and energy
  - CO_2, organic matter
  - energy from chemistry of rocks + water
  - energy from the sun
- Mechanisms of renewal and recycling
  - Nutrients limited
  - Space = habitat limited
    - **Mechanism = Tectonism.**

Water Elsewhere in the Solar System Ice - Rafts on Europa

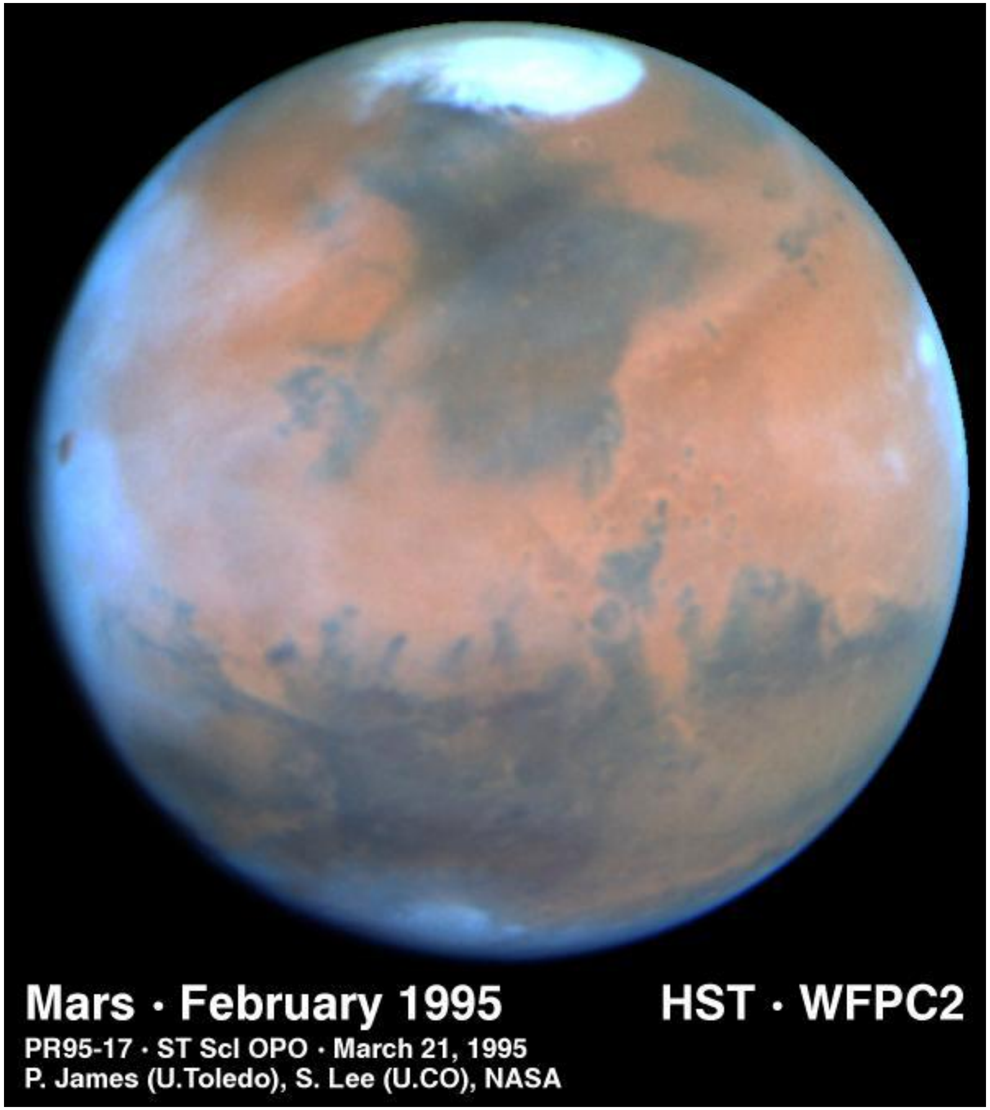


Courtesy NASA/JPL/University of Arizona

Water Elsewhere in Solar System

CO2 + Water Ice on Mars

http://photojournal.jpl.nasa.gov/

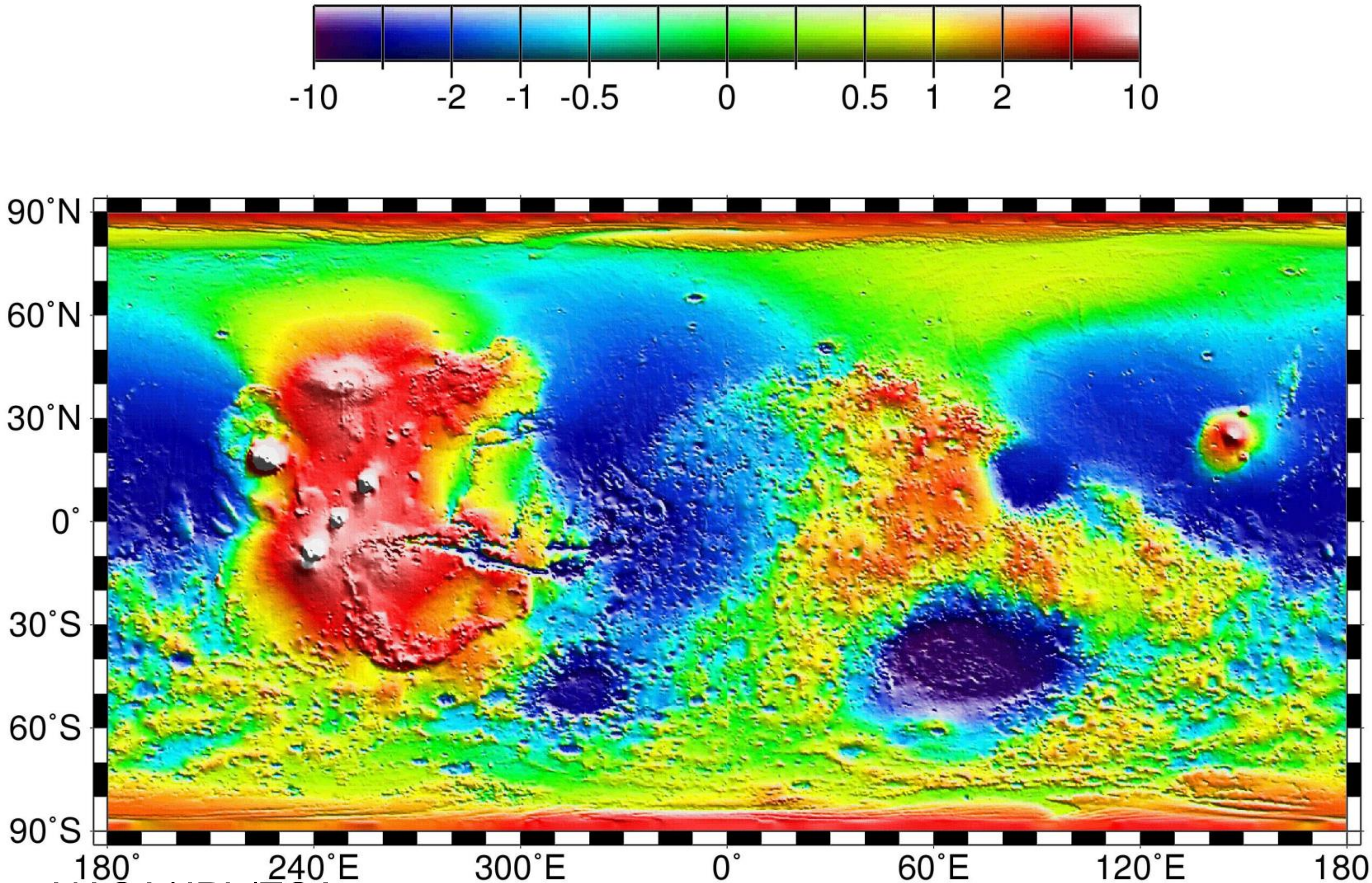


Courtesy NASA

Water Elsewhere in Solar System

Flat topography of Mars Northern Hemisphere

http://photojournal.jpl.nasa.gov/

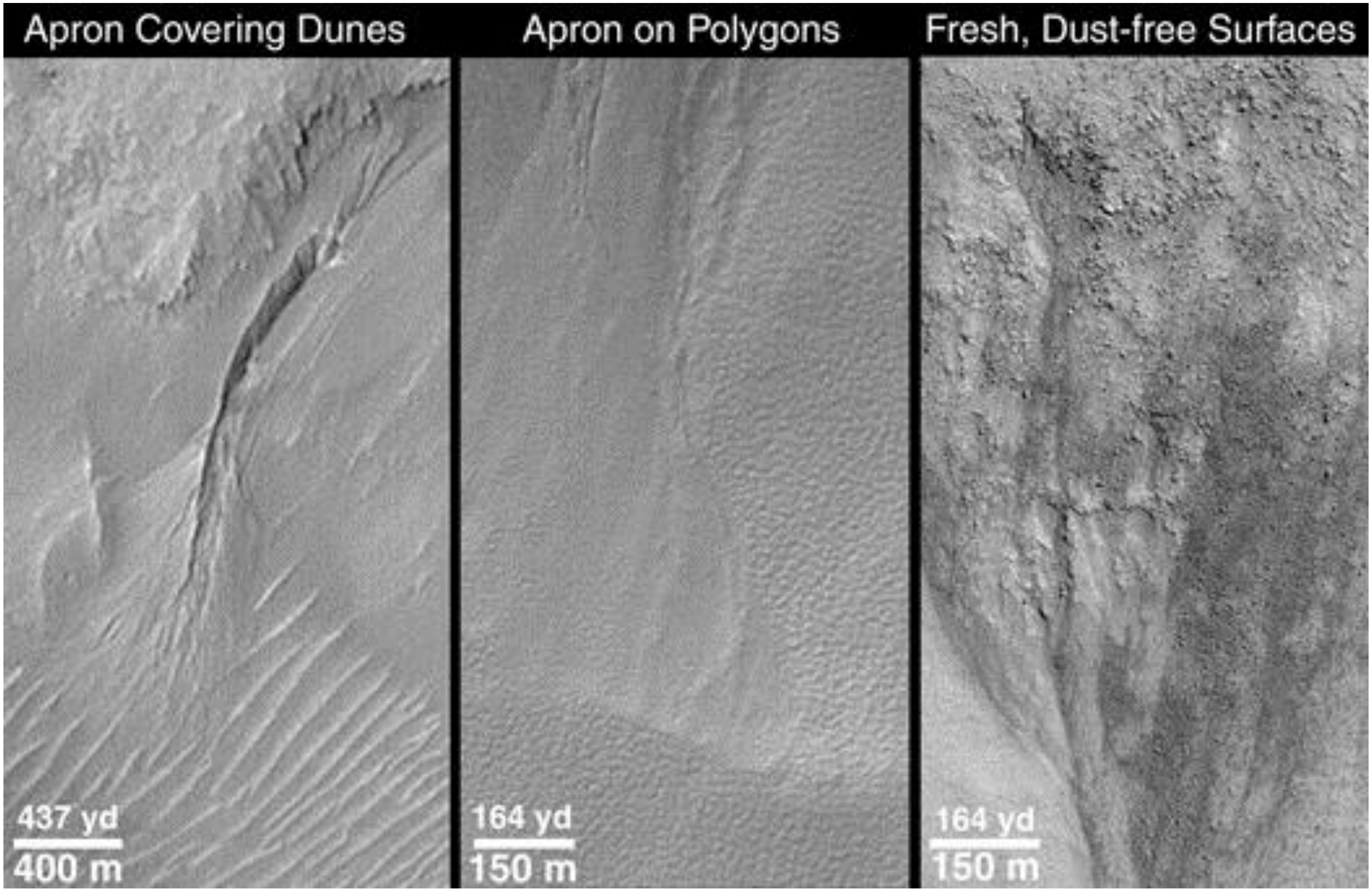


Courtesy NASA/JPL/ESA

Water Elsewhere in Solar System

Evidence of recent water flow on Mars

http://www.msss.com/mars_images/moc/june2000/age/index.html



Courtesy NASA/JPL/Malin Space Science Systems

Curiosity's primary scientific goal is to explore and quantitatively assess a local region on Mars' surface as a potential habitat for life, past or present

- Biological potential
- Geology and geochemistry
- Role of water
- Surface radiation

Courtesy NASA/JPL-Caltech

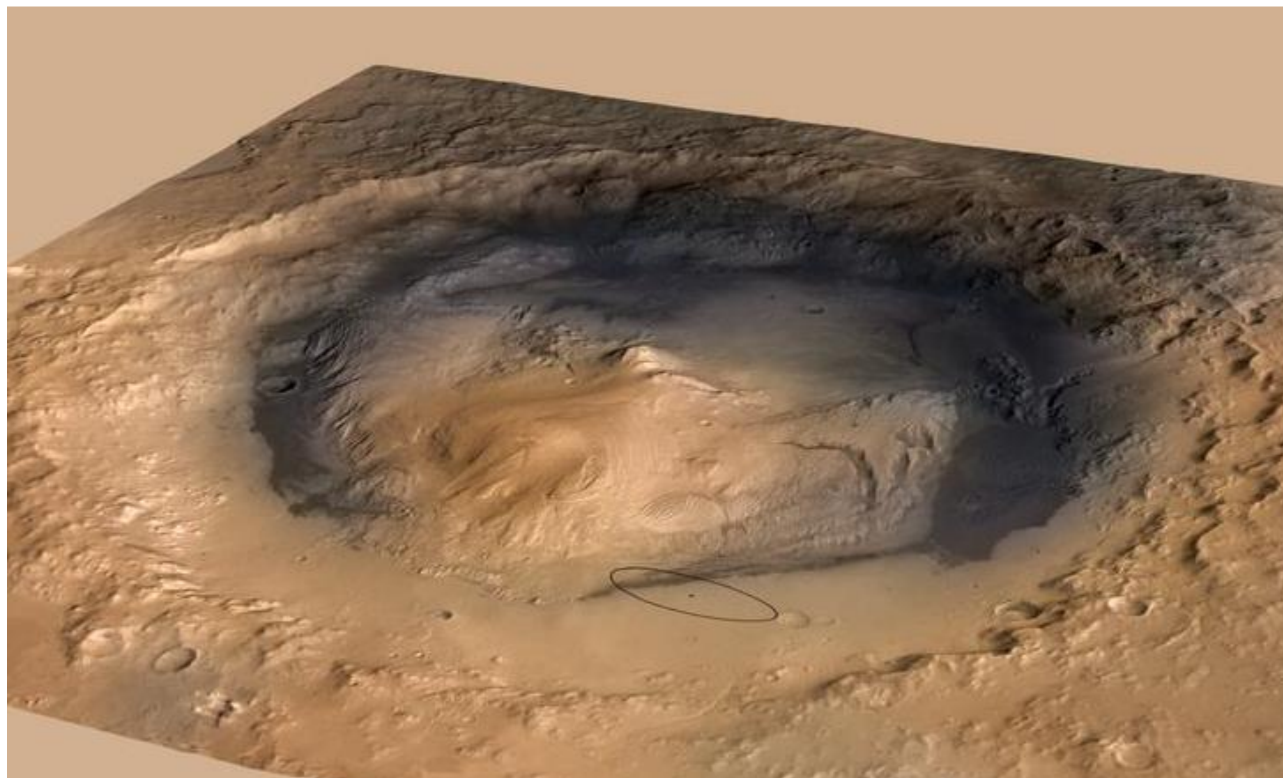
Curiosity's Science Objectives

Courtesy NASA/JPL-Caltech

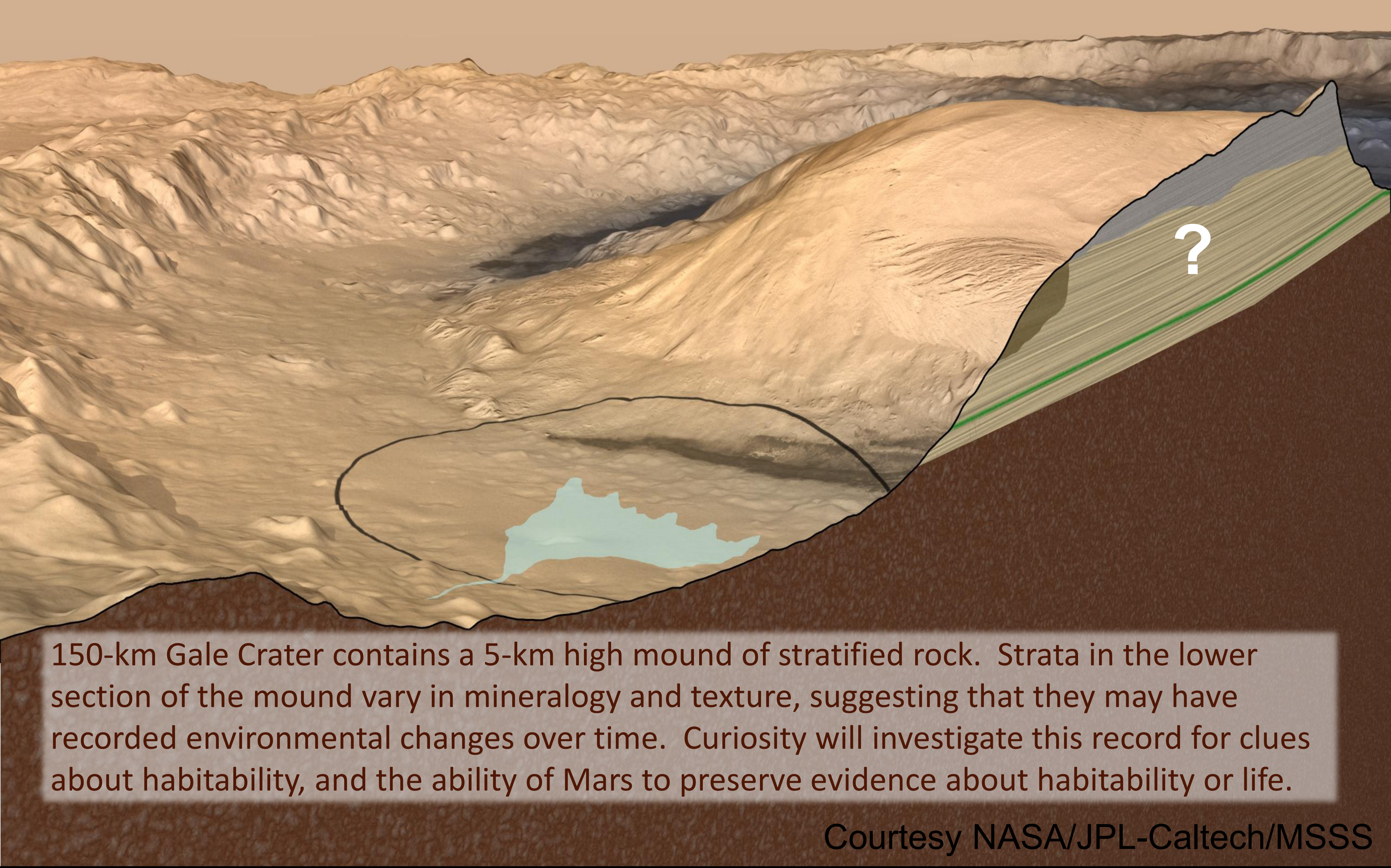
Image of “Key science targets at Gale crater” removed due to copyright restrictions.
See Figure 6 in this paper:
Grotzinger, John P., Joy Crisp, Ashwin R. Vasavada, Robert C. Anderson, Charles J. Baker, Robert Barry, David F. Blake et al. "Mars Science Laboratory mission and science investigation." *Space science reviews* 170, no. 1-4 (2012): 5-56.

CURIOSITY

Courtesy NASA/JPL-Caltech



Courtesy NASA/JPL-Caltech/ESA/DLR/FU Berlin/MSSS



150-km Gale Crater contains a 5-km high mound of stratified rock. Strata in the lower section of the mound vary in mineralogy and texture, suggesting that they may have recorded environmental changes over time. Curiosity will investigate this record for clues about habitability, and the ability of Mars to preserve evidence about habitability or life.

Courtesy NASA/JPL-Caltech/MSSS

CURIOSITY

Target: Gale Crater and Mount Sharp

Courtesy NASA/JPL-Caltech

Courtesy NASA/JPL-Caltech/MSSS

CURIOSITY

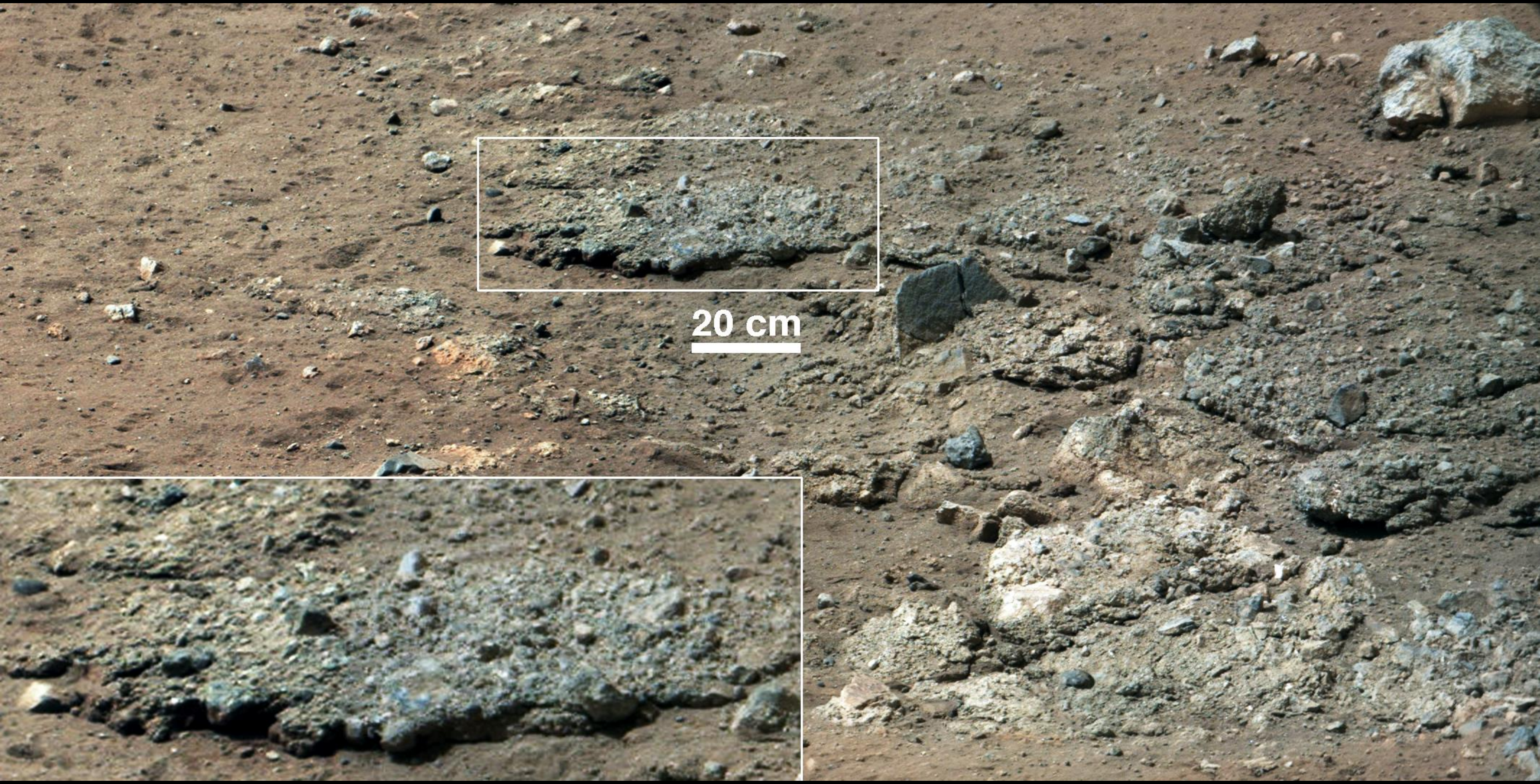
Mastcam-34 mosaic of Mount Sharp, descent rocket scours, and rover shadow

Courtesy NASA/JPL-Caltech

Courtesy NASA/JPL-Caltech/MSSS

Bedrock exposed by the landing engines in the scour mark named Goulburn

Courtesy NASA/JPL-Caltech

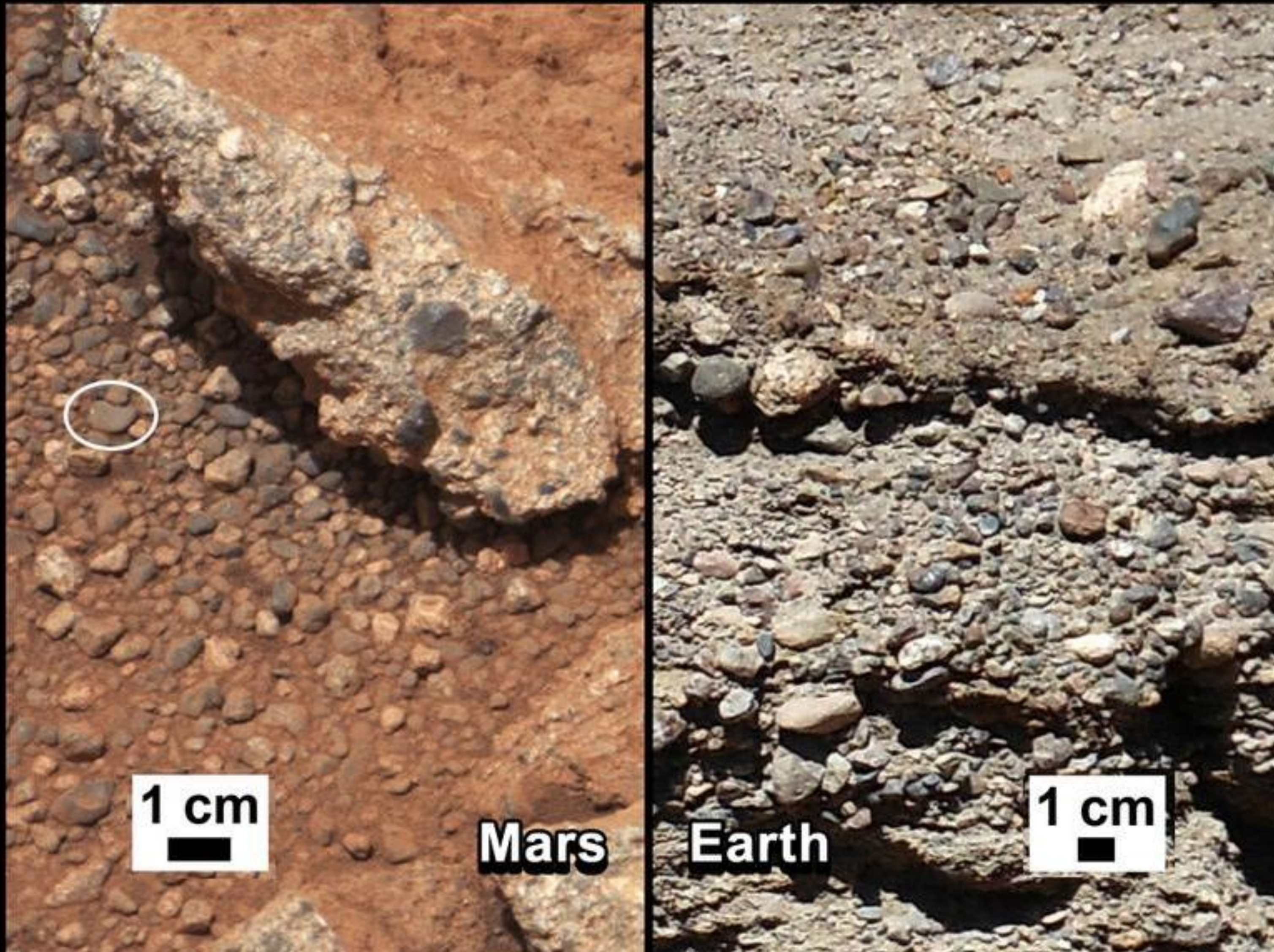


Courtesy NASA/JPL-Caltech/MSSS

CURIOSITY

The Goulburn scour revealed the first look at underlying bedrock

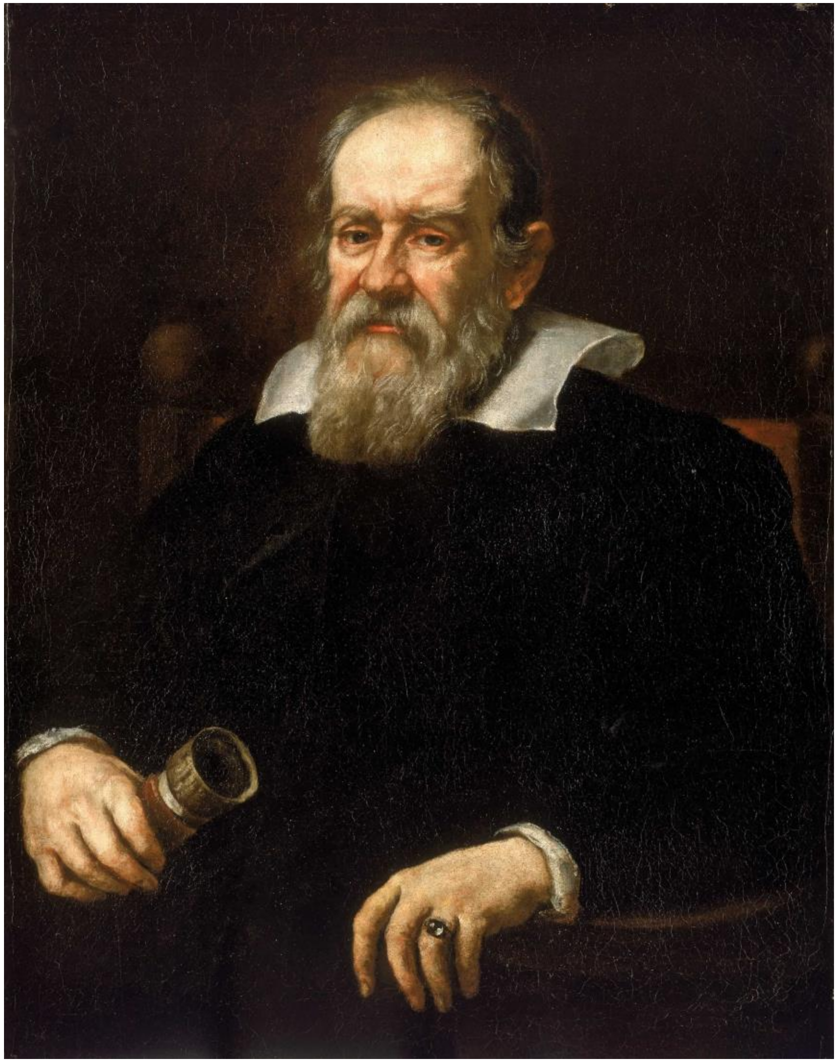
Courtesy NASA/JPL-Caltech



Courtesy NASA/JPL-Caltech/MSSS

CURIOSITY

The conglomerate “Link” with associated loose, rounded pebbles



Copernicus 1473-1543
Hypothesised Earth circularly orbited Sun c. 1543 slow to publish. German printer took liberty of adding unwlecome preface. Saw it on his deathbed

Tycho Brahe 1546-1601
Observed planet positions. Hired Kepler but was mean with the data and died before the results c. 1600

Johannes Kepler 1571-1630 Analysed Tycho's data and developed Kelper's laws and eliptical orbits c. 1610

Galileo Galilei 1546-1642
Built good telescopes, confirmed Kepler c. 1610 and wore the wrath of Rome c. 1623

Isaac Newton 1642-1727
Principia 1687

Portrait of Galileo Galilei by Justus Sustermans