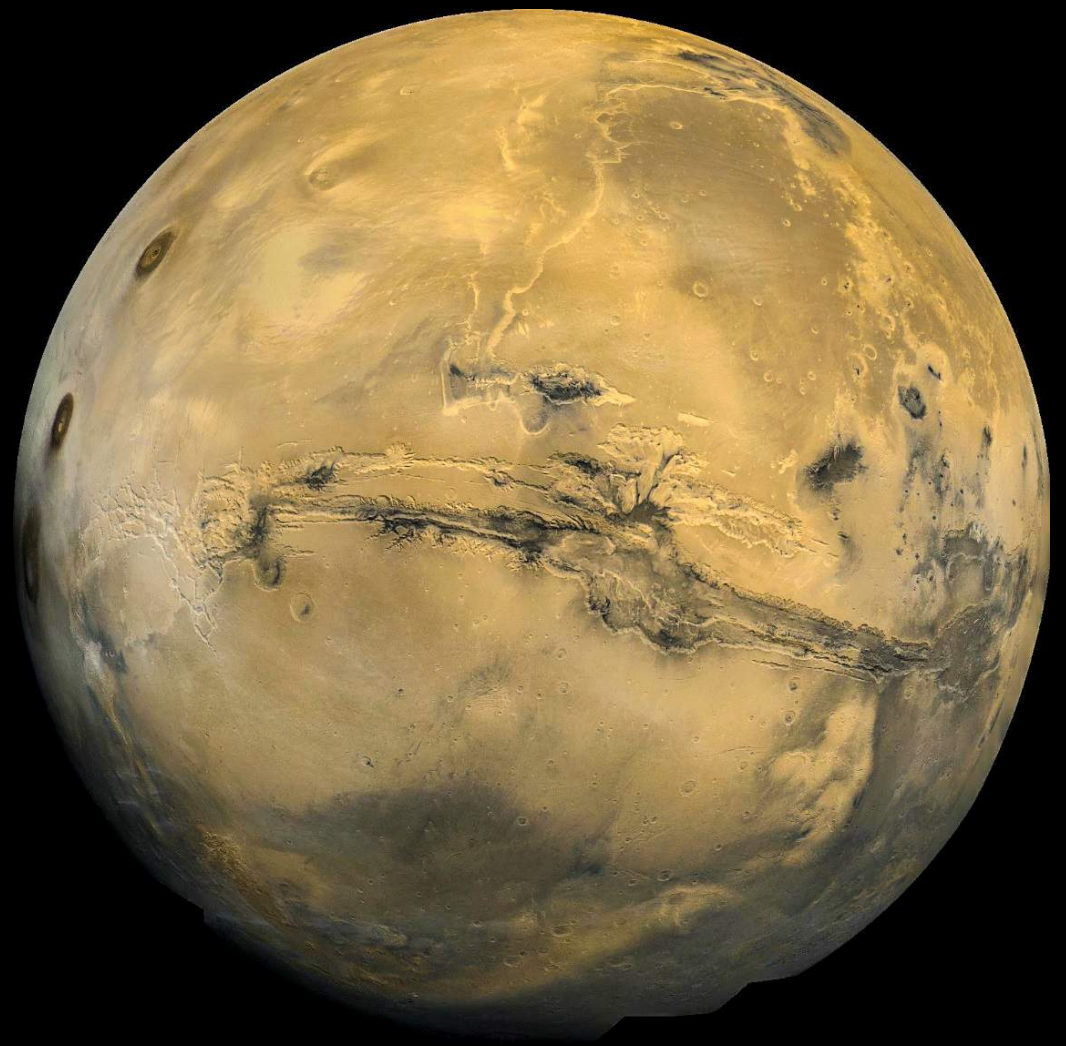
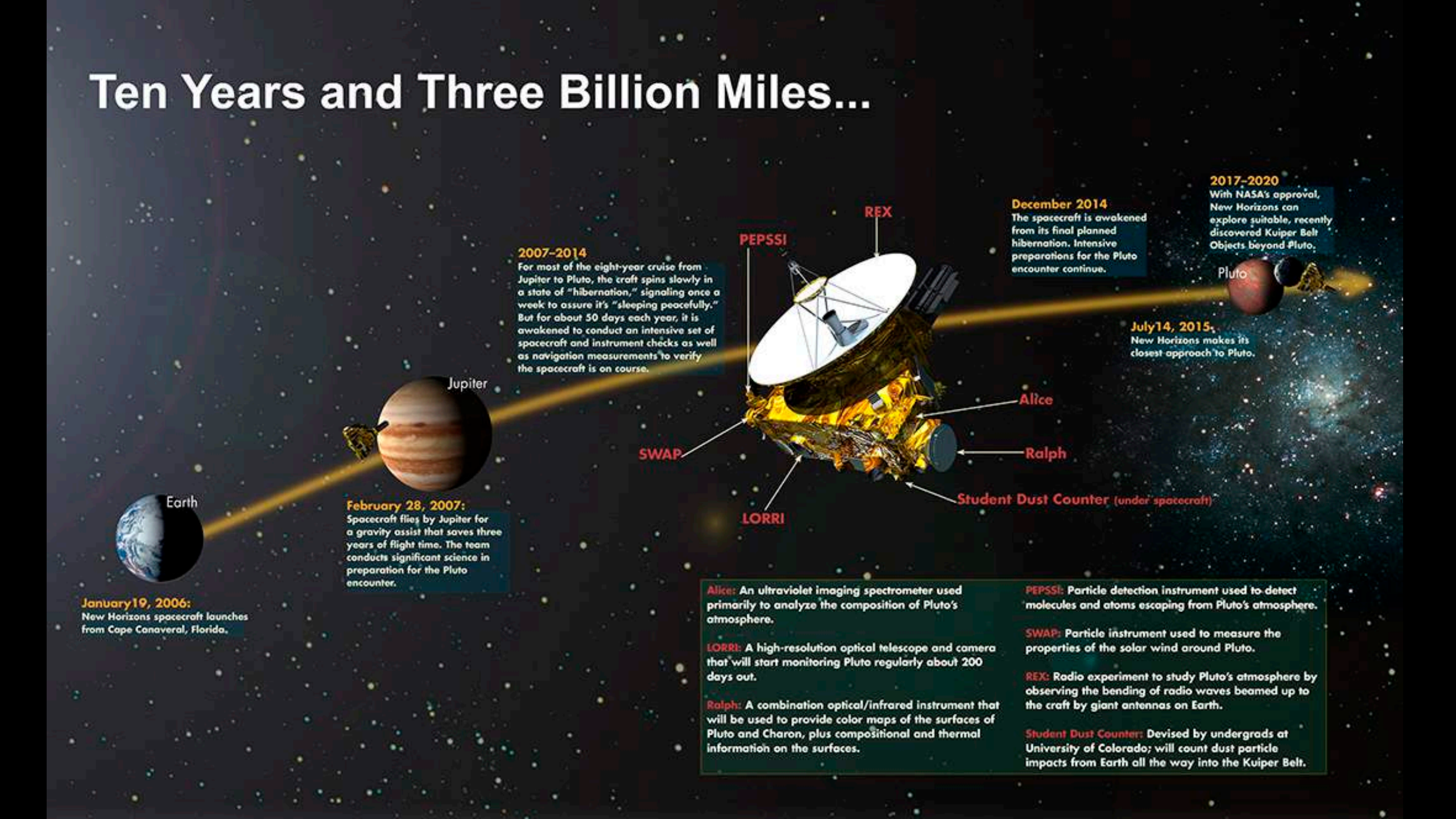
Geology of Pluto and Mars-The Amazing New Horizons & Mars Science Lab Missions

(&others)

Michael Adler



Ten Years and Three Billion Miles...



January 19, 2006:
New Horizons spacecraft launches from Cape Canaveral, Florida.

February 28, 2007:
Spacecraft flies by Jupiter for a gravity assist that saves three years of flight time. The team conducts significant science in preparation for the Pluto encounter.

2007–2014
For most of the eight-year cruise from Jupiter to Pluto, the craft spins slowly in a state of "hibernation," signaling once a week to assure it's "sleeping peacefully." But for about 50 days each year, it is awakened to conduct an intensive set of spacecraft and instrument checks as well as navigation measurements to verify the spacecraft is on course.

December 2014
The spacecraft is awakened from its final planned hibernation. Intensive preparations for the Pluto encounter continue.

July 14, 2015:
New Horizons makes its closest approach to Pluto.

2017–2020
With NASA's approval, New Horizons can explore suitable, recently discovered Kuiper Belt Objects beyond Pluto.

Alice: An ultraviolet imaging spectrometer used primarily to analyze the composition of Pluto's atmosphere.

LORRI: A high-resolution optical telescope and camera that will start monitoring Pluto regularly about 200 days out.

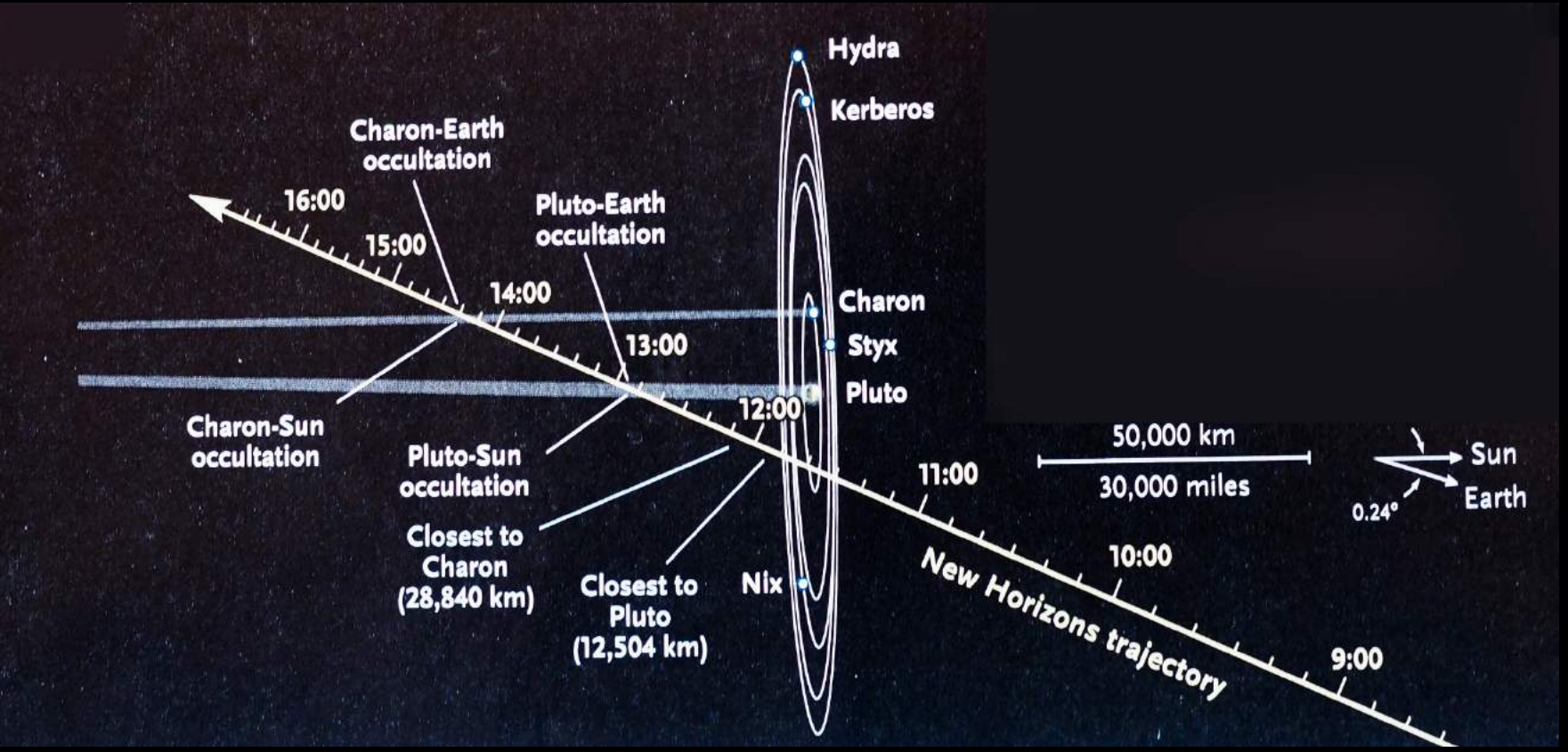
Ralph: A combination optical/infrared instrument that will be used to provide color maps of the surfaces of Pluto and Charon, plus compositional and thermal information on the surfaces.

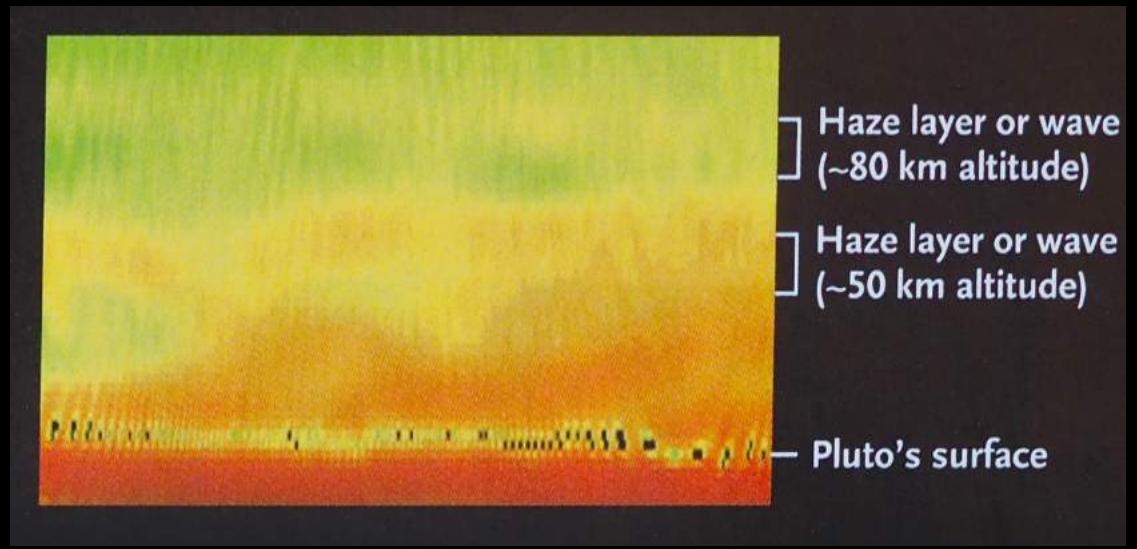
PEPSSI: Particle detection instrument used to detect molecules and atoms escaping from Pluto's atmosphere.

SWAP: Particle instrument used to measure the properties of the solar wind around Pluto.

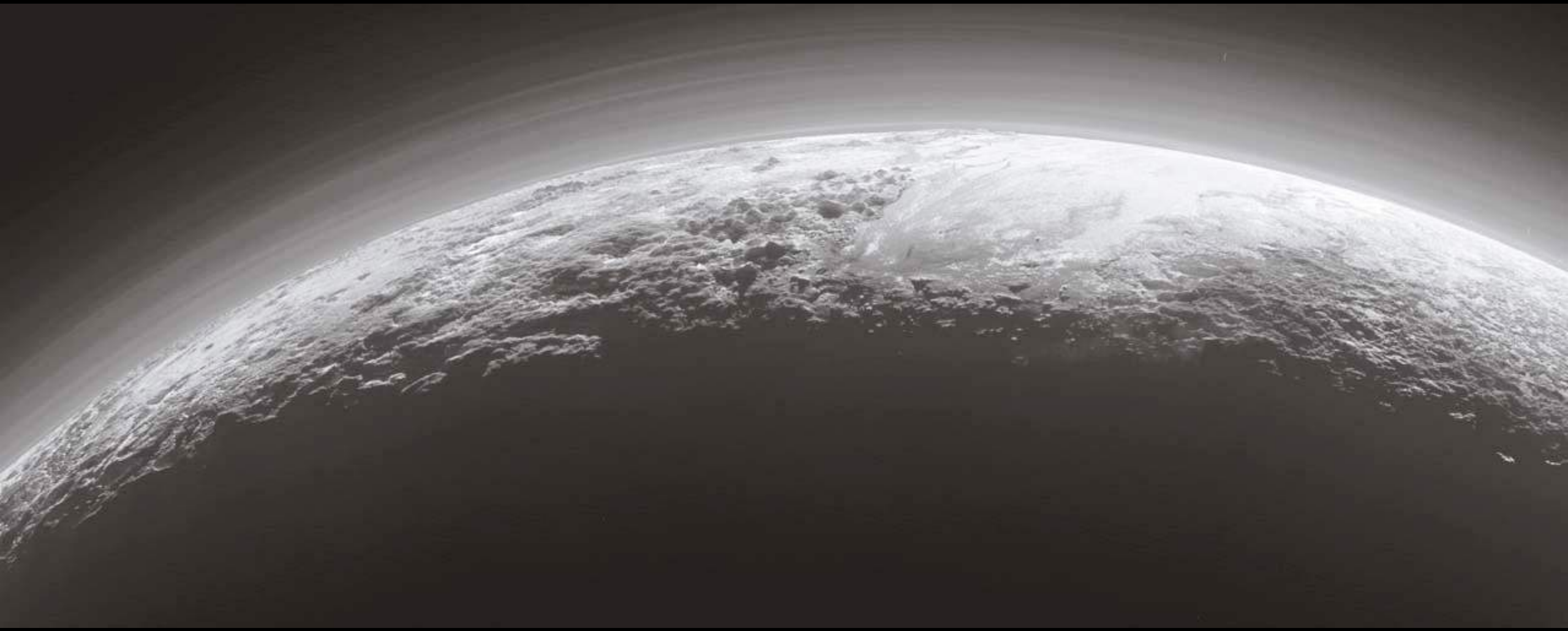
REX: Radio experiment to study Pluto's atmosphere by observing the bending of radio waves beamed up to the craft by giant antennas on Earth.

Student Dust Counter: Devised by undergrads at University of Colorado; will count dust particle impacts from Earth all the way into the Kuiper Belt.

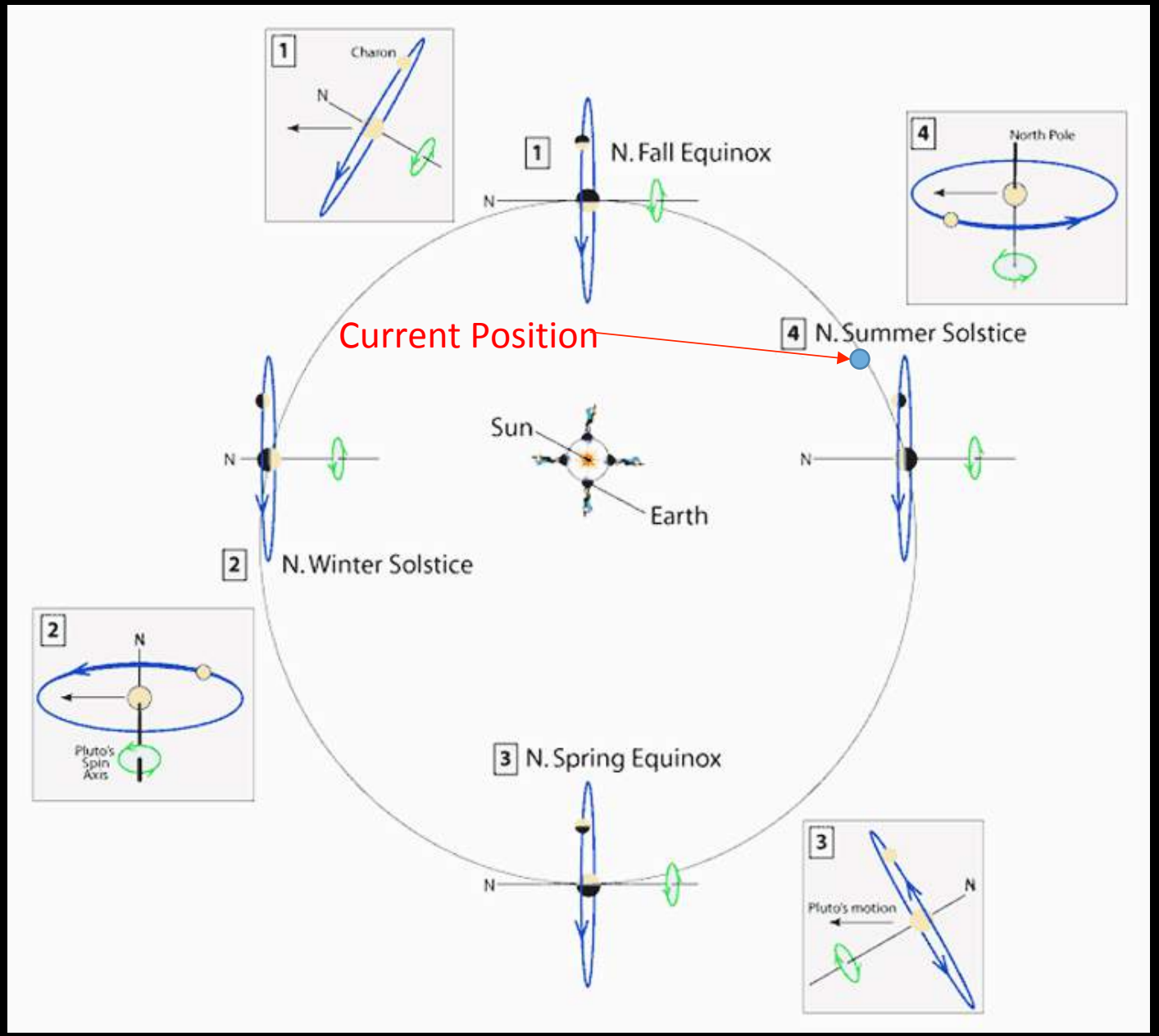


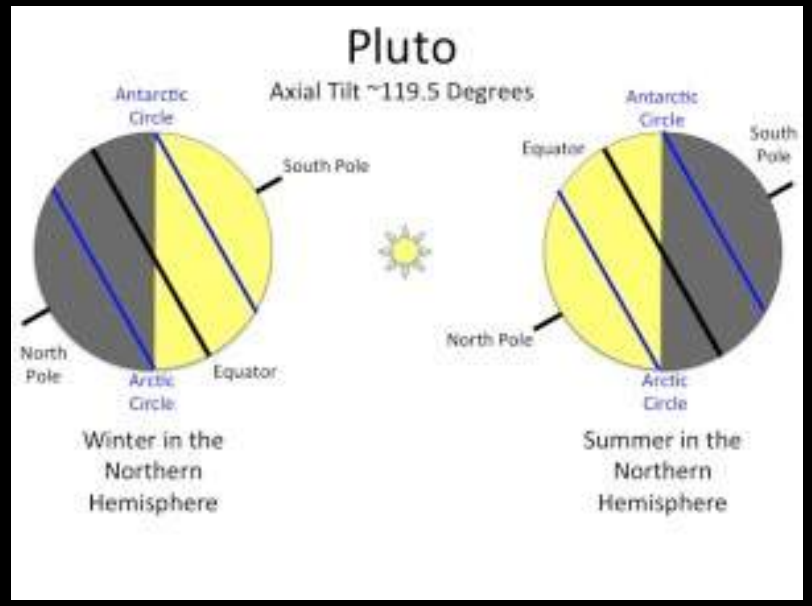


- This shows New Horizon's final approach on July 14 2015
- It was traveling 14 km/sec and the entire close encounter was begun at 9AM and was over by 4PM
- On July 15 while still within 2 million km it flew through Pluto's shadow and made the images shown here
- Several haze layers are seen extending up 80 km above the surface consisting of mostly nitrogen but some acetylene, ethylene & methane
- However, the surface pressure is 0.001 % of that on earth
- The atmosphere is colder and hugs the surface much closer than thought
- Little gas is now escaping so the atmosphere is there to stay(1)

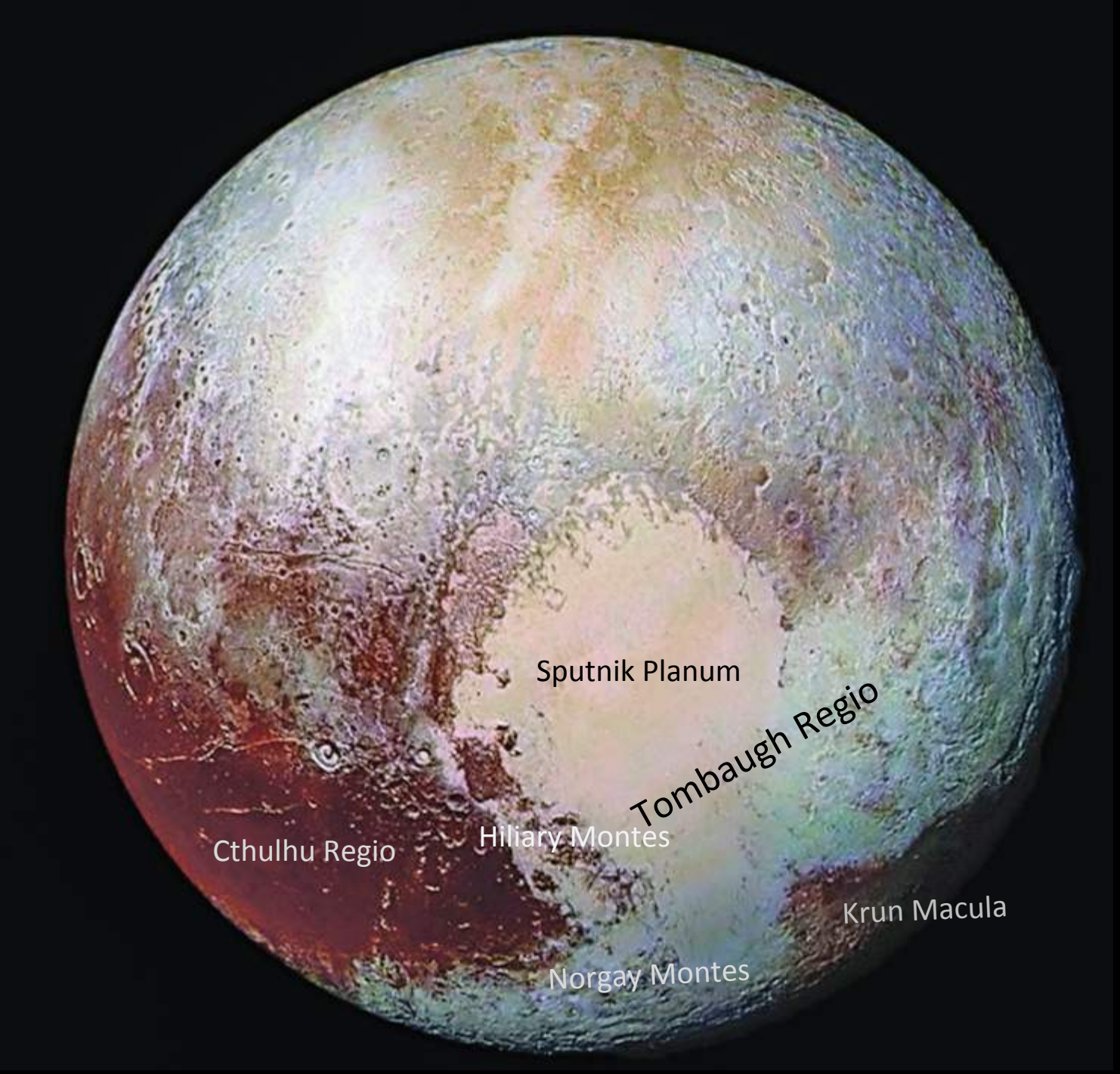


Taken shortly after New Horizons came closest to Pluto on July 14, 2015, this image reveals about 20 distinct haze layers in the tenuous atmosphere surrounding Pluto. The scene is 1,200km (750miles) wide.



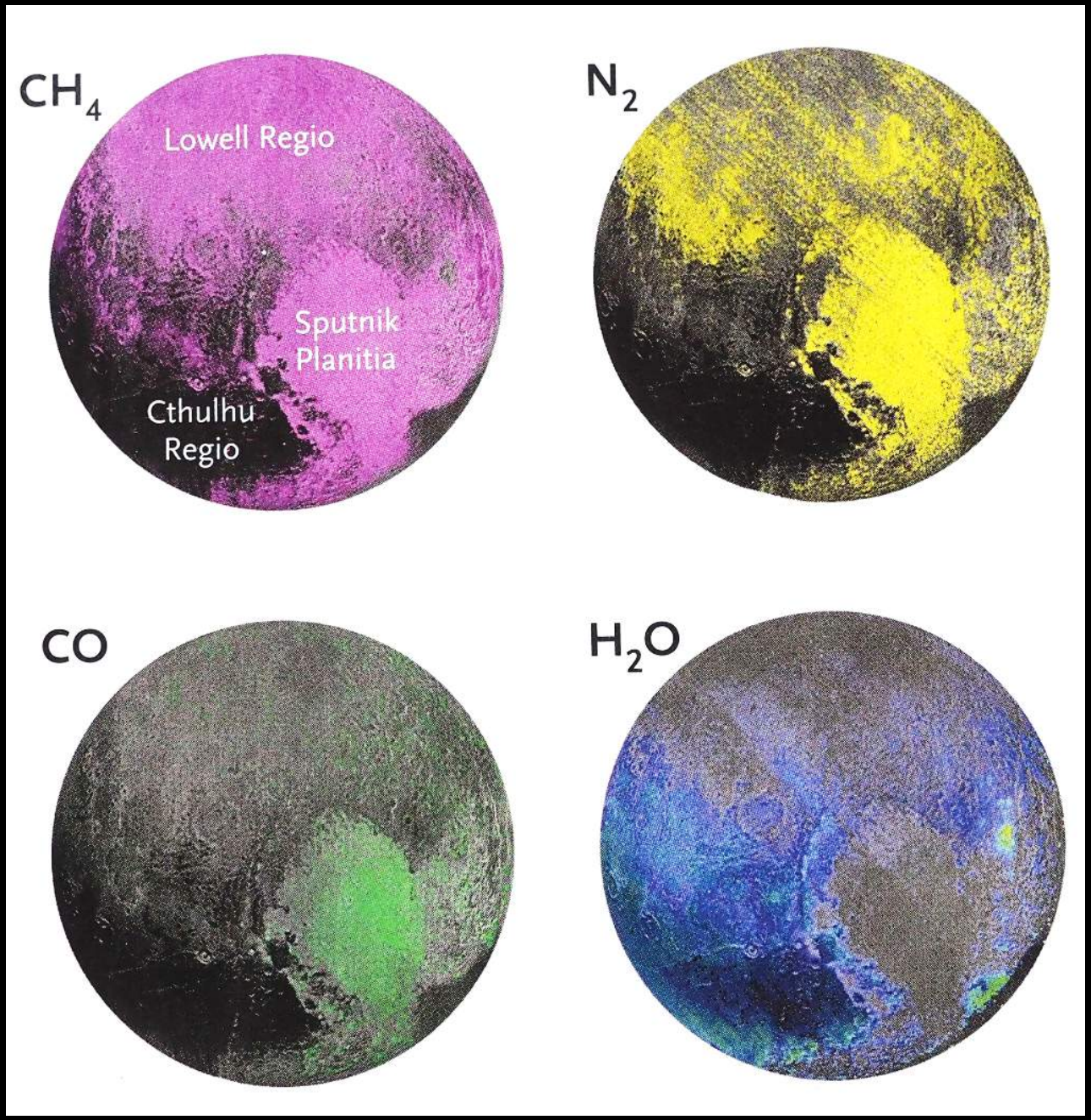


- Because Pluto's polar axis points 120 degrees from the Sun, most of the southern hemisphere was completely hidden in shadow during the flyby
- Pluto's day is 6.39 earth days and Pluto's year is 248 earth years
- Due to this, some of that unseen territory won't be in sunlight for another 100 years

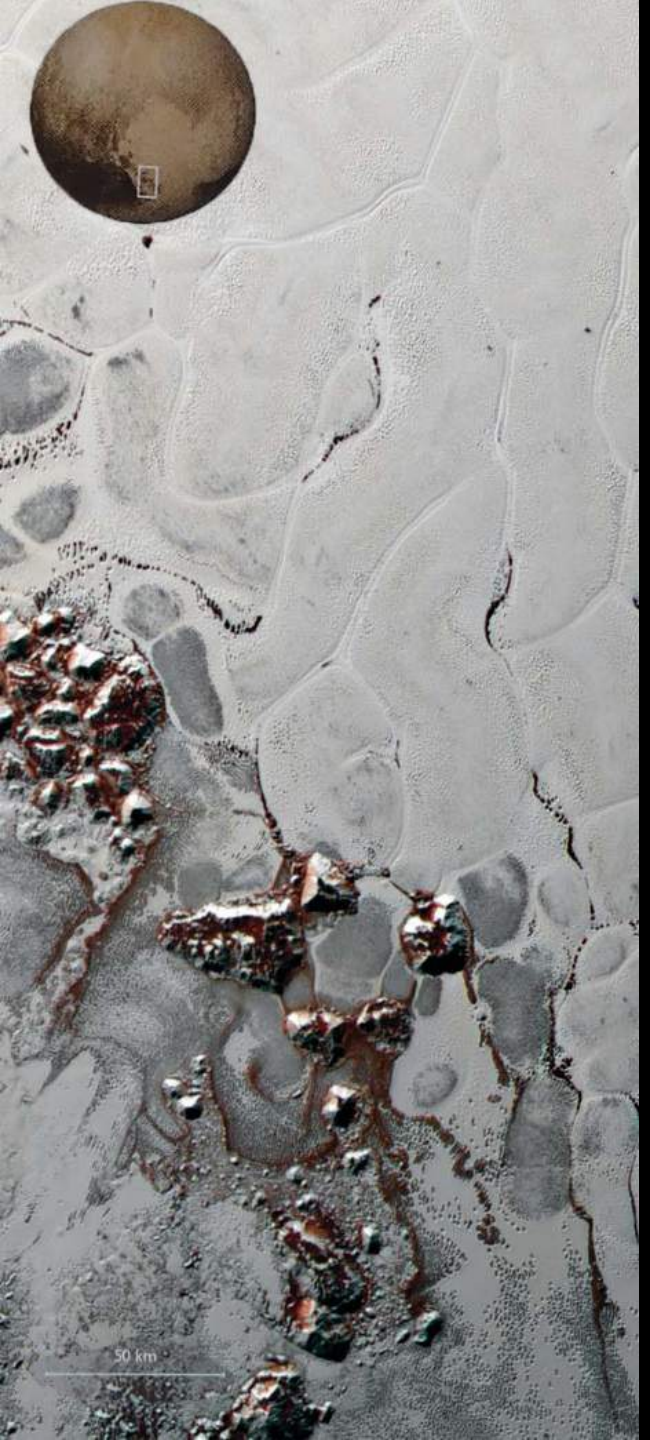


- One of the most prominent features first spotted a month before and 70 million miles away from the flyby was the highly reflective heart shaped region
- This was named the Tombaugh Regio after Pluto's discoverer
- The smoother western portion was named the Sputnik Plantia
- It was first thought to be a raised area but later was found to be an enormous depression 3-4km deep

- The spacecraft's color images and near-infrared spectra reveal that Pluto's surface has a coating of red-tinged material
- Most likely this is a mixture of complex carbon rich organic compounds called tholins(1) formed by uv exposure, a possible precursor to life found in the outer solar system
- Another aspect of the mission was an accurate measurement of Pluto's size which is 2370km up from 2302km
- This makes Pluto the largest of the Kuiper belt objects by a small margin over Eris at 2336±12km
- Based on its mass and size ,its composition is 35% ice and 65% rock
- However, the surface of Pluto is ice of some form, either water, nitrogen, methane, or CO



- Pluto might be mostly silicate-based rock by mass, but no rocks lie on its surface. Instead, everything is ice of one form or another
- Spectral maps acquired by the spacecraft's LEISA show this to be a ubiquitously ice landscape consisting of water, nitrogen, methane and carbon dioxide
- Mission scientists do not understand the distribution of the various ices



A Surprisingly Active Surface

- The total lack of impact craters in the Sputnik Planitia was another big surprise
- Because of this the first estimates were that the region is less that 10 million years old
- Another very interesting feature is that the Sputnik Planitia contains a pattern of interconnected polygons 10-40 km across
- The polygons are evidence that Pluto is still active geologically with trace elements still releasing heat from radioactive decay
- They are tops of solid state bubbles percolating from below and since frozen nitrogen melts at 63K it should flow even at the 37K surface temperature of the Planitia(1)
- The evidence also indicates that the upwelling convection pushes the top most ice along at rates of a few centimeters/year
- This causes a re-surfacing of the Sputnik Planitia in just 500,000 to 1,000,000 years explaining why there are no craters

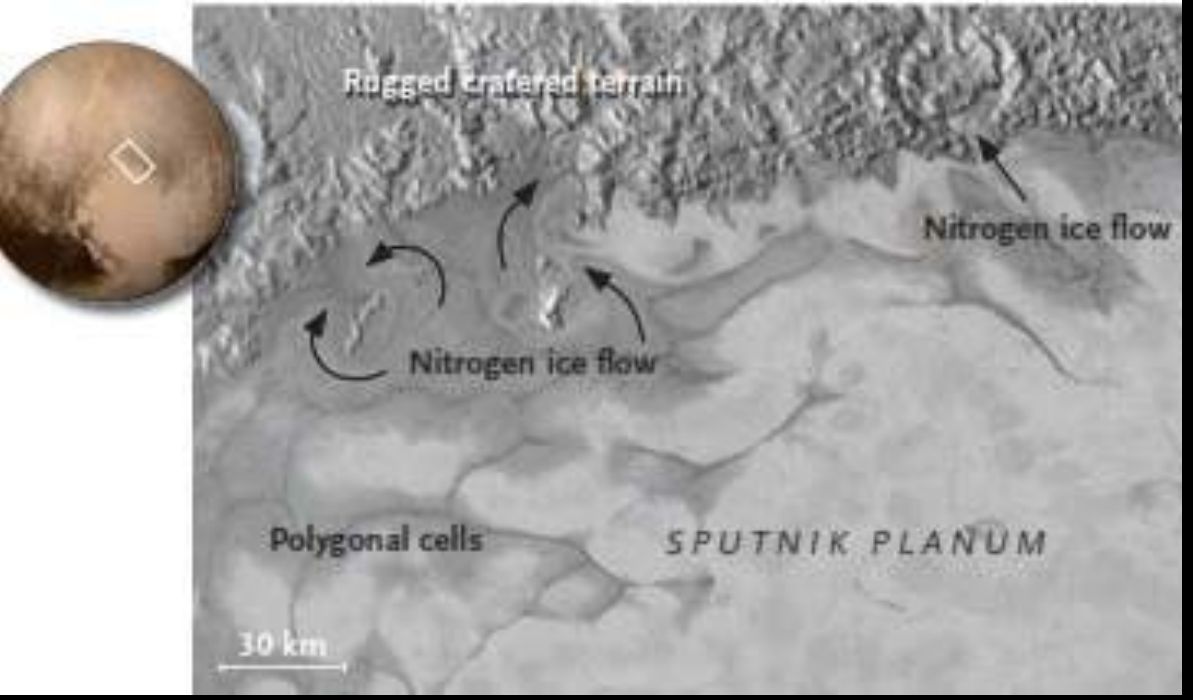
A Buried Sea Under Sputnik Plantia

- Because of the evidence of surface activity there is speculation that there is a buried ocean of salty water underneath(1)
- Inaddition, this is the region of Pluto that is facing Pluto's large moon Charon which is tidally locked
- Because of this it is likely that the region has a positive mass anomaly
- This has also led to further conjecture that there is a dense buried semi liquid water layer 100km thick with a salt content of 30% similar to the Dead Sea(1)

Further Analysis of a Buried Water Layer on Mars

- Heat was required to move the solid state bubbles to the surface of SP
- This heat should have melted Pluto's water-ice mantle, creating a global layer 50 to 150 km thick. (1)
- But does the deep-seated reservoir still exist ?
- If it was frozen it would have caused Pluto to have contracted by 13km in radius which would have caused compressional fractures-but none are seen

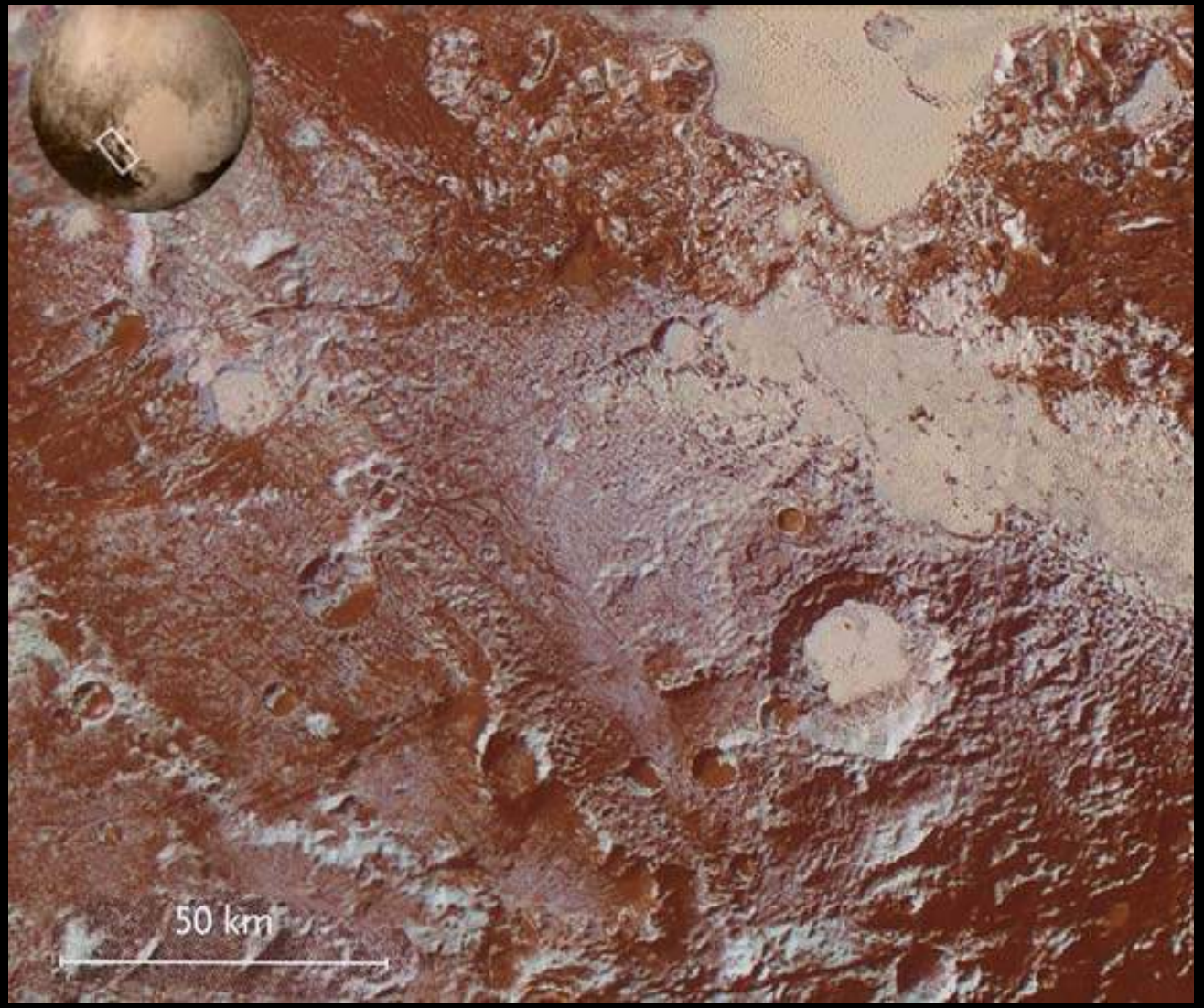
- The Serenity Chasma on Charon seems to be a case in point
- It is 50km wide and 5km deep and the Mandjet Chasama reaches 7km in depth
- The most logical explanation is that Charon once had an interior ocean of water that expanded as it slowly froze
- Estimates are that this resulted in a 1% increase in surface area and a 3km increase in radius(2)
- To achieve this there had to be an outer shell of water 35km thick to freeze from top down



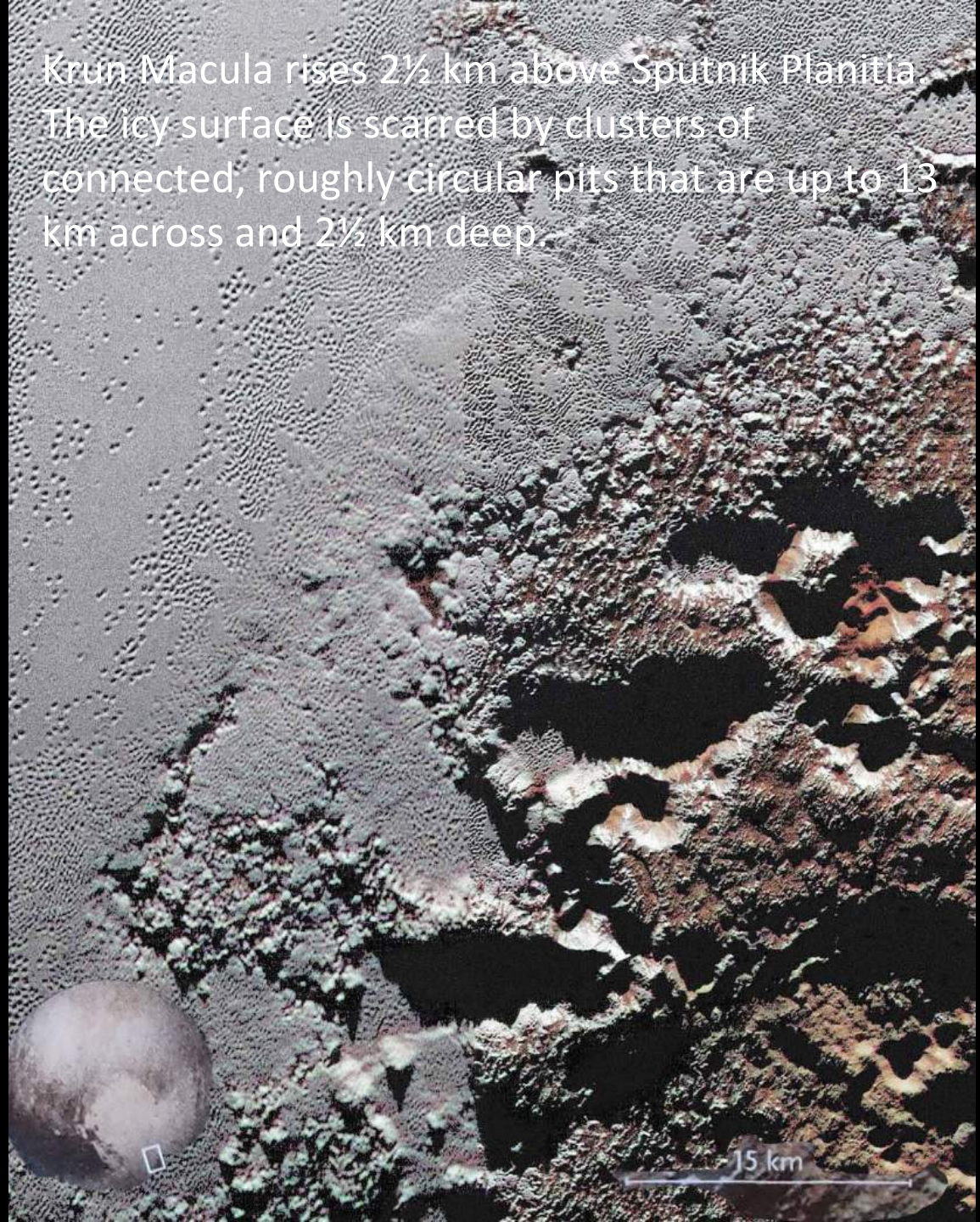
Mountains of Floating Water Ice

- The north polar region above the "heart" resembles glaciers on earth but cannot be water ice because at 38K it does not flow.
- It is likely frozen nitrogen, methane, and carbon monoxide which can flow at 38K
- Close inspection also shows clusters of hills that stick up through the plain's surface.
- Reflectivity measurements rule out the possibility that they could be rocky(1)

- Thus, they have to be water ice since volatile nitrogen, methane, and CO are not strong enough to support their size(2)
- These "islands" may be floating in SP's sea of frozen nitrogen since water ice is less dense than frozen nitrogen
- The water ice mountain ranges in the SW edge of the SP are named after Edmund Hillary and Tenzing Norgay. They rise 11000' above the surrounding plane



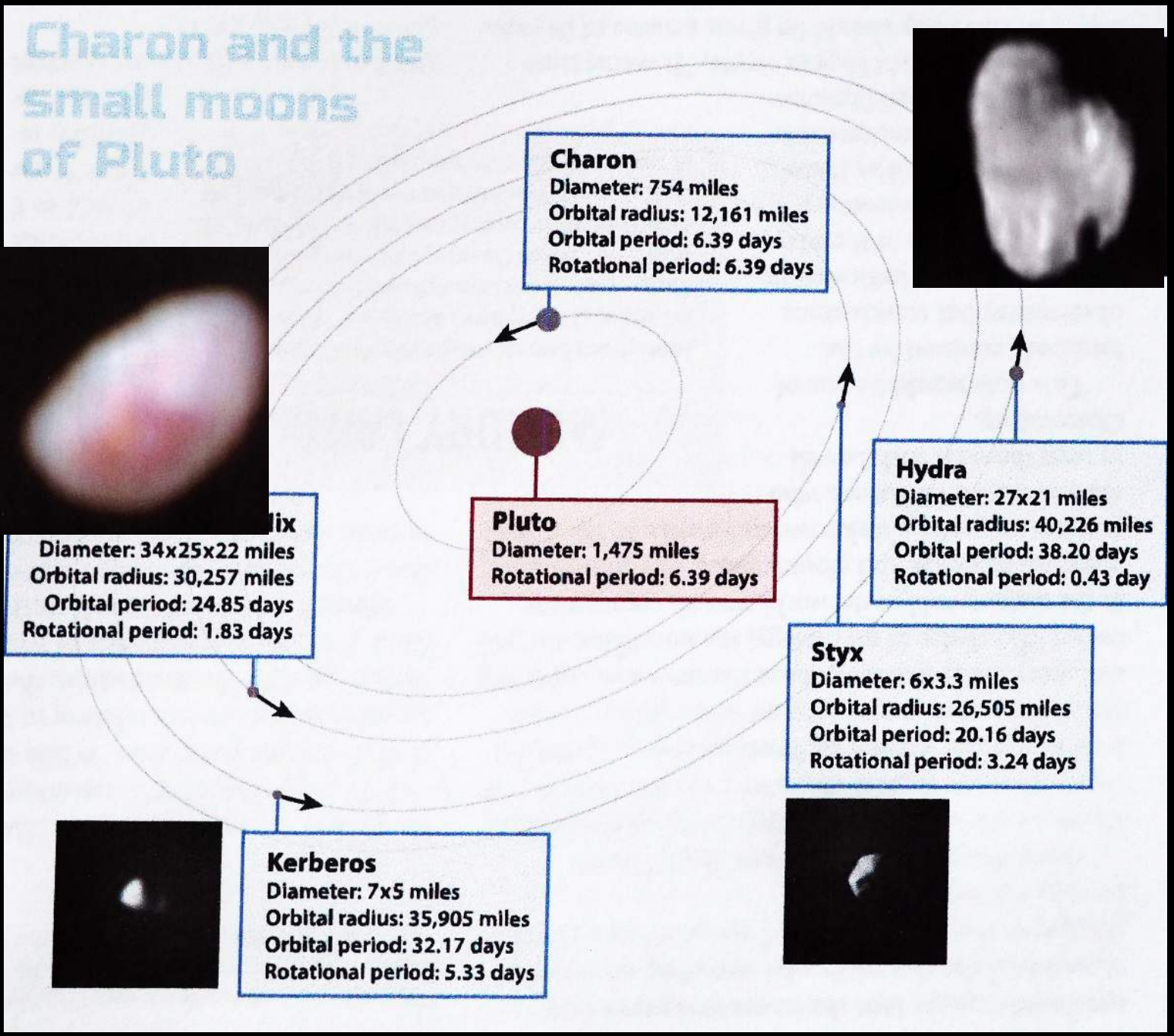
A vast stretch of ancient, heavily cratered Cthulhu Regio along Pluto's equator(above) has been dated as 4 Bya. This is an amazing contrast to nearby Sputnik Plantia to the east which may be in constant flux



Pluto’s Moons

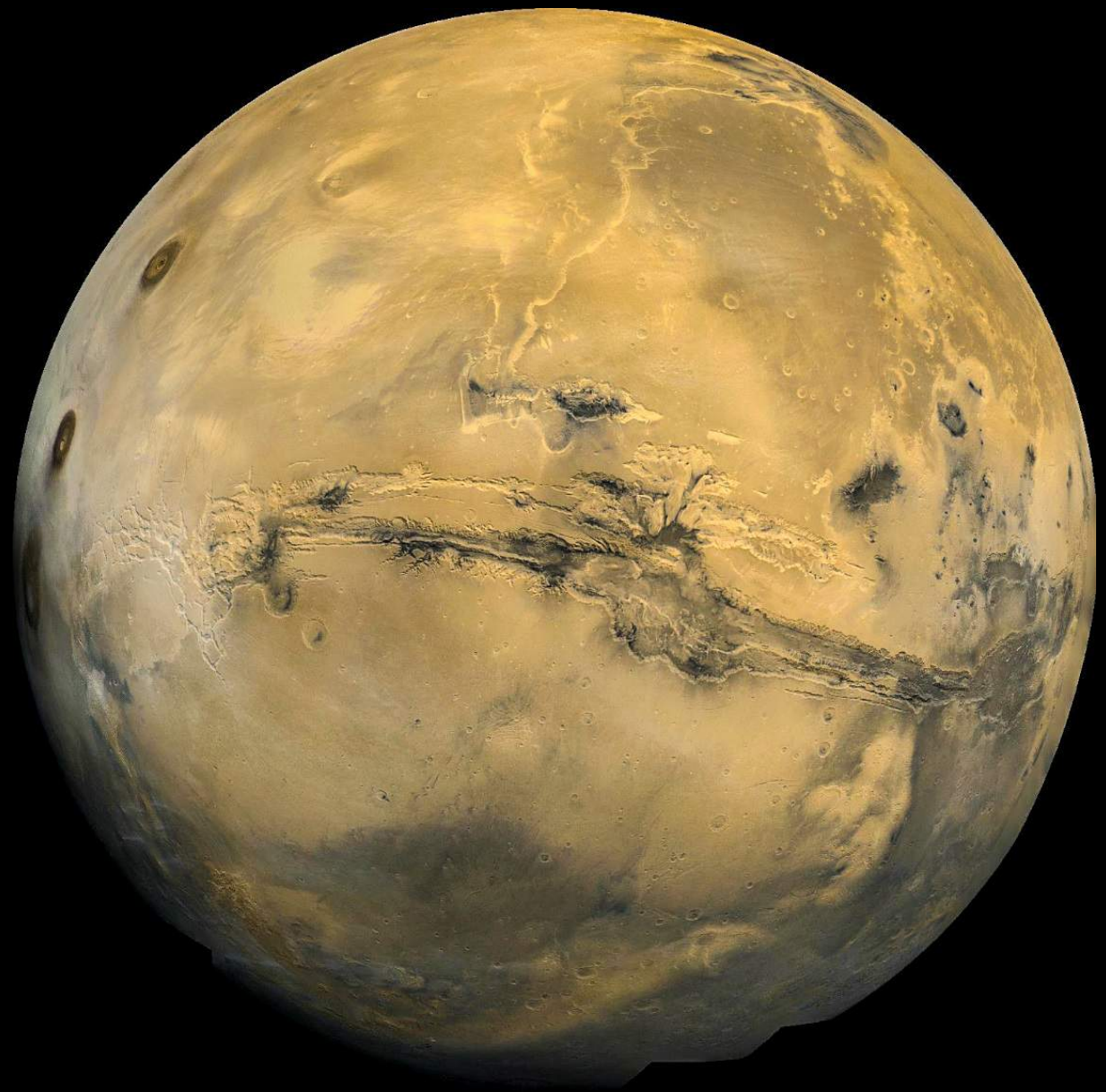
Thanks to results from New Horizons, planetary scientists are more convinced than ever that Pluto’s precursor collided with a somewhat smaller object in early solar system history.

This collision of ice-encrusted worlds left Pluto spinning on its side and five moons, sizable Charon and four small siblings orbiting nearby

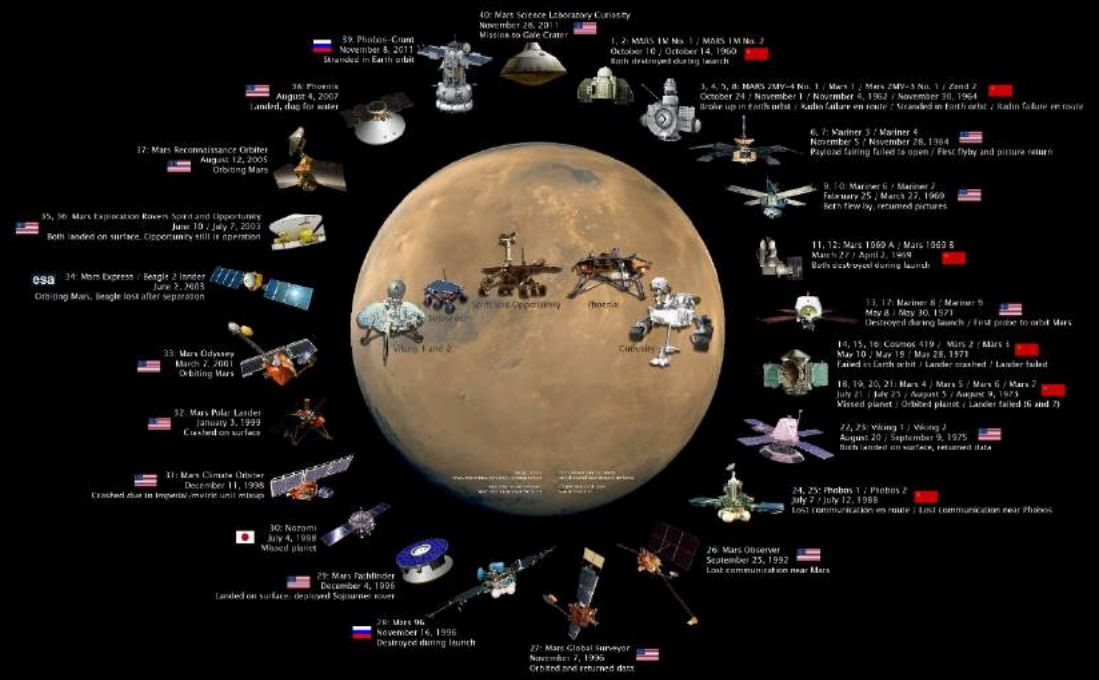


- New Horizon's flyby did not allow for observation of Pluto's 4 small moons
- However images taken at long range allowed the sizes, orbits, and rotation rates to be determined
- The normal situation for moons like these is that they would be tidally locked to the planet
- Except for Charon which is tidally locked, all four small moons are spinning chaotically at rates much faster than their orbital periods
- Hydra spins 89 times during its 38 earth day orbit
- In addition, their rotation axes are parallel to their orbital plane and they are in effect rolling on their sides
- This rotational chaos and their composition is evidence for their "big splat" origin
- All four moons have very high albedos between 60%-80%, near that of pure ice

Mars Exploration

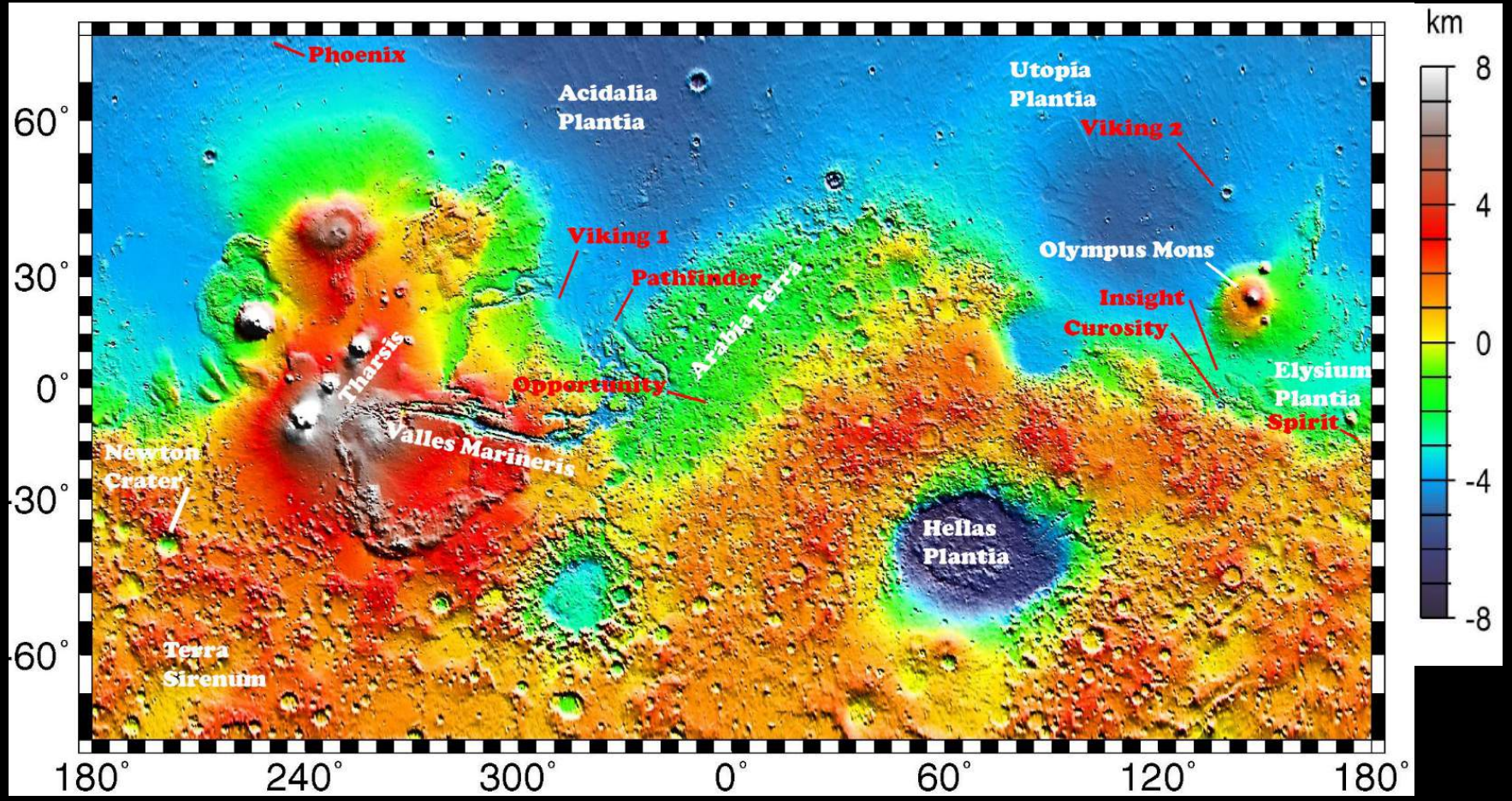


Mars Exploration Family Portrait



- There have been 44 missions to Mars and 21 that were successful
- The US has had 21 missions and 18 successful
- The US Mariner 4 flyby launched 11/28/1964 was the first successful mission and captured and returned pictures
- The USSR Mars 3 in 1971 was the first lander
- The 1997 US Mars Pathfinder consisted of a lander and a small 10.6 kilograms (23 lb) wheeled robotic rover named Sojourner, which was the first rover to operate on the surface of Mars.

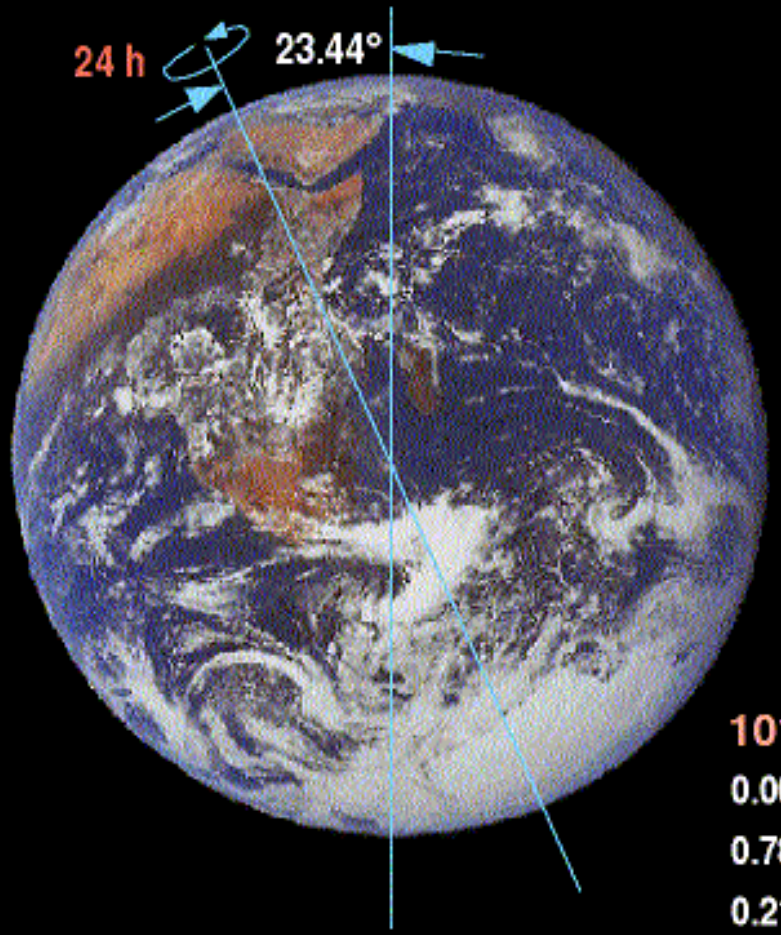

Sojourner(1996), Opportunity(2004), and
Curiosity(2012) Rovers



- This is a composite of images from the Mars Global Surveyor mission from 1997-2006
  Dark blue is -27500 ft thru green, yellow and red(+13750 ft) to white(+27500 ft).
- The white peaks are volcanos Mars is a little like Earth, only smaller, drier and colder with very little atmosphere.

- Olympus Mons may be the largest volcano in our solar system. At 25,000m it is three times taller than Mt. Everest and as big as the state of New Mexico. Valles Marineris is a grand canyon almost as long as the United States of America is wide.
- Mars has two moons, Phobos (fear) and Deimos (panic). Phobos is slowly moving towards Mars and will crash into Mars or break apart in about 50 million years.

EARTH COMPARISON MARS



YEAR

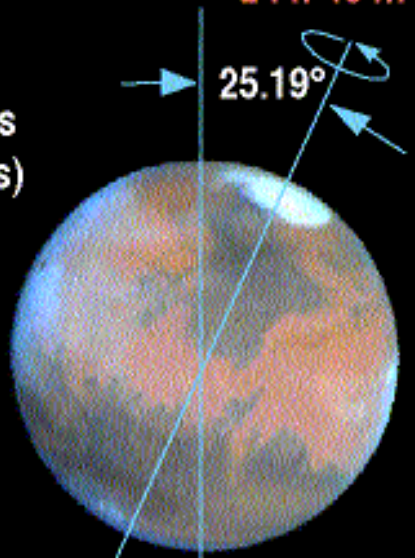
365 Days 686 Days
(667 Sols)

GRAVITY

38% of earth

SUNLIGHT

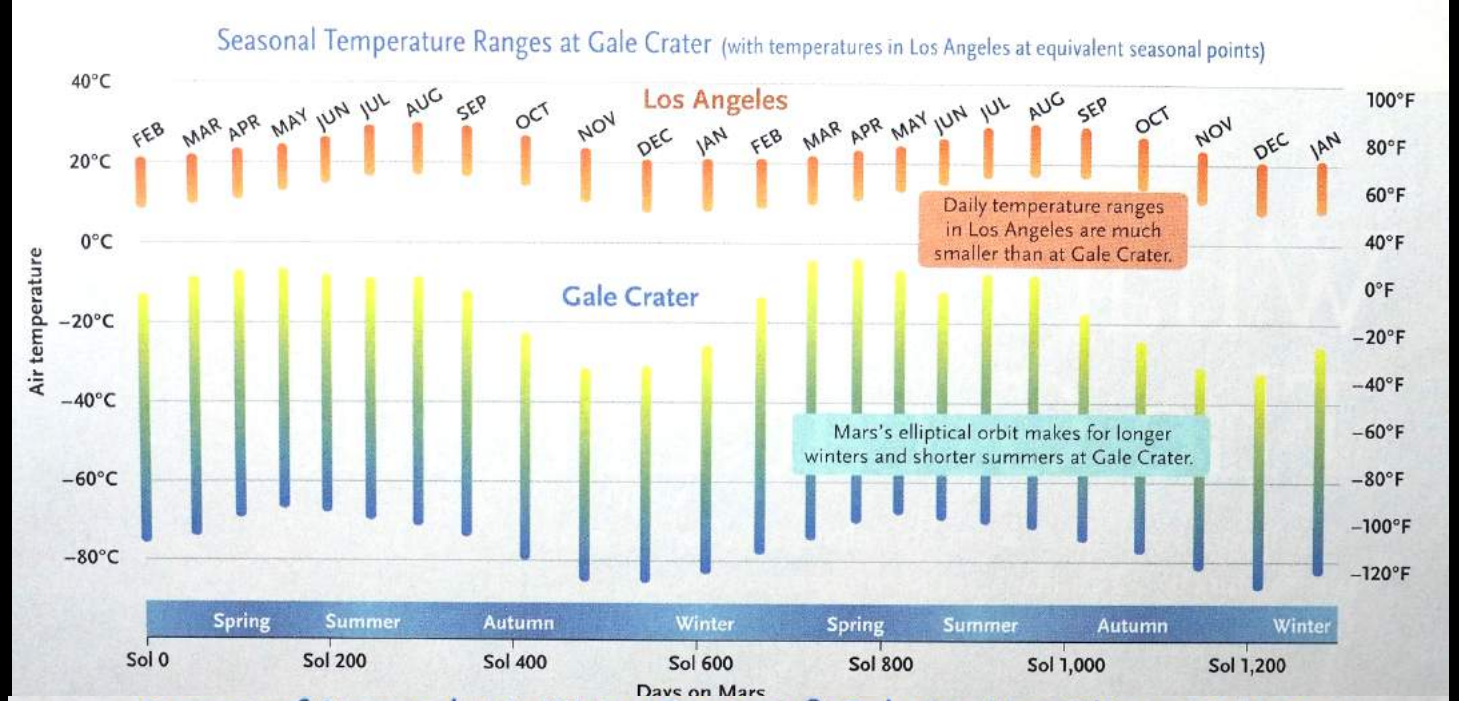
44% of earth

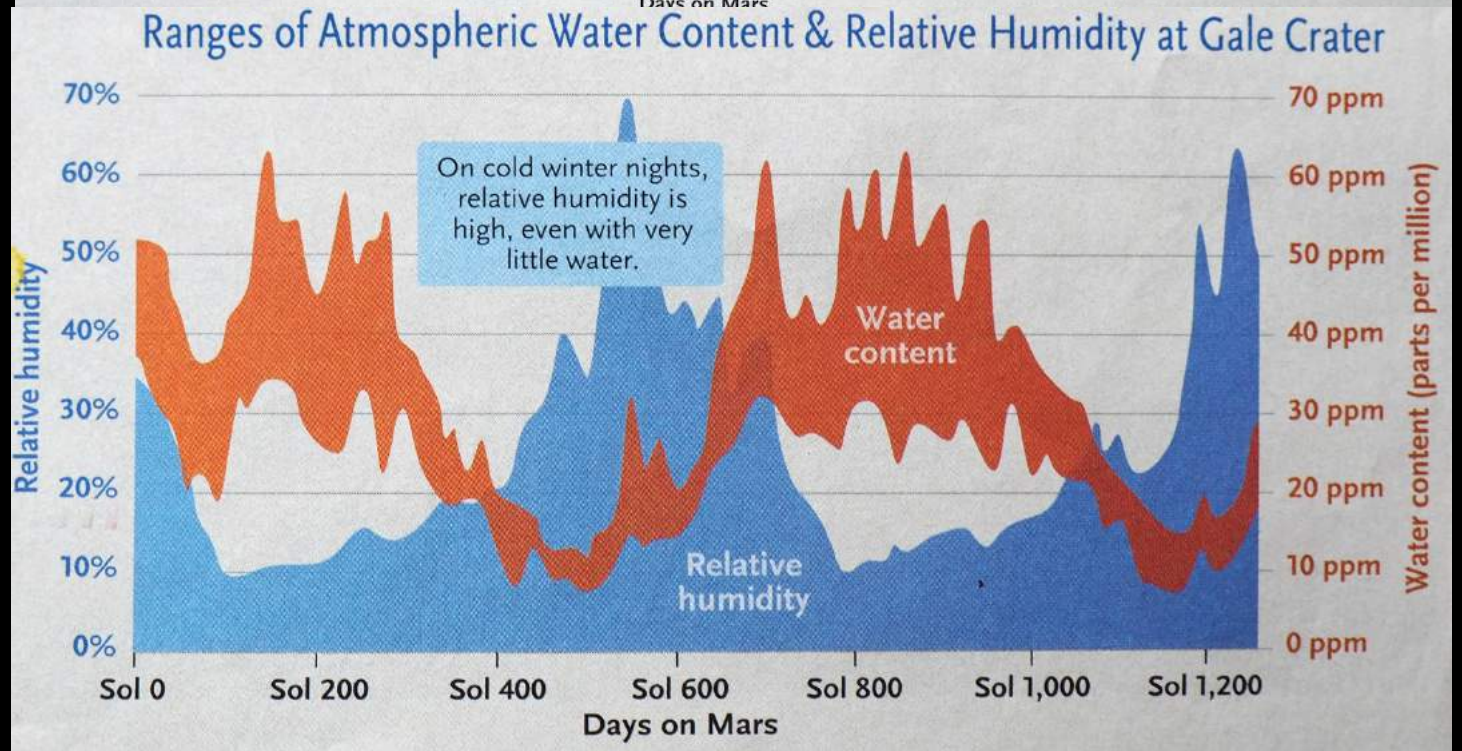


ATMOSPHERE

1013mb	Total	7.6 mb
0.00035	CO_2	0.95
0.781	N_2	0.027
0.210	O_2	0.0013
0 to 0.04	H_2O	0 to 0.00021
0.0093	Ar	0.016

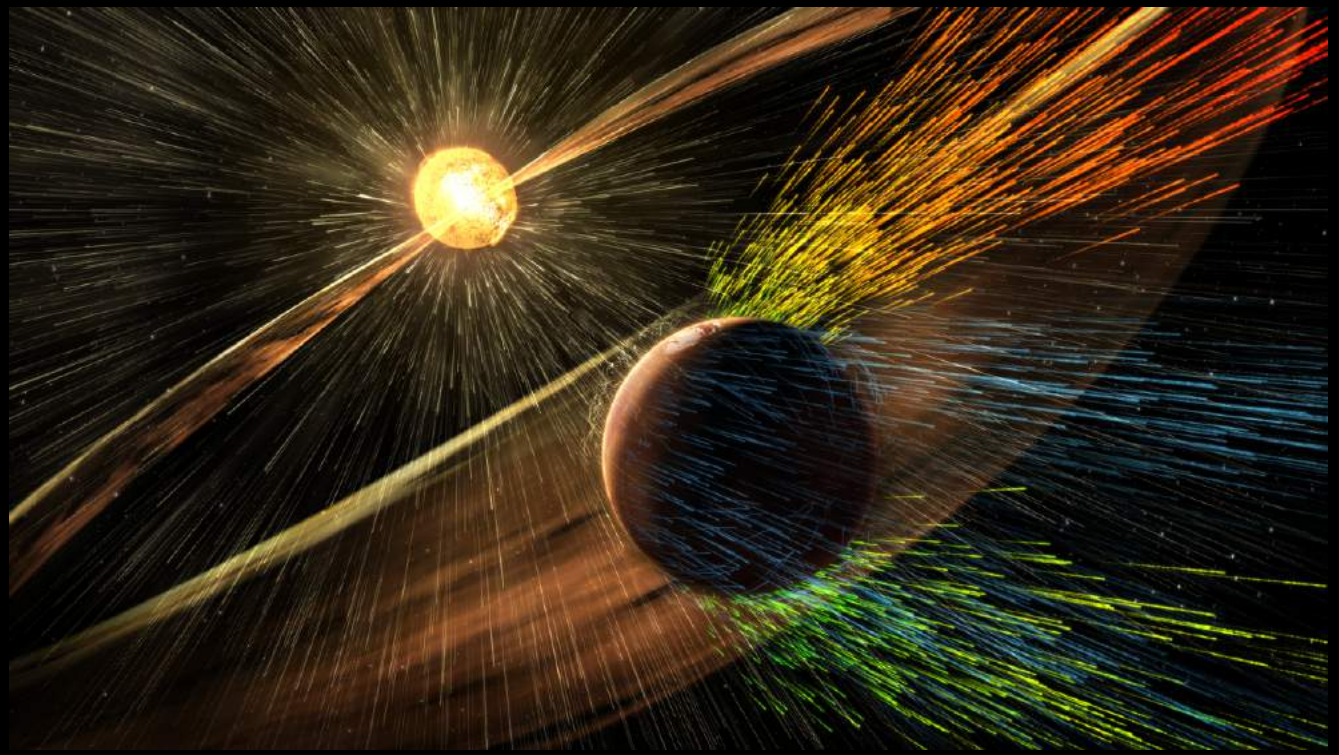
Mars, courtesy
P. James and NASA





- Mars has very large temperature excursions
- Curiosity has measured temperatures of 16C(60F) on a summer afternoon and -100C(-148F) on a winter evening
- The air is extremely dry and Mars has a content of 40ppm on average compared to 20,000ppm on Earth
- Inspite of that the humidity is very high in the winter and frost can form

Mar’s Atmosphere



• Composition of Mars' atmosphere is 95% CO_2 which is similar to Venus, yet over 10,000 times thinner

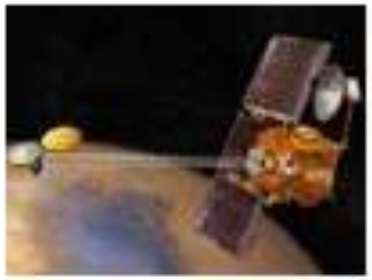
• The runoff channels indicate that early (about 4 billion years ago) Mars probably had a fairly dense atmosphere,

•In the first billion years, the atmosphere disappeared

- MAVEN satellite(1) was launched in 2013 to study the atmosphere and has been in orbit over 1000 days
- CO_2 deposits on the surface are much too small to explain the loss of the CO_2 in the atmosphere
- It has shown that with no magnetic field, the solar wind caused loss of most of the atmosphere in a process called “sputtering”

- With little atmosphere Mars cooled and has likely undergone the largest climate change in its history of any of the inner planets

Mars Current Missions



Mars Odyssey
Launch: Apr. 7, 2001
Arrival: Oct. 24, 2001

2001 Mars Odyssey is an orbiting spacecraft designed to determine the composition of the planet's surface, to detect water and shallow buried ice, and to study the radiation environment.

Mars Express
Launch: Jun. 2, 2003
Arrival: Dec. 2003

NASA is participating in Mars Express, a mission planned by the European Space Agency (ESA) and the Italian Space Agency. The mission is exploring the atmosphere and surface of Mars from polar orbit.

Mars Exploration Rovers (Spirit and Opportunity)
Spirit Launch: Jun. 10, 2003; Mars Landing: Jan. 3, 2004
Opportunity Launch: Jul. 7, 2003; Mars Landing: Jan. 24, 2004

These rovers had far greater mobility than the 1997 Mars Pathfinder rover. Each rover carries a sophisticated set of instruments to search for evidence of liquid water that may have been present in the planet's past.

Mars Current Missions

Mars Reconnaissance Orbiter

Launch: Aug. 12, 2005; Arrival: Mar. 10, 2006

NASA's Mars Reconnaissance Orbiter is capturing unique views of Mars with the most powerful telescopic camera ever to another planet. Its five other scientific instruments are collecting data about the Red Planet.

Mars Atmosphere and Volatile EvolutioN (MAVEN)

Launch: Nov. 18, 2013

Arrival: Sept. 21, 2014

The Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft is providing information about the Red Planet's atmosphere, climate history and potential habitability in greater detail than ever before.

Mars Science Laboratory-aka Curiosity

Launched: Nov 26, 2011

Landed : Aug 6, 2012

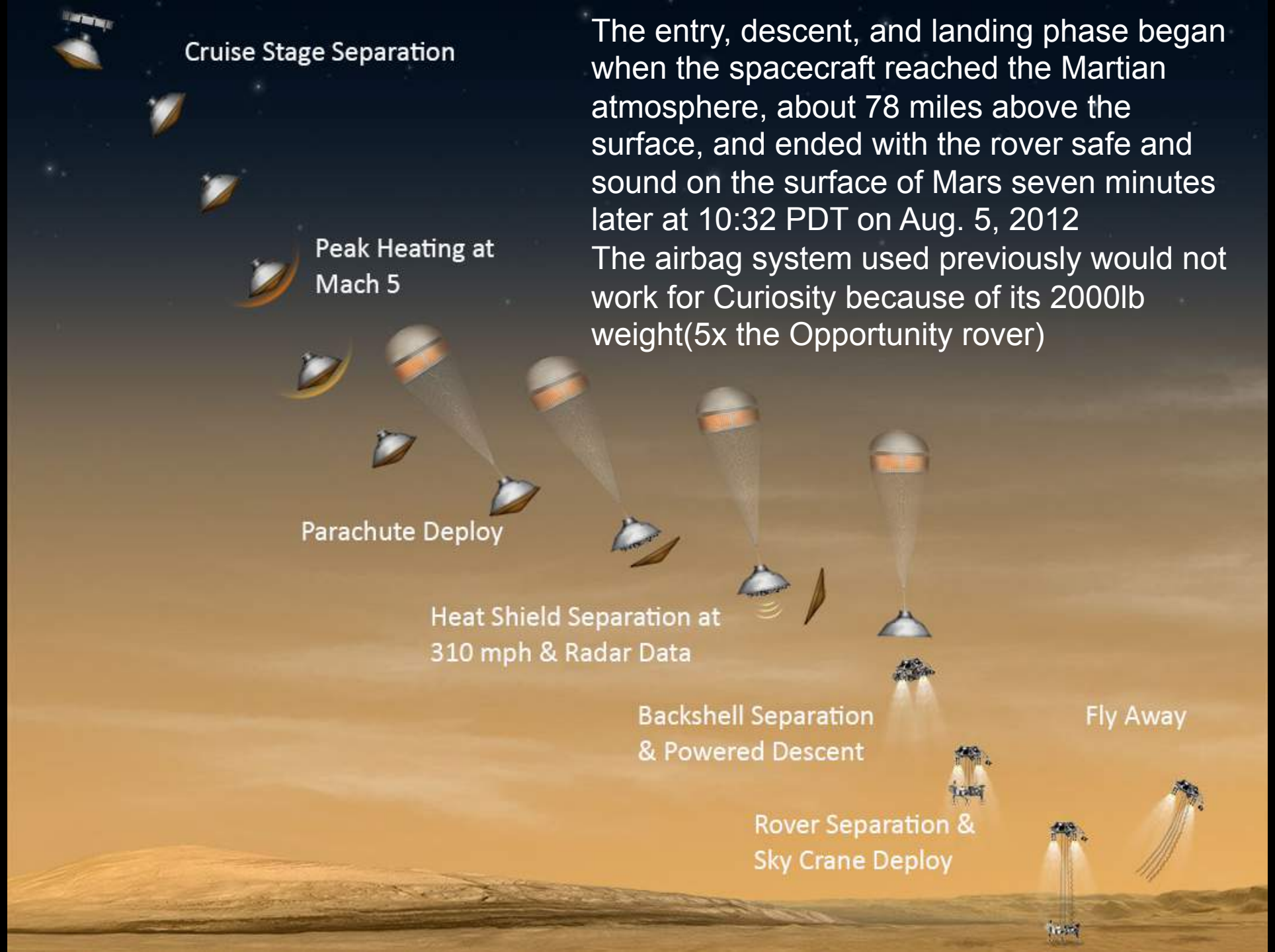
Original Mission: Two years

- Curiosity is twice as long and five times as heavy as the Mars Exploration Rovers Spirit
- It is not actually looking for life itself as it is not equipped to do that but is assessing whether Mars ever had an environment able to support life forms
- Curiosity is collecting Martian soil samples and rocks and analyzing them for the building blocks of life(carbon, hydrogen, nitrogen, oxygen, phosphorous, and sulfur)
- It is assessing the present and long term history of the atmosphere and surface water
- It is also studying the near surface geology and the processes that formed and modified the rocks and soils

The Mars Science Labratory(Curiosity)

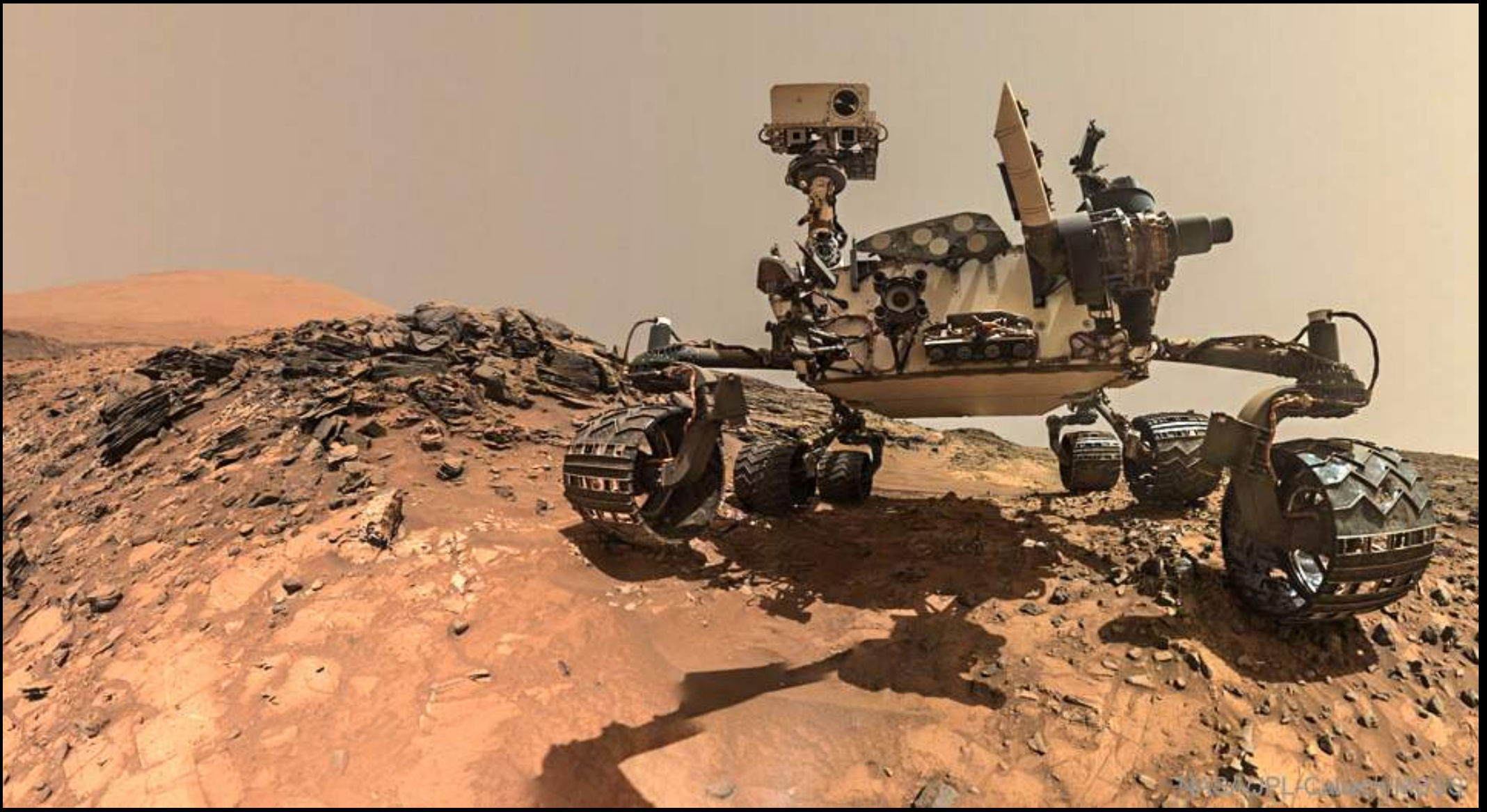
	Mass in lbs (kg)
Rover	1,982 lbs (899 kg)
EDL System (Aeroshell and fueled descent stage)	5,293 lbs (2,401 kg)
Cruise Stage (Fueled)	1,188 lbs (539 kg)

- The spacecraft is the protective "spaceship" that enables the rover to travel between Earth and Mars
- The Mars Science Laboratory mission had a total launch mass, including the rockets that lifted it away from Earth, of 1.17 million pounds



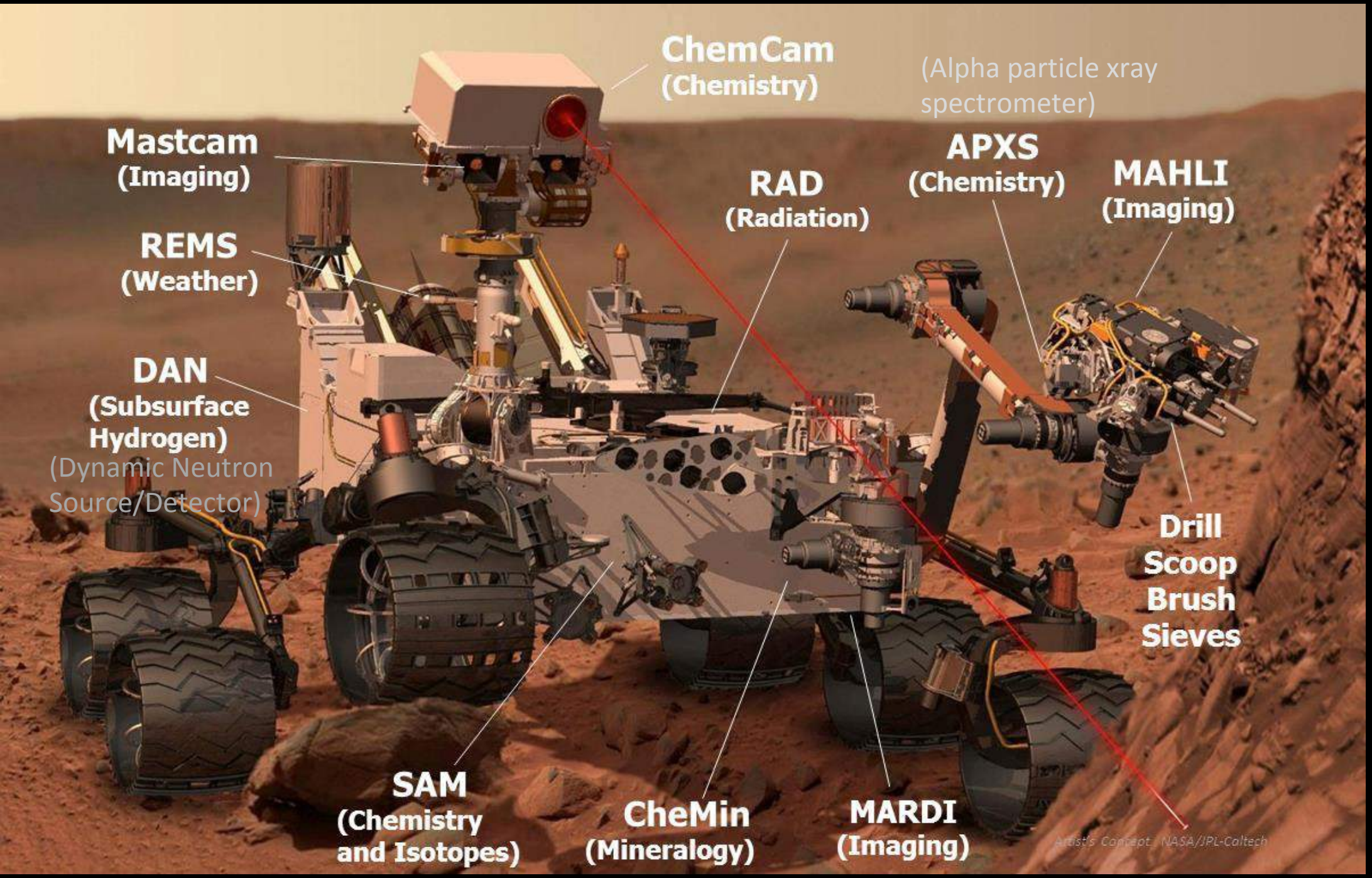
The entry, descent, and landing phase began when the spacecraft reached the Martian atmosphere, about 78 miles above the surface, and ended with the rover safe and sound on the surface of Mars seven minutes later at 10:32 PDT on Aug. 5, 2012

The airbag system used previously would not work for Curiosity because of its 2000lb weight(5x the Opportunity rover)



- This selfie of Curioisty was compiled from many smaller images -- which is why the mechanical arm holding the camera is not visible.
- Taken in mid-2015 it shows layered rocks, the light colored peak of Mount Sharp, and the rusting red sand that pervades Mars.

- The rover is able to roll over obstacles up to 75 centimeters (29 inches) high and travel up to 90 meters (295 feet) per hour and is now climbing Mt Sharp
- The plutonium power source may last for up to 14 years



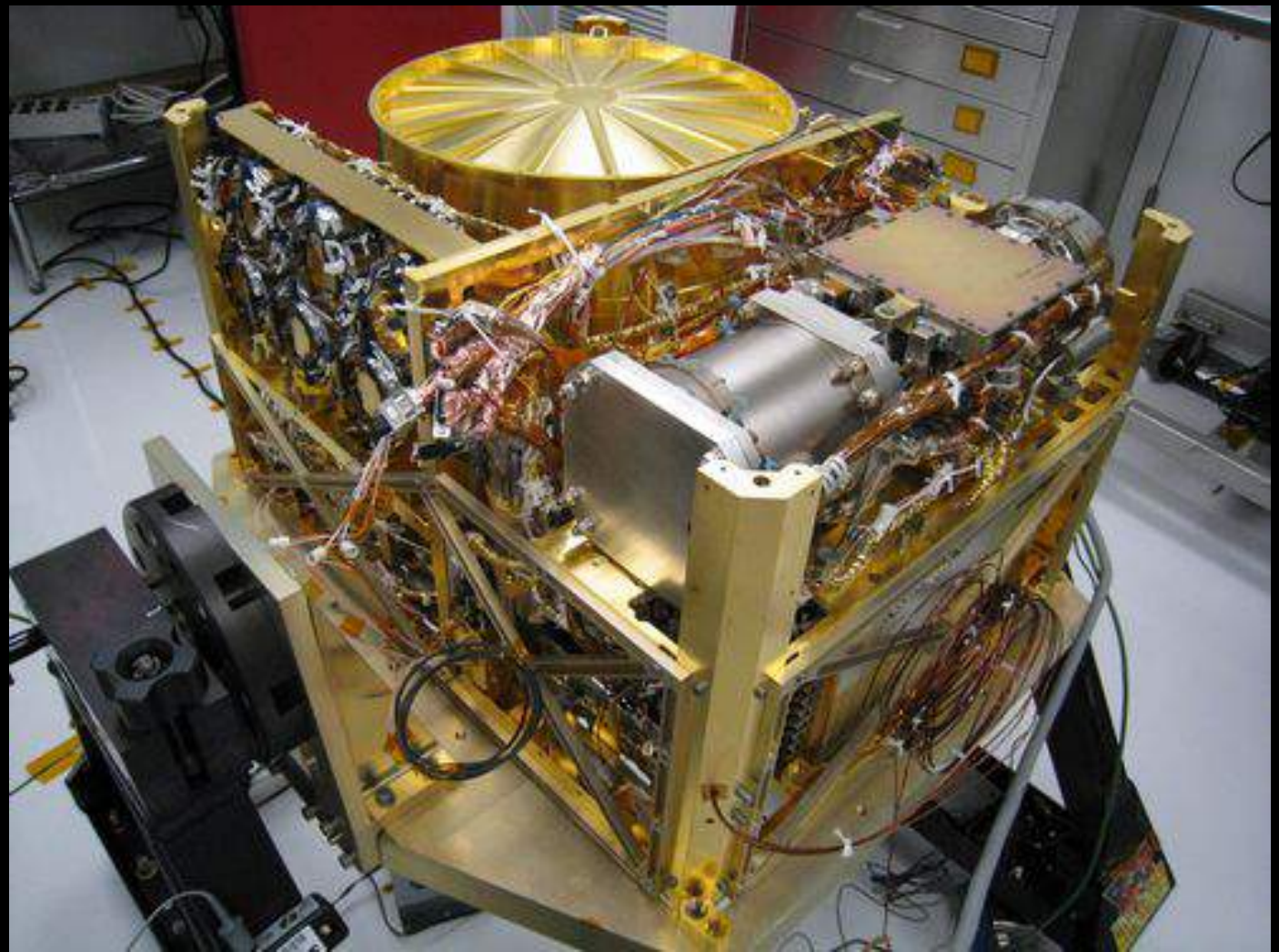
There are 17 cameras on Curiosity. Nine are for navigation and the rest for some form of imaging

The MastCam has a 34mm and a 100mm color camera

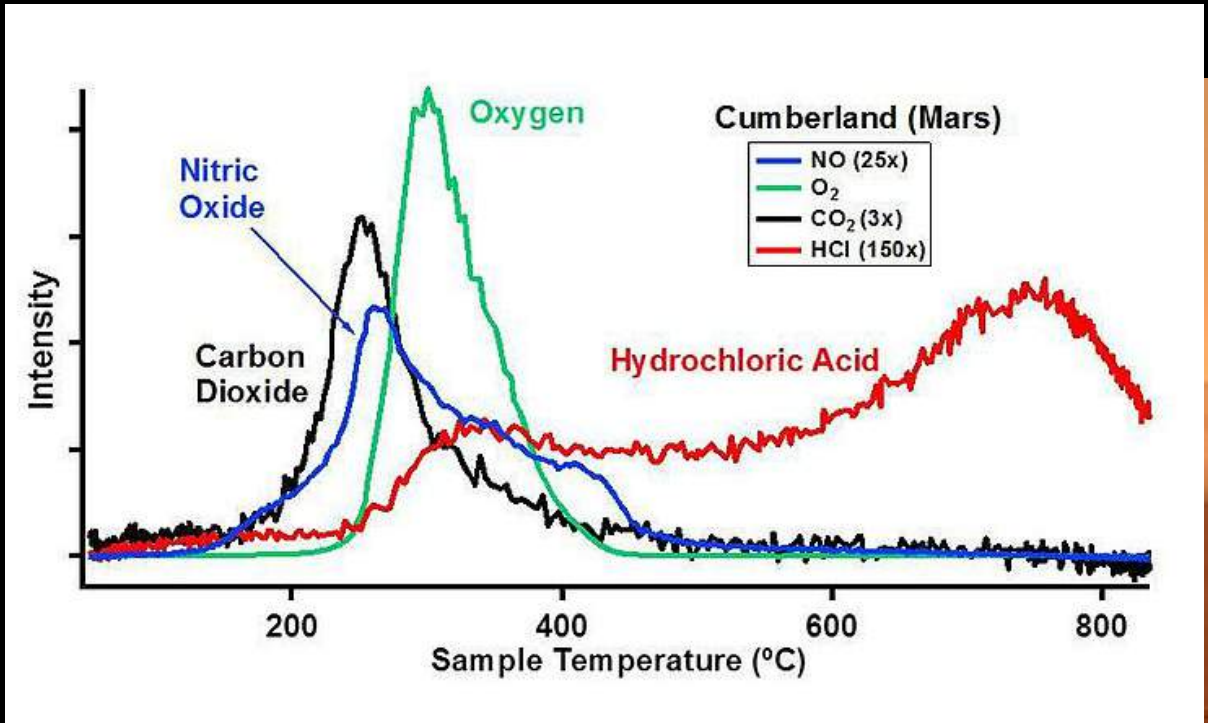
MAHLI is a hand imaging camera for sample analysis

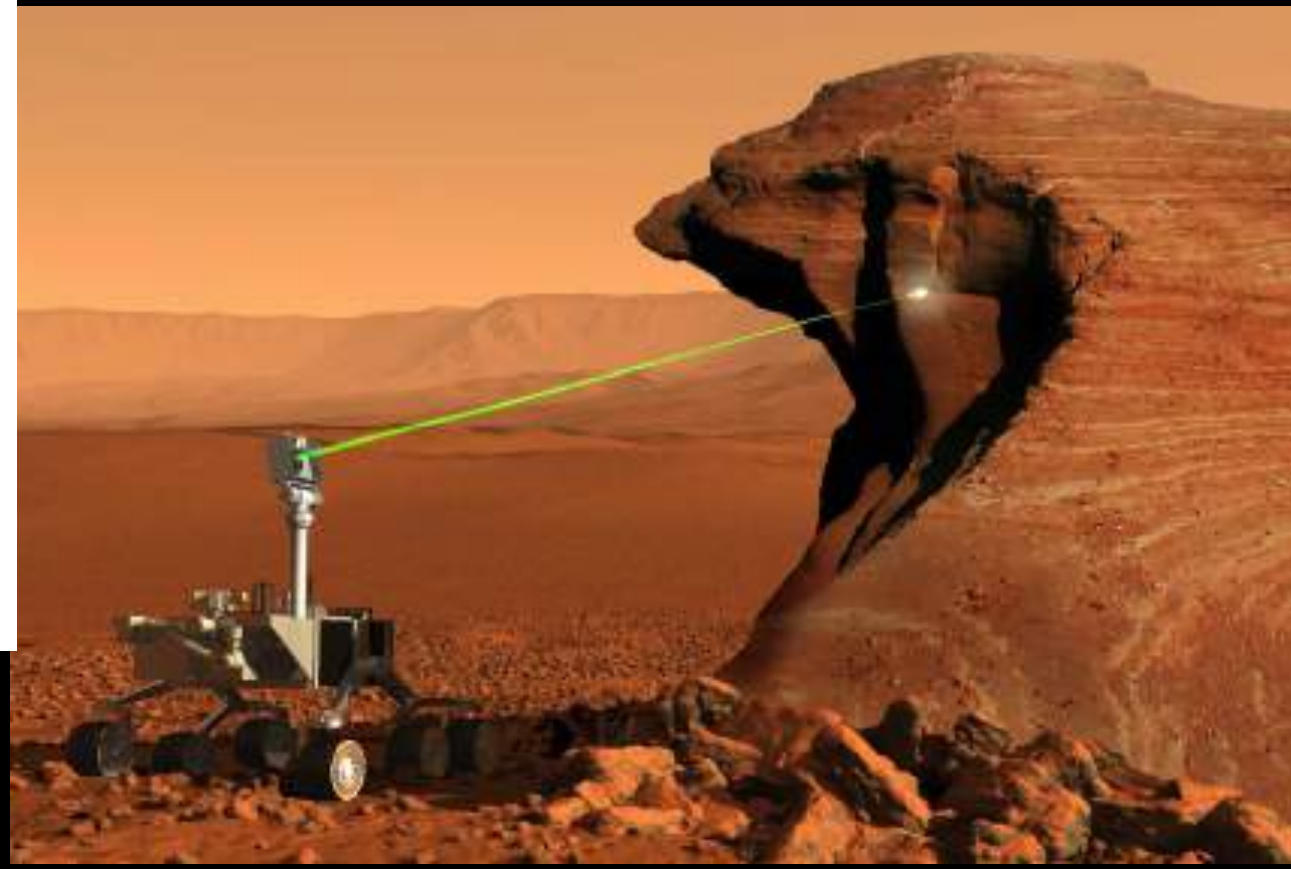
Curiosity's Main Scientific Instruments

- ChemCam can vaporize and analyze rock for its composition
- There are two lab instruments that can ingest drilled powder,
- CheMin, which measures mineral composition and
- SAM(Sample Analysis at Mars) instrument suite that takes up more than half the science payload



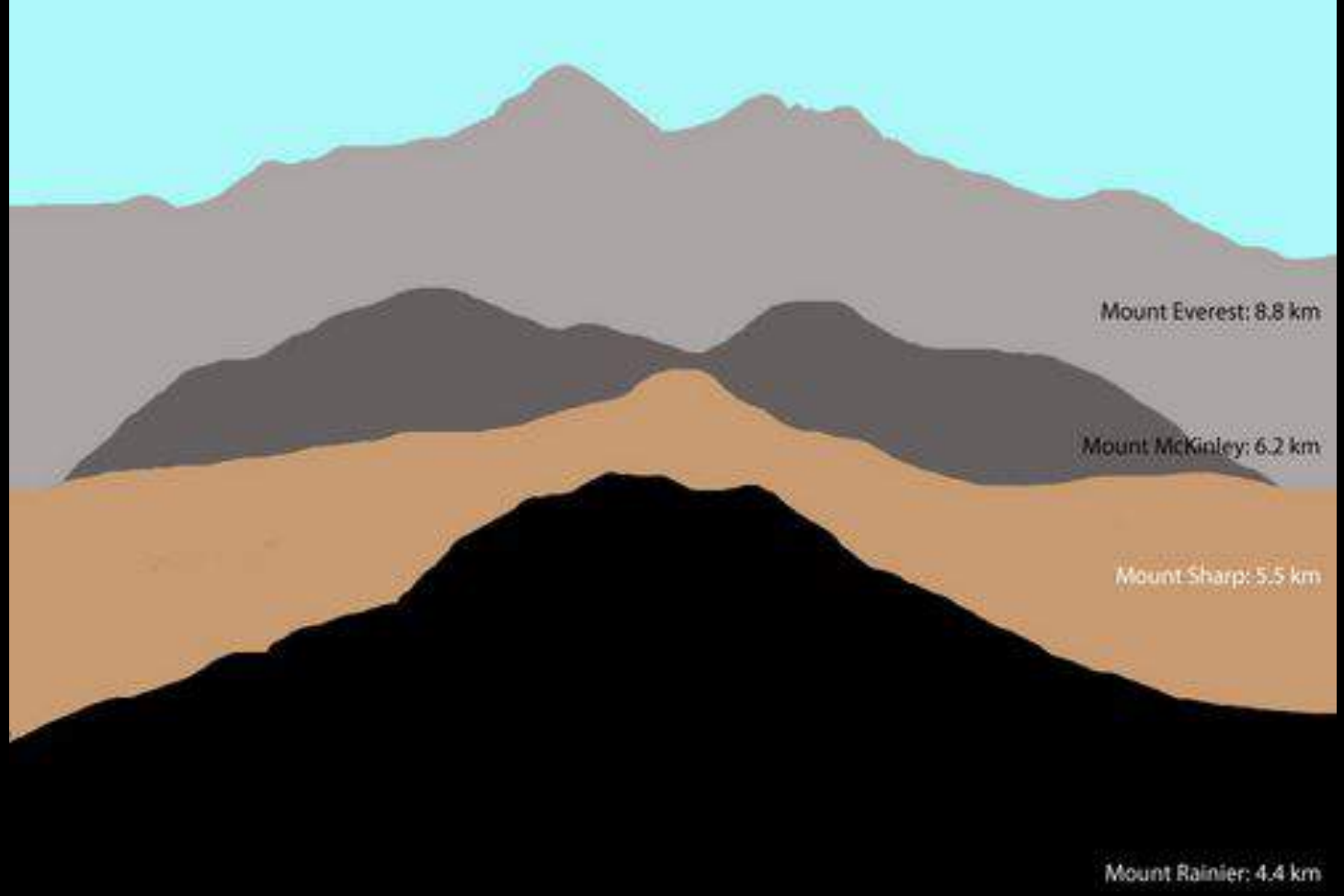
Science Analysis at Mars





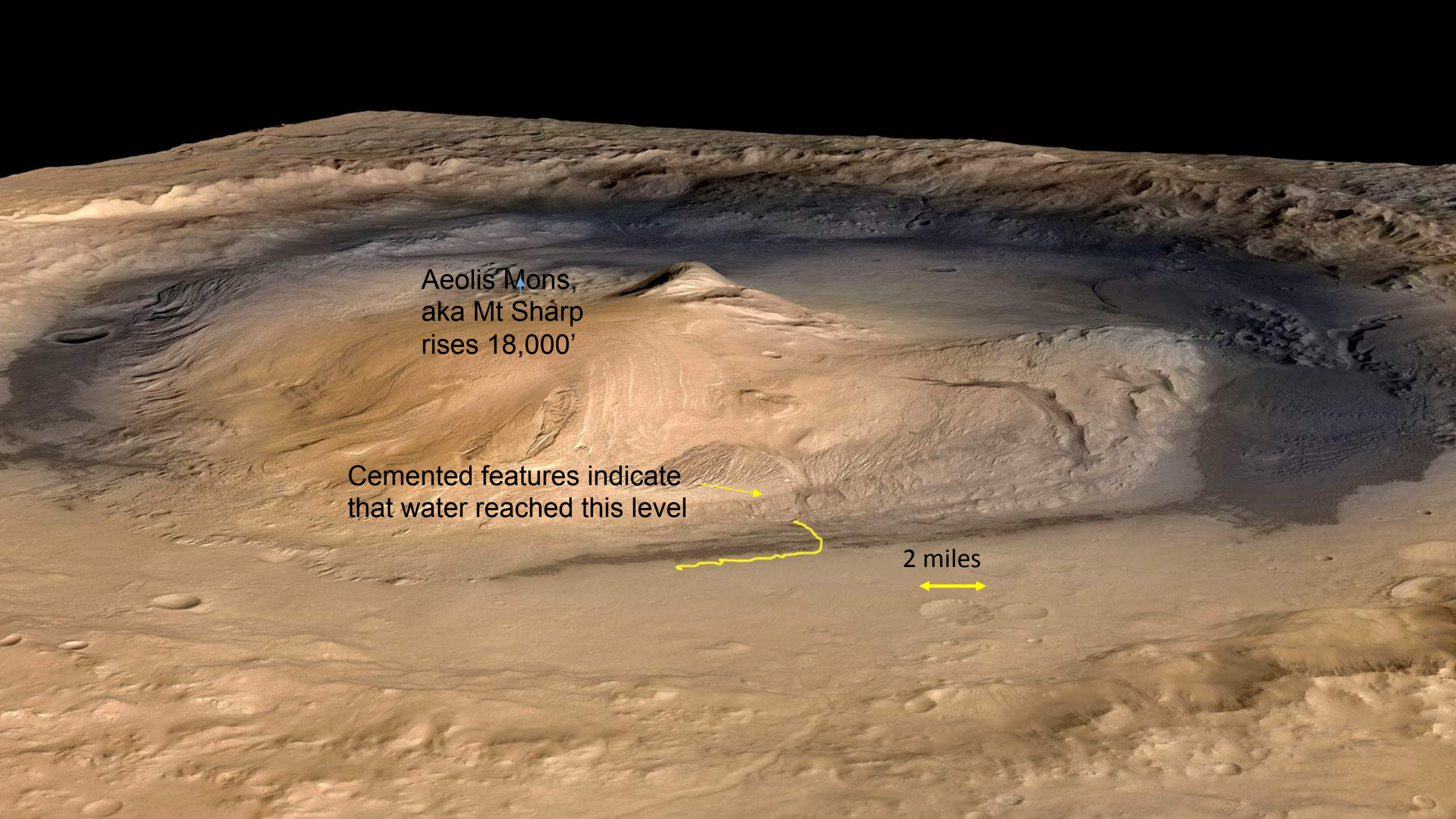
- SAM heats cups of sample in a high-temperature oven, measuring composition and isotopes to search for organics.
- It consists of a suite of three instruments, including a quadrupole mass spectrometer, gas chromatograph, and tunable laser spectrometer,
- It searches for compounds of the element carbon, including methane, as well as other light elements, such as hydrogen, oxygen, and nitrogen, associated with life.

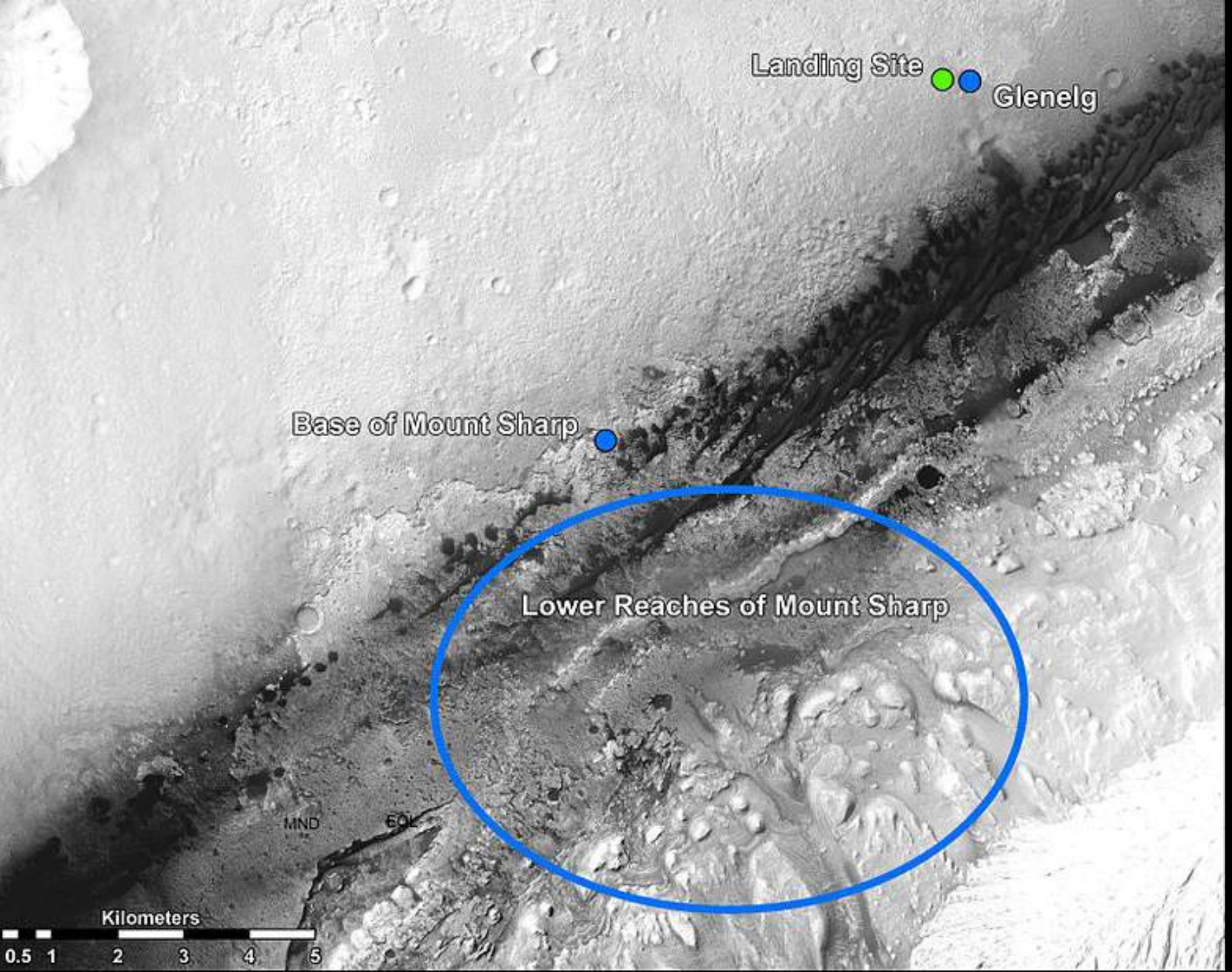
The are two parts to ChemCam. The laser instrument can target a rock or soil sample from up to 7 m (23 ft) away, vaporizing a small amount of it with about 50 to 75 5-nanosecond pulses from a 1067 nm infrared laser and then a camera observes the spectrum of the light emitted by the vaporized rock.



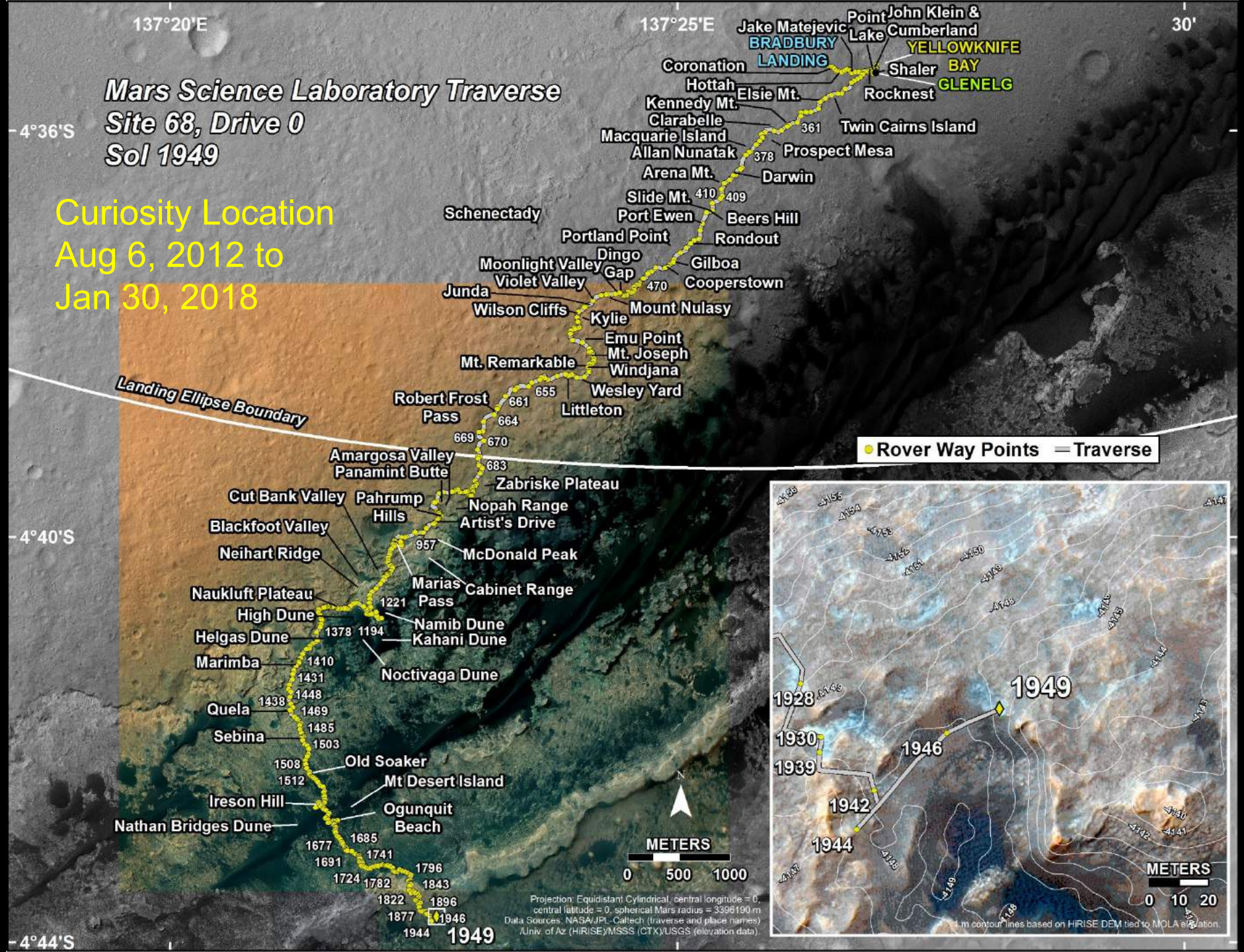
- Gale Crater formed when a meteor hit Mars in its early history, about 3.5 to 3.8 billion years ago.
- The explosion ejected rocks and soil that landed around the crater.
- Scientists chose Gale Crater as the landing site for Curiosity because it has many indications that water was present over its history.
- In addition its has many layers that should provide information about the geological history of Mars

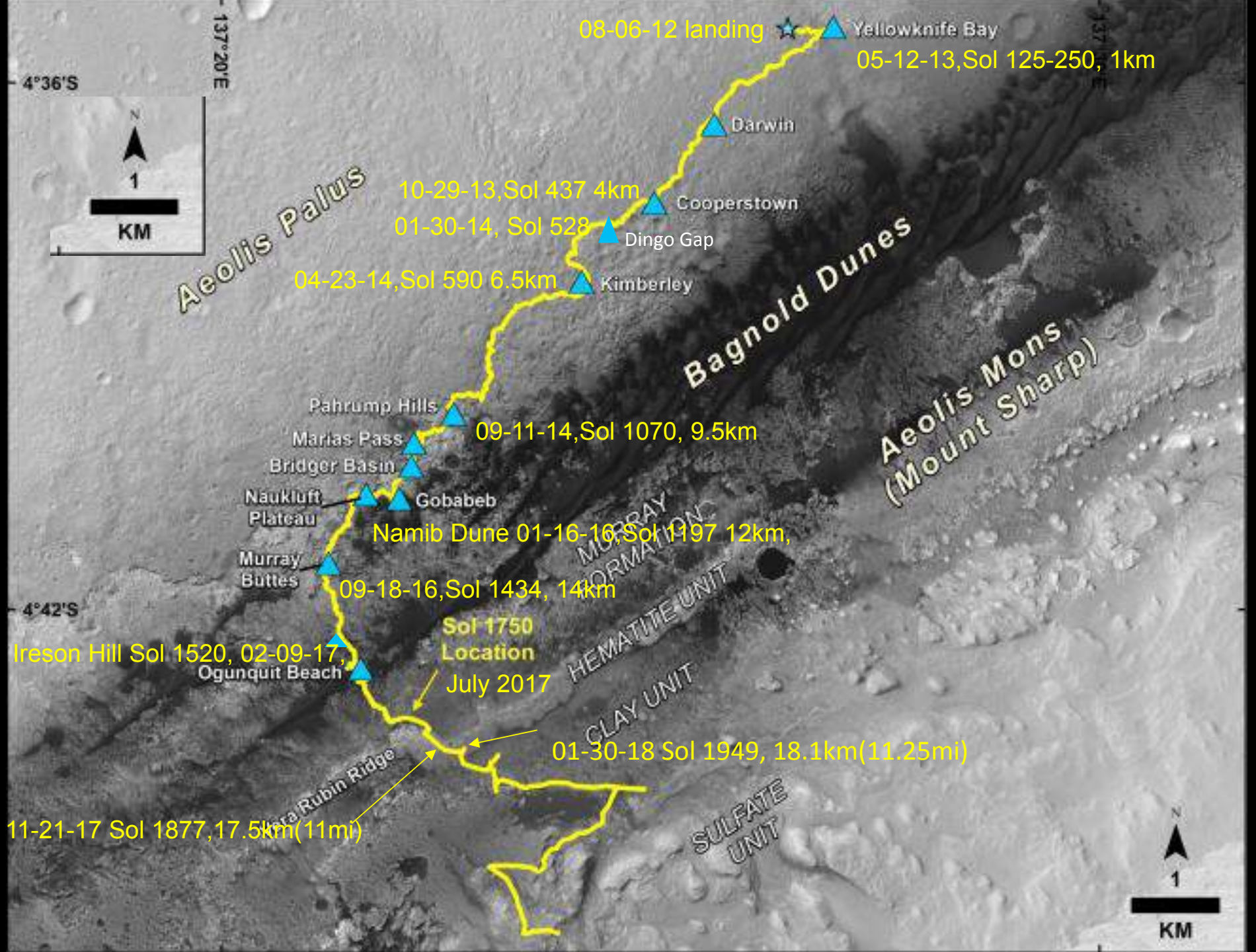
- Gale Crater spans 96 miles (154 kilometers) in diameter and holds a mountain (which is informally named "Mount Sharp" (to pay tribute to geologist Robert P. Sharp)
- Gale is about the combined area of Connecticut and Rhode Island.


Aeolis Mons,
aka Mt Sharp
rises 18,000’
Cemented features indicate
that water reached this level
2 miles

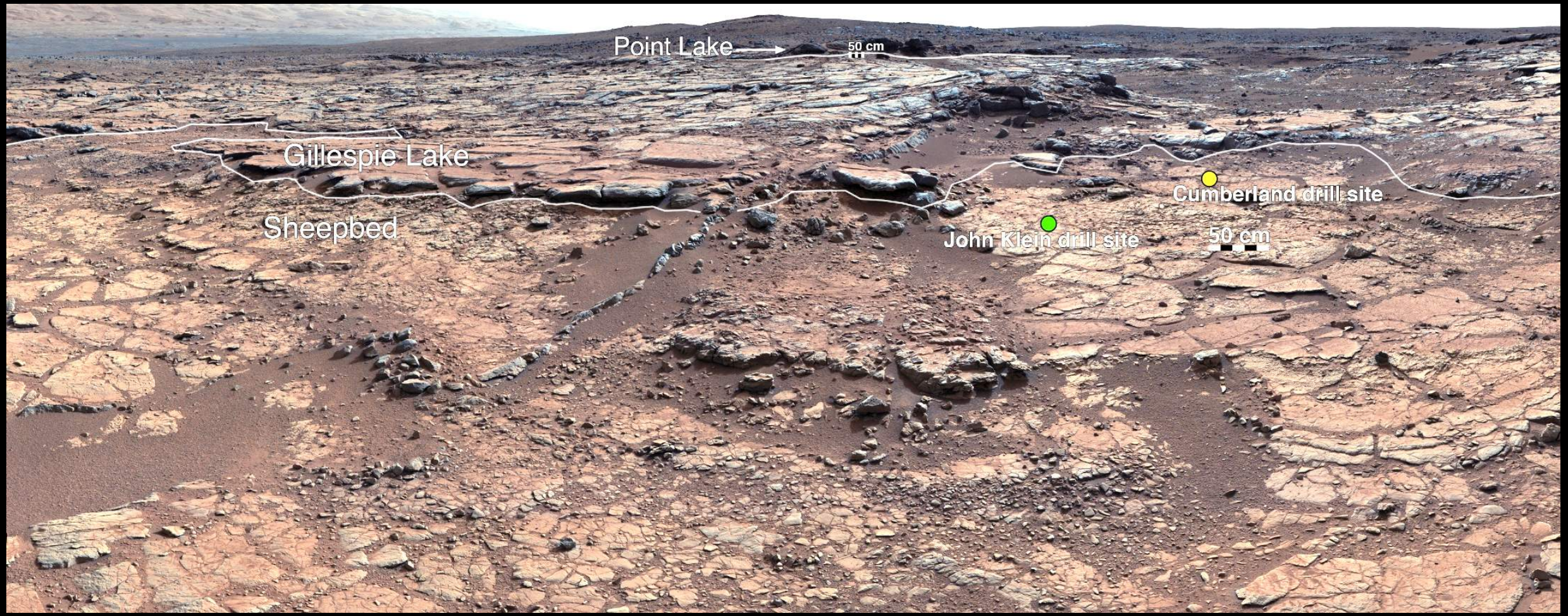


- This image shows the landing site of NASA's Curiosity rover and destinations scientists want to investigate.
- The first is Glenelg that area marks the intersection of three kinds of terrain
- The rover drove to the blue spot marked "Base of Mt. Sharp", which is a natural break in the dunes that will allow Curiosity to begin scaling Mount Sharp.
- At the base of Mt. Sharp are layered buttes and mesas that scientists hope will reveal the area's geological history.

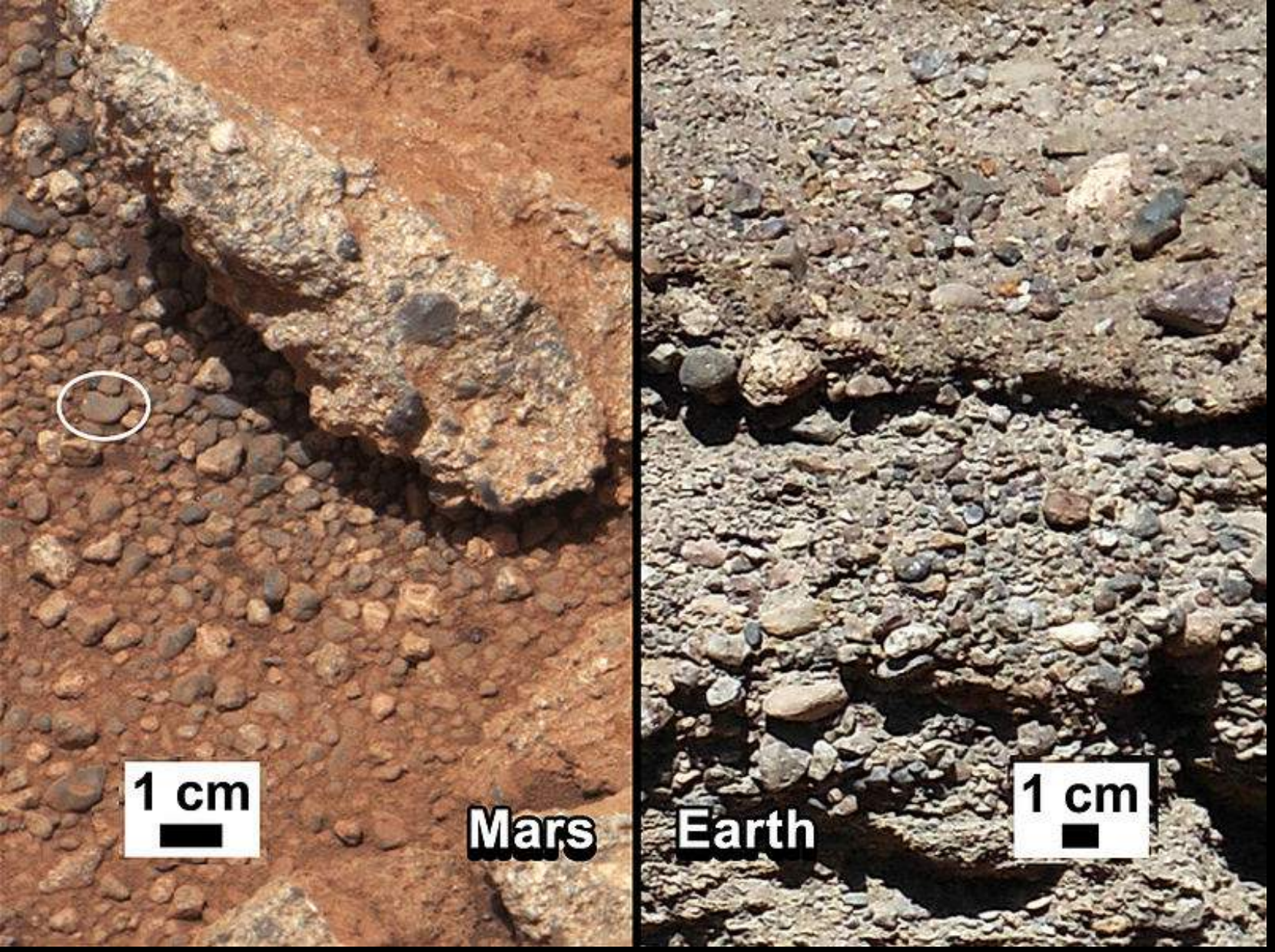

Mars Science Laboratory Traverse
Site 68, Drive 0
Sol 1949
Curiosity Location
Aug 6, 2012 to
Jan 30, 2018
137°20'E
137°25'E
30'
4°36'S
4°40'S
4°44'S
Landing Ellipse Boundary
Rover Way Points
Traverse
Jake Matejevic
Point Lake
John Klein & Cumberland
BRADBURY LANDING
YELLOWKNIFE BAY
GLENELG
Coronation
Shaler
Hottah
Elsie Mt.
Rocknest
Kennedy Mt.
Clarabelle
361
Twin Cairns Island
Macquarie Island
Allan Nunatak
378
Prospect Mesa
Arena Mt.
Darwin
Slide Mt.
410
409
Schenectady
Port Ewen
Beers Hill
Portland Point
Rondout
Dingo Gap
Moonlight Valley
Violet Valley
Gilboa
470
Cooperstown
Junda
Wilson Cliffs
Mount Nulasy
Kylie
Emu Point
Mt. Joseph
Mt. Remarkable
Windjana
Wesley Yard
655
Robert Frost Pass
661
664
Littleton
669
670
Amargosa Valley
Panamint Butte
683
Zabriske Plateau
Cut Bank Valley
Pahrump Hills
Nopah Range
Artist's Drive
Blackfoot Valley
957
Neihart Ridge
McDonald Peak
Marias Pass
Cabinet Range
Naukluft Plateau
1221
High Dune
Namib Dune
Helgas Dune
1378
1194
Kahani Dune
Marimba
1410
1431
Noctivaga Dune
1448
1438
Quela
1469
1485
Sebina
1503
1508
Old Soaker
1512
Mt Desert Island
Ireson Hill
Ogunquit Beach
Nathan Bridges Dune
1685
1677
1741
1691
1796
1724
1782
1843
1822
1896
1877
1946
1944
1949
METERS
0
500
1000
1928
1930
1939
1942
1944
1946
1949
METERS
0
10
20
Projection: Equidistant Cylindrical, central longitude = 0, central latitude = 0, spherical Mars radius = 3396190 m
Data Sources: NASA/JPL-Caltech (traverse and place names) /Univ. of Az (HiRISE)/MSSS (CTX)/USGS (elevation data)
1 m contour lines based on HiRISE DEM tied to MOLA elevation.


08-06-12 landing
Yellowknife Bay
05-12-13,Sol 125-250, 1km
Darwin
10-29-13,Sol 437 4km
Cooperstown
01-30-14, Sol 528
Dingo Gap
04-23-14,Sol 590 6.5km
Kimberley
Aeolis Palus
Bagnold Dunes
Aeolis Mons
(Mount Sharp)
Pahrump Hills
09-11-14,Sol 1070, 9.5km
Marias Pass
Bridger Basin
Naukluft
Plateau
Gobabeb
Namib Dune 01-16-16,Sol 1197 12km,
MURRAY
FORMATION
Murray
Buttes
09-18-16,Sol 1434, 14km
HEMATITE UNIT
Sol 1750
Location
July 2017
Ireson Hill Sol 1520, 02-09-17,
Ogunquit Beach
CLAY UNIT
01-30-18 Sol 1949, 18.1km(11.25mi)
Kimberley Rubin Ridge
11-21-17 Sol 1877,17.5km(11mi)
SULFATE
UNIT
137°20'E
4°36'S
4°42'S
N
1
KM

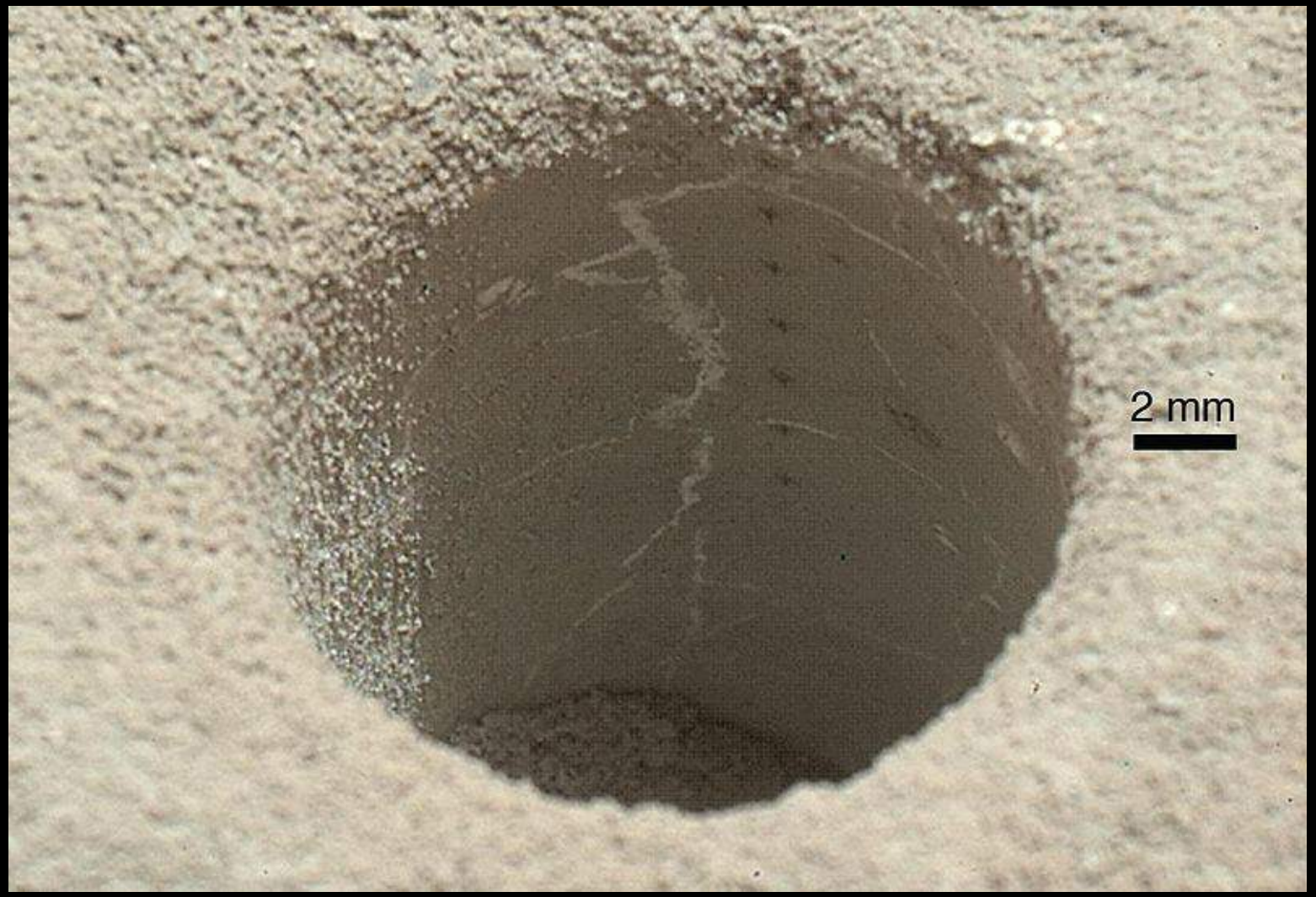
- The image shows the layered geology history at the base of Mount Sharp, the rover's science destination taken from Yellowknife Bay. The picture was taken from the MastCam on Aug 23, 2012
- For scale, The pointy mound in the center of the image, looming above the rover-sized rock, is about 1,000 feet (300 meters) across and 300 feet (100 meters) high.



- Initially Curiosity was sent east to Yellowknife Bay hoping to find evidence of water
- Two holes were drilled and analysis by SAM showed that the rock was a mudstone containing 20% clay minerals that formed in contact with water
- This was not the acidic, sulfate rich water that had been seen by the Opportunity rover but the still, neutral water of a crater lake, an ancient habitable environment
- A key finding was that the water may have been drinkable

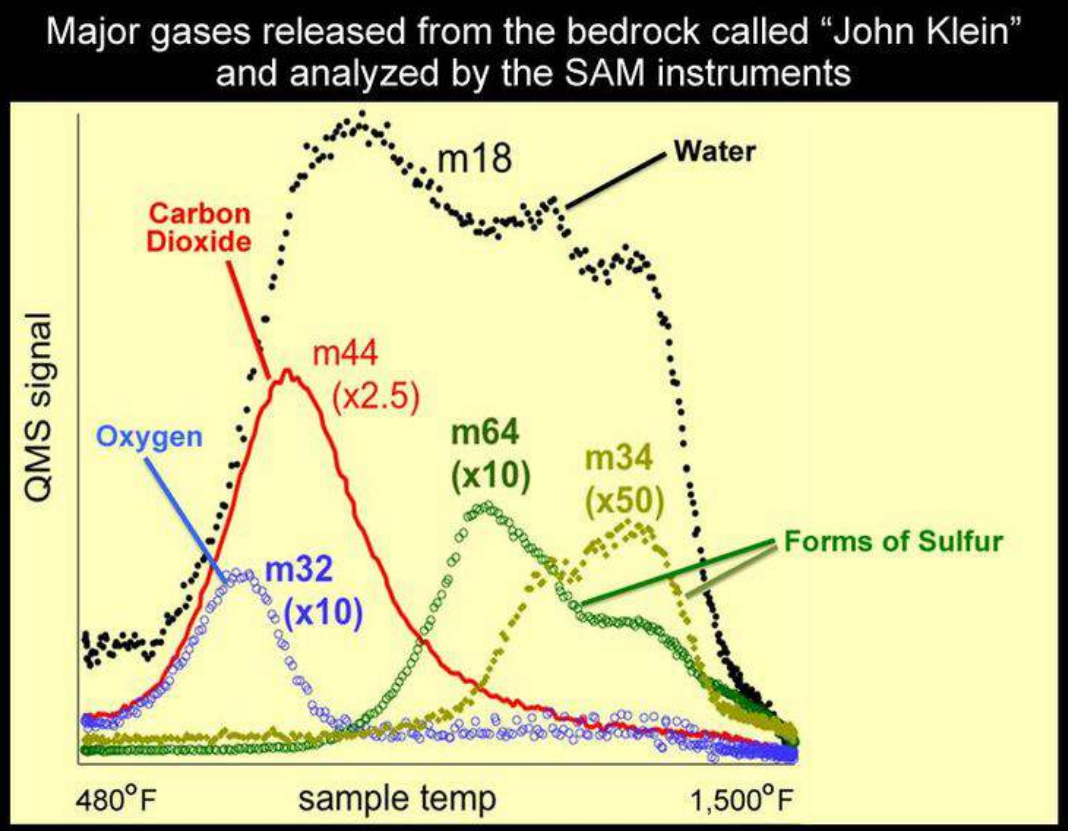


Sedimentary conglomerates were found with clear evidence that they had been tumbled in fast moving water 10-100cm deep in ancient Martian hillside streams



Existance of an Ancient Lake

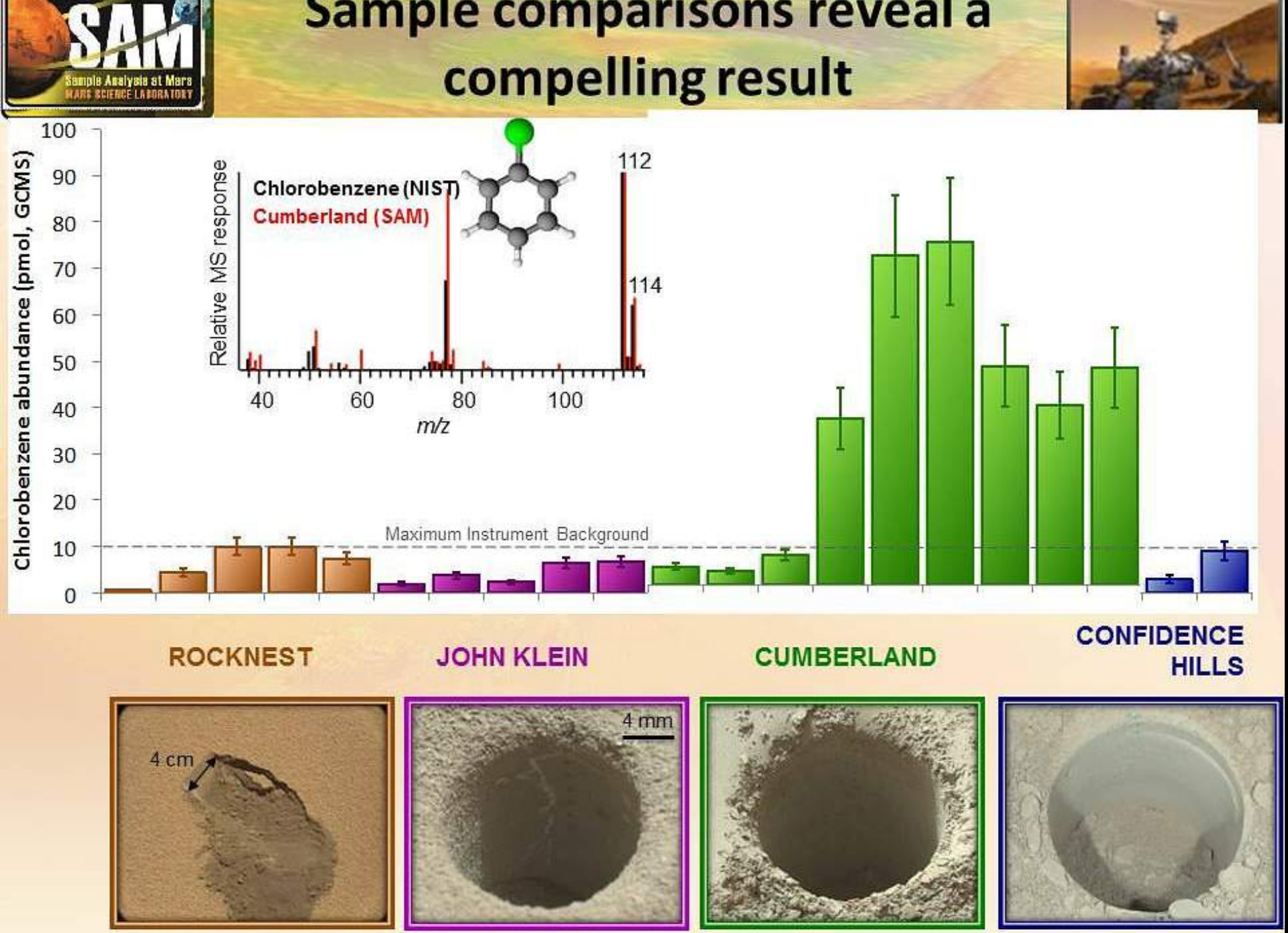
- The rock is part of the Sheepbed mudstone deposit in the Yellowknife Bay area of Gale Crater.
- This shows a homogeneous, fine grain mudstone, and the irregular network of sulfate-filled hairline fractures.
- The fine grained nature of the rock is of the type where sediments had been carried into a lake and slowly settled to the lake bed.
- It was precisely the kind of environment that Curiosity had been sent to find



- Using SAM's quadrupole mass spectrometer (QMS) the signatures of more than five hundred mass values were sampled
- Inaddition there are two forms of sulfur (sulfur dioxide, the oxidized form, and hydrogen sulfide, the reduced form
- This indicates a significant amount of available chemical energy because oxidized and less oxidized versions of molecules are present.
- Combined with the high likelihood of suitable aqueous conditions at this site in the distant past, made this a potentially habitable environment

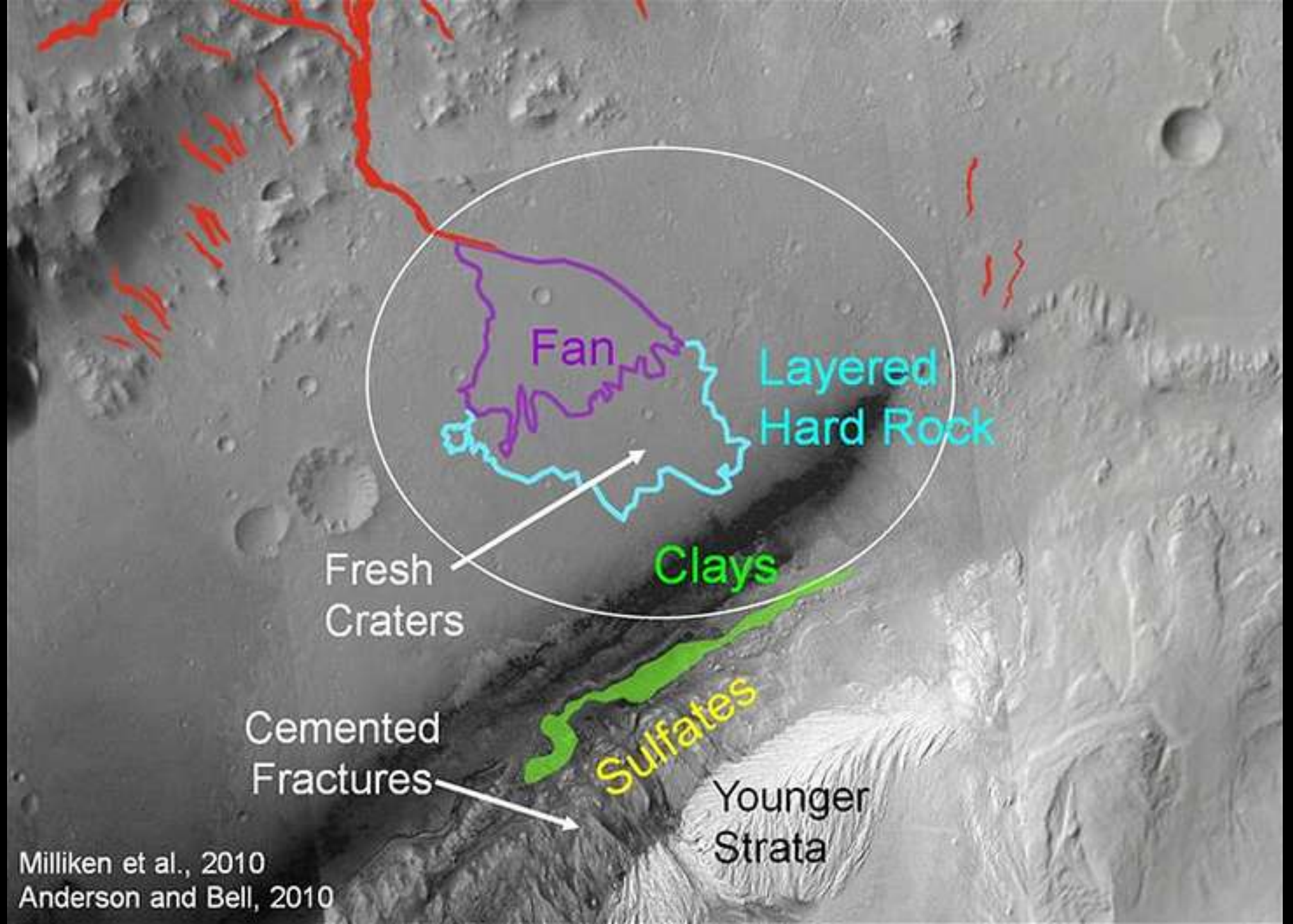
- Another interesting result was that the ratio of deuterium to hydrogen in water from the rocks was 3:1 where the present ratio in the atmosphere is 6:1
- This indicates that the ancient rocks formed at a time when the air was much denser since it is likely that the ratio was 1:1 initially as it is on Earth(more later)

The range of chemical ingredients...is impressive and suggests pairings such as sulfates and sulfides (that) indicate a possible energy source for micro-organisms" said Paul Mahaffy, principal investigator of the SAM suite, Nasa Goddard



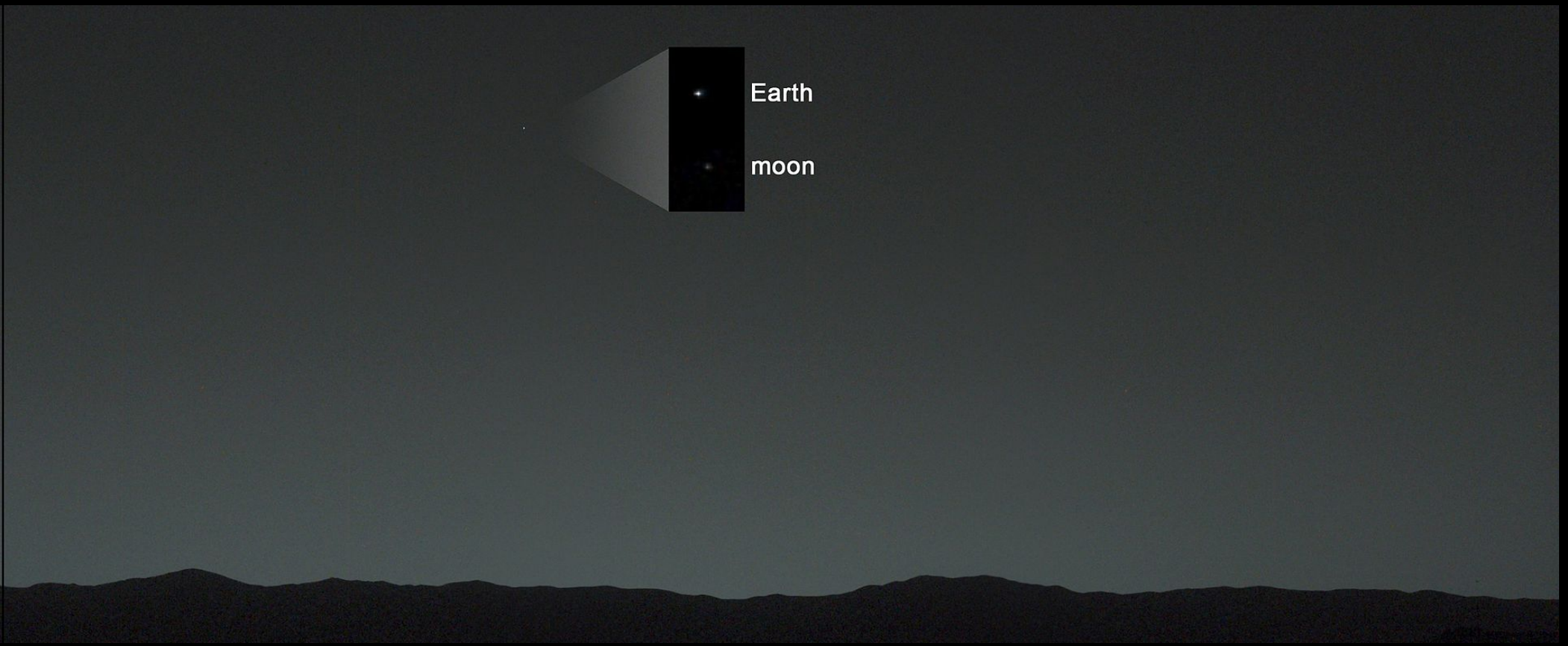
First Detection of Organic Molecules

- Curiosity also detected Martian organic chemicals in powder drilled from the Cumberland rock drill site in Yellowknife Bay
- This was the first definitive detection of organics in surface materials of Mars.
- The measurement was done by SAM's gas chromatograph



The net result of the analysis is that the Yellowknife Bay area was likely the end of an ancient river or an intermittently wet lake

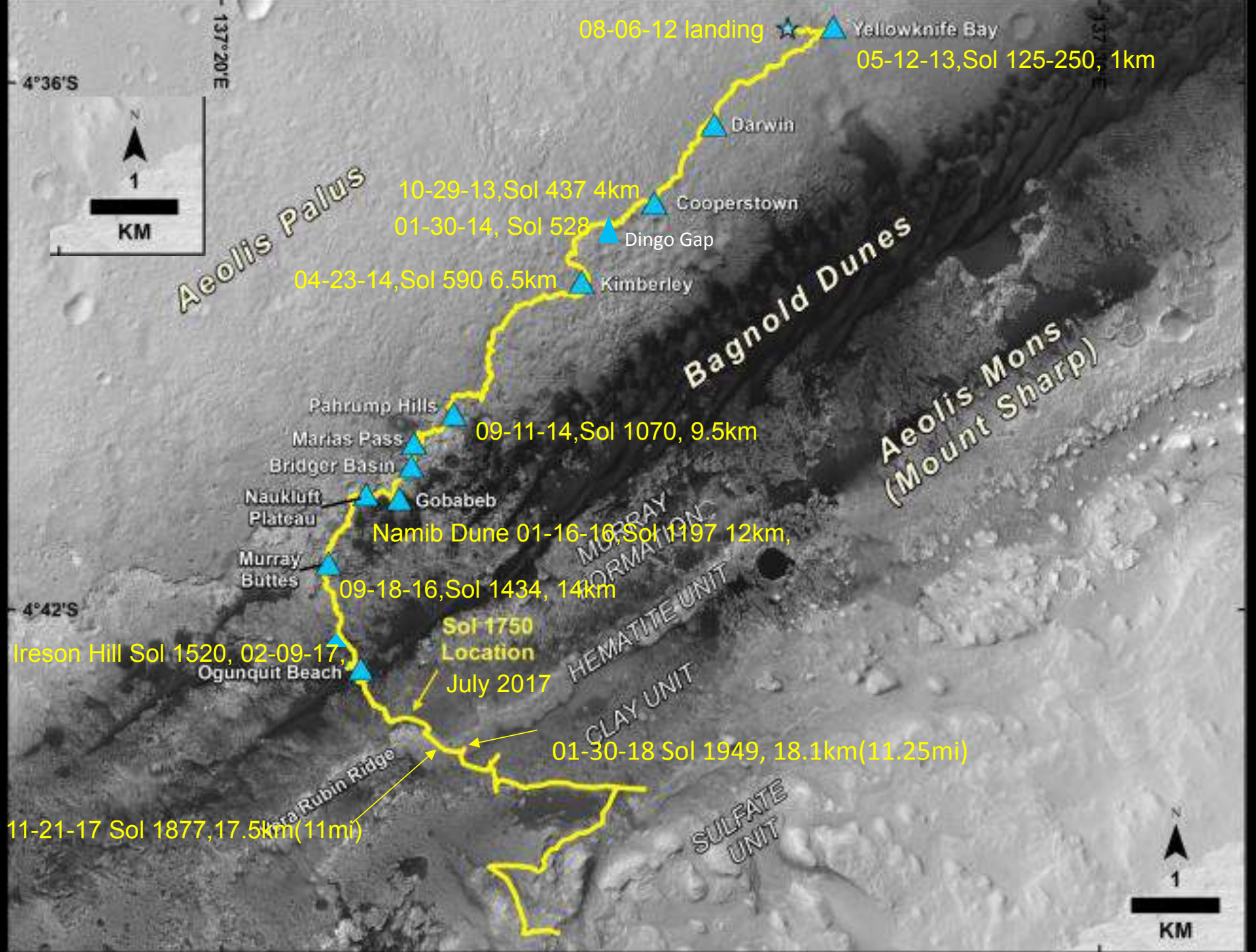
Martian moon, Phobos, recorded by Curiosity. This set of three images taken on Aug 20, 2013 shows views three seconds apart



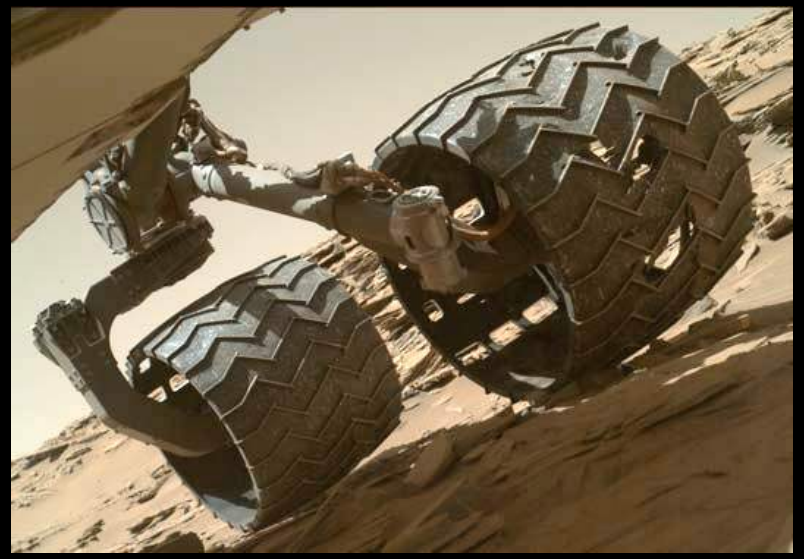
- Curiosity's first view of the Earth and the Moon on January 31, 2014
- Earth is the brightest point of light in the twilight sky. Earth is a little left of center in the image, and our moon is just below Earth.

HIRISE captures Curiosity on Dec 11, 2013 several km from Yellowknife Bay
Its track, the two parallel lines of the wheel tracks are about 3 meters apart

- The Yellowknife investigation was very successful but it had taken 7 months and so Curiosity then covered 6 km of the 10 km to the base of Mt Sharp in the following year
- This view at a location called Dingo Gap combines several frames taken by the Mast Camera (MastCam), looking into a valley to the west early afternoon, local solar time, of the 528th Martian day, or sol on Jan. 30, 2014
- The foreground dune is about 3 feet high in the center and the dark rocks are about 2 feet high

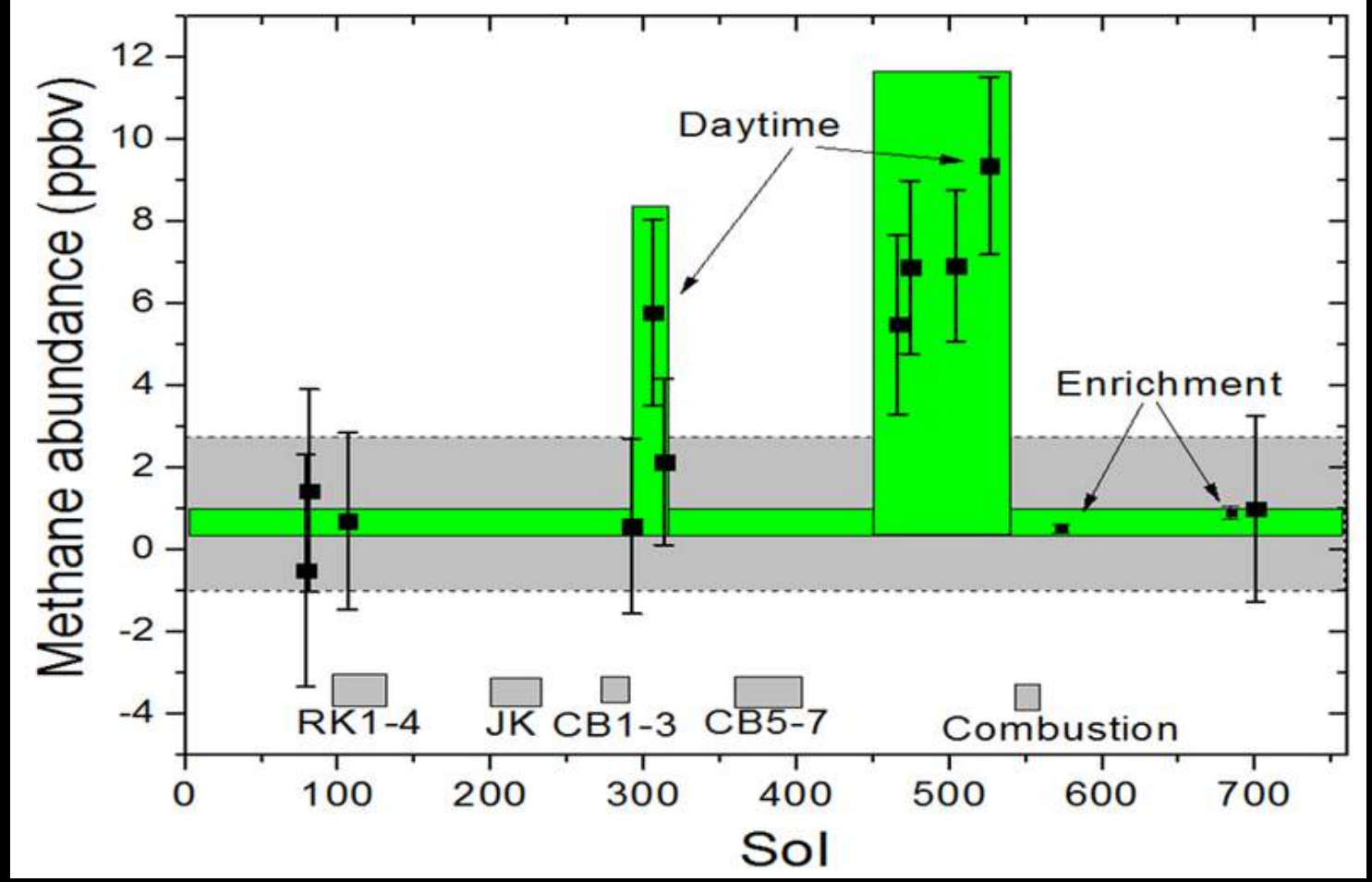

08-06-12 landing
Yellowknife Bay
05-12-13,Sol 125-250, 1km
Darwin
10-29-13,Sol 437 4km
Cooperstown
01-30-14, Sol 528
Dingo Gap
04-23-14,Sol 590 6.5km
Kimberley
Aeolis Palus
Bagnold Dunes
Aeolis Mons
(Mount Sharp)
Pahrump Hills
09-11-14,Sol 1070, 9.5km
Marias Pass
Bridger Basin
Naukluft
Plateau
Gobabeb
Namib Dune 01-16-16,Sol 1197 12km,
MURRAY
FORMATION
Murray
Buttes
09-18-16,Sol 1434, 14km
HEMATITE UNIT
Sol 1750
Location
July 2017
Ireson Hill Sol 1520, 02-09-17,
Ogunquit Beach
CLAY UNIT
01-30-18 Sol 1949, 18.1km(11.25mi)
Kimberley Rubin Ridge
11-21-17 Sol 1877,17.5km(11mi)
SULFATE
UNIT
137°20'E
4°36'S
4°42'S
N
1
KM

The rover had driven over the dune at Dingo Gap three days earlier. For scale, the distance between the parallel wheel tracks is about 9 feet (2.7 meters). The dune is about 3 feet (1 meter) tall in the middle of its span across an opening called "Dingo Gap." This view is looking eastward.



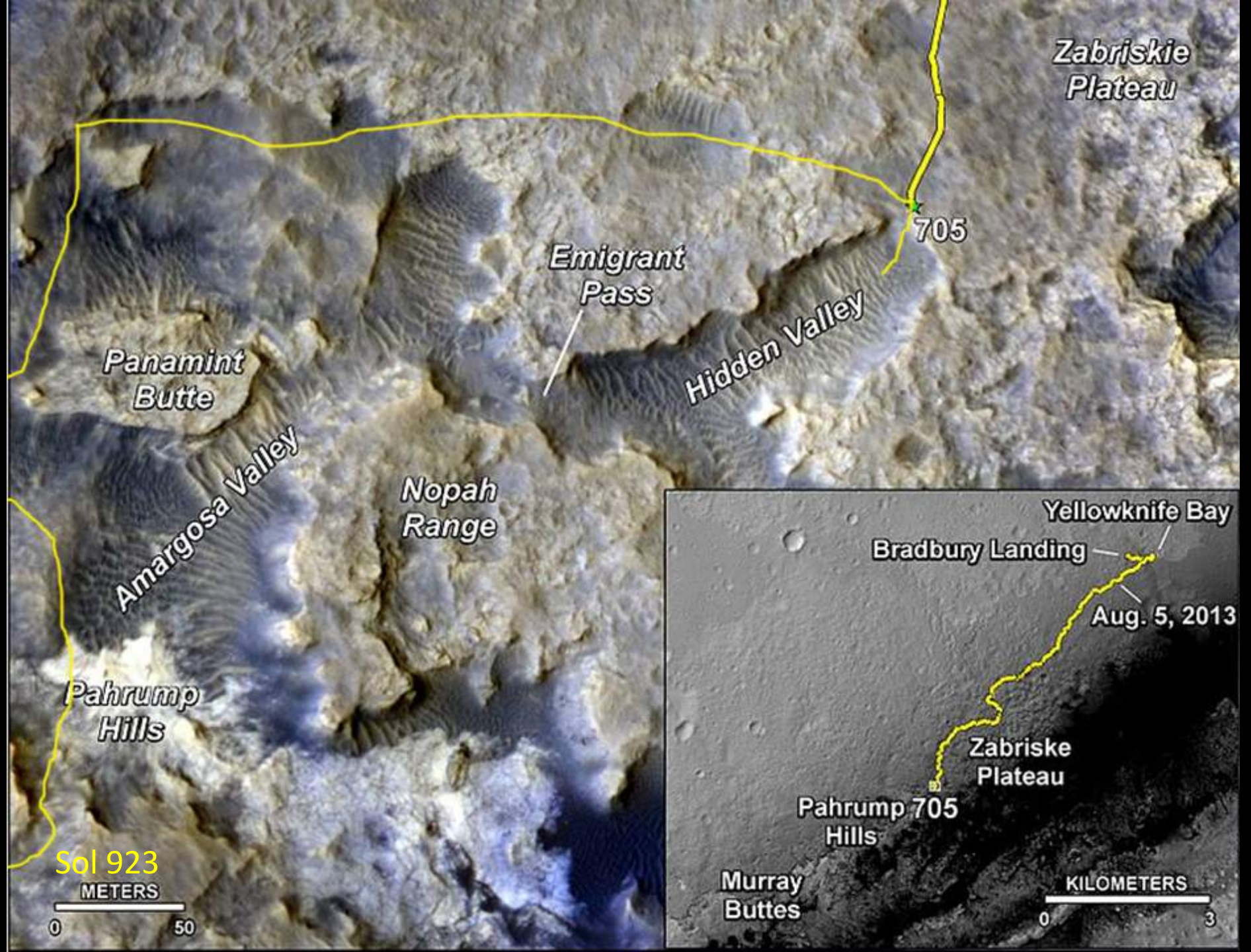
- Curiosity at one year showing tire wear
- As a result Curiosity had to be driven more carefully avoiding rocky areas where possible

- This image of the "Kimberley" formation on Mars was taken by the MastCam on sol 580.
- Observations from Curiosity strongly indicate that a series of long-lived streams and lakes existed on Mars from 3.8 and 3.3Bya
- This analysis has led to the conclusion that the ancient climate on Mars was warmer and wetter than has been assumed.
- Previously it was believed that the Gale crater was infilled by dust and wind.
- Based on the new analysis, however, it is now believed that 150-200m of in-filling occurred primarily due to ancient river and lake sediments over a period of less than 500 million years.



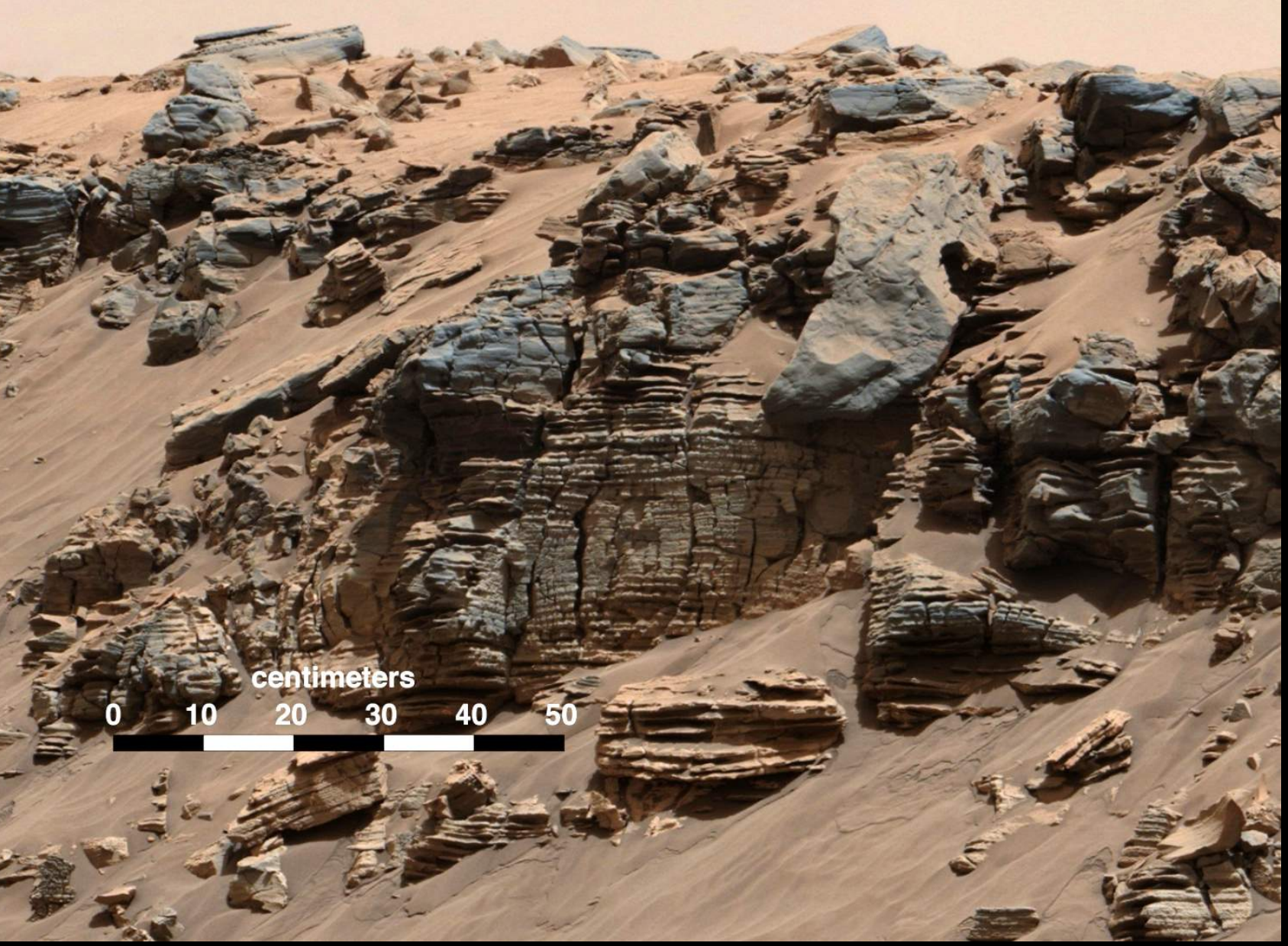
Methane Detected by the Tunable Laser Sp

- The graph covers a span of time from August 2012 to September 2014, labeled on the horizontal axis by the number of sols, or Martian days, since the rover's landing on Mars -- sols 1 through 750.
- The methane was detected starting on sol 466 with a sudden surge of 7 ppb
- After two years of noticing that the presence of methane varies by season, the SAM team felt it was due to the breakup of organic matter caused by uv radiation rather than from microbes



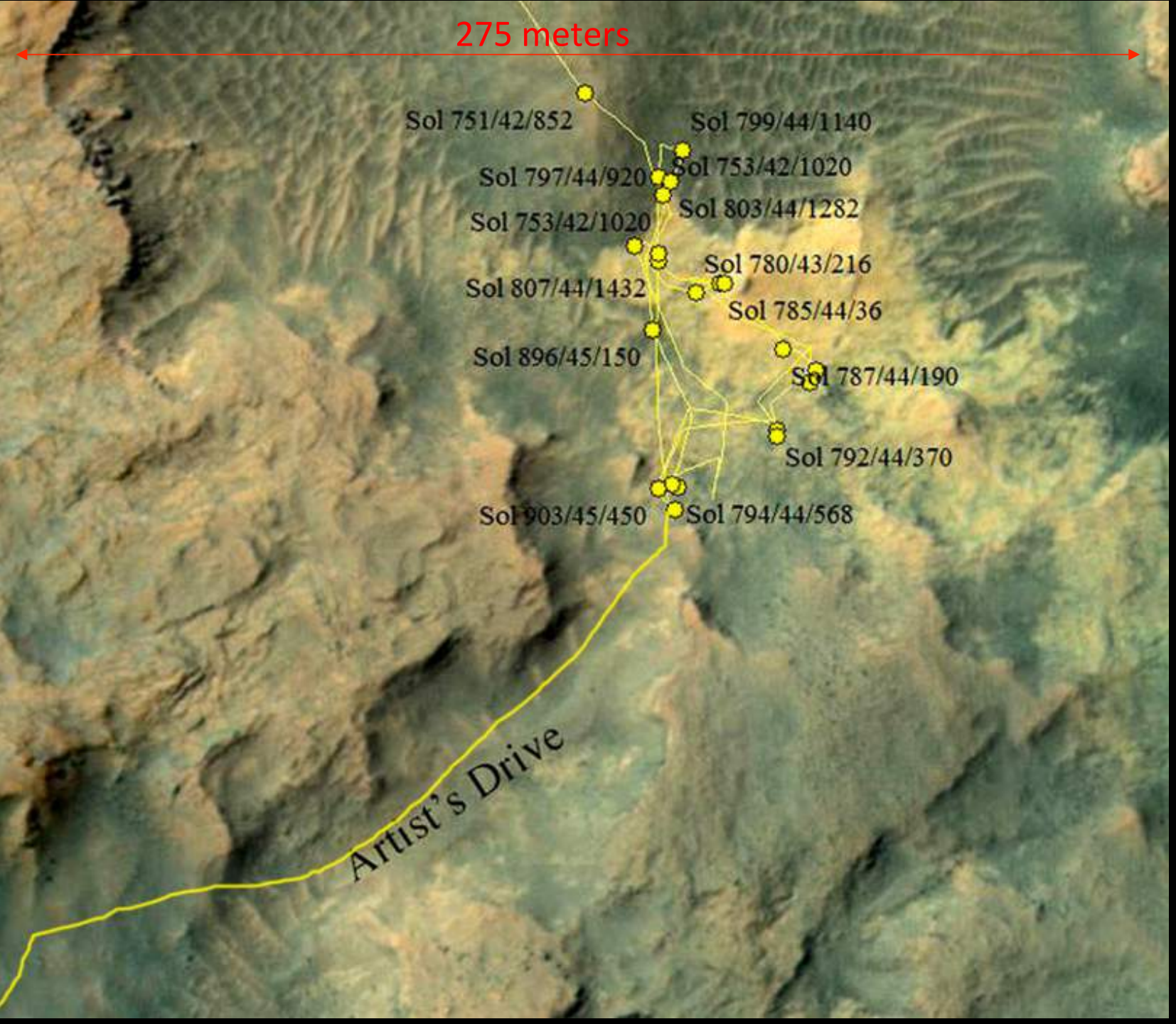
Pahrump Hills at the Base of Mt Sharp

- This is the base of Mt Sharp reached 09-11-14 sol 705 and Curiosity had driven 9.5km
- Curiosity traverses this complex area and only leaves on Sol 923



The scene combines multiple frames taken with Mastcam's right-eye camera on Aug. 7, 2014, during the 712th Martian day, or sol. It shows an outcrop at the edge of "Hidden Valley," seen from the valley floor.

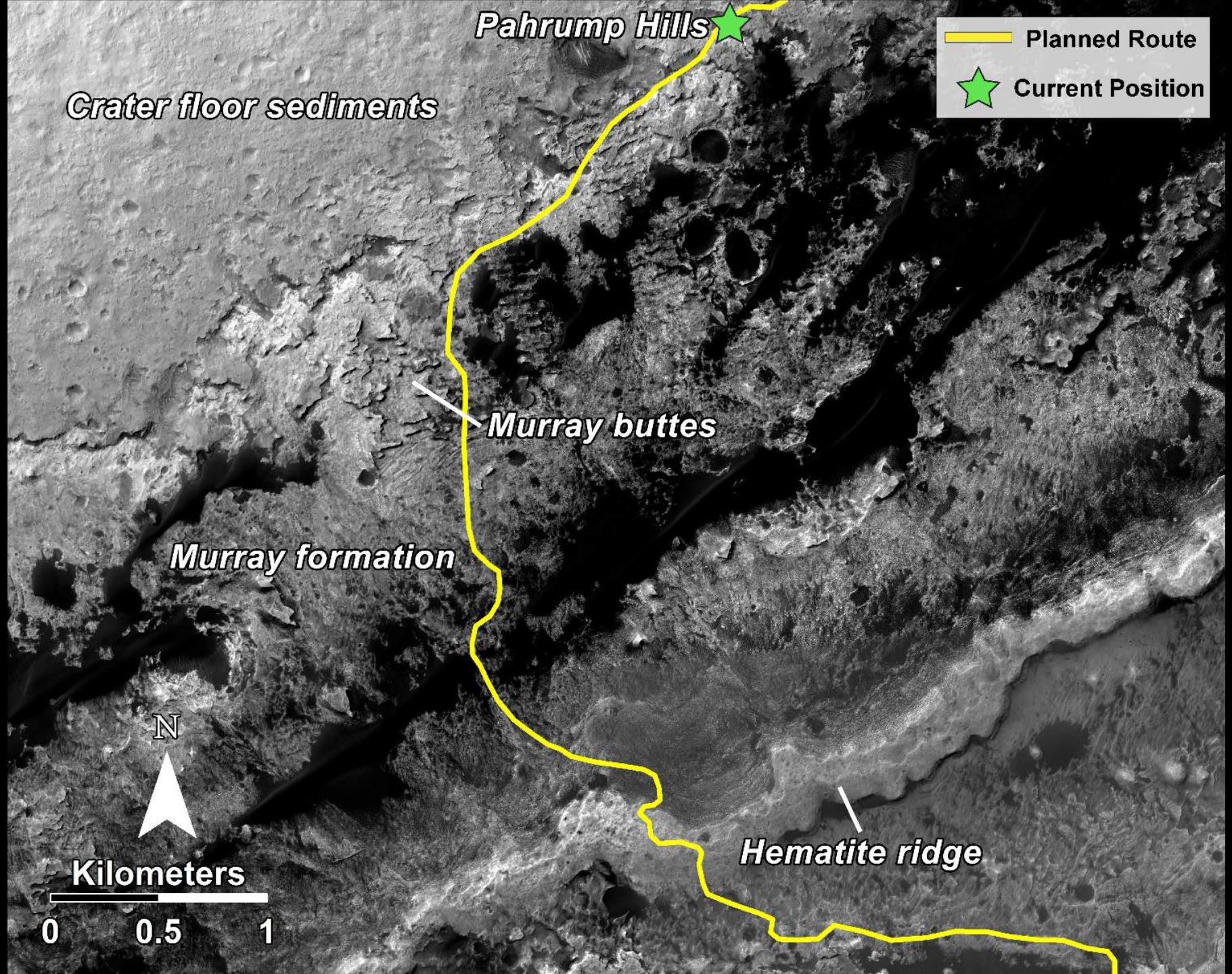
- This is an example of a thick-laminated, evenly-stratified rock type
- These rocks were formed from a river delta where sediment settled out of a water column onto the lake floor.



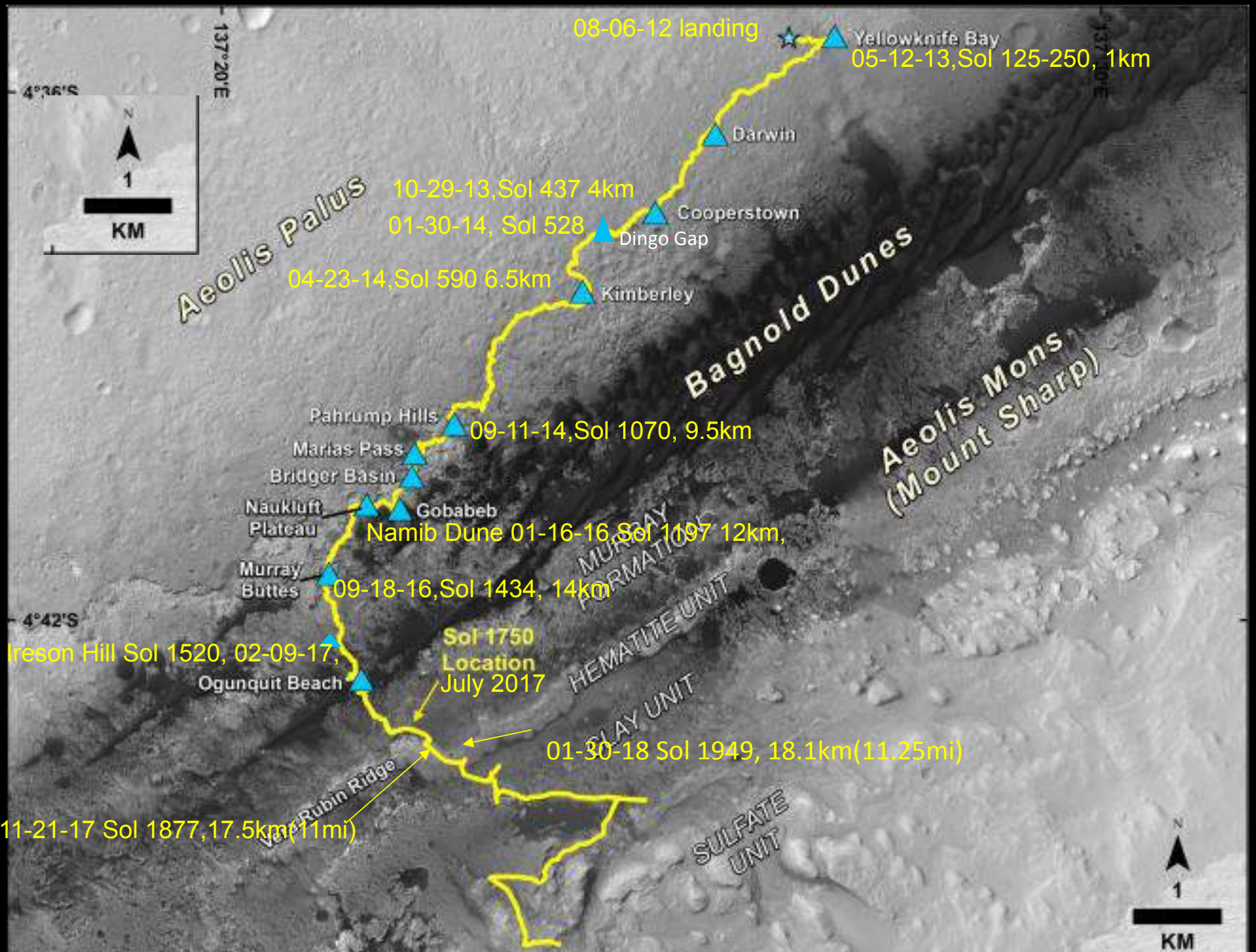
Six Month's Stay at Pahrump Hills

The yellow lines indicate the route driven by Curiosity between Sol 751 (the 751st Martian day of the mission, on Sept. 16, 2014) and Sol 903 (Feb. 19, 2015), about 5 months.

The rover stayed at the Sol 903 location for three weeks, during drilling of rock target "Telegraph Peak" and analysis of a short circuit that occurred during transfer of rock powder acquired during that drilling



This mosaic, taken with HiRISE camera on NASA's Mars Reconnaissance Orbiter, shows the planned route of Curiosity rover from "Pahrump Hills" at the base of Mount Sharp, through the "Murray Formation," and south to the hematite ridge further up the flank of Mount Sharp.


08-06-12 landing
Yellowknife Bay
05-12-13,Sol 125-250, 1km
Darwin
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Kimberley
Aeolis Palus
Bagnold Dunes
Aeolis Mons
(Mount Sharp)
Pahrump Hills
09-11-14,Sol 1070, 9.5km
Marias Pass
Bridger Basin
Naukluft
Plateau
Gobabeb
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MURRAY FORMATION
Murray
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09-18-16,Sol 1434, 14km
HEMATITE UNIT
4°42'S
Ireson Hill Sol 1520, 02-09-17,
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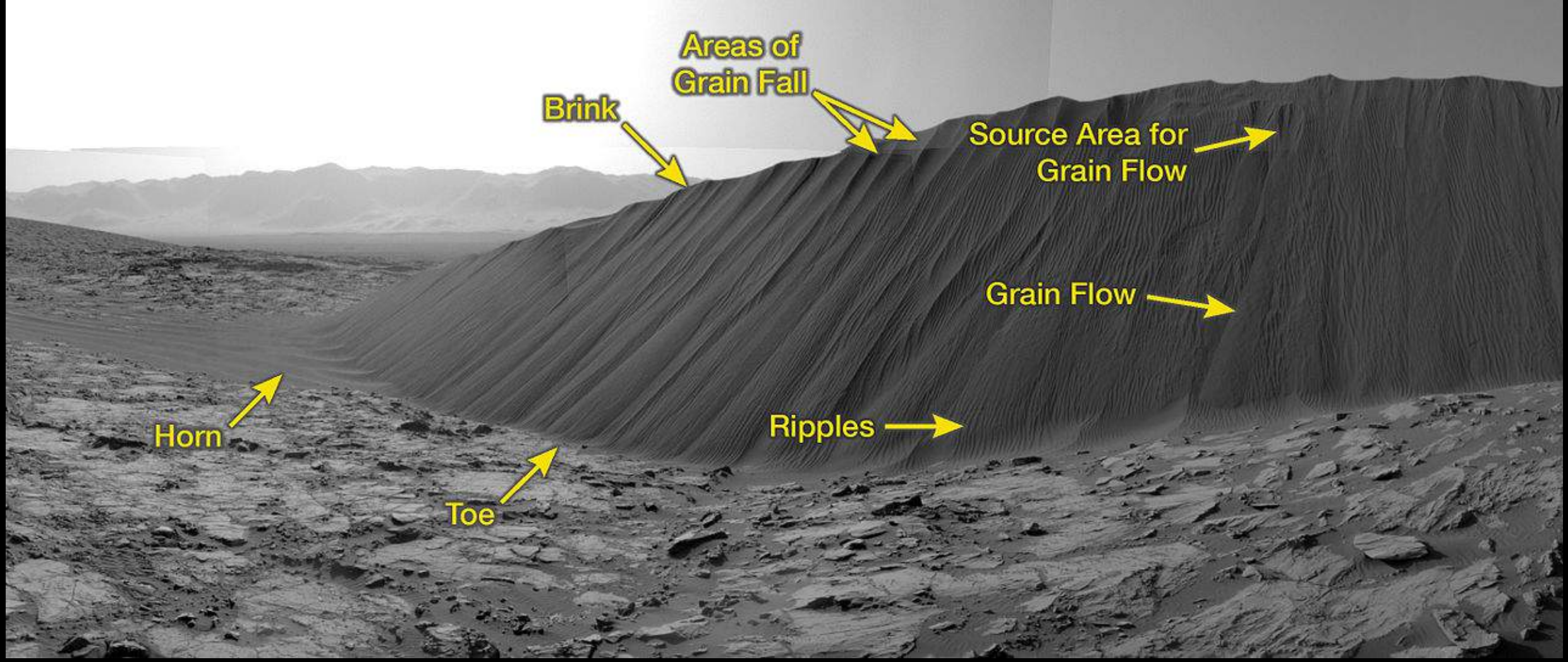
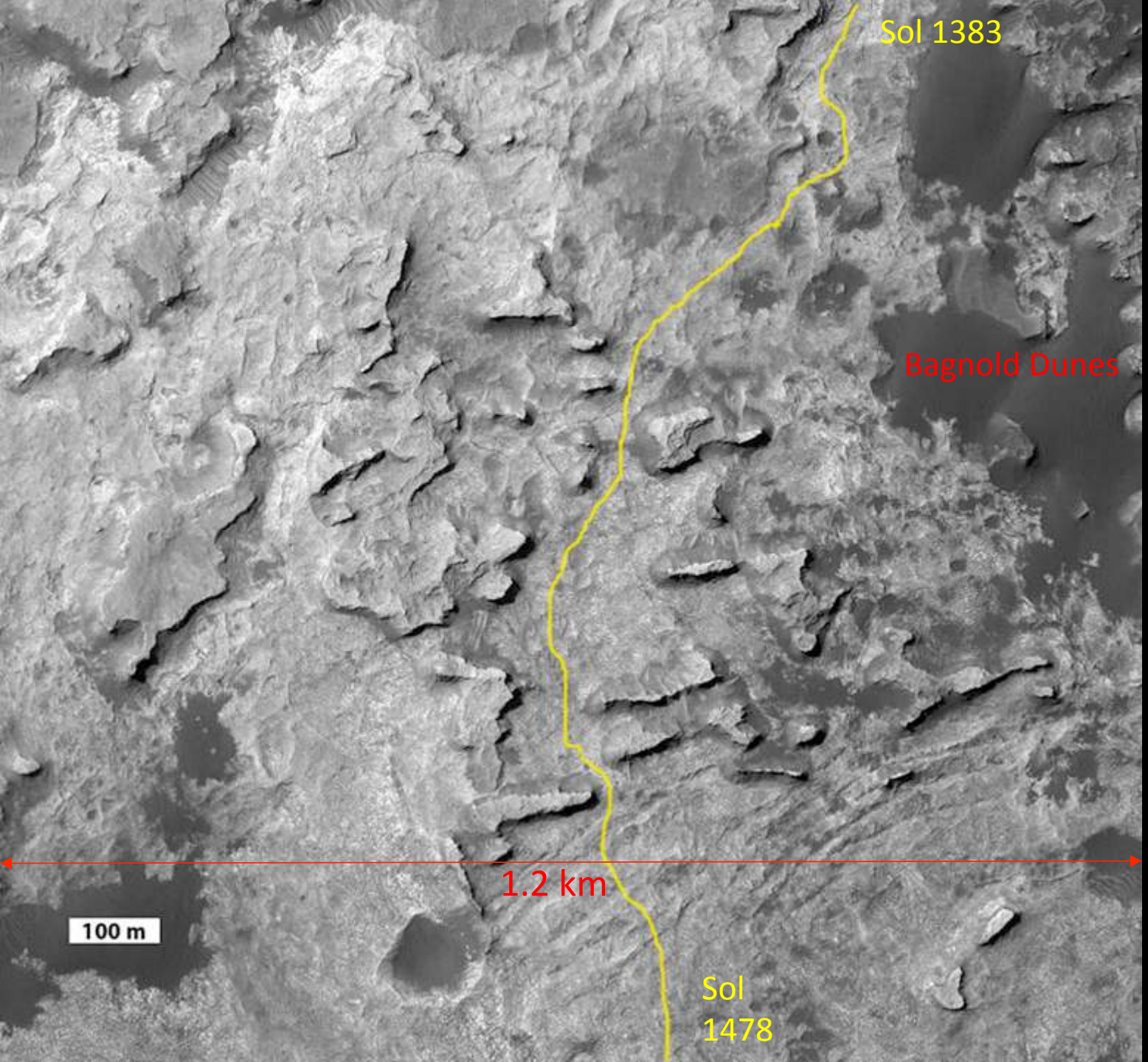
Location
July 2017
Ogunquit Beach
CLAY UNIT
01-30-18 Sol 1949, 18.1km(11.25mi)
Vera Rubin Ridge
11-21-17 Sol 1877,17.5km(11mi)
SULFATE
UNIT
137°20'E
1
KM
1
KM

This view from the Mast Camera (MastCam) in NASA's Curiosity Mars rover shows the "Marias Pass" area where a lower and older geological unit of mudstone -- the pale zone in the center of the image – lies unconformily in contact with a newer overlying geological unit of coarse sandstone, called Stimson.

- These investigations included many more readings from ChemCam, plus elemental composition measurements by the Alpha Particle X-ray Spectrometer (APXS) on the rover's arm and mineral identification of rock-powder samples by the Chemistry and Mineralogy (CheMin) instrument inside the rover.
- At a site called Buckskin, the rover discovered an unusual silica mineral called tridymite.
- On Earth, tridymite is only found in environments with low pressures but extremely high temperatures— typically, explosive, silica-rich volcanic eruptions, something not found on Mars previously



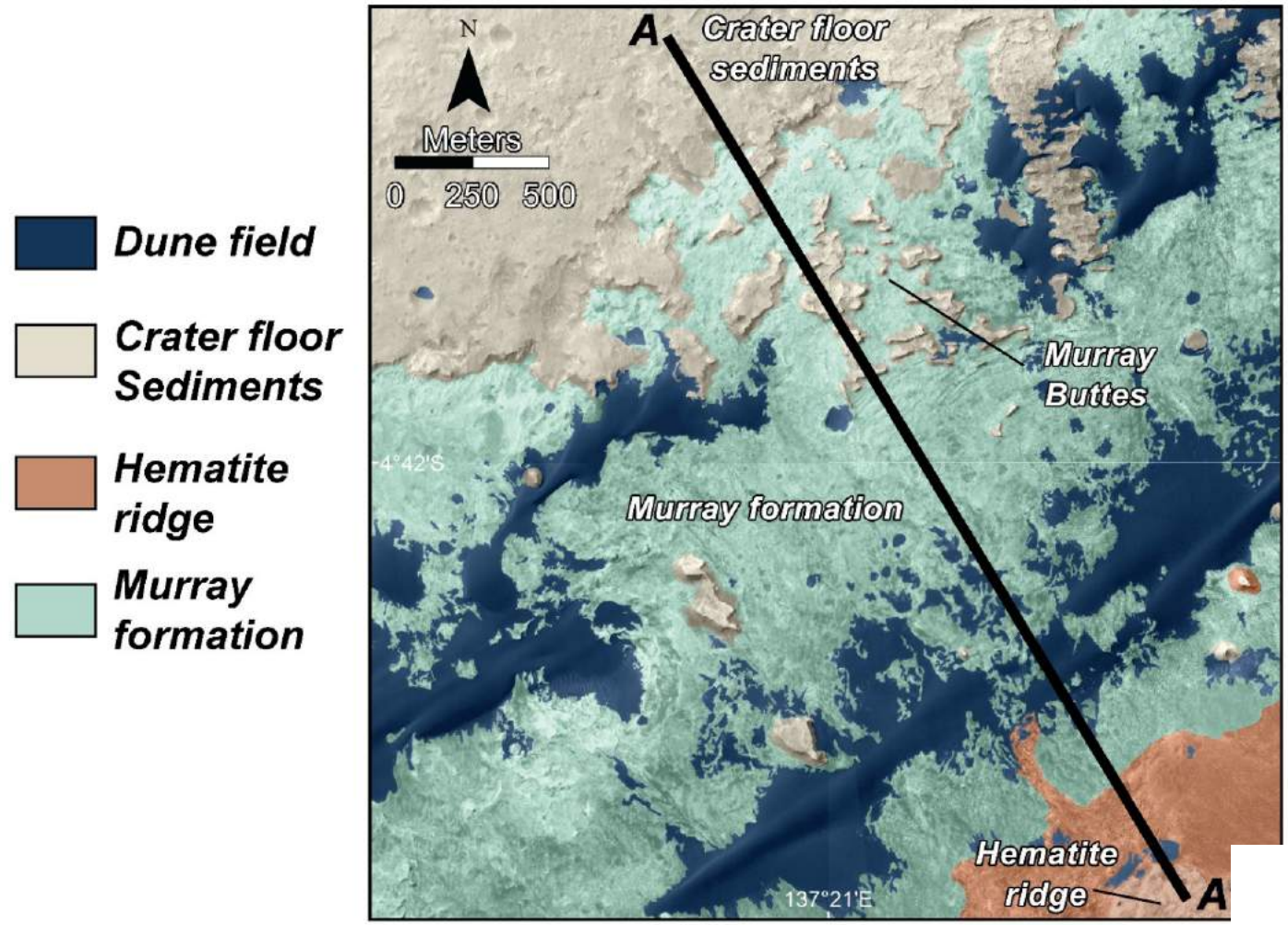
- This view from NASA's Curiosity Mars Rover on Dec 17,2015, sol 1196, shows the downwind side of "Namib Dune," which stands about 13 feet (4 meters) high.
- The site is part of Bagnold Dunes, a band of dark sand dunes along the northwestern flank of Mars' Mount Sharp.
- Curiosity is conducting the first up-close studies ever made of active sand dunes anywhere but on Earth.
- Under the influence of Martian wind, the Bagnold Dunes are migrating up to about one yard or meter per Earth year.
- The sand is blowing over the top of the dune and cascading down the leeward side



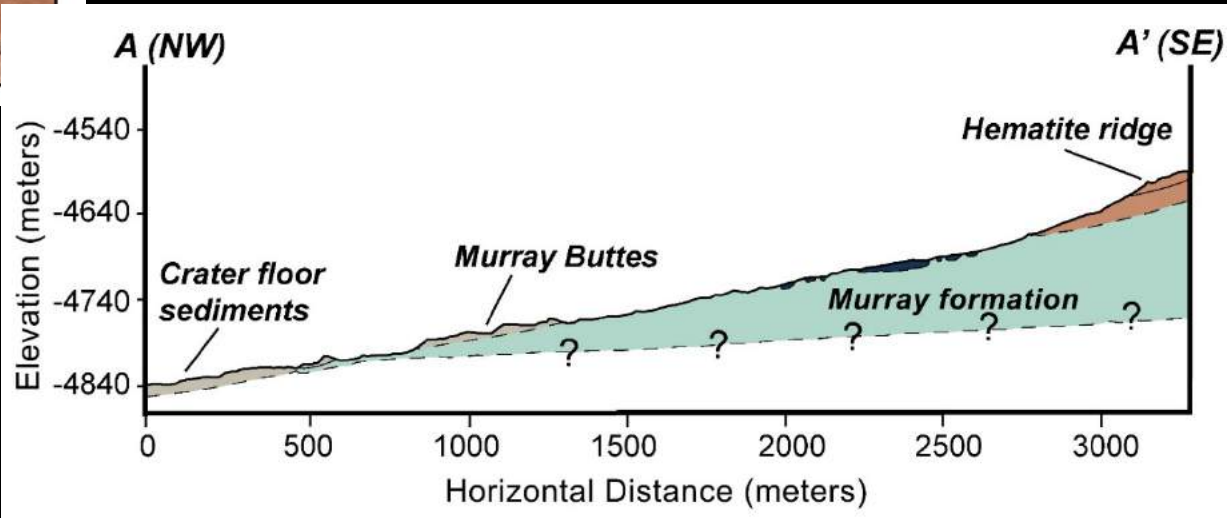
Murray Buttes

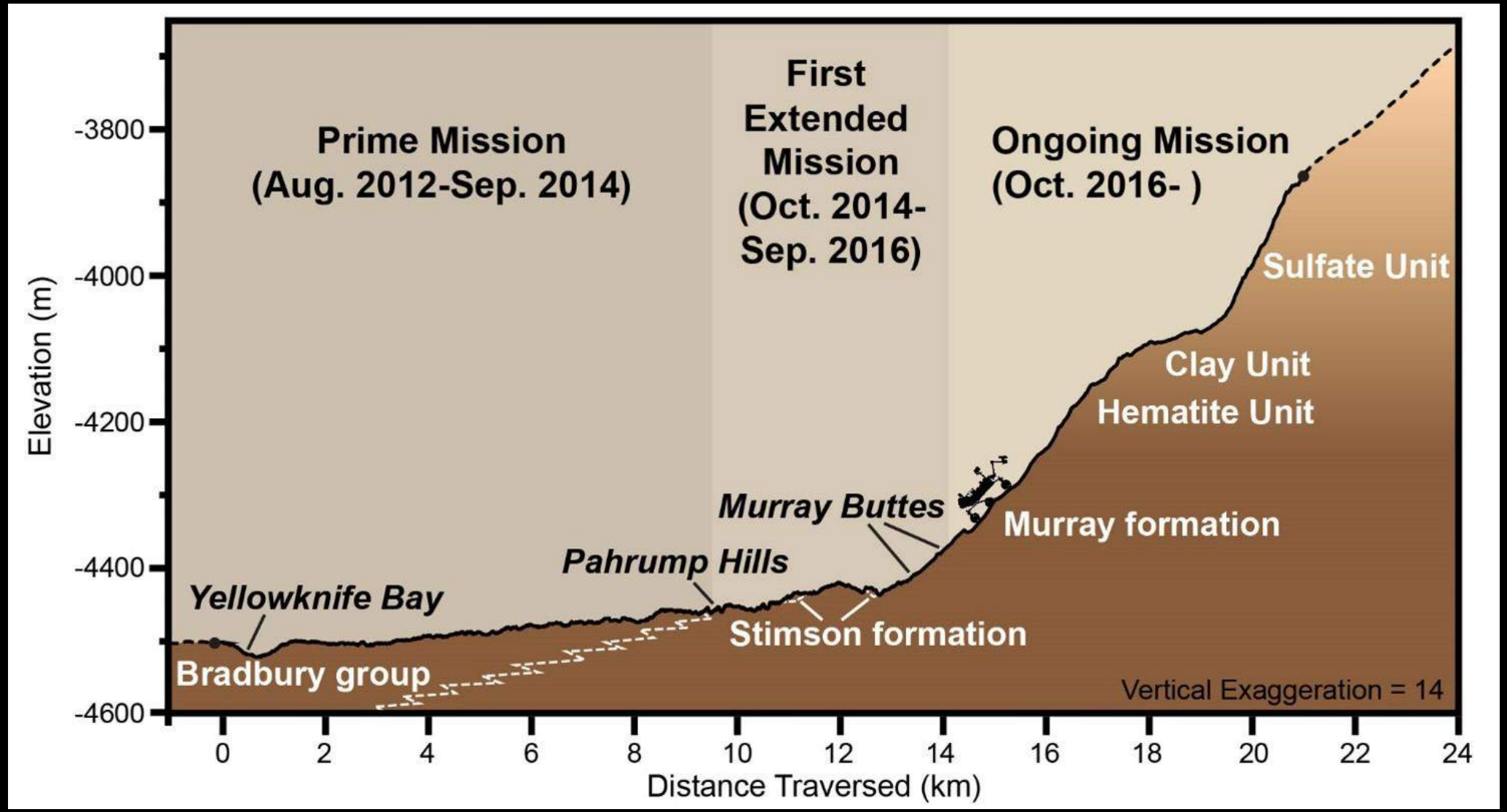
- Up until June 2016, Curiosity had been traversing along the Bagnold Dunes looking for a way across
- The Murray formation is fine grained mudstone with sulfate veins
- The scene covers a patch of ground about 1.2 km (0.8 mi) across. North is up. The largest buttes in the group are about 100m across and 10m high
- Darker ground at upper right and lower left is part of Bagnold sand dunes along the northern edge of Mount Sharp, within Gale Crater.
- Murray Buttes is located at a gap in that band of dunes, making passage through this area an attractive access route to the mountain slopes just south of this scene.
-

- The view combines more than 130 images taken on Aug. 5, 2016, during the afternoon of the mission's 1,421st sol
- This date also was the fourth anniversary of Curiosity's landing.
- The dark, flat-topped mesa seen to the left of Curiosity's robotic arm is about 300 feet (about 90 meters) from the rover's position. It stands about 50 feet (about 15 meters) high.
- The relatively flat foreground is part of a geological layer called the Murray formation, which formed from lakebed mud deposits.
- The buttes and mesas rising above this surface are eroded remnants of ancient sandstone that originated when



- This is a map of lower Mount Sharp on Mars, showing the major geologic units identified from orbit.
- The rocks of the "Murray Formation," likely represent the oldest layers of Mount Sharp that NASA's Curiosity rover will explore.
- This graphic shows the geologic cross-section through lower Mount Sharp on Mars
- The cross-sectional view also highlights the impressive thickness of the Murray Formation - around 650 feet (200m)





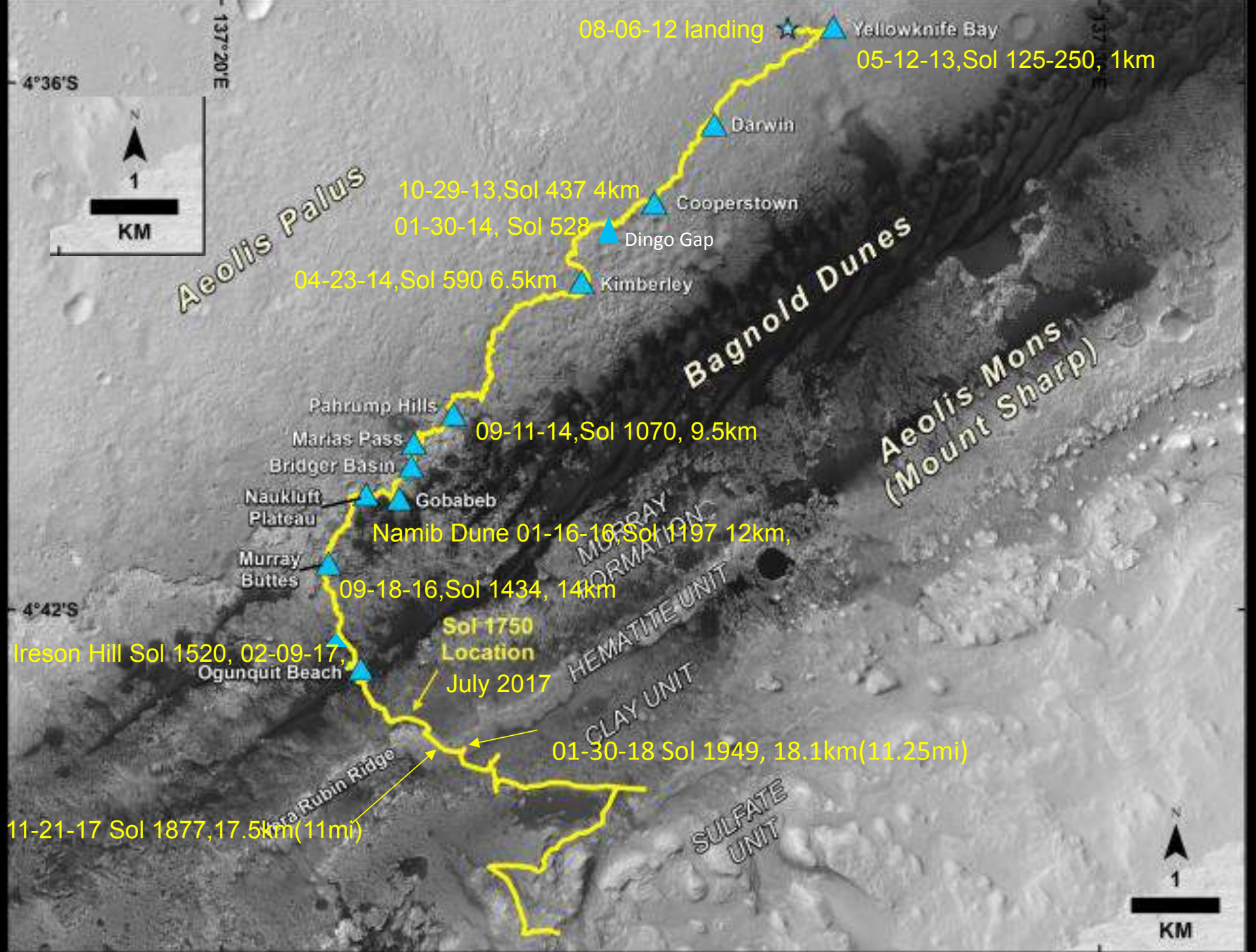
- This graphic depicts aspects of the driving distance, elevation, geological units and time intervals of NASA's Curiosity Mars rover mission, as of late 2016.
- As of early December 2016, Curiosity had driven 9.3 miles (15 kilometers) since its August 2012 landing on the floor of Gale Crater near the base of Mount Sharp. It had climbed 541 feet (165 meters) in elevation.

- The dark, smooth-surfaced meteorite in this Oct. 30, 2016 was examined with laser pulses and confirmed to be an iron-nickel meteorite.
- The meteorite is about the size of a golf ball.
- Iron-nickel meteorites are a common class of space rocks found on Earth, and previous examples have been found on Mars, but this one is the first on Mars to be examined with a laser-firing spectrometer.

- This composite image looking toward the higher regions of Mount Sharp was taken on September 9, 2015
- In the foreground is a long ridge containing hematite, an iron oxide about 2 miles distant.
- Just beyond is an undulating plain and just beyond that are a multitude of rounded buttes, all high in sulfate minerals.
- The changing mineralogy in these layers suggests a changing environment in early Mars, though all involve exposure to water billions of years ago.
- Further back in the image are striking, light-toned cliffs in rock that may have formed in drier times and now is heavily eroded by winds.

- This picture was taken on Nov. 10, 2016, sol 1,516
- Variations in color of the rocks hint at the diversity of their composition on lower Mount Sharp. In the purple tone rocks of the foreground the CheMin instrument has detected hematite.
- The orange-looking rocks just above the purplish foreground ones are in the upper portion of the Murray formation, which is the basal section of Mount Sharp, extending up to a ridge-forming layer called the iron rich Hematite Unit.
- Beyond that is the Clay Unit, which is relatively flat and hard to see from this viewpoint. And the next rounded hills are the Sulfate Unit, Curiosity's highest planned destination.

- This unusual dark mound, called "Ireson Hill," rises about 16 feet (5 meters) above redder layered outcrop material of the Murray formation on lower Mount Sharp
- The darker rock is Stimson sandstone although it is not known why the rock is so dark
- The faint ridge in the background is the Gale crater rim
- The image was made on Feb. 2, 2017, during the sol 1598 using the MastCam to take the 41 images that were combined into this scene.

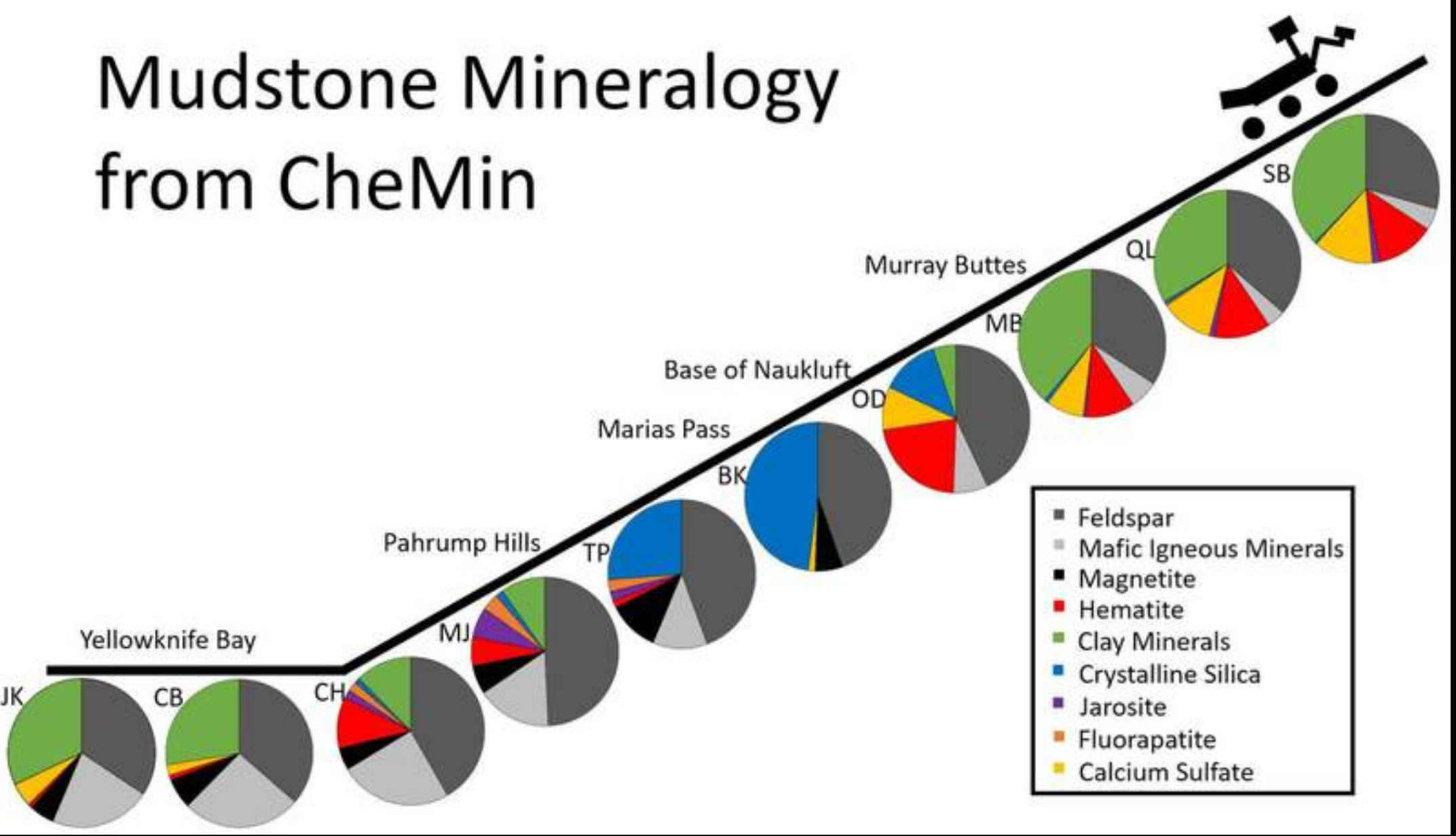

08-06-12 landing
Yellowknife Bay
05-12-13,Sol 125-250, 1km
Darwin
10-29-13,Sol 437 4km
Cooperstown
01-30-14, Sol 528
Dingo Gap
04-23-14,Sol 590 6.5km
Kimberley
Aeolis Palus
Bagnold Dunes
Aeolis Mons
(Mount Sharp)
Pahrump Hills
09-11-14,Sol 1070, 9.5km
Marias Pass
Bridger Basin
Naukluft
Plateau
Gobabeb
Namib Dune 01-16-16,Sol 1197 12km,
MURRAY
FORMATION
Murray
Buttes
09-18-16,Sol 1434, 14km
HEMATITE UNIT
Sol 1750
Location
July 2017
Ireson Hill Sol 1520, 02-09-17,
Ogunquit Beach
CLAY UNIT
01-30-18 Sol 1949, 18.1km(11.25mi)
Kimberley Rubin Ridge
11-21-17 Sol 1877,17.5km(11mi)
SULFATE
UNIT
137°20'E
4°36'S
4°42'S
N
1
KM

This panorama shows details of the sedimentary rocks that make up the "Vera Rubin Ridge."

- The rocks making up the lower part of the ridge are characterized by distinct horizontal stratification with individual rock layers of the order of several inches thick.
- From this distance it is not possible to know if they were formed by aqueous or wind-blown processes.
- The stratified rocks are cross cut by veins filled with a white mineral, likely calcium sulfate, that provide evidence of later episodes of fluid flow through the rocks
- Curiosity will be spending the foreseeable future examining the ridge

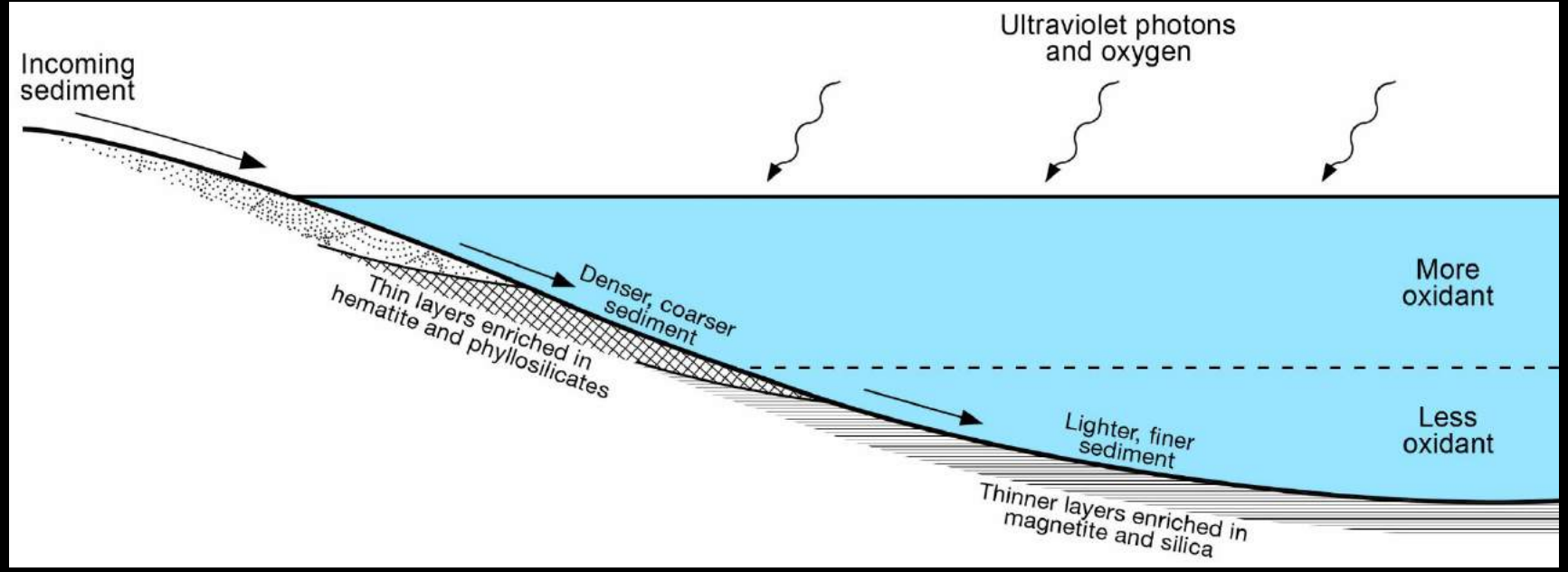
A picture from ChemCam on July 3, 2017 looking up at the Vera Rubin ridge

Mudstone Mineralogy from CheMin



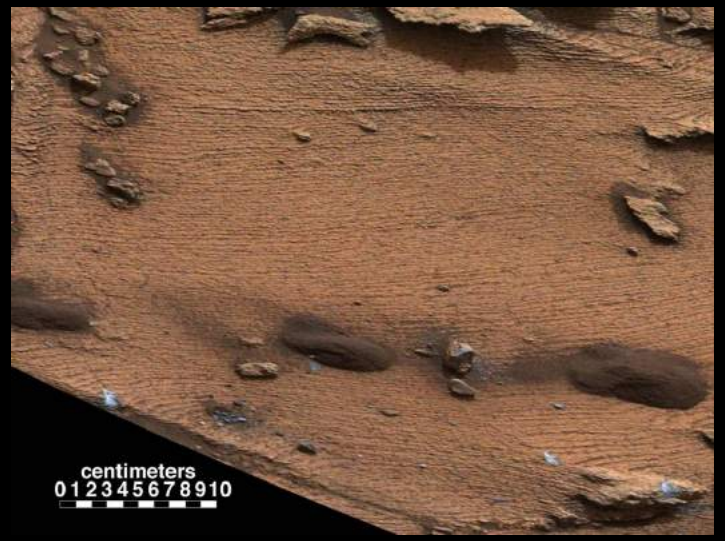
- Clay minerals, shown as green, declined in abundance at sites midway through this series, then came back as the rover climbed higher.
- One significant factor is that silica materials are concentrated in the Marias Pass area

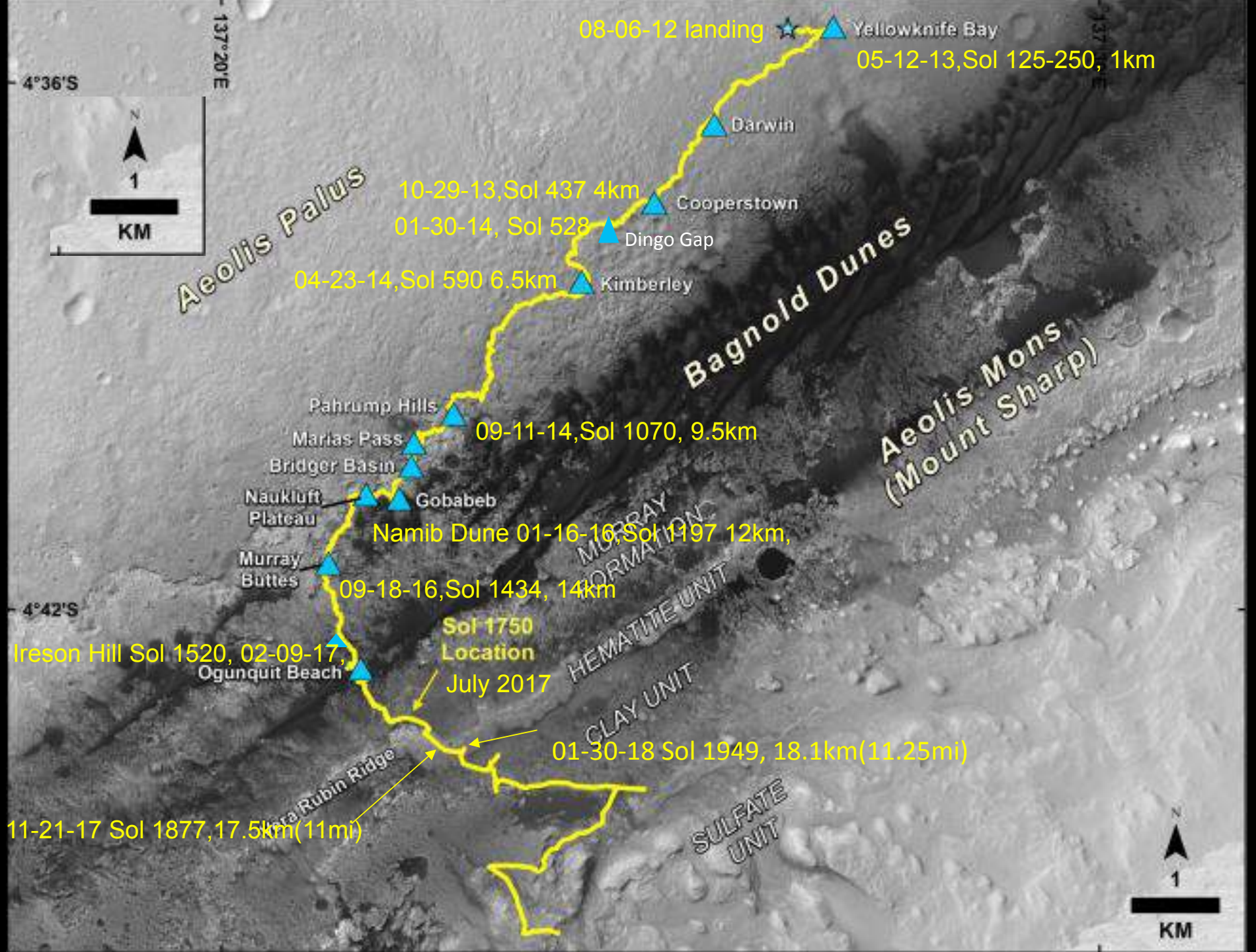
- Another trend that stands out is that the mineral Jarosite(iron sulfate) -- shown in purple -- was more prominent in the "Pahrump Hills" area of lower Mount Sharp than at sites examined either earlier or later. Jarosite is an indicator of acidic water.



It is Highly Likely That Gale Crater Held a Lake

- The sedimentary rocks deposited within a lake in Mars' Gale Crater more than three billion years ago differ from each other in a pattern that matches what is seen in lakes on Earth.
- As sediment-bearing water flows into a lake, bedding thickness and particle size progressively decrease as sediment is deposited in deeper and deeper water

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(Mount Sharp)
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Marias Pass
Bridger Basin
Naukluft
Plateau
Gobabeb
Namib Dune 01-16-16,Sol 1197 12km,
MURRAY
FORMATION
Murray
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137°20'E
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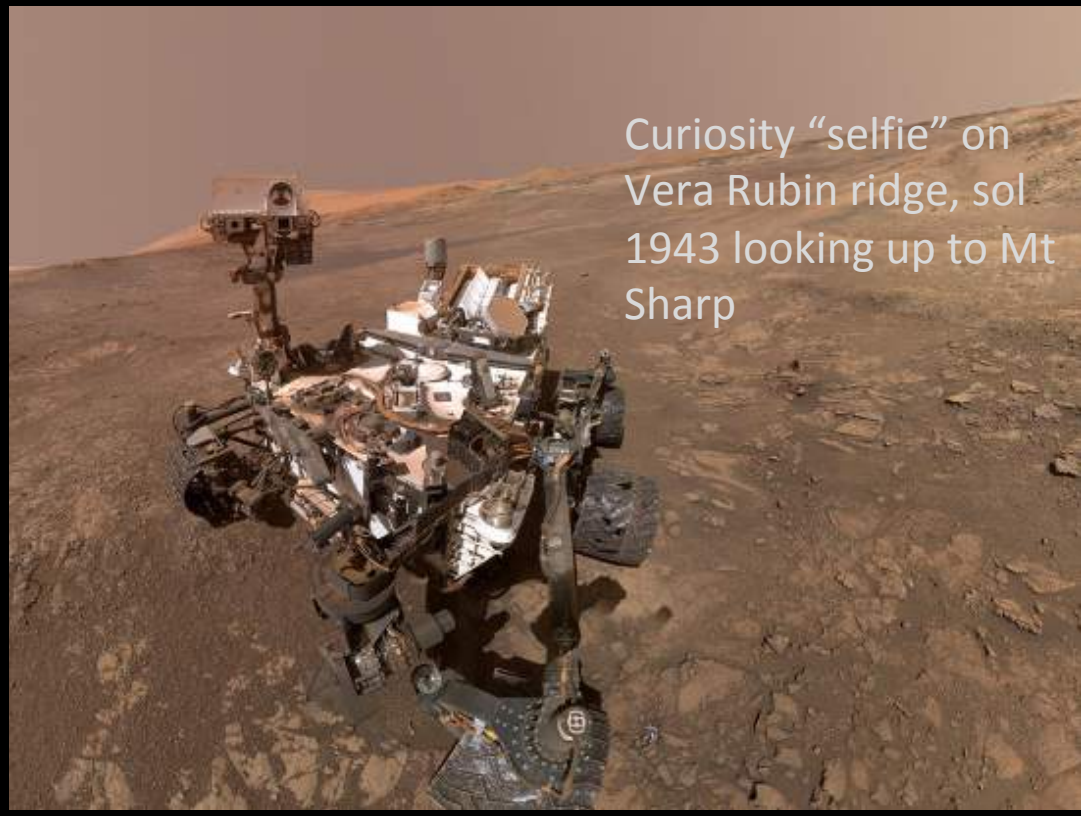
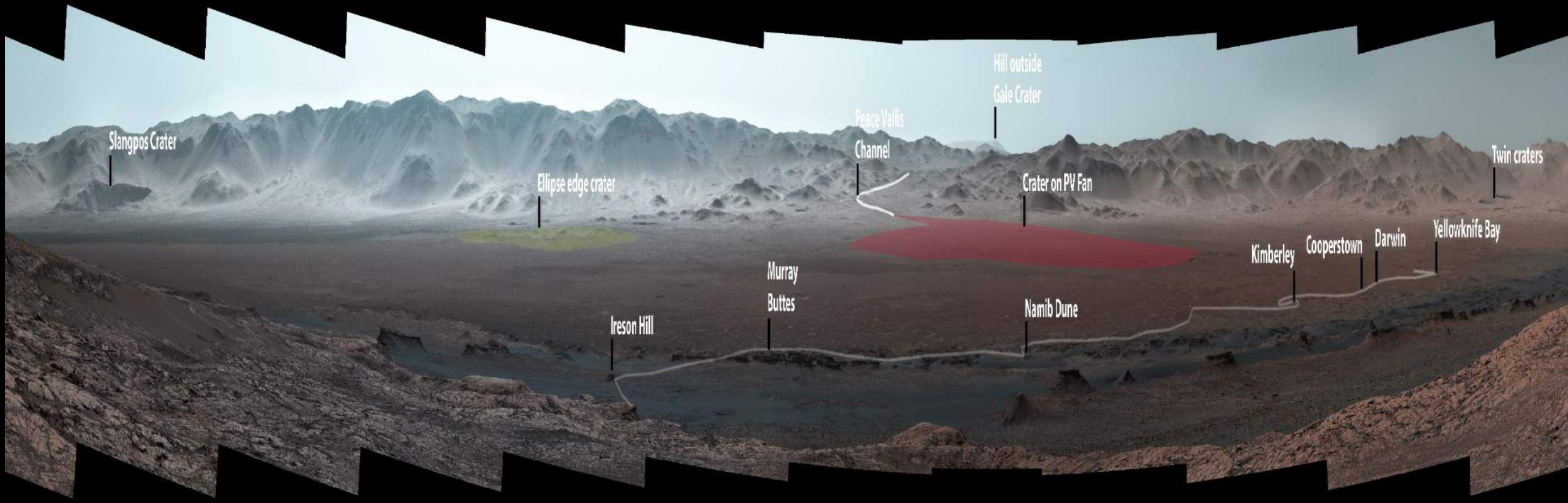
4°42'S
N
1
KM



Curiosity “selfie” on Vera Rubin ridge, sol 1943 looking up to Mt Sharp

- NAVCAM picture taken 1-29-18, Sol 1949 on Vera Rubin ridge looking NNE towards the Gale Crater rim 25 mi distant
- Curiosity will be studying this area for the forseeable future and will not venture much further up Mt Sharp



- Climbing "Vera Rubin Ridge" provided this sweeping vista of the interior and rim of Gale Crater, including much of the rover's route during its first five-and-a-half years on Mars and features up to about 50 miles (85 kilometers) away.
- The scene spans from southwest on the left to northeast on the right, combining 16 side-by-side images taken by the left-eye, wider-angle-lens camera of Curiosity's Mast Camera (Mastcam
- The component images were taken on Oct. 25, 2017, Sol 1856,
- At that point, Curiosity had gained 1,073 feet (327 meters) in elevation and driven 10.95 miles (17.63 kilometers) from its landing site.
- https://www.washingtonpost.com/news/speaking-of-science/wp/2018/02/03/curiositys-five-year-journey-across-mars-in-one-stunning-photo/?utm_term=.0bdb7a7bf9b6

Summary of Curiosity's Findings

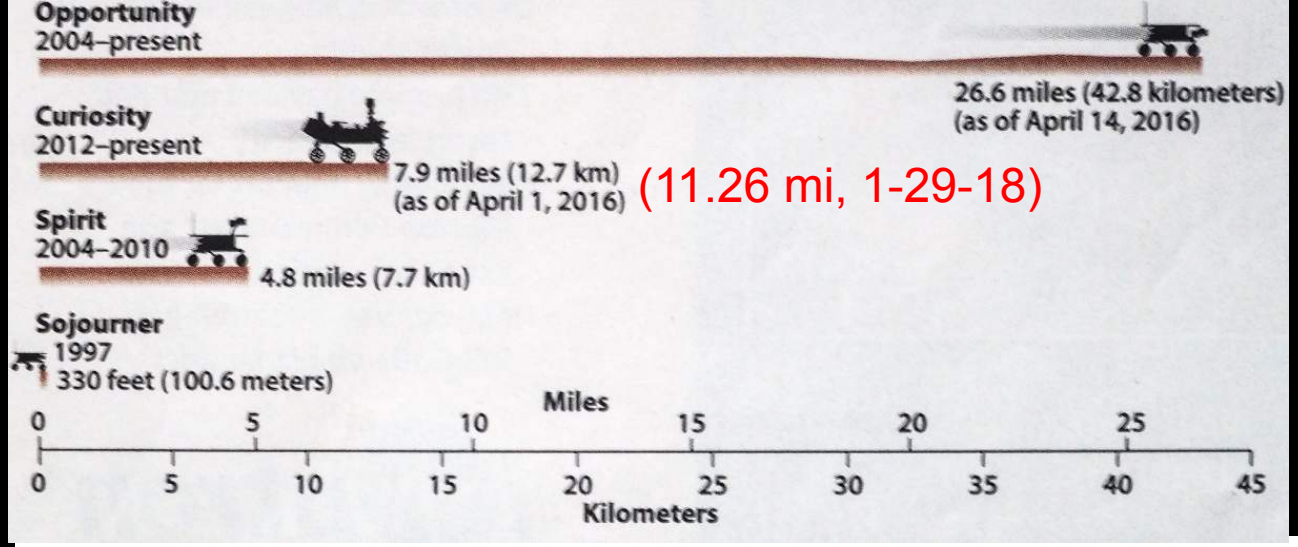
- Clear evidence for the existence of diverse water features such as flowing streams, deltas and lakes were found
- Key ingredients for life such as carbon, hydrogen, oxygen, phosphorus and sulfur, were found in the 12 rock samples that Curiosity analyzed.
- The first definitive detection of organics in surface materials of Mars was found through Curiosity's sophisticated chemical analysis capability
- The existence of an energy source for the possible creation of micro-organisms was identified through the presence of pairings of chemicals such as sulfides and sulfates
- The possibility that drinkable water may have existed was found through analysis of clay minerals that showed a low level of salt
- A significant geological diversity was found that offer clues as to Mars's history such as the many mudstones, the presence of sand, dunes, volcanics, and the many minerals

Overall Curiosity more than met the goals set for the mission and determined that Mars could have supported ancient life

Spirit and Opportunity are identical twin robotic rovers that have gone far beyond their original scientific objectives

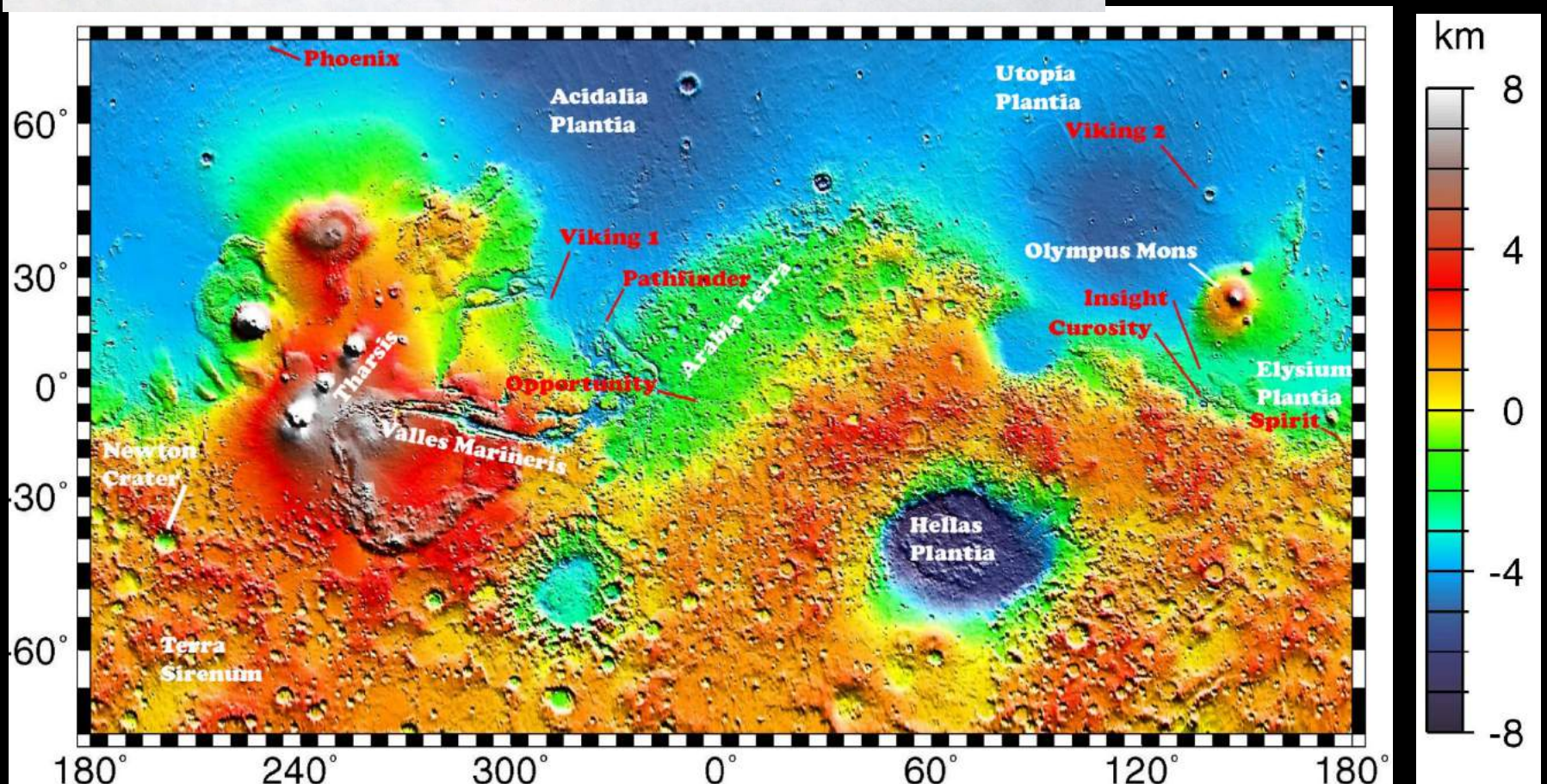
Each rover far outlasted its design lifetime of 90 days. Opportunity continues to operate in its 14’th year.

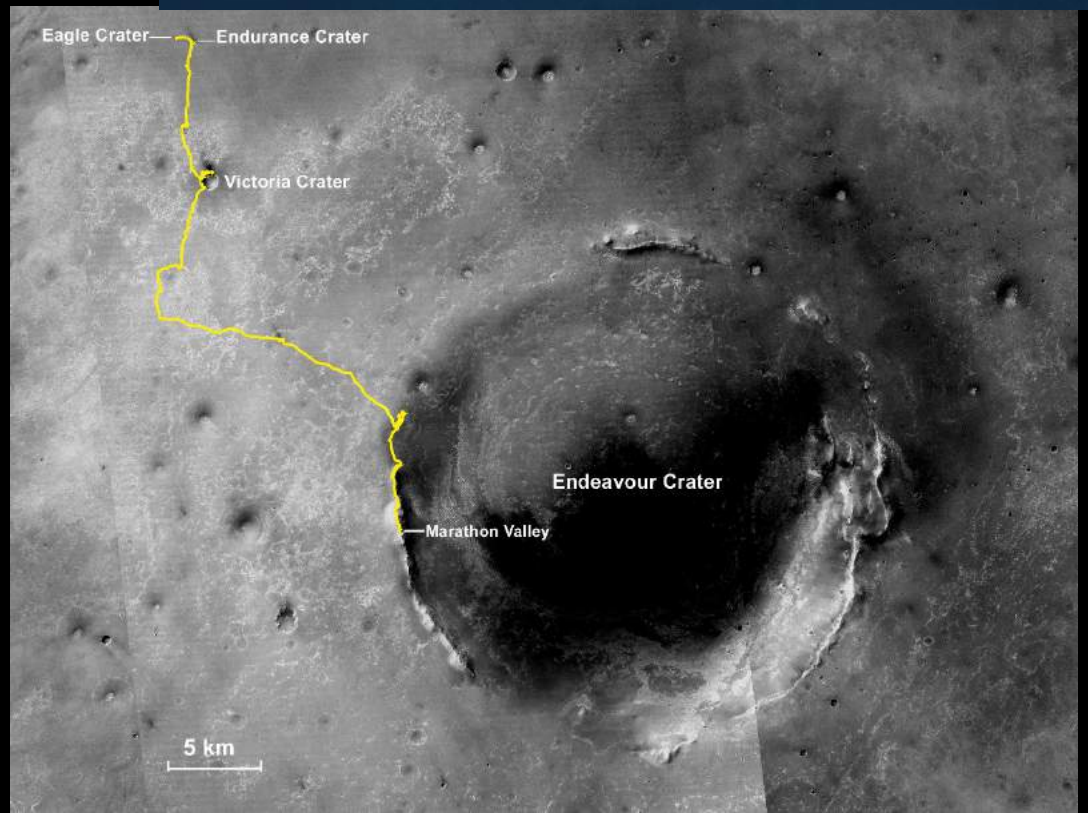
- **Launch**: July 7, 2003
- **Arrival**: Jan. 24, 2004 PST
- **Landing Site**: Meridiani Planum
- **Mission Duration**: Originally 92 days, Still roving!
- **Odometry**: >27 miles
- **Raw Images Returned**: 187,000
- **Instruments**: Panoramic camera, Miniature thermal emission spectrometer, Moessbauer spectrometer, Alpha particle X-ray spectrometer, Microscopic imager, Rock abrasion tool, Navigation camera, Hazard-avoidance cameras



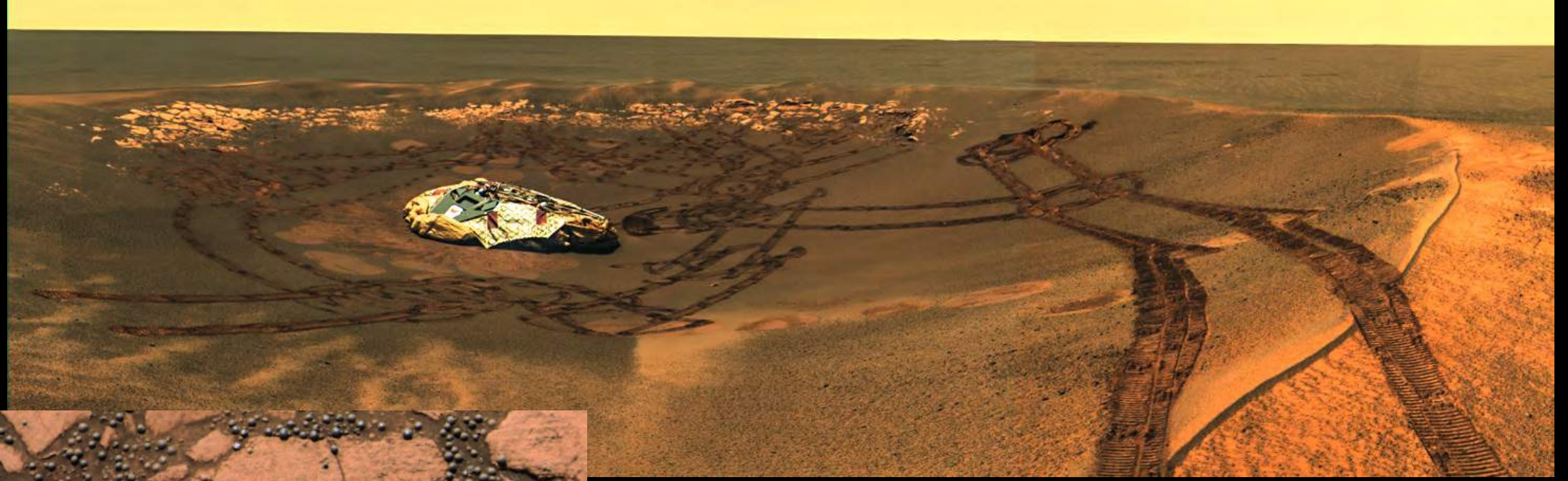
(11.26 mi, 1-29-18)

Martian Rovers Driving Records





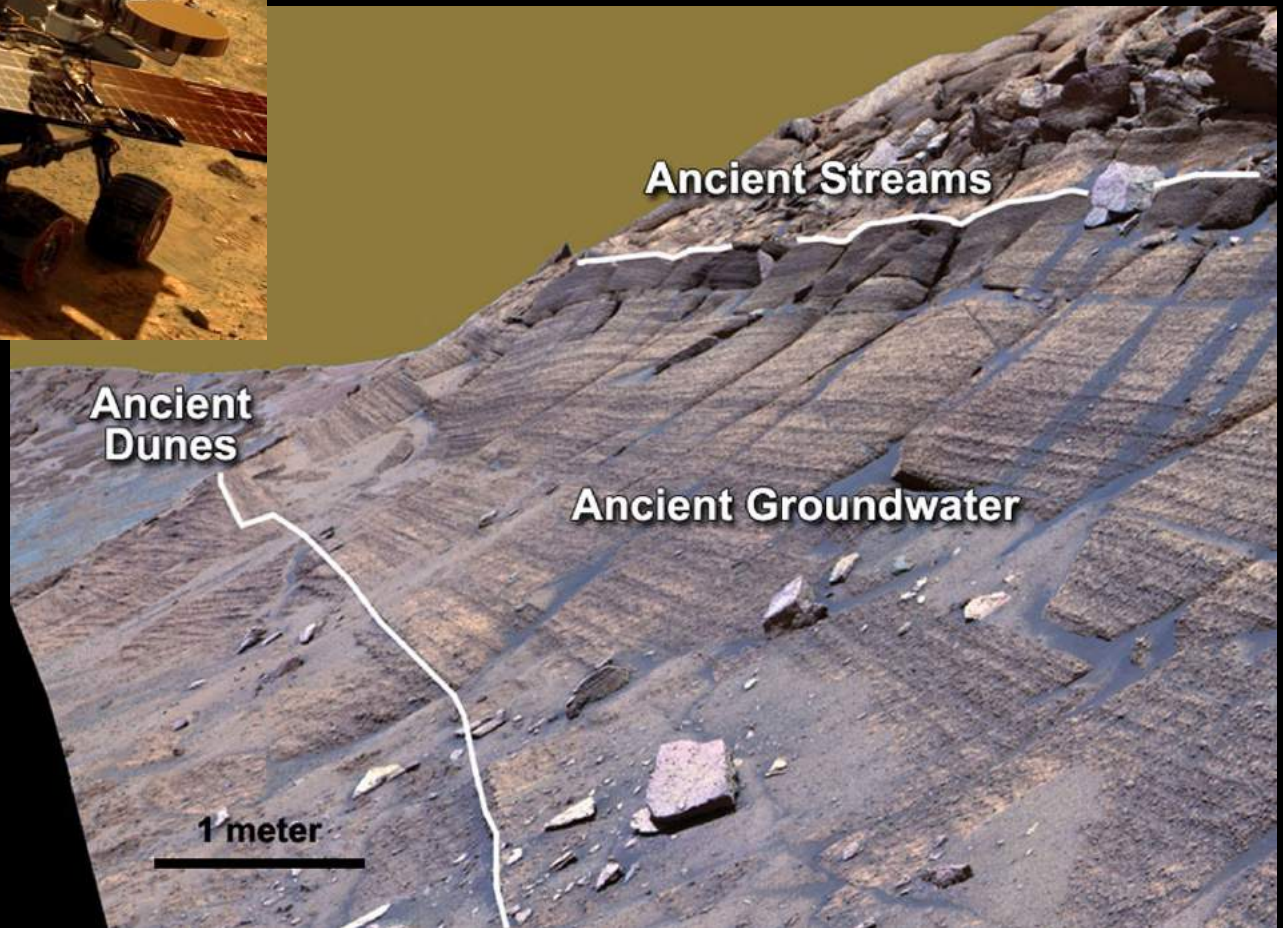
- As of March 24 2015, the long lived Opportunity rover traveled the distance of a Marathon, 26.2 miles in a period of 11 years and 2 months
- The journey was from the Endurance crater to the Endeavor crater
- Opportunity's & Spirit's goal were to find evidence of liquid water



- Opportunity's landing is often referred to as a "hole-in-one" because the spacecraft unexpectedly came to rest inside a small indentation called Eagle Crater which would quickly reveal secrets of a wet past.
- The image shows the airbags that cushioned the landing as Opportunity was leaving Eagle Crater

- Opportunity found blueberry-shaped concretions of hematite. The rock outcrop contained jarosite, a mineral that can only result from rock exposed to acidic water.

Opportunity in Endurance Crater



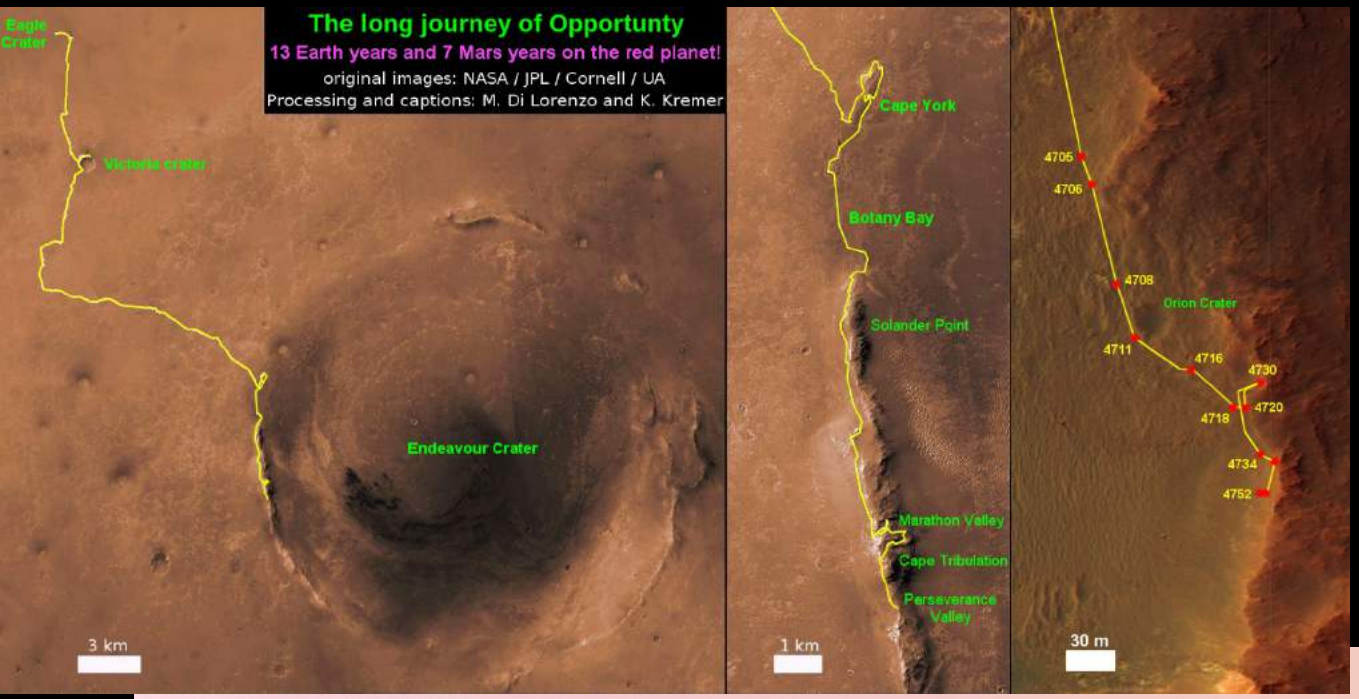
- NASA's Mars Exploration Rover Opportunity studied layers in the Burns Cliff slope of Endurance Crater in 2004.
- The layers show different types of deposition of sulfate-rich sediments.
- Opportunity's panoramic camera recorded this image.

- As NASA's Mars Exploration Rover Opportunity crept farther into "Endurance Crater," the sinuous 1 meter high field of dunes on the crater floor appears even more dramatic.
- Care was taken when entering the field to avoid being trapped.
- Also evident is a "blue" tint on the flat surfaces as compared to the dune flanks. This results from the presence of the hematite-containing spherules ("blueberries") that accumulate on the flat surfaces.

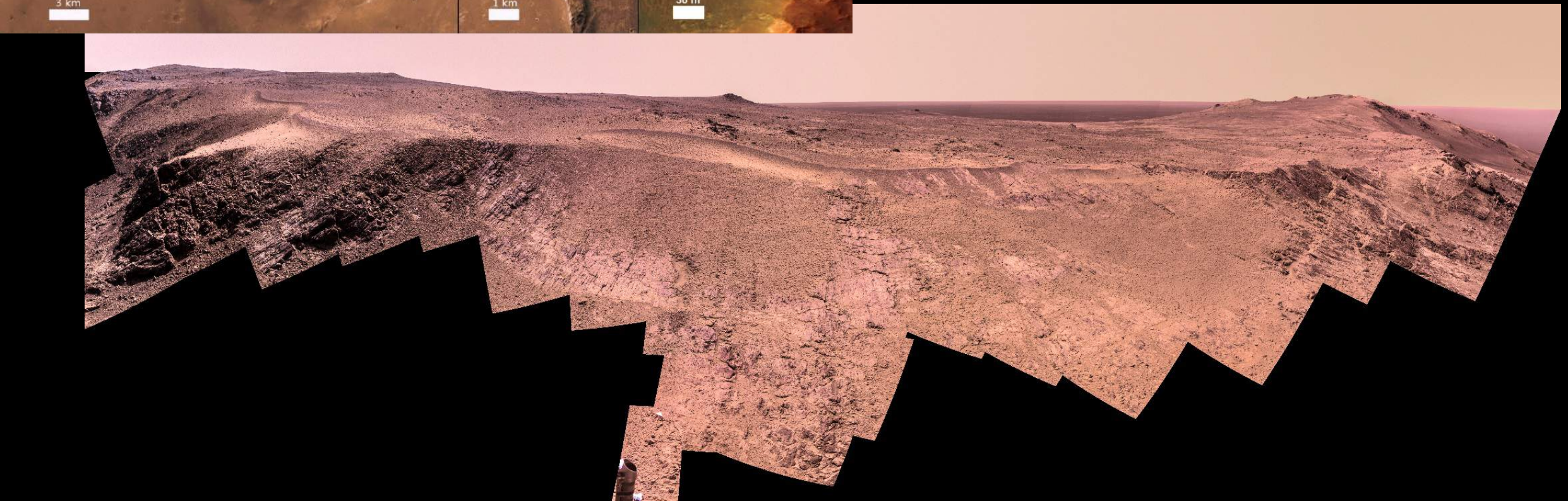
- With joints in its arm and wheels showing signs of age, Opportunity gamely pressed on in its fourth year of operation on Mars to deliver fresh and intriguing scientific results inside Victoria Crater, about 4.5 miles from the landing site.
- Around the rim of Victoria Crater, the rover found large and abundant numbers of hematite spherules most likely formed in water.
- Analysis suggested that water once soaked a layer buried beneath the surface long enough to form the spherule concretions which were subsequently blasted out by the impact

Victoria Crater

- This image from the High Resolution Imaging Science Experiment (HIRISE)on NASA's Mars Reconnaissance Orbiter shows "Victoria crater," an impact crater at Meridiani Planum, near the equator of Mars.
- The crater is approximately 800 meters (half a mile) in diameter. It has a distinctive scalloped shape to its rim, caused by erosion and downhill movement of crater wall material.
- The floor of the crater is occupied by a striking field of sand dunes.



- Opportunity began exploring the western rim of Endeavour Crater in 2011 at Cape Tribulation
- The view extends from south-southeast on the left to north on the right.
- The PanCam took the component images for this panorama on Feb. 25, 2017, during the 4,654th Martian day.



January 25, 2018 Opportunity's 14'th Anniversary on Mars

Opportunity

Mars Exploration Rover

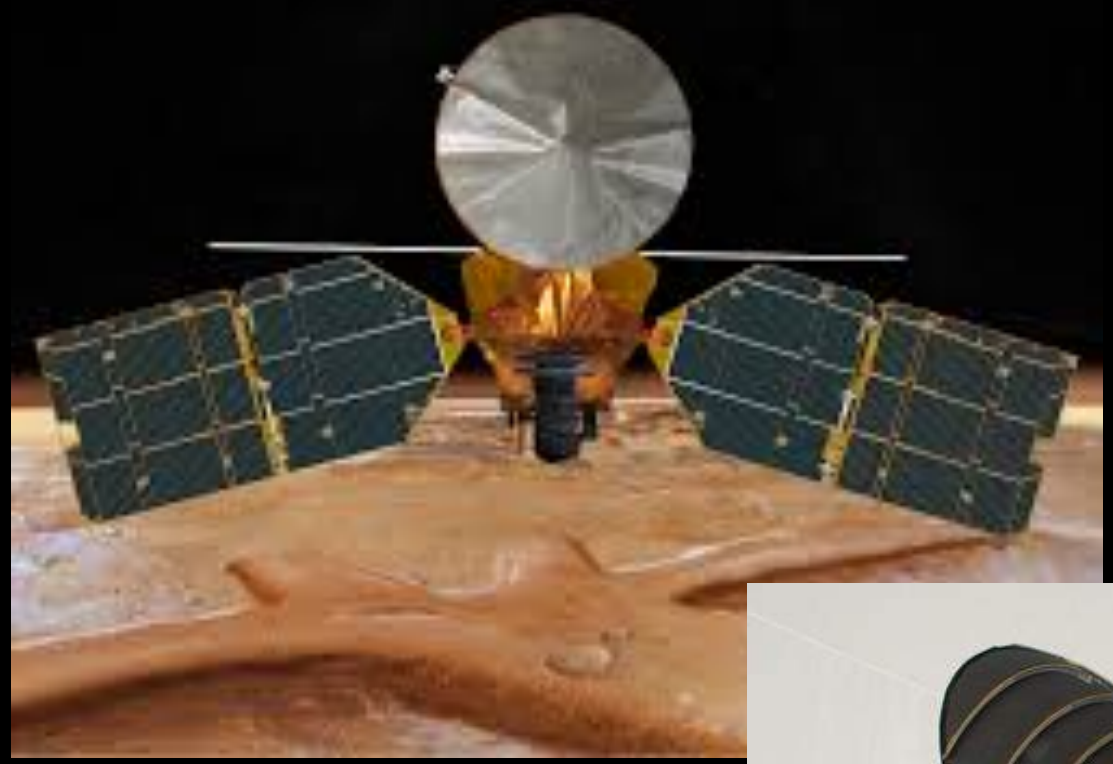
Field Notes from Mars

New Mexico Museum of Natural History & Science

Thursday January 26, 2018– Sol 4978

This location is called "Robledo" – using our Camino Real naming theme

Floor of Perseverance Valley



Mars Reconnaissance Orbiter

Arrival: March 10, 2006
Weight: 2,180 kilograms (4,806 pounds) at launch, including fuel
Mission Duration: 2006 - Ongoing

Cameras

High Resolution Imaging Science Experiment (HiRISE)

Context Camera (CTX)

Mars Color Imager (MARCI)

Spectrometer

Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)

Radiometer

Mars Climate Sounder (MCS)

Radar

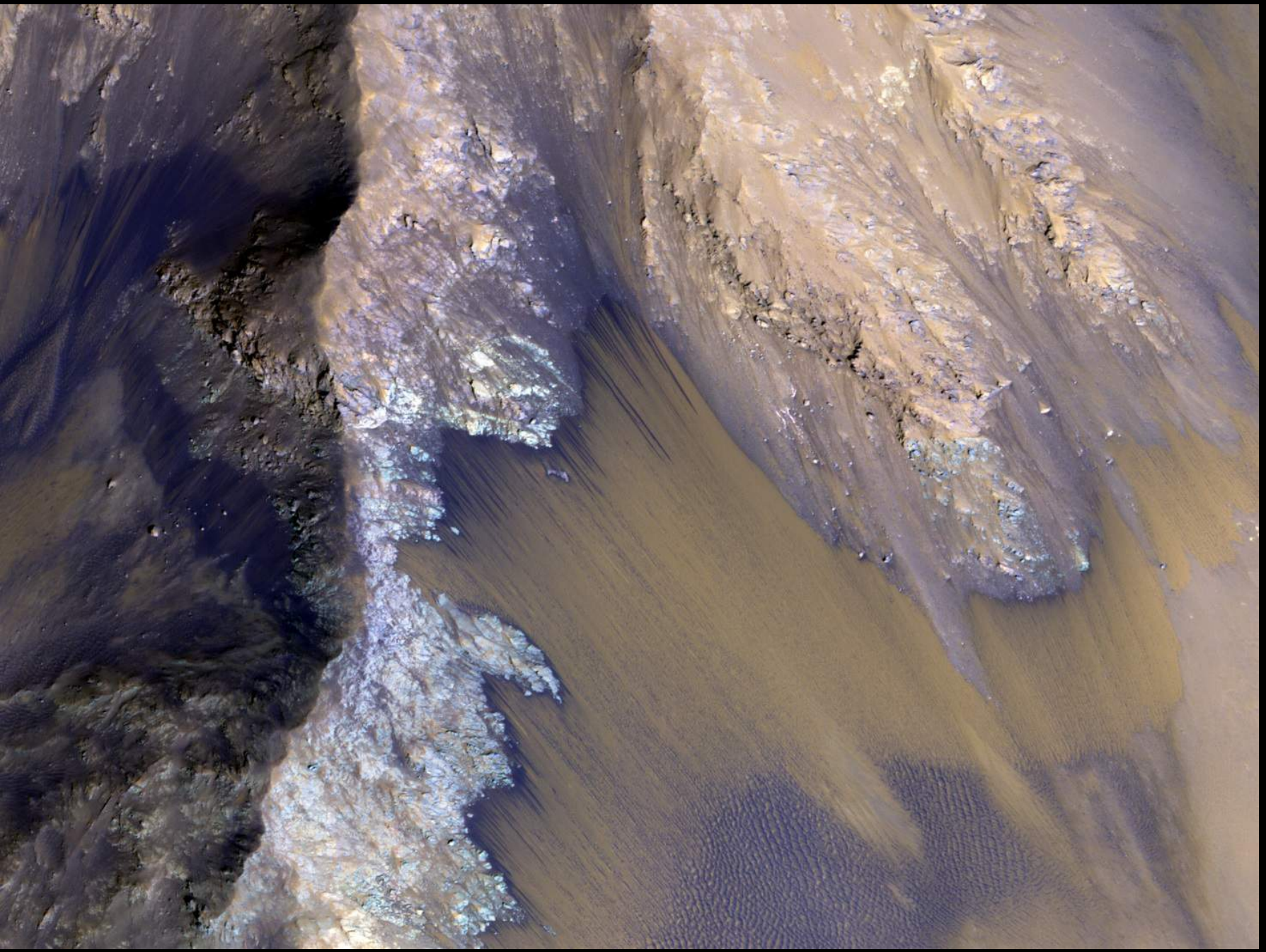
Shallow Radar (SHARAD)

The HIRISE camera is the highest resolution camera in orbit other than on Earth
From an altitude that varies from 200 to 400 HIRISE acquires surface images with resolutions of 4 to 8 feet(30-60cm/px)

Water and Ice on Mars

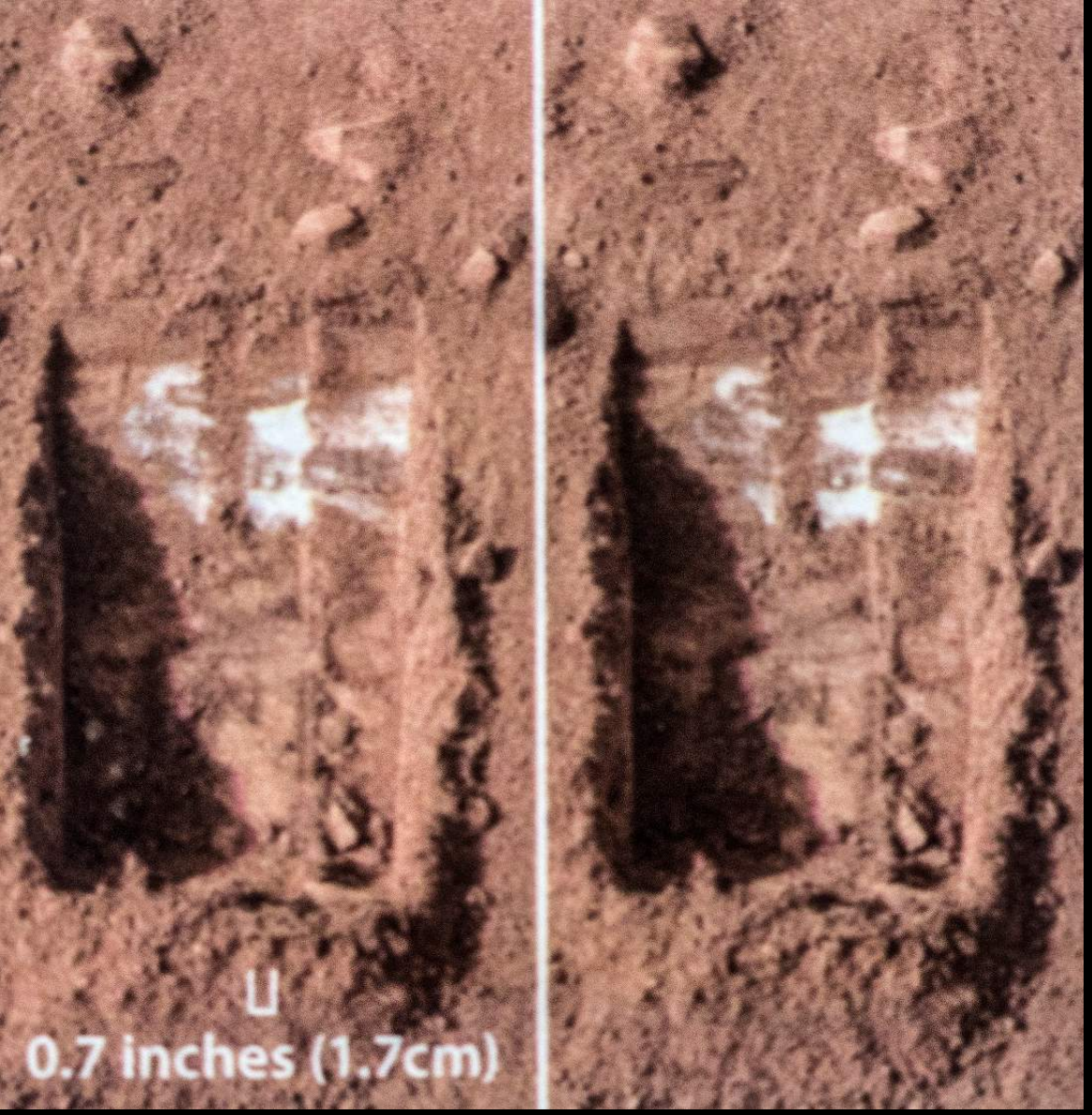
- One of the discoveries by the MRO are seasonal flows on steep features called Recurring Slope Linae(RSL)
- The flow features are narrow (one-half to five yards or meters wide), relatively dark markings on steep (25 to 40 degree) slopes at several southern hemisphere locations.
- Repeat imaging by HiRISE shows the features appear and incrementally grow during warm seasons and fade in cold seasons
- Up until very recently it was assumed that these “slope limae” were caused by flows of salty water, with the source of the water originating from seasonal adsorbed water provided by the atmosphere.(1)
- These flows are interpreted by new research as granular flows, where grains of sand and dust slip downhill to make dark streaks, rather than the ground being darkened by seeping water.(2)
- The image was made May 30, 2011, by the High HIRISE camera on the MRO in the Newton Crater

https://www.nasa.gov/images/content/577359main_pia14472-946b.gif



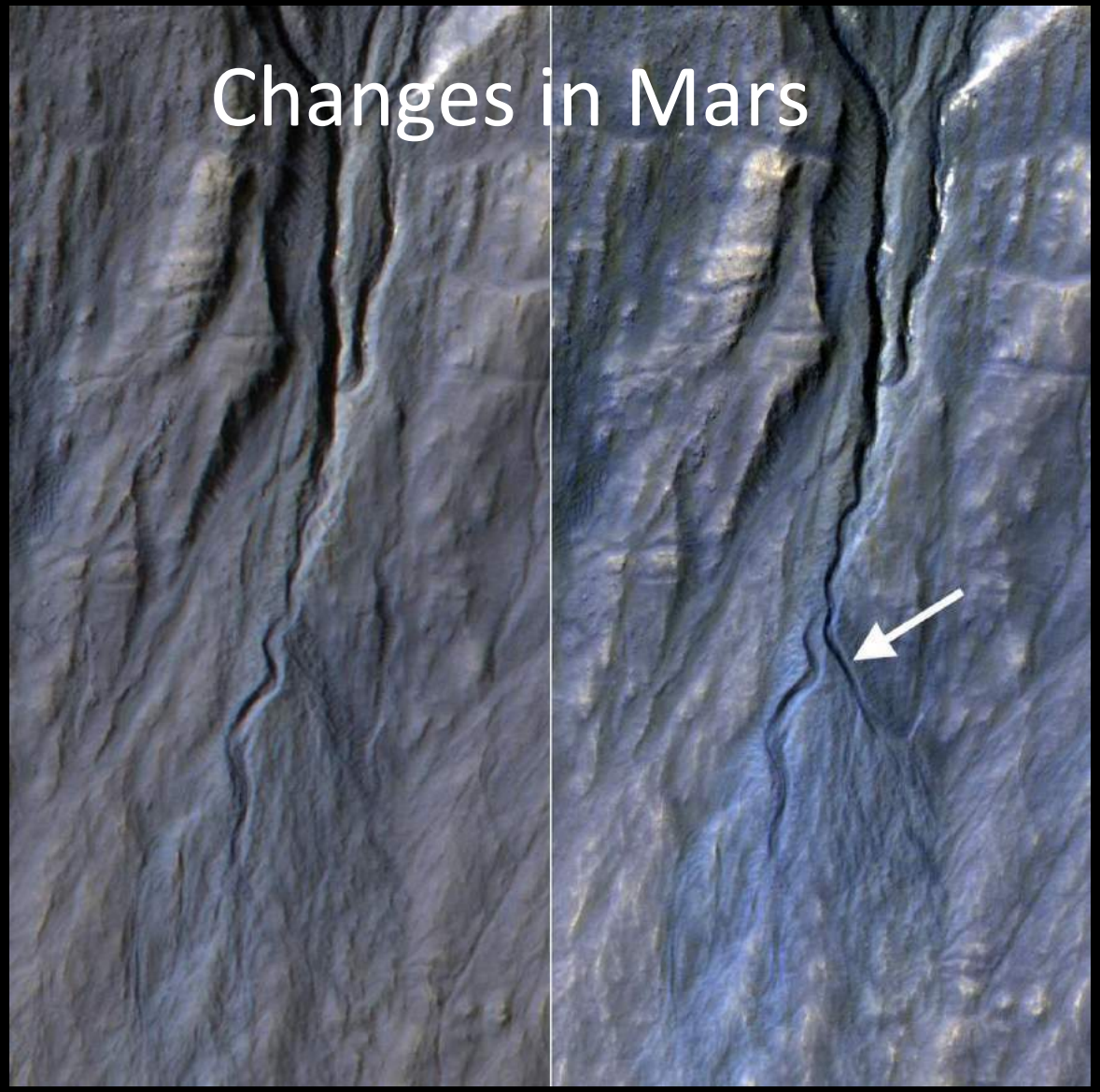
More Signs of “Flowing Water” on Mars

- They are called recurring slope lineae because they fade and disappear during cold seasons and reappear in warm seasons, repeating this pattern every Martian year.
- The flows in this image are in a part of Valles Marineris,and are on a north-facing slope so they are active in northern spring.
- The flows emanate from the relatively bright bedrock and flow onto sandy fans, where they are remarkably straight, following linear channels.
- Valles Marineris contains more of these flows than everywhere else on Mars combined, and they are always active although on changing slope aspects with season.

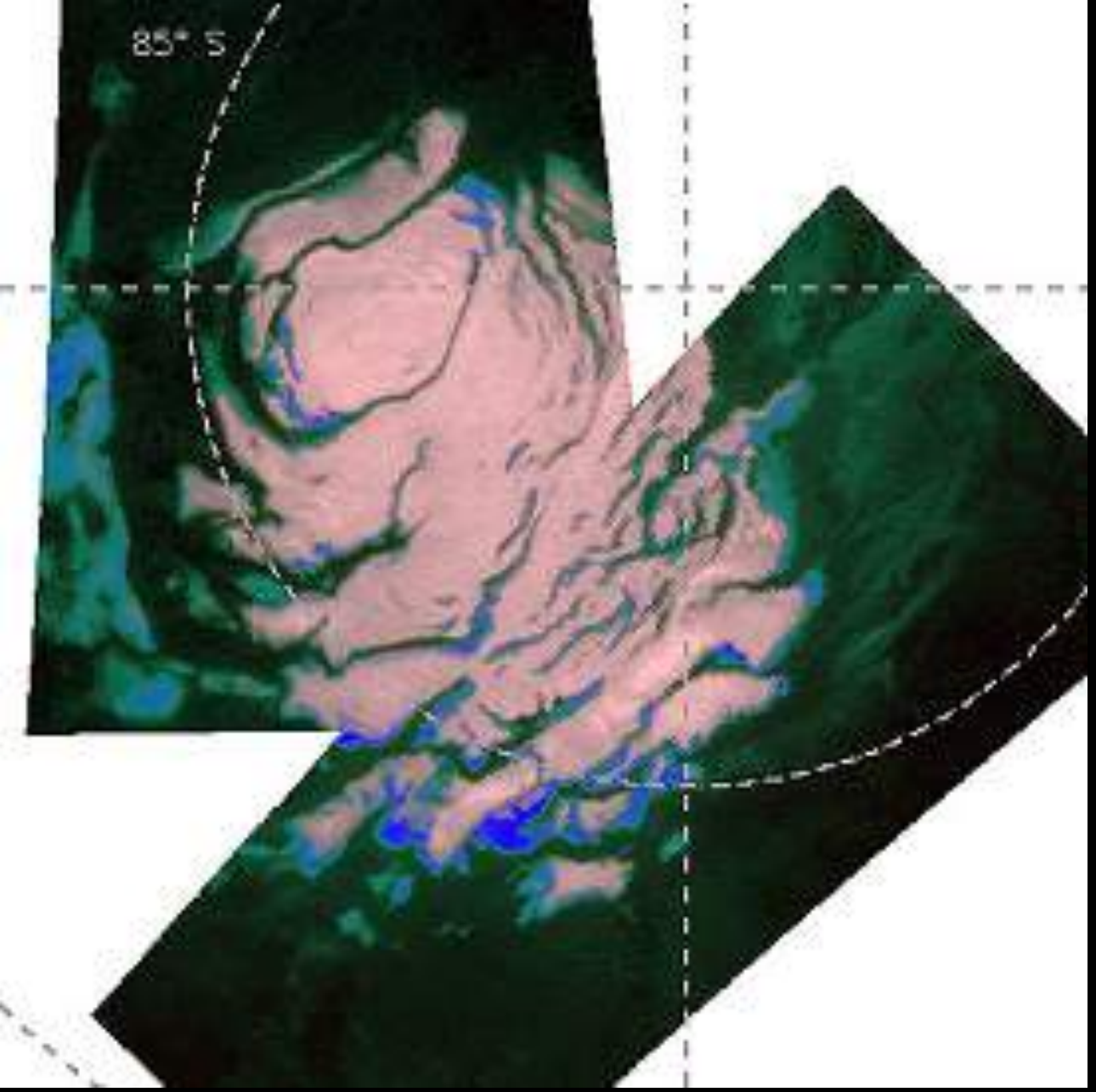


Buried water ice is exposed just centimeters below the surface in this image by the Phoenix lander. The two pictures were taken 3 days apart.

Changes in Mars

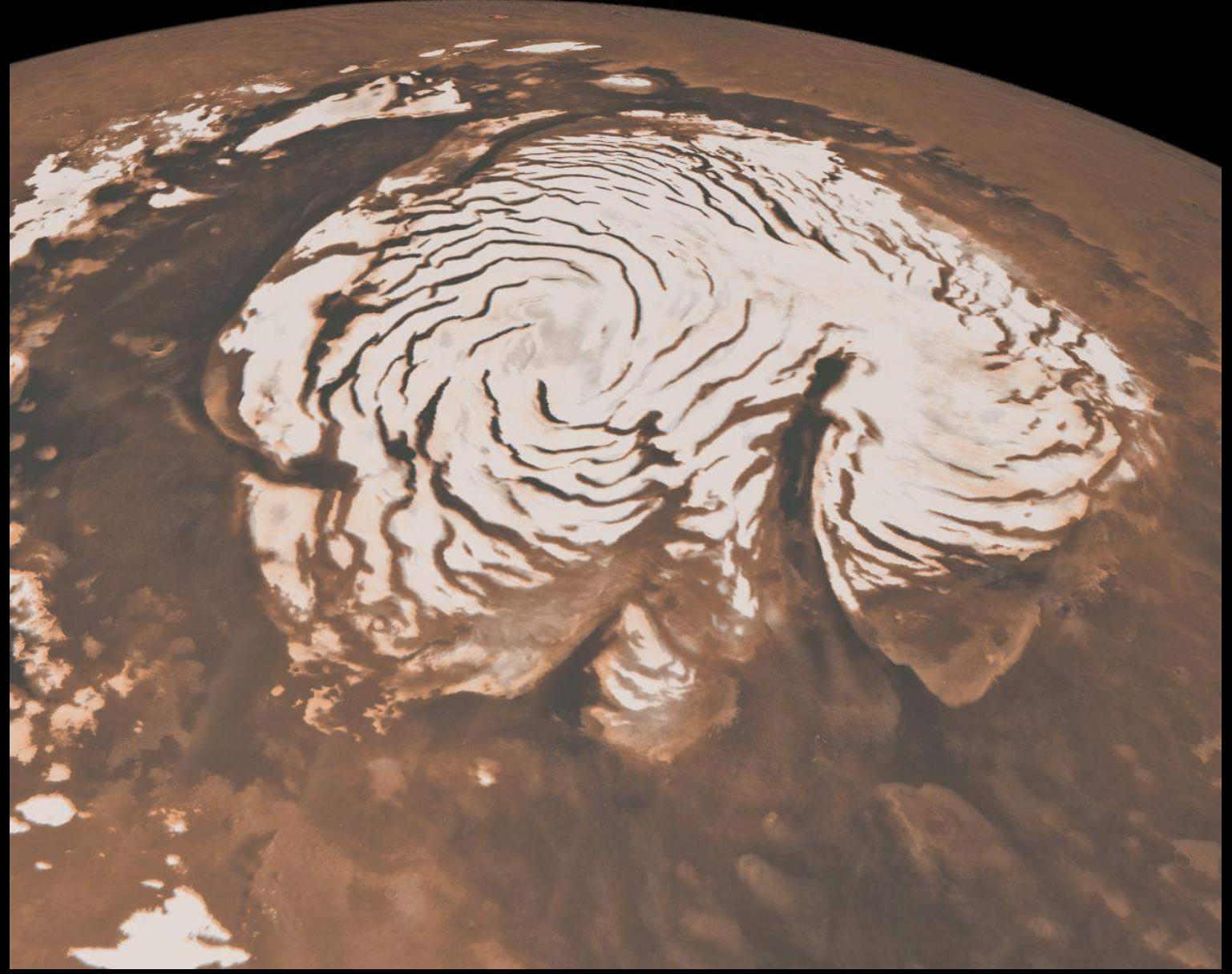


Comparing the newer and older images, there is a new channel formed sometime between November 2010 and May 2013. It is caused most likely by seasonal CO_2 frost



Finding the Water-Probing the Poles

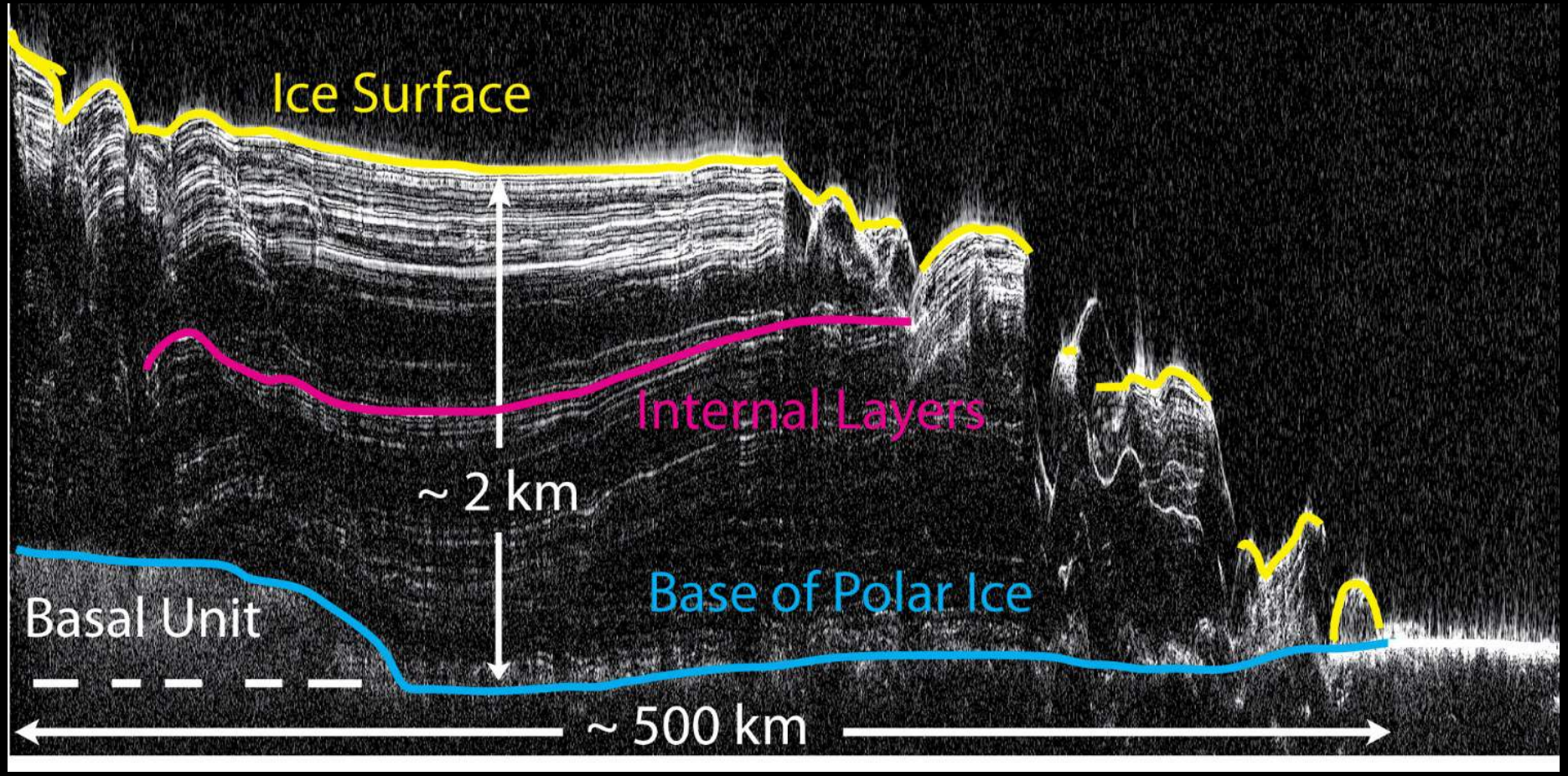
- IN 2004 THE OMEGA infrared spectrometer on the ESA Mars Express orbiter investigated the south polar cap and discerned three areas of water ice. (1,2)
- The south polar cap itself was found to be a mixture of 85 per cent highly reflective carbon dioxide ice and 15 per cent water ice.
- Next to the pole was steep scarps that are almost pure water ice.
- The most unexpected discovery was vast plains of permafrost water ice stretching 10’s of km from the scarps
- These permafrost areas consist of a mixture of water and soil which is frozen to the hardness of solid rock in the low Martian temperatures.
- NASA estimated that the combined ice amounts to a Global Equivalent Layer(GEL) of water 11m in depth(2) or 1.6 Million km^3(3)



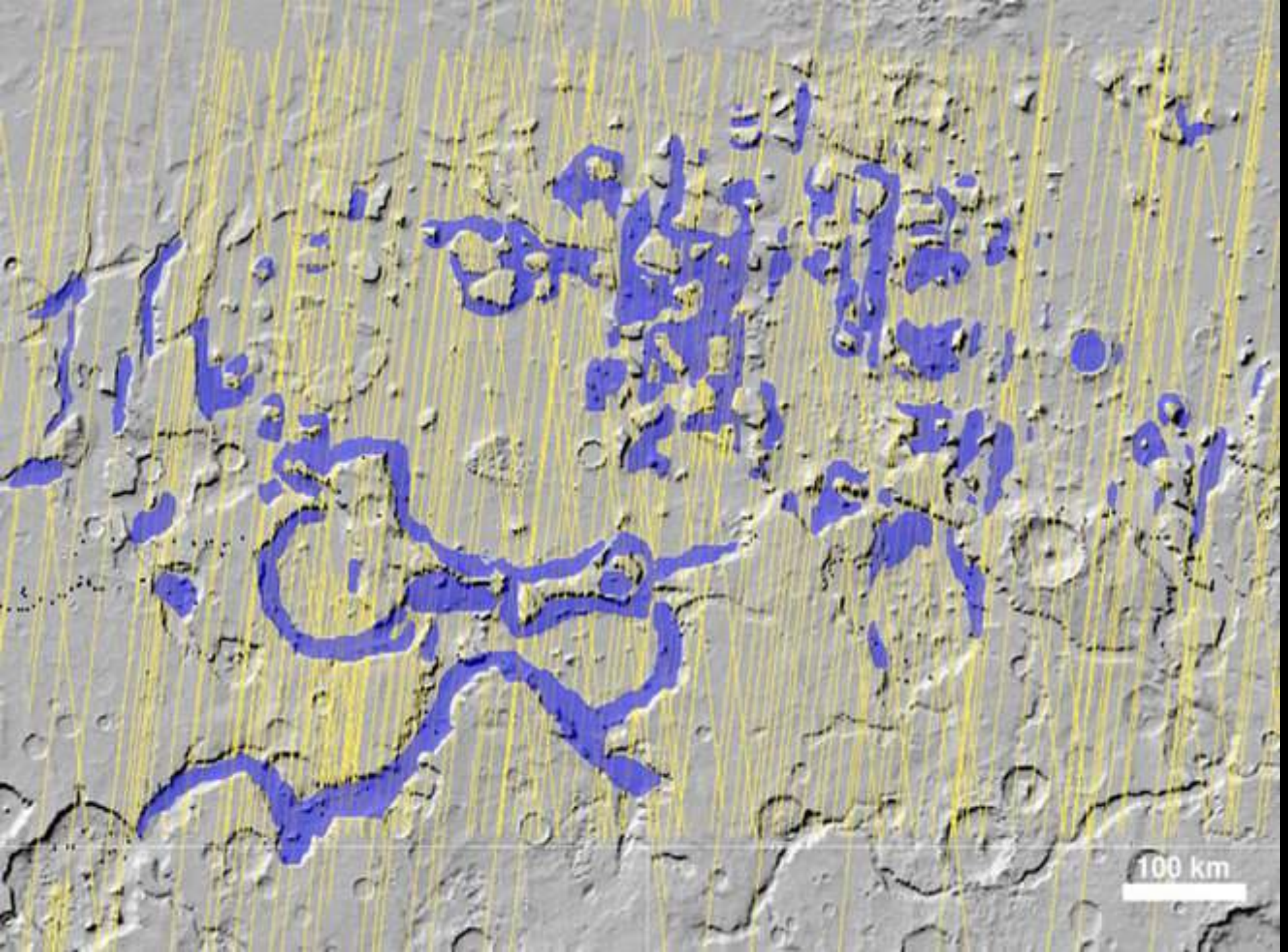
- The ice-rich north polar cap is approximately 1,000 kilometers across
- The dark, spiral-shaped bands are deep troughs that are in shadow.
- The large Chasma Boreale is about the length of the Grand Canyon and up to 2 kilometers (1.2 miles) deep.

The image synthesized topographic data from Mars Orbiter Laser Altimeter (MOLA) and images from the Mars Orbiter Camera (MOC) on board the Mars Global Surveyor orbiter

This enhanced-color HIRISE image shows the north polar layered deposits at top and darker materials at bottom exposed in a scarp at the head of Chasma Boreale, a large canyon eroded into the layered deposits. The polar layered deposits appear red because of dust mixed within them, but are ice-rich as indicated by previous observations.

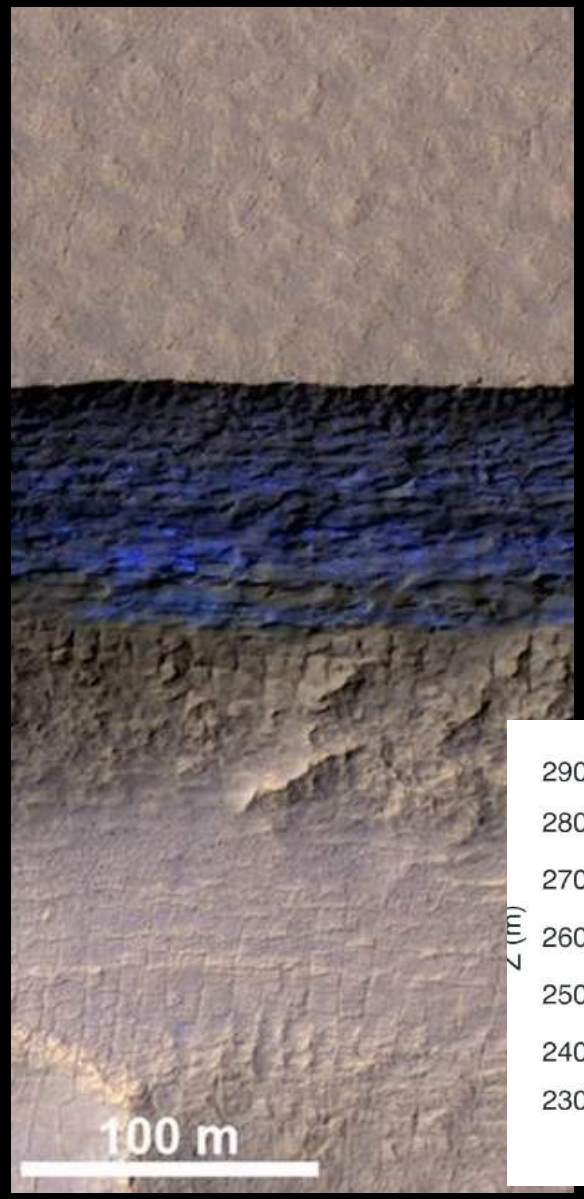


- This image(1) shows a cross-section of a portion of the north polar ice cap of Mars, derived from data acquired by the Mars Reconnaissance Orbiter's Shallow Radar (SHARAD)
- The ice depicted in this graphic is approximately 2 kilometers (1.2 miles) thick and 500 kilometers (310 miles) across.
- Overall it is estimated that there is 1.7 million km^3 of ice yielding a GEL of 12m(2)
- This compares with 2.85 million km^3 for the Greenland ice cap
- Together with the south polar region this gives a GEL of 23m

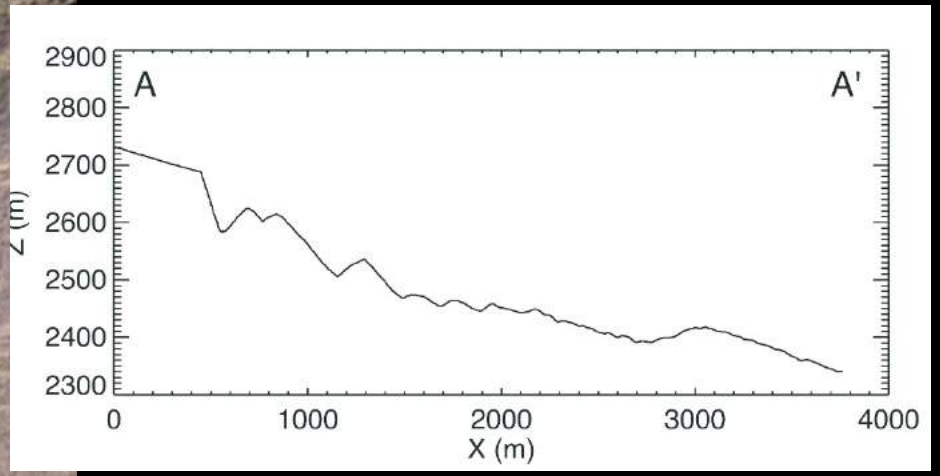


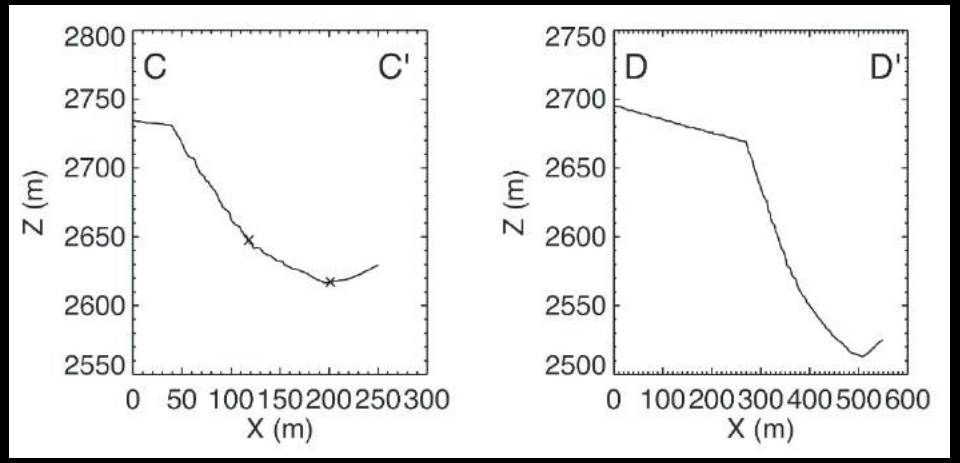
The Shallow Radar instrument on NASA's Mars Reconnaissance Orbiter has detected widespread deposits of glacial ice in the mid-latitudes of Mars. This map of a region known as Deuteronilus Mensae(44N, 337W), in the northern hemisphere, shows locations of the detected ice deposits in blue.

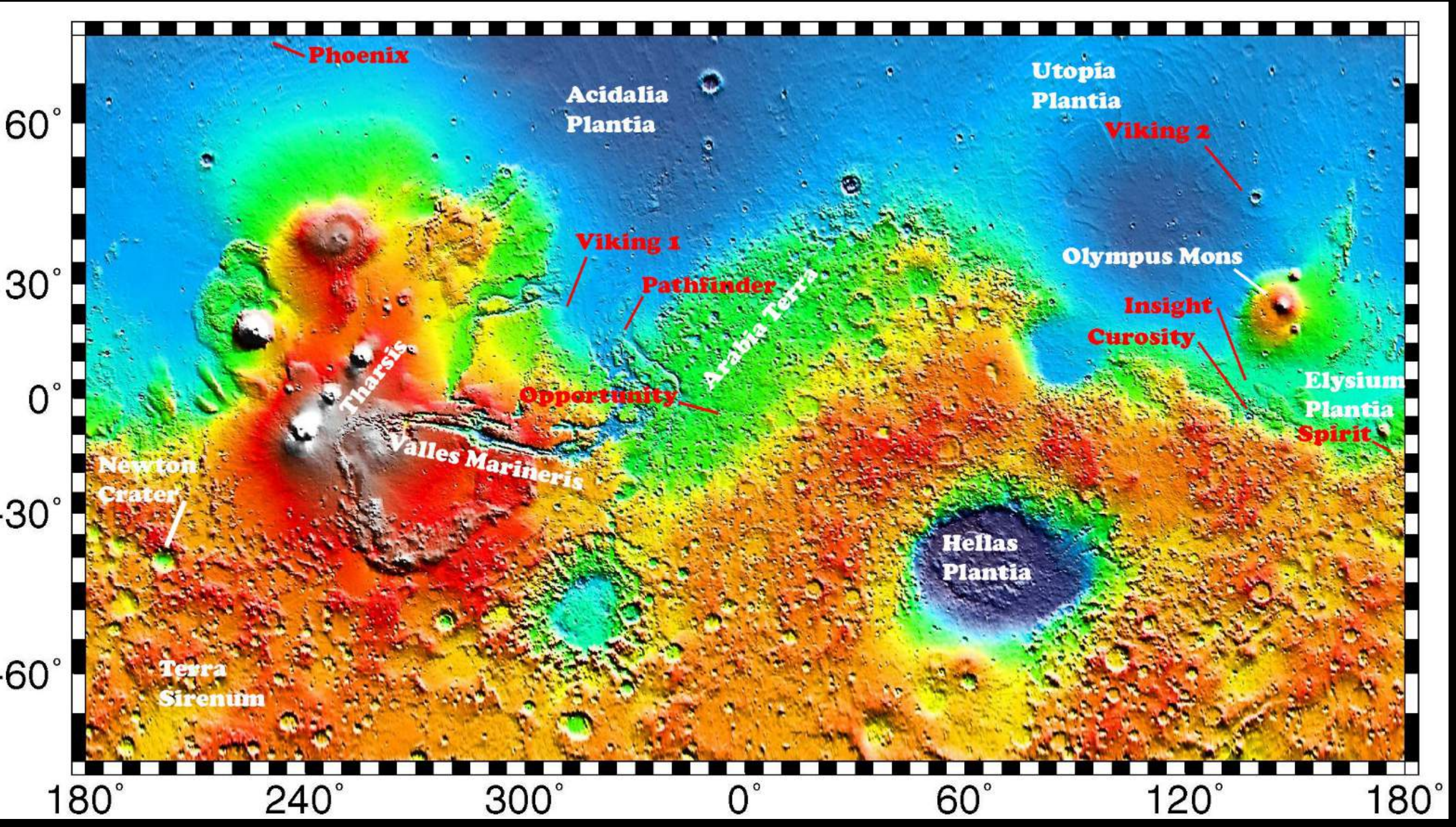
Recent Discoveries of Massive Amounts of Mid-Latitude Buried Ice



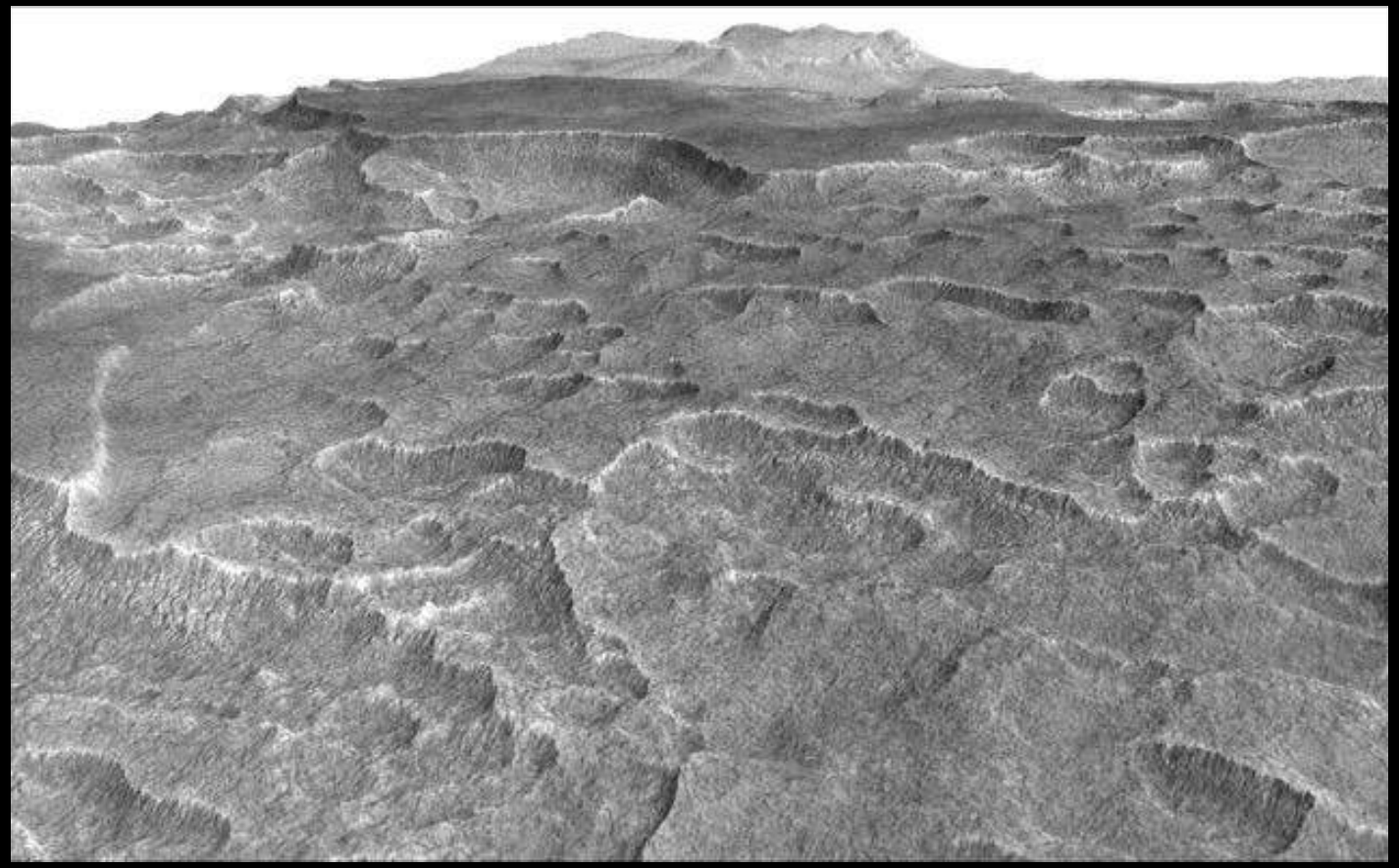
- Using the Mars Reconnaissance Orbiter (MRO) HIRISE camera and SHARAD shallow radar eight steep and eroded scarps at mid latitudes across Mars were investigated. (1,2)
- Seven of these scarps were located near 55 degrees South and one was located at 55 degrees North
- At each of these locations, they found thick shelves of relatively pure water ice located as little 1 meter below the planet's surface and extending over 100m deep
- This ice originated as snow less than 10 Mya and was transformed into massive ice sheets preserved very close to the surface
- These results were reported in Science, Jan 12,2018





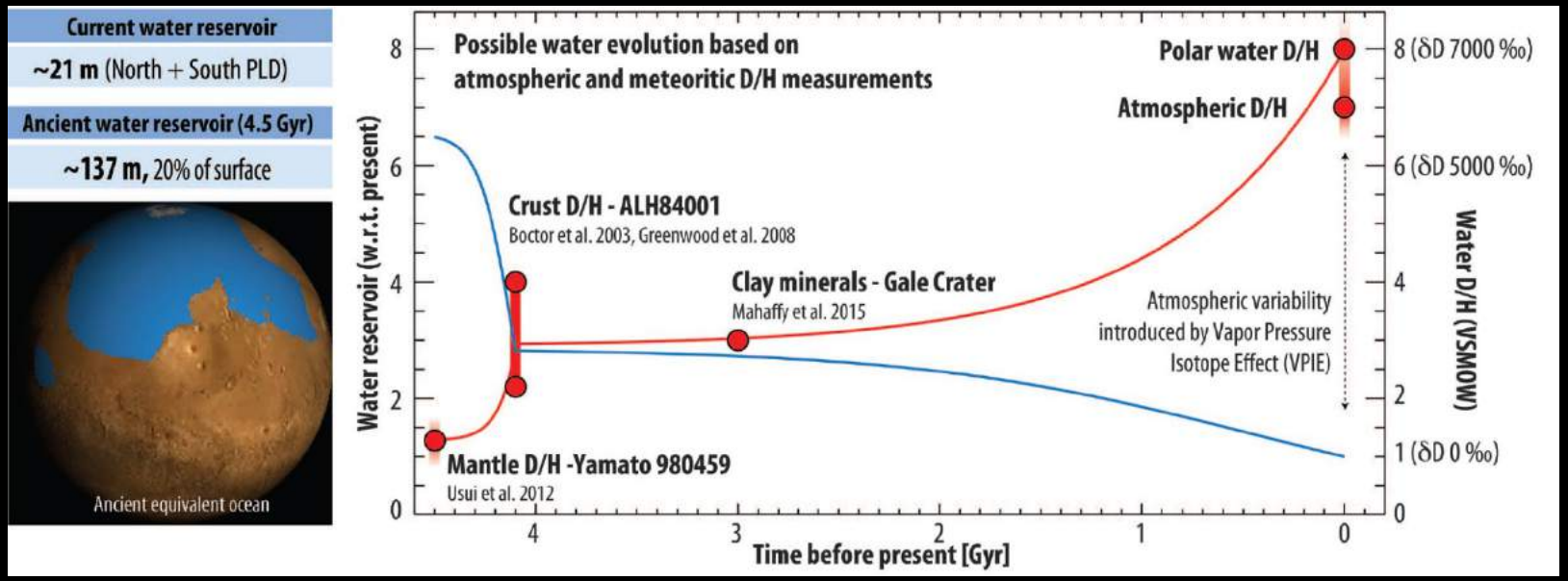

Phoenix
Acidalia Plantia
Utopia Plantia
Viking 2
Viking 1
Pathfinder
Arabia Terra
Olympus Mons
Insight
Curosity
Tharsis
Opportunity
Elysium Plantia
Spirit
Valles Marineris
Newton Crater
Hellas Plantia
Terra Sirenum
60°
30°
0°
-30°
-60°
180°
240°
300°
0°
60°
120°
180°

Recent Discoveries of Massive Amounts of Mid-Latitude Buried Ice



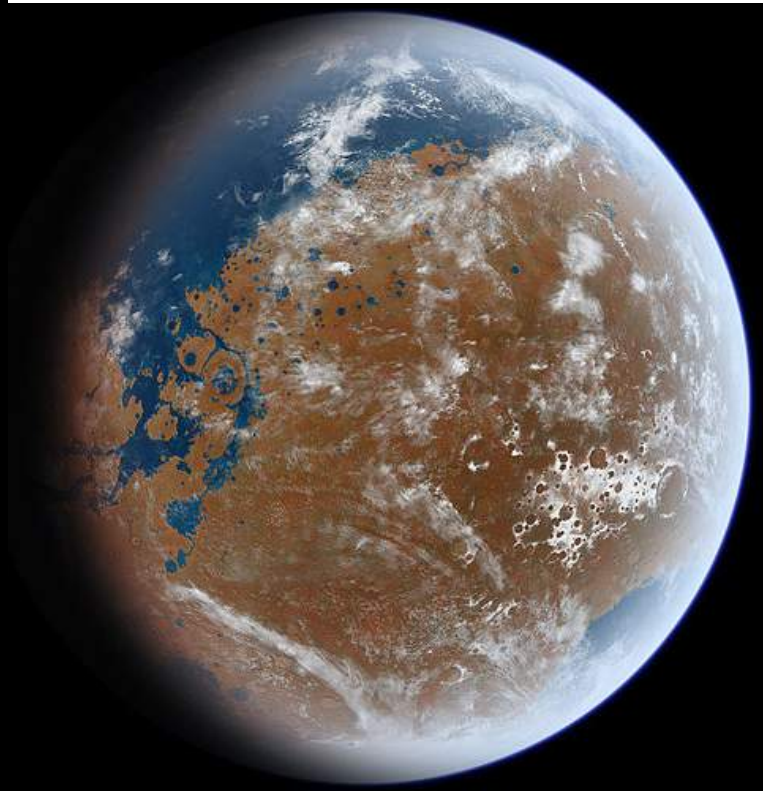
Together with the polar ice the estimate is that 5 million km^3 of ice remain on Mars(3) which amounts to a Global Equivalent Layer of 35m(115')

- This vertically exaggerated view shows scalloped depressions in Mars' Utopia Planitia region, one of the area's distinctive textures that prompted researchers to check for underground ice
- More than 600 overhead passes with the MRO's Shallow Radar (SHARAD) instrument provided data for determining that about as much water as the volume of Lake Superior lies in a thick layer(1)
- Another region also in the Arcadia Plantia was found with a similar amount of water ice(2)
- These ice layers are estimated to have originated 10-20Mya(3) and a third to a half of the original have been preserved
- These results were reported in 2015 and 2016



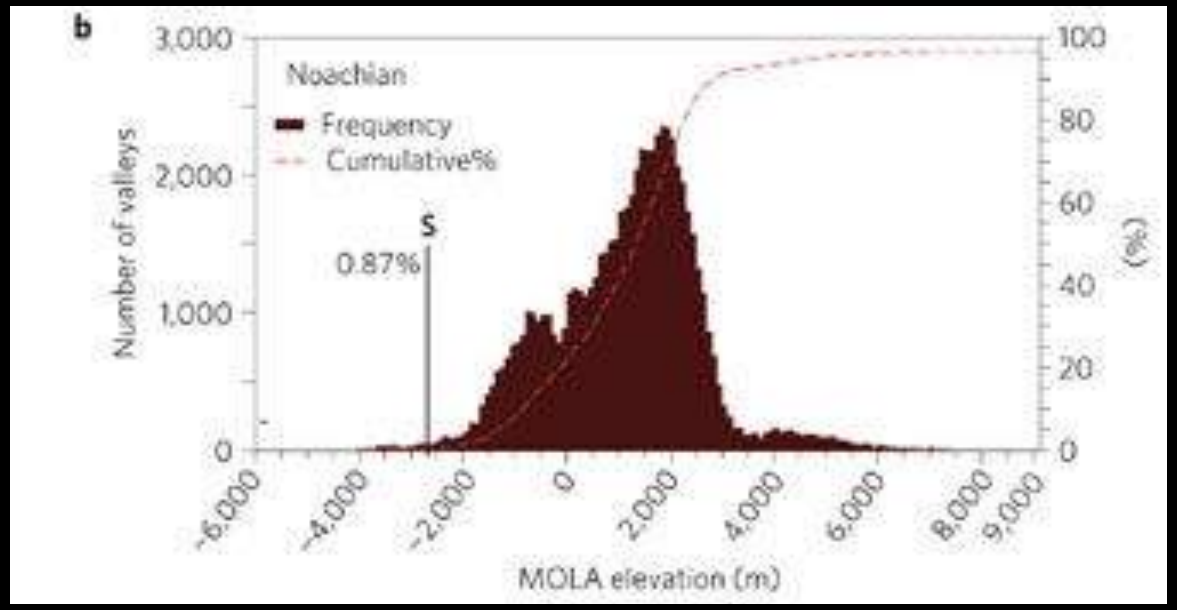
Evidence for Oceans on Ancient Mars

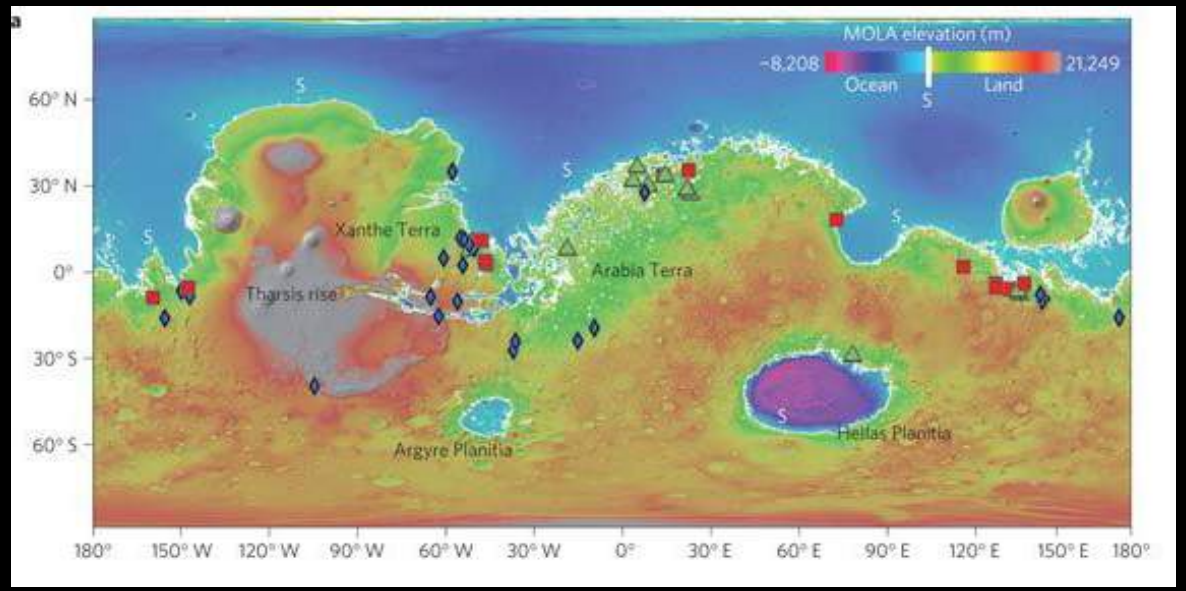
- Earth based measurements of Hydrogen Deuterium water(HDO) and regular water(H20) have been made for Mars at different times of the year(1)
- The D/H ratio overall is 8 for polar ice and 7 in the atmosphere compared to 1 on Earth



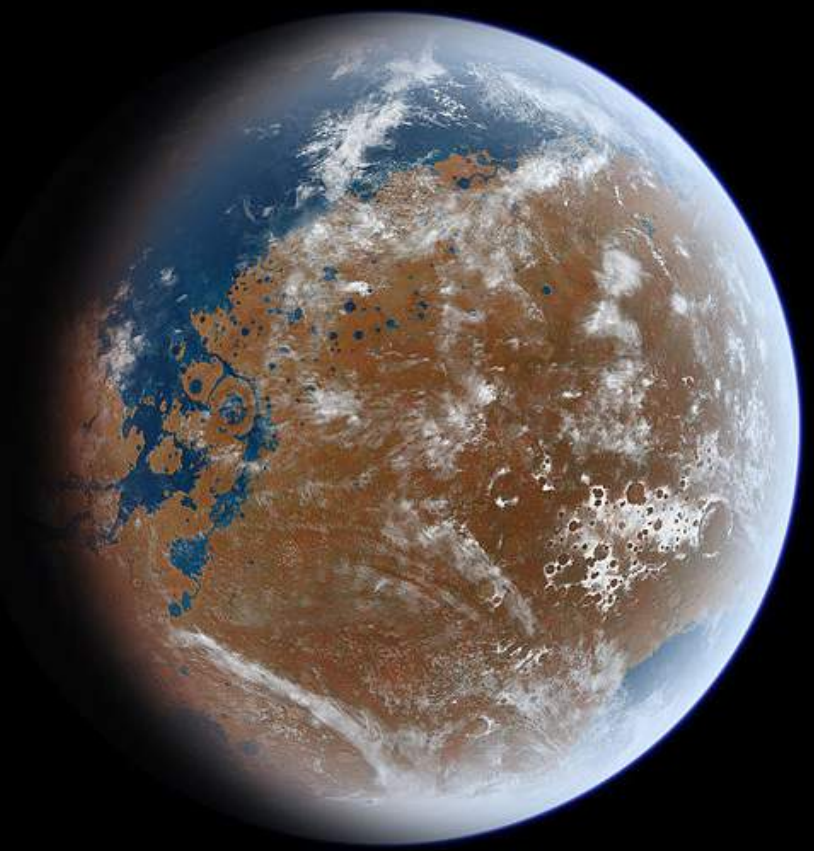
- Using this data together with measurements by Curiosity of clays and in meteoritic records 4.5Bya(2) the estimate is that a volume 6.5 times larger than the volume in the polar caps now has been lost . (1,3)
- This implies that the loss of water from Mars occurred in stages with a substantial amount of water being lost in the first 0.5 billion years.
- That means the volume of Mars' early ocean must have been at least 20 million km^3
- This translates to a global depth of 137m GEL(Global Equivalent Layer) and would likely occupy 19% of the Martian surface(3)
- This compares to 16% occupied by the Atlantic ocean on earth and 71% of the entire earth covered by water

Water on Ancient Mars





- A 2010 study using topography from the Mars Observer Laser Altimeter(MOLA) has reconstructed the shoreline of a vast ocean covering the northern hemisphere of Mars around 3.5 billion years ago.
- The chart at left determines a probable shoreline at -2700m based on having 99% of the valleys above this elevation
- The lower plot shows the outline of the proposed shoreline and if filled would be 124 million km³.
- Such as ocean would have covered 36% of the Mars and would have resulted in a GEL of 550m
- The watershed for such an ocean would have covered 75% of the planet(2)



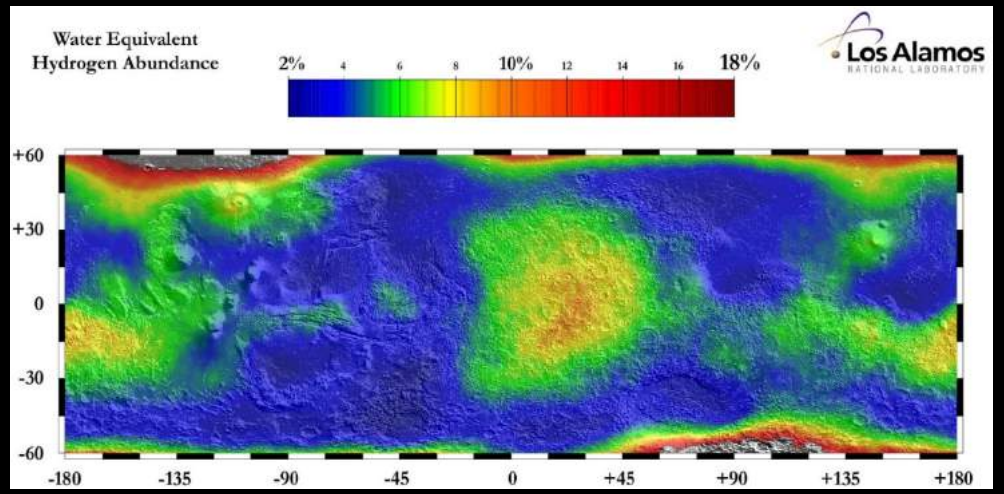
A Dense Atmosphere on Ancient Mars

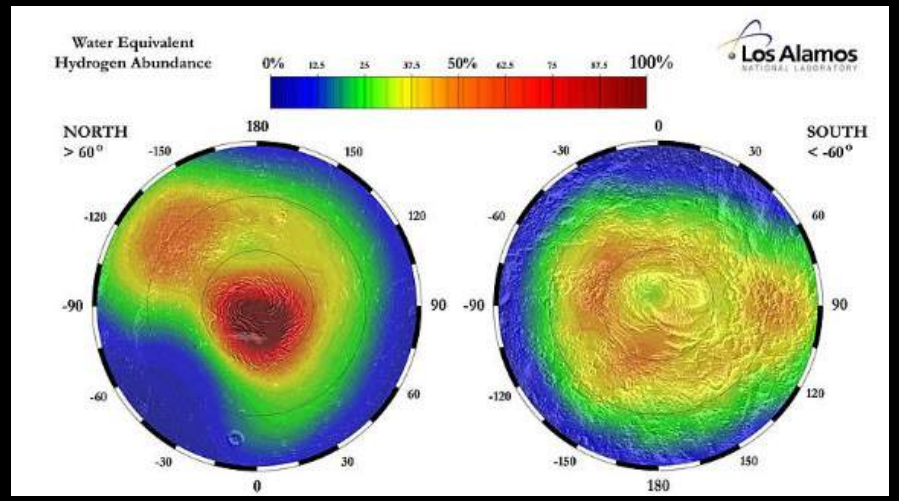
- The existence of liquid water on the surface of Mars requires both a much warmer and thicker atmosphere.
- Analysis shows that the presence of CO2 would not warm the planet sufficiently particularly when the sun was 25% less bright than now(3)
- However, the potential formation of a secondary atmosphere(1,3,4) by outgassing dominated by the Tharsis volcanoes, could have provided sufficient greenhouse warming to support liquid water.
- This may have included significant quantities of H_2O, CO_2, and SO_2 which date to this period

- The end of this period at 4Bya coincides with the termination of the internal magnetic field which would have allowed evaporation, sublimation, and then unimpeded atmospheric stripping by the solar wind. (5)
- When compared with their terrestrial counterparts, $^{38}Ar/^{36}Ar$, $^{15}N/^{14}N$, and $^{13}C/^{12}C$ ratios of the Martian atmosphere are consistent with ~60% loss of Ar, N_2, and CO_2 by solar wind stripping of an upper atmosphere enriched in the lighter isotopes (6)

Where did the Water Go

- A part of the answer is that it is in the polar regions and buried underneath the present Martian crust with a Global Equivalent Layer of 35m
- Supporting this is the above plots from the Mars Odyssey spacecraft neutron spectrometer which show the proportion of water ice present in the upper meter of the Martian surface for lower(left) and higher (right) latitudes. (2)



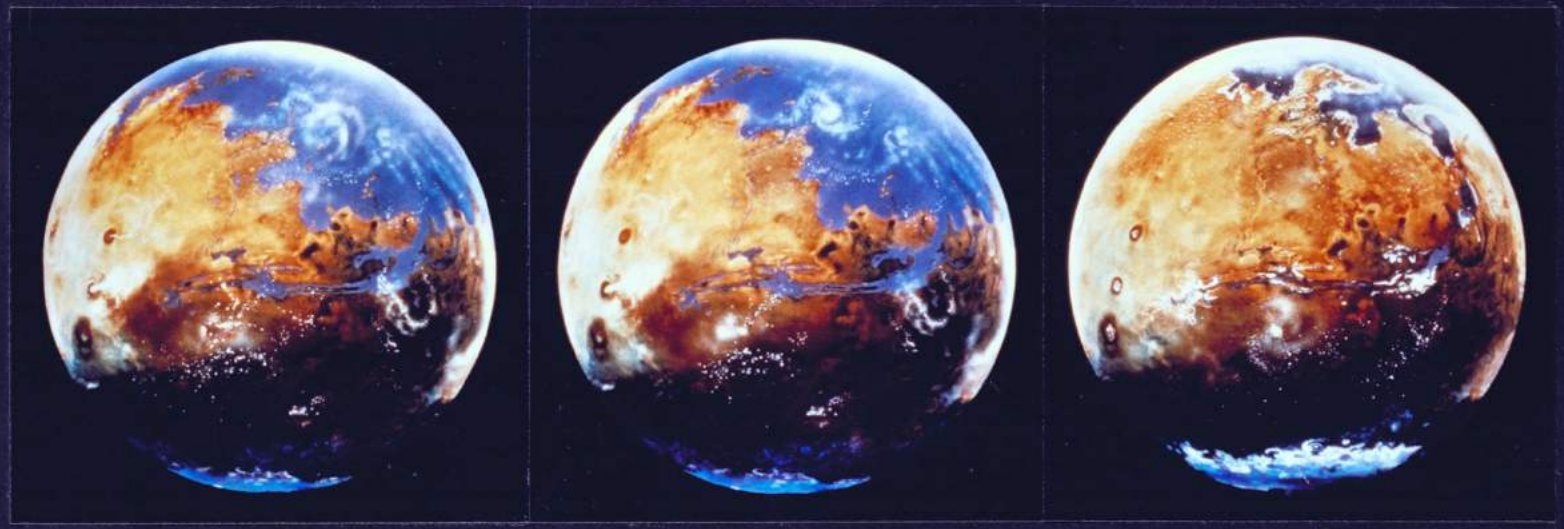


- In addition most of the rock on Mars is basalt which can be chemically weathered to incorporate water and the sulfate deposits found by Opportunity could contain 22% of water by weight(3)

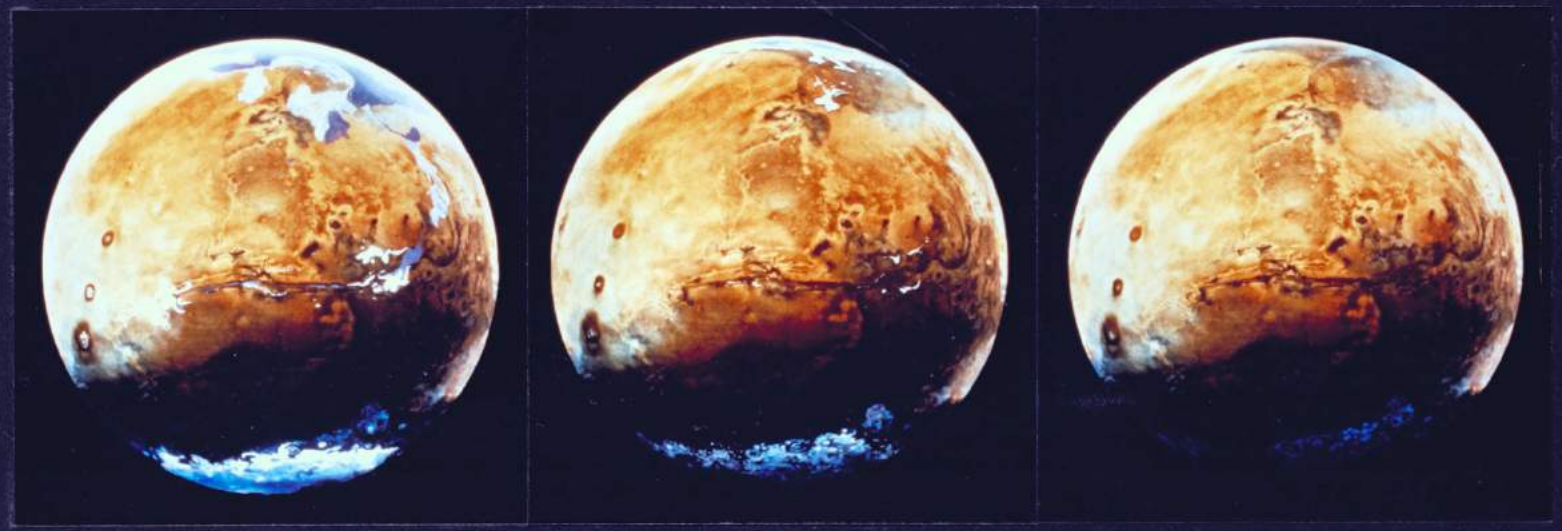
The bulk of the water is presumed to have evaporated once the atmosphere disappeared and this is supported by the high Deuterium to Hydrogen ratio of the water that remains(4)

HISTORY OF WATER ON MARS

b.y.a.



4.0 3.8 3.5

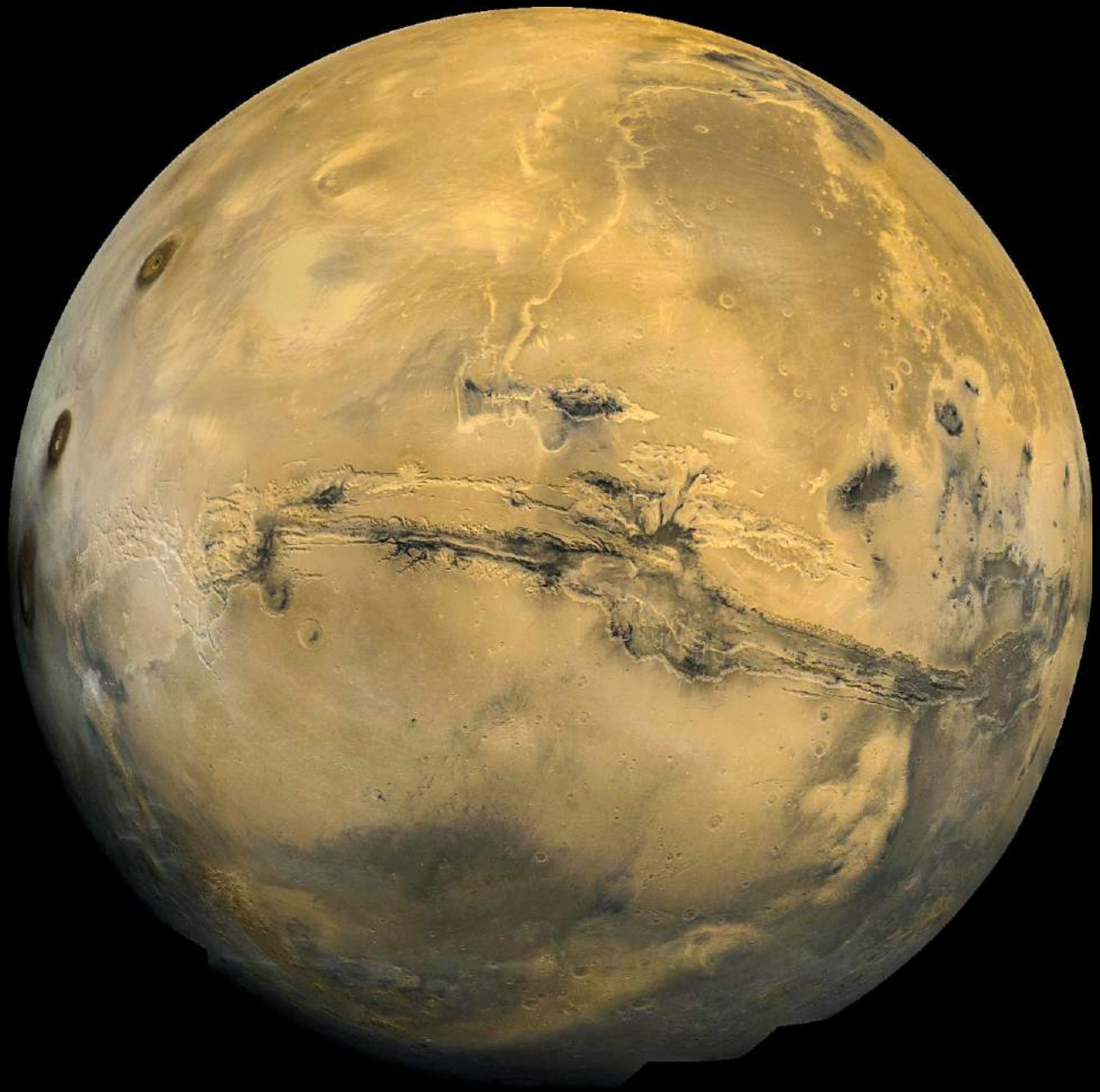


2.0 1.0 Now

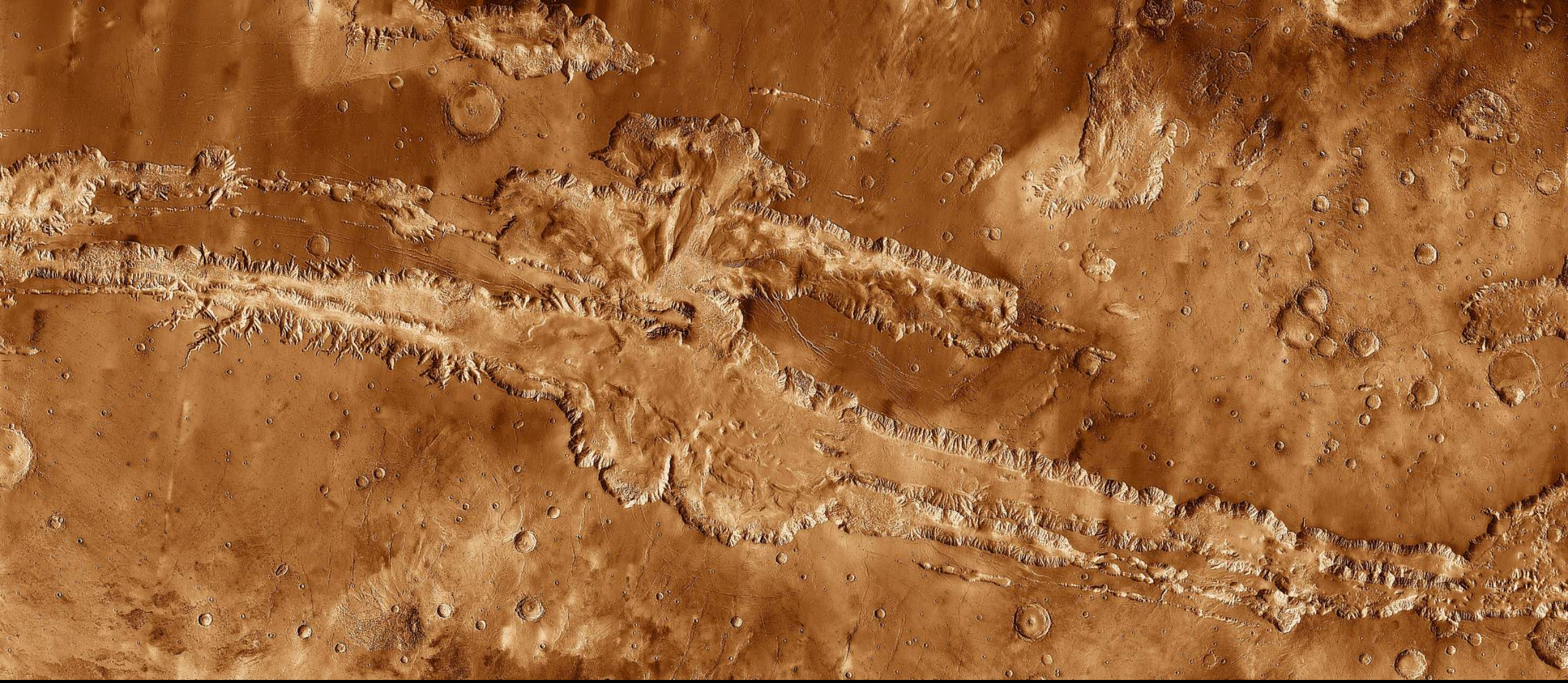
Mars Water Summary

- The issue of whether there is or has been water on Mars is one of the continuing major questions about Mars considering that it is necessary for life
- From previous tenuous information about the likelihood of water on Mars, the last 10 years has provided a wealth of data
- To begin with Mars at present has the equivalent of 35m of water covering the entire planet based on measurements of the polar regions as well as discoveries of large permafrost layers in the mid latitudes
- Evidence also strongly suggests that Mars once had oceans, lakes, deltas, and streams
- The data from measuring the Deuterium/Hydrogen ratio from Mar's past and present makes a very clear case for at least a 6x greater water content in the ancient past covering 19% of the planet
- Other studies of the likely shoreline of large oceans provides estimates for water coverage of up to 36% of the surface compared to 71% of the Earth
- Inaddition there is evidence that Mars once had a dense atmosphere that supported these water resources until the Mars magnetic field vanished about 4 Bya

Images of Mars



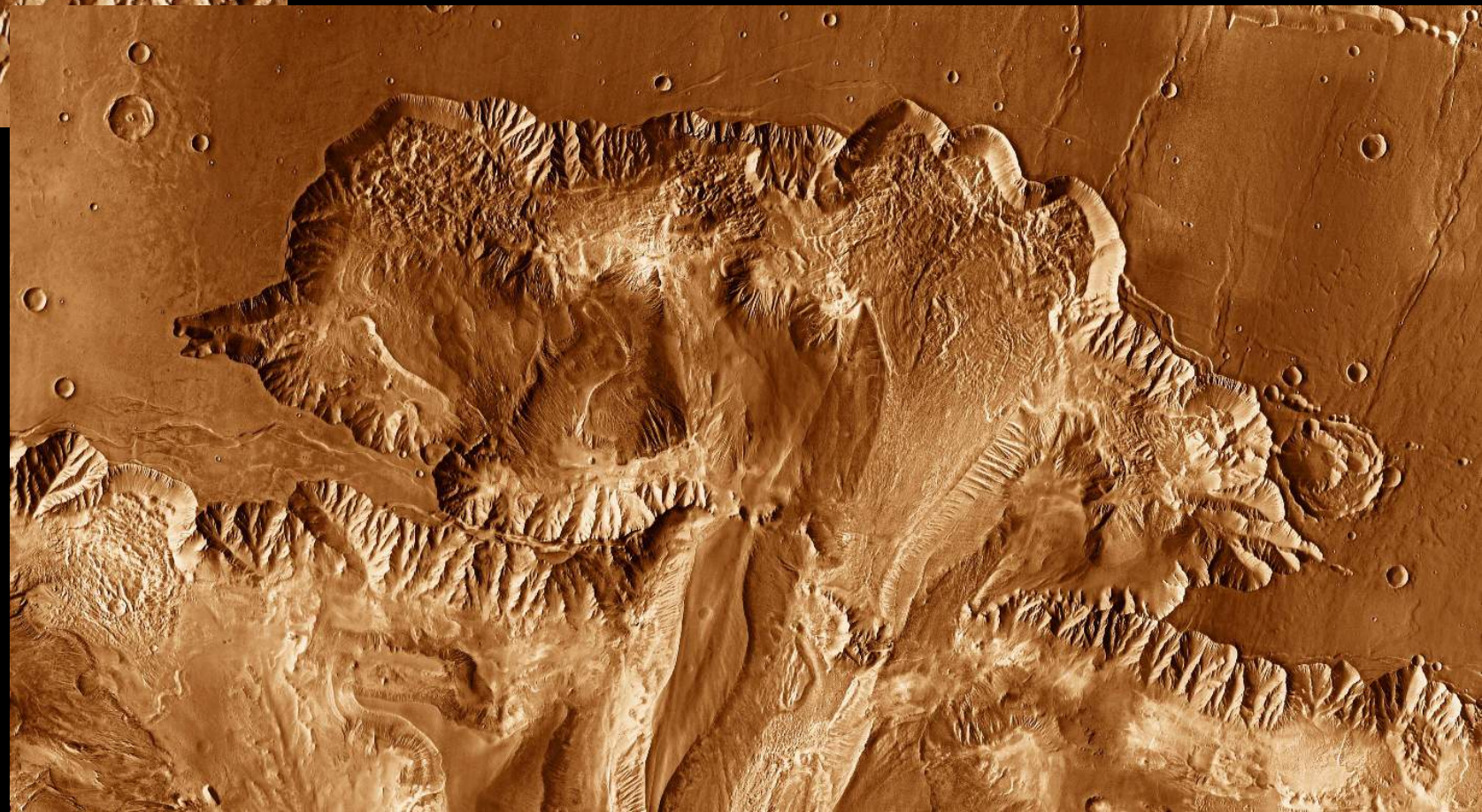
- Valles Marineris (named after the Mariner 9 Mars orbiter of 1971–72 which discovered it) is a system of canyons that runs along the Martian surface
- The Valles Marineris is the largest canyon in the Solar System and cuts a wide swath across the face of Mars.
- The canyon extends over 4,000 km, spans as much as 600 km across, and delves as much as 8 km (24000’)deep.
- By comparison, the Earth's Grand Canyon in Arizona, USA is 800 kilometers long, 30 kilometers across, and 1.8 km deep.



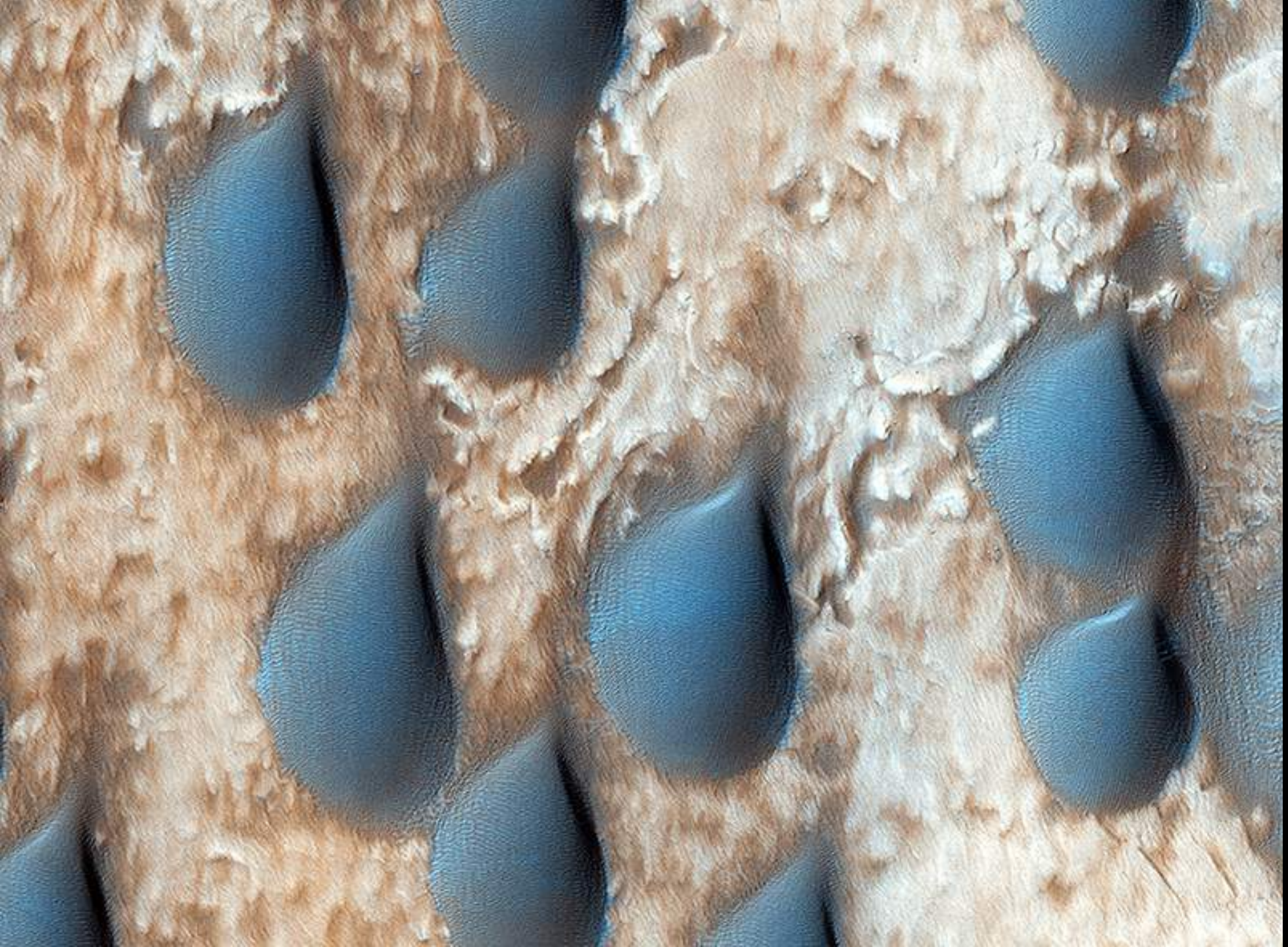
- The above infrared image was taken by the Themis thermal imaging camera on the 2001 Mars Odyssey
- The origin of the Valles Marineris remains unknown, although a leading hypothesis holds that it started as a crack billions of years ago as the planet cooled and has grown since through erosion
- It is 2500mi long and 4mi deep compared to the Grand Canyon which is 500mi long and 1mi deep

Ius Chasma image mosaic from 2001 Mars Odyssey orbiter, showing side canyons created by ground water sapping.

This section which looks like a flower is the north most portion

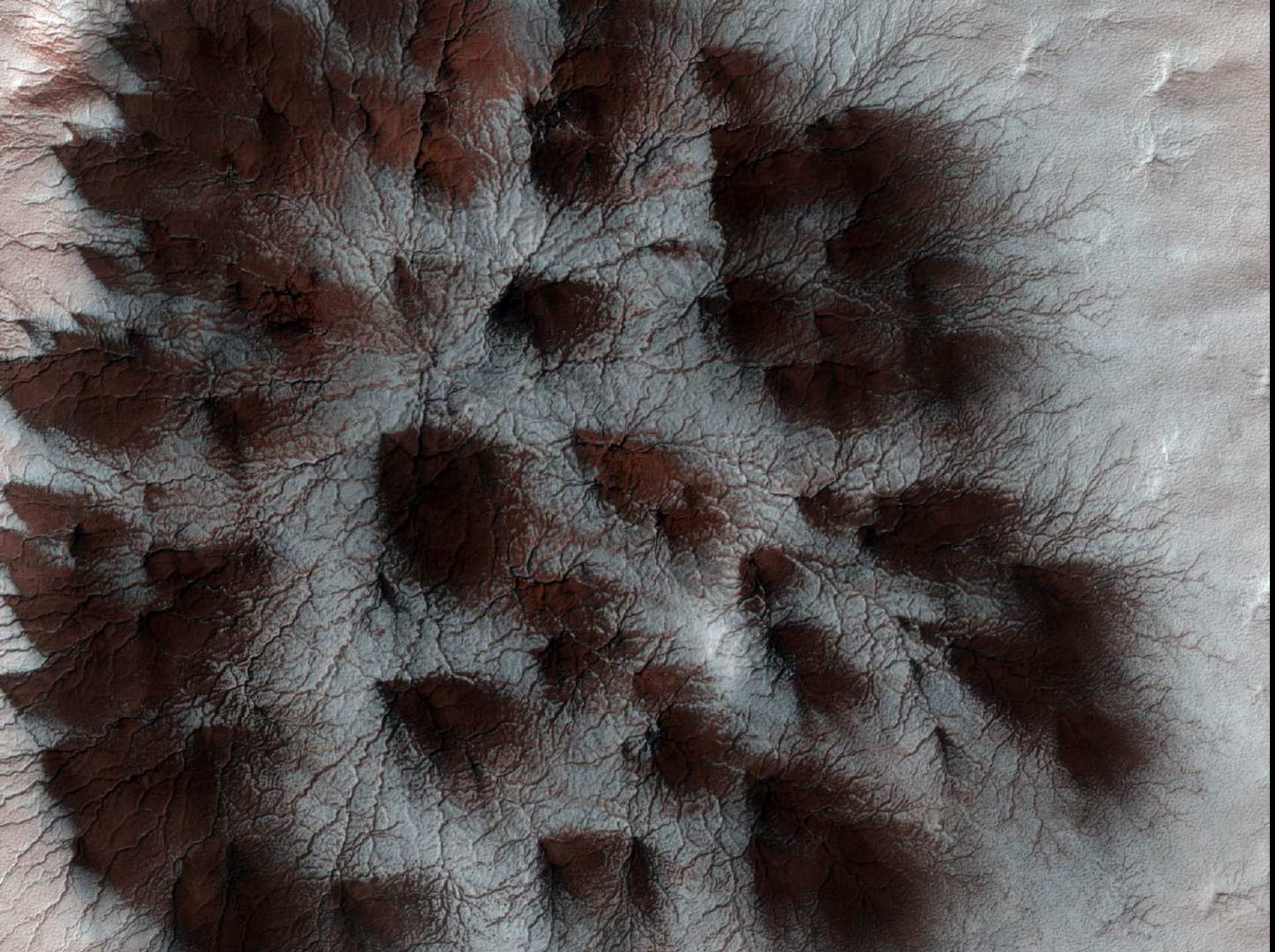


HIRISE image of sand dunes covered with seasonal carbon dioxide frost, about 1km across and is 80N, 156E



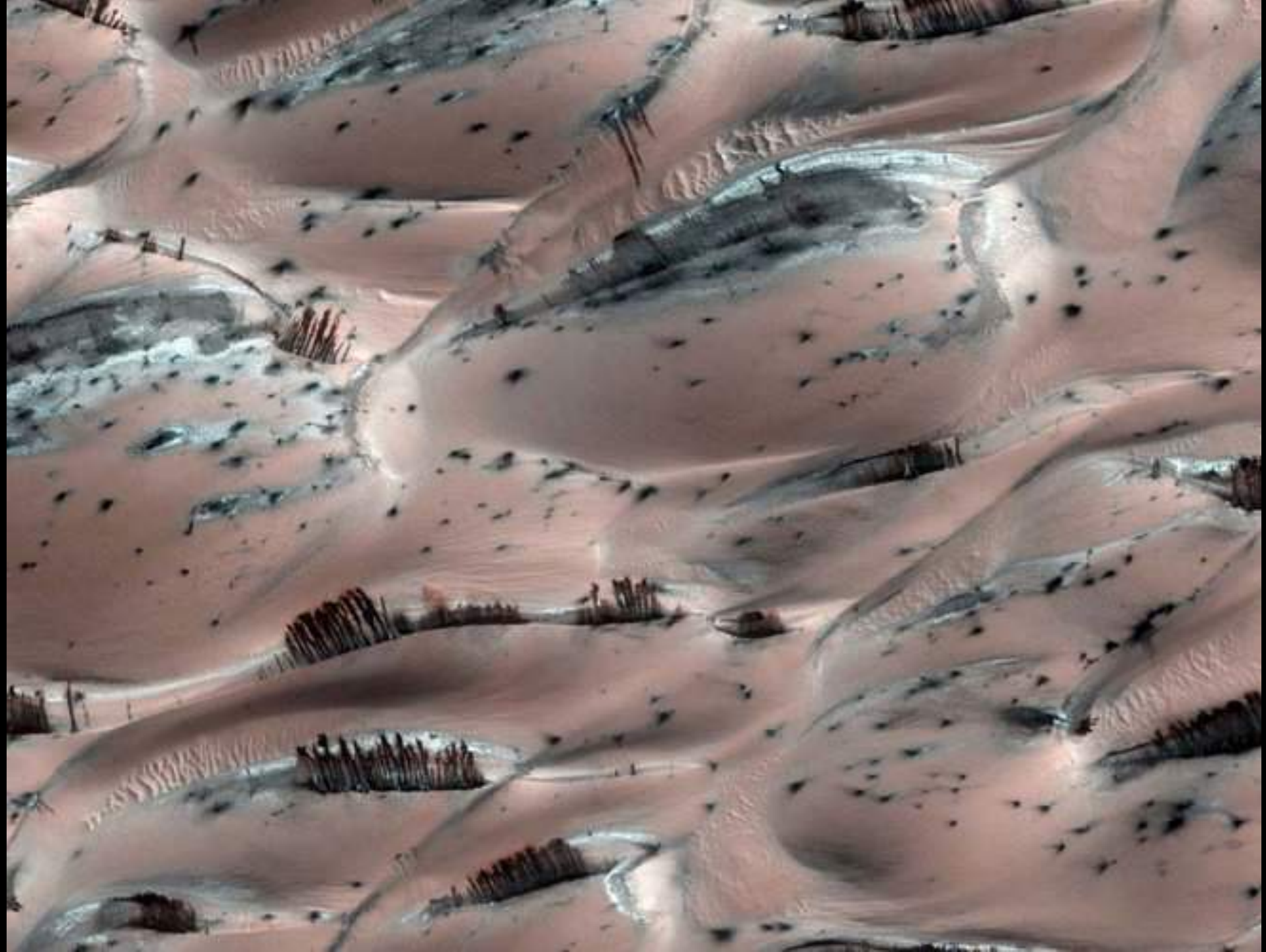
HIRISE image that look like raindrops, but are olivine rich sand dunes located in the Copernicus crater. The location is 48S, 192E, and is about 1km across

Sequences of cyclic sedimentary rock layers exposed in an unnamed crater (located at 8N, 353E) in Arabia Terra, Mars.



Solid carbon dioxide, commonly known as dry ice, thaws directly to gas and forms starburst patterns under the seasonal carbon dioxide ice caps when spring comes to Mars' polar regions.

This HIRISE image show portions of the Martian surface in unprecedented detail. This one shows many channels from 1 meter to 10 meters wide on a scarp in the Hellas impact basin.



What appears to be trees rising from the Martian surface are actually dark streaks of collapsed material running down sand dunes due to carbon dioxide frost evaporation.

This HIRISE image has captured a Martian avalanche, or debris fall, in action. It was taken on February 19, 2008,

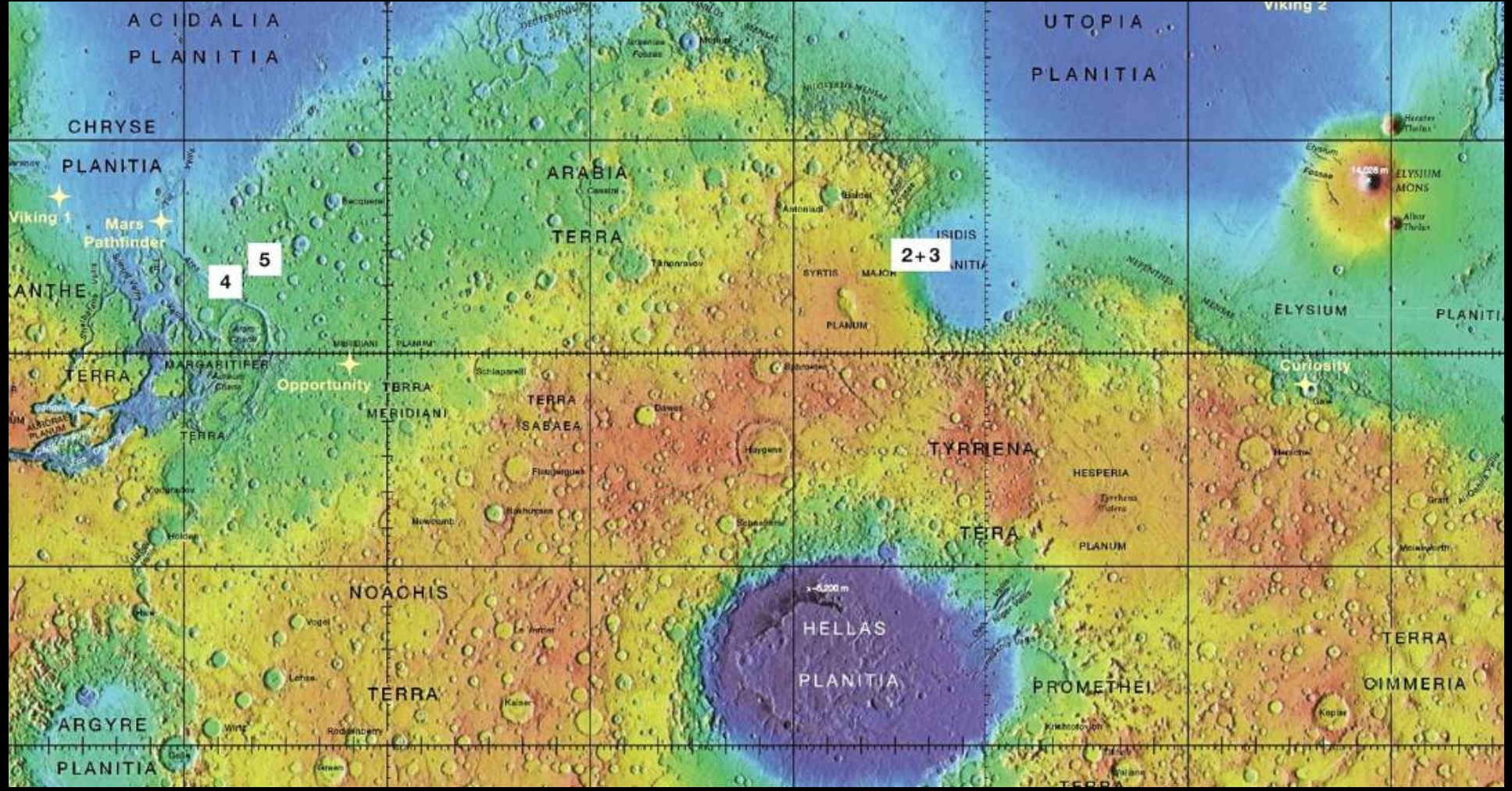
This HIRISE image was captured by on Nov. 19,2012. Scientists know the feature formed sometime between July 2010 and May 2012, "The crater spans approximately 100 feet (30 meters) in diameter and is surrounded by a large, rayed blast zone

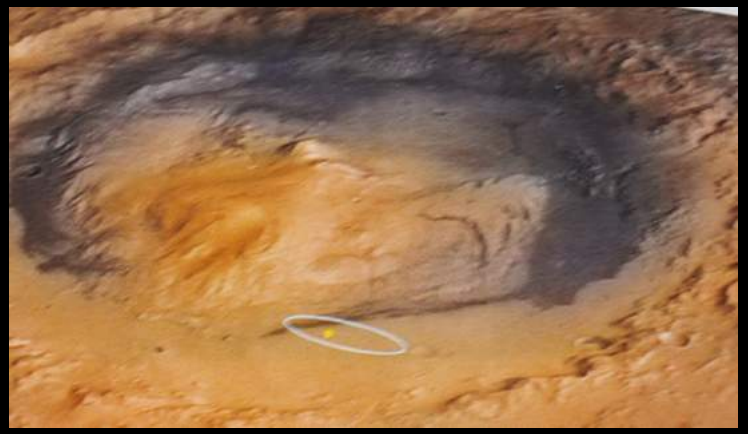
HIRISE image of dark streaks down Acheron Fossae, a 700 kilometer long trough. Streaks are likely caused by dark sand sliding down the trough.

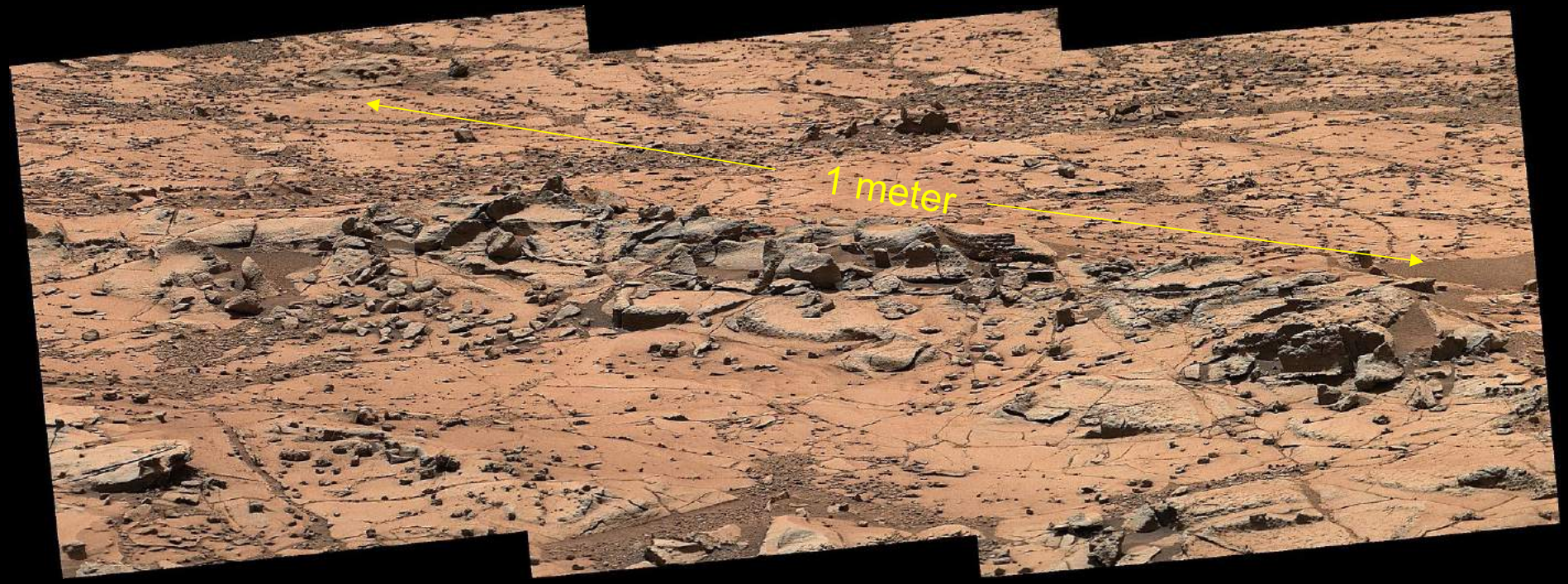
South polar area by ESA

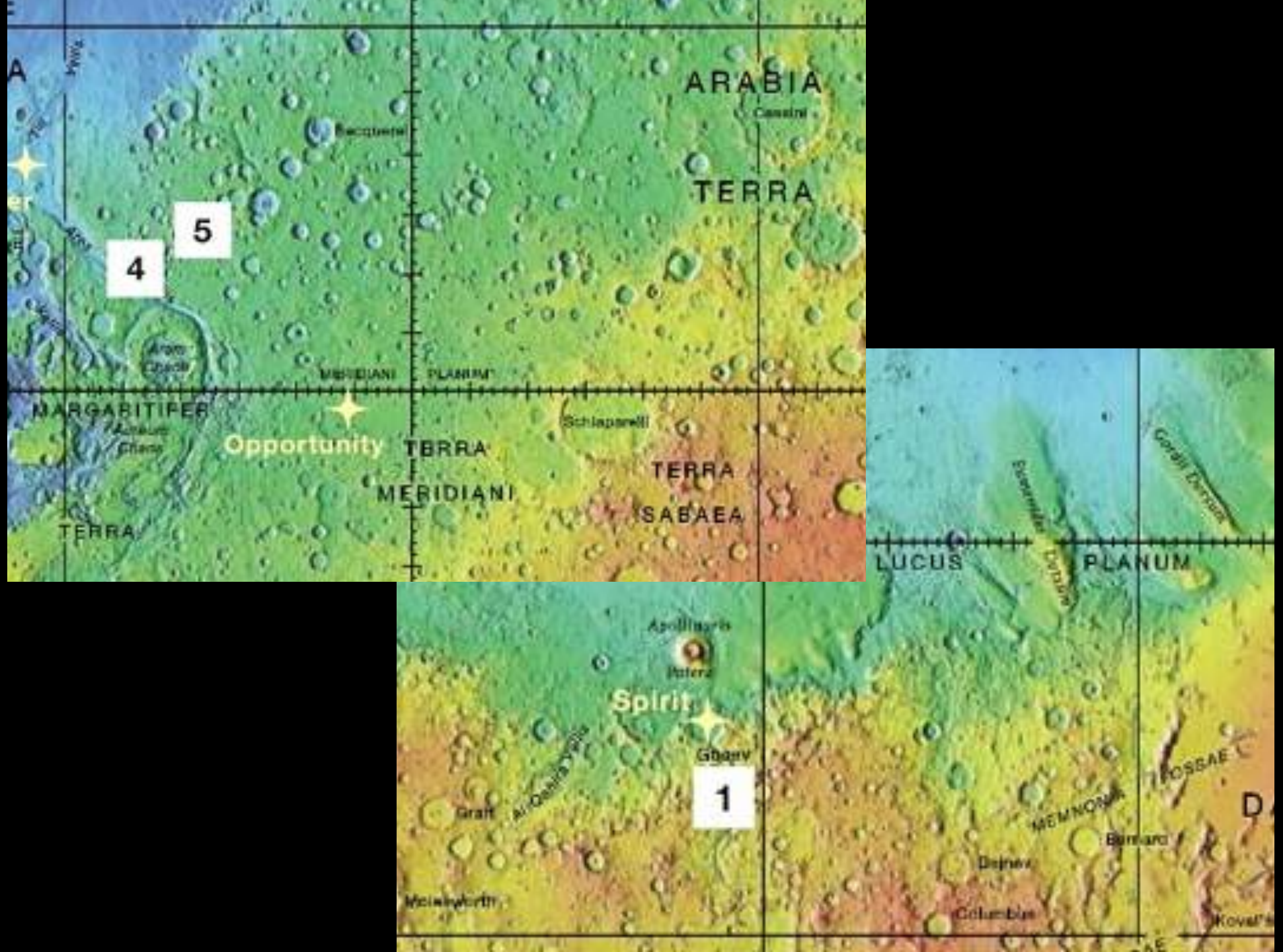
HIRISE image of gullies Formed From CO_2 Defrosting or Weight Last Season

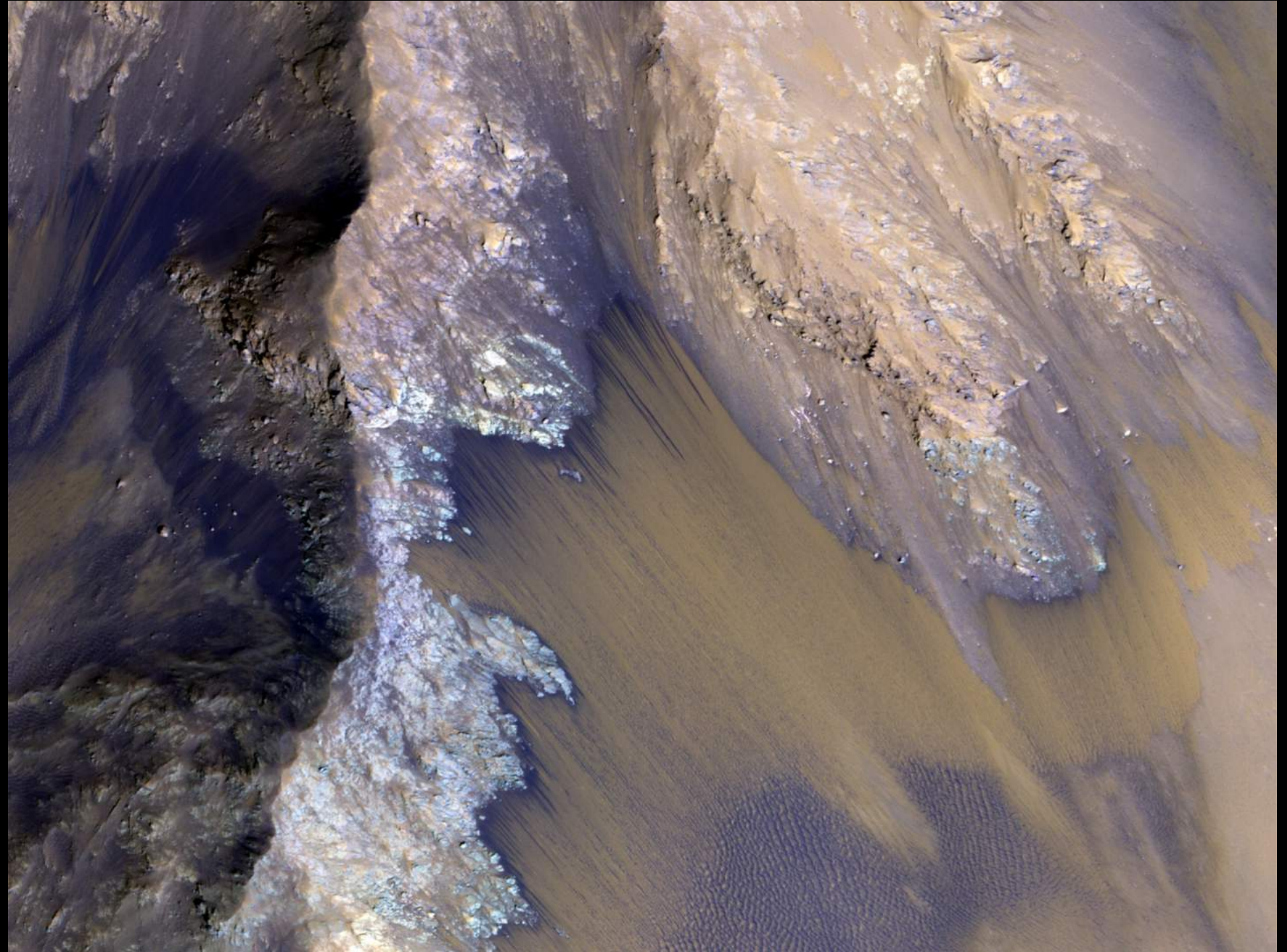

~5 cm
centimeters
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20


ACIDALIA
PLANITIA
CHRYSE
PLANITIA
UTOPIA
PLANITIA
Viking 2
Viking 1
Mars
Pathfinder
4
5
ARABIA
TERRA
2+3
ISIDIS
SYRTIS
MAJOR
PLANUM
ELYSIUM
MONS
ELYSIUM
PLANITIA
MARGARITIFER
TERRA
Opportunity
TERRA
MERIDIANI
TERRA
SABAEA
TERRA
Curiosity
TYRRHENA
HESPERIA
PLANUM
NOACHIS
TERRA
HELLAS
PLANITIA
PROMETHEI
TERRA
CIMMERIA
ARGYRE
PLANITIA



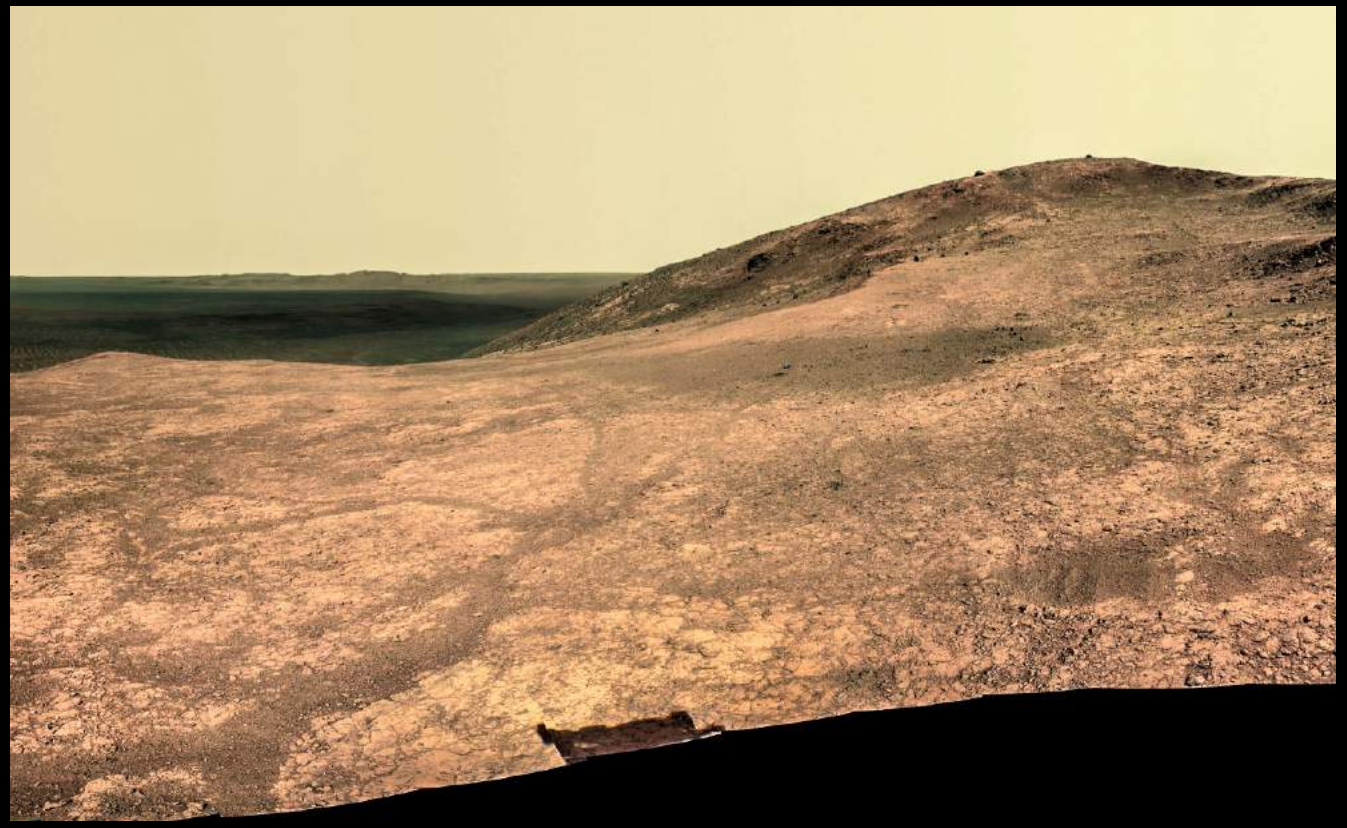

1 meter


ARABIA
TERRA
5
4
MARGARITIFER
Opportunity
TERRA
MERIDIANI
Schiaparelli
TERRA
SABAEA
TERRA
LUCUS
PLANUM
Spirit
1
MEMNONIA
Daniell
Columbus

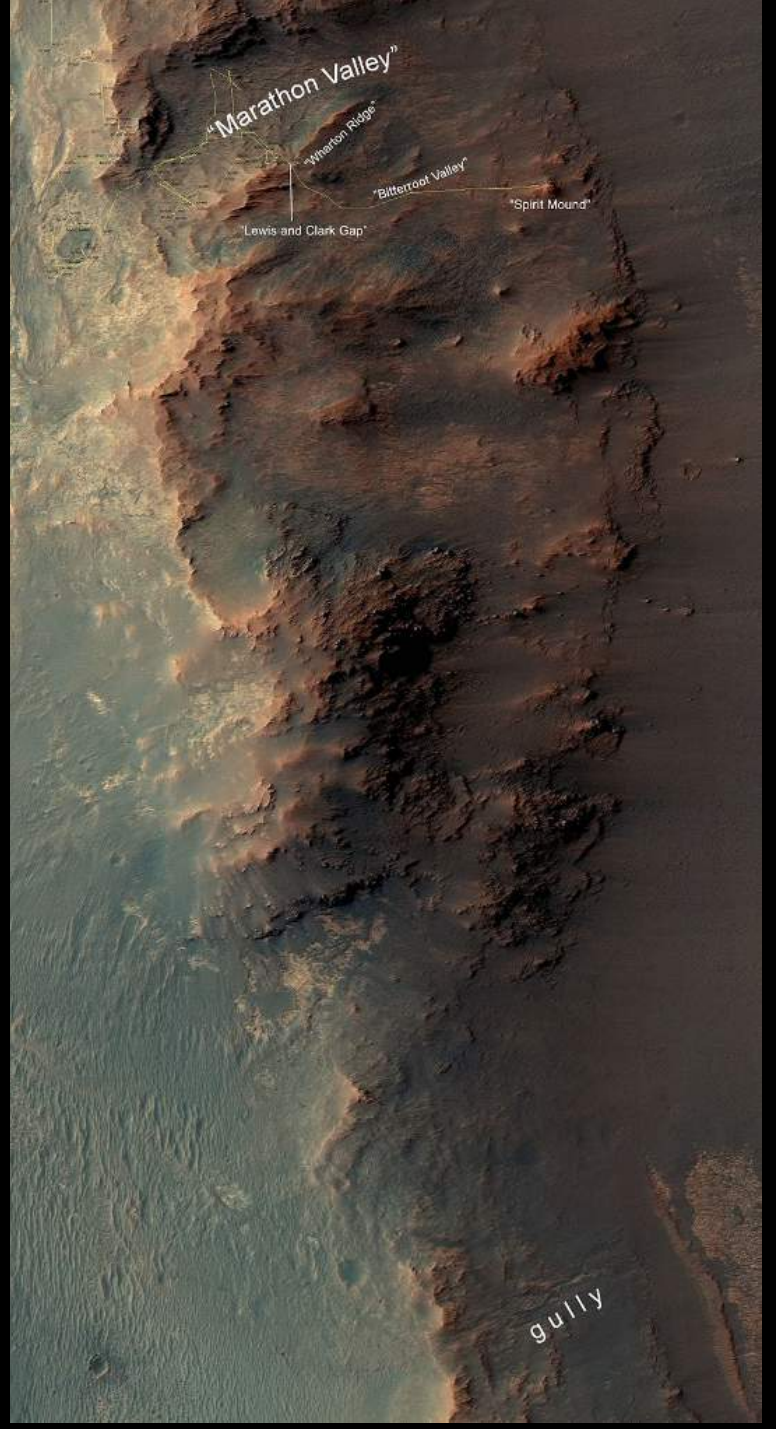


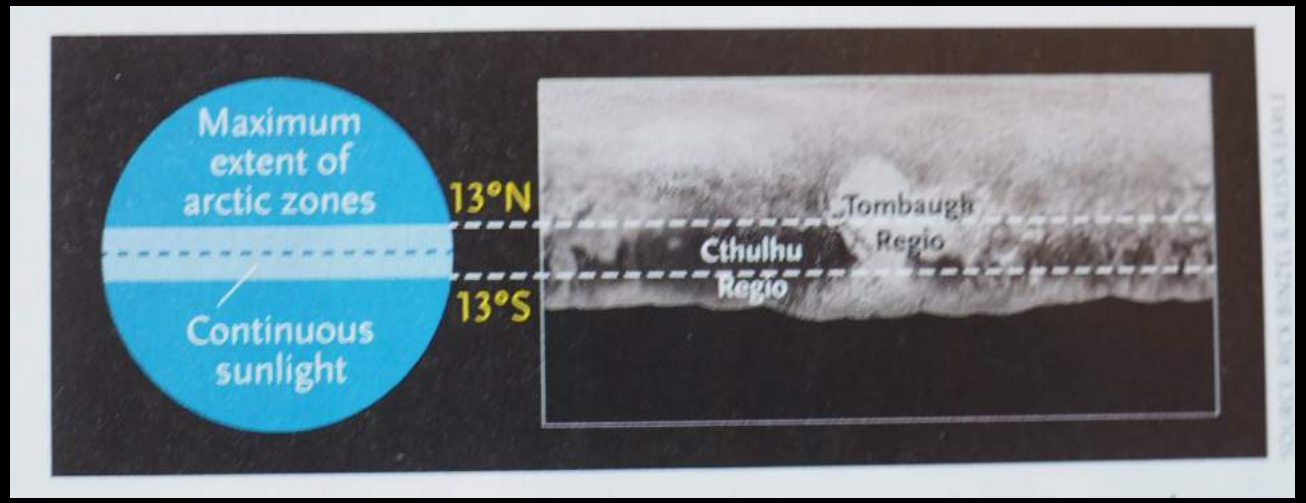
Seasonal flows
of salty water

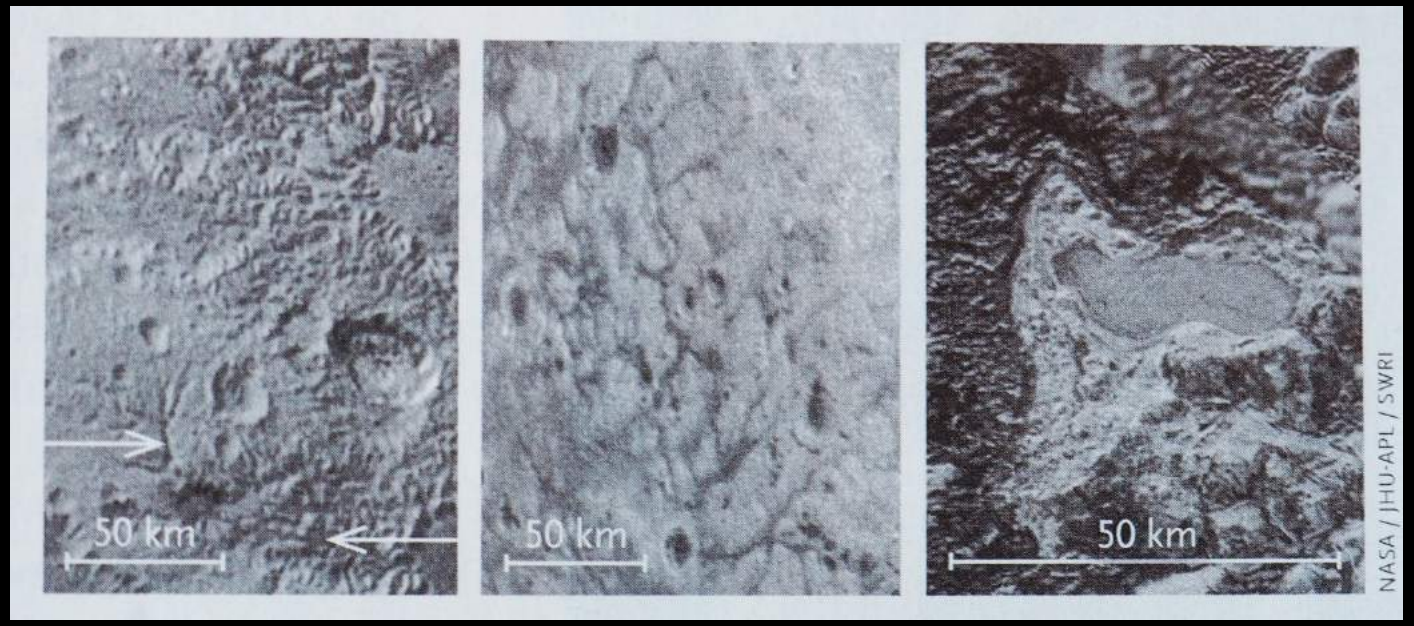

30 cm
40 cm



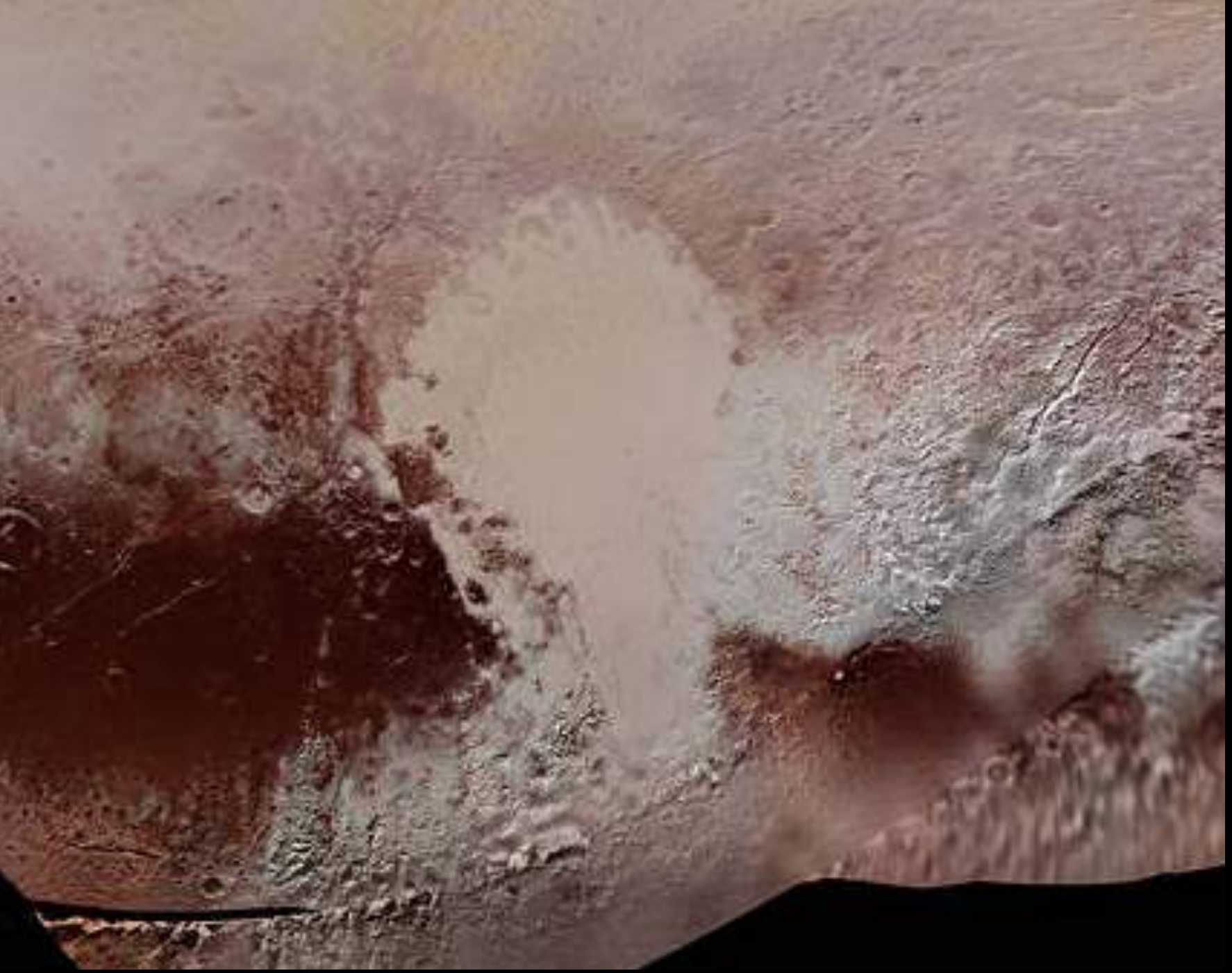
- This image shows a portion of Endeavour Crater's western rim that includes the "Marathon Valley"
- Opportunity entered the northern end of the mapped area in January 2015 and entered Marathon Valley in July 2015. This marked a “Marathon” or 26mi in distance for Opportunity
- The gully near the south end of the map was incised into Endeavour's rim long, possibly a water-lubricated debris flow or a flow with mostly water.
- Driving into this gully is one of the goals for a mission extension ending in September 2018.
- http://earthsky.org/space/video-sweep-across-mars-marathon-valley





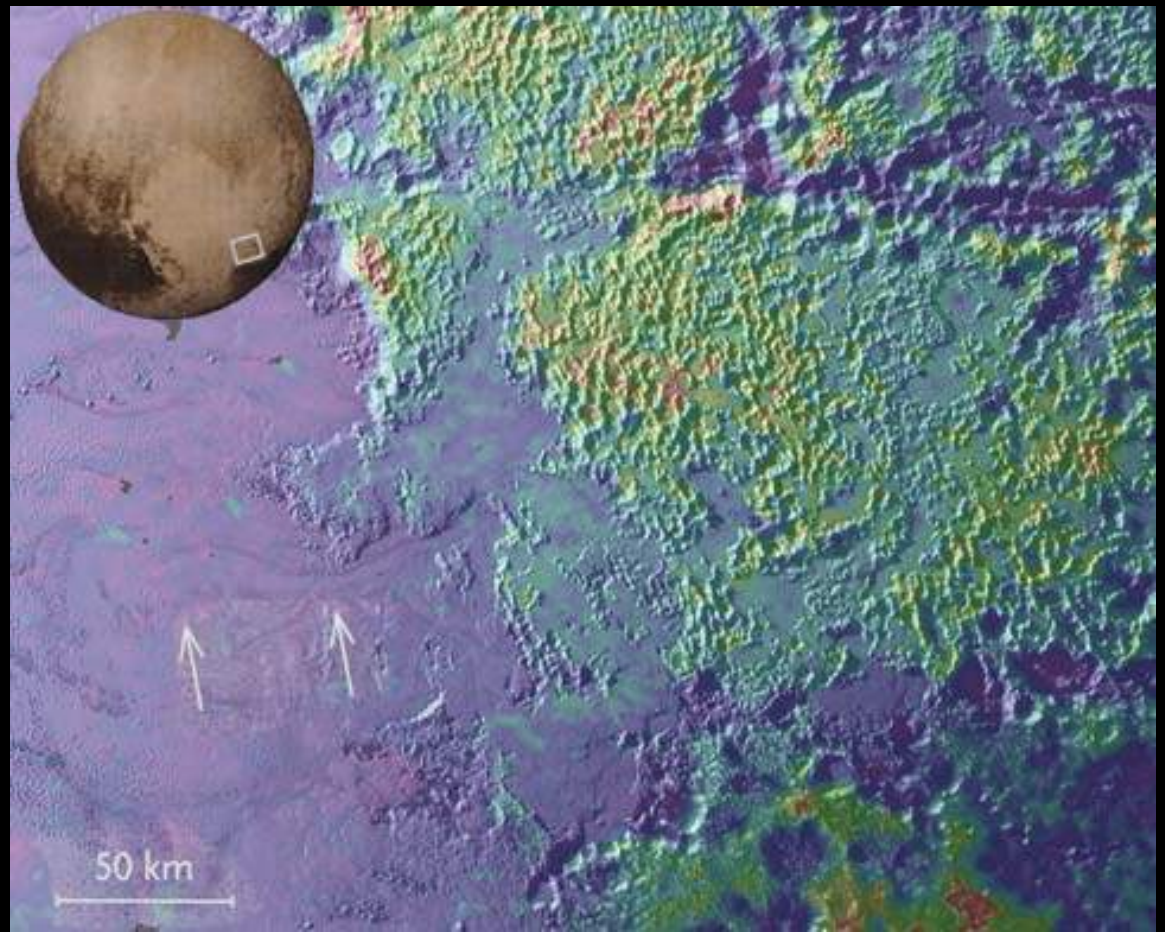


- Due to its extreme tilting of its polar axis, Pluto has very large polar regions and only a small tropic region that always has sunlight
- The temperatures in this band vary from 43K in the nearly black Cthulhu Regio to 37K in the Tombaugh Regio(1)
- Also, its axis of tilt varies between 103 deg and 127 deg over a 2.8 million year cycle and its orbit varies between 2.8 billion miles and 4.6 billion miles during its 280 earth year path around the sun
- As a result Pluto has experienced a wide range of climates with the possibility that nitrogen may have flowed on the surface
- Evidence in the pictures show signs of such a flow with dendritic channels, interconnected terrain, and a frozen lake
- Analysis also shows that the atmosphere pressure could have risen to 280 millibars which is about 25% of the earth's sea level pressure

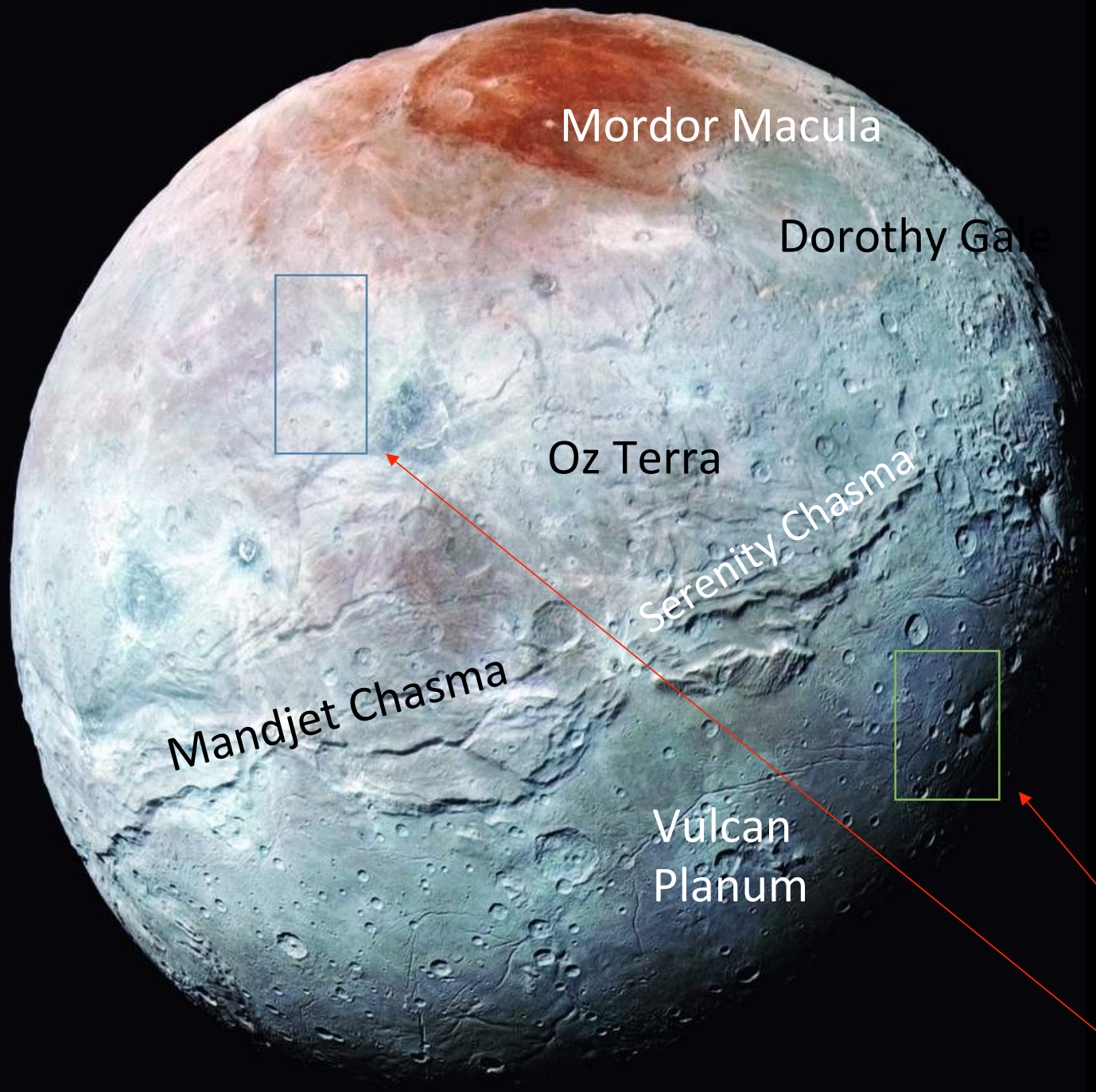


- The image is a panorama mosaic of Pluto with the equator lying in the band of reddish material called the Cthulhu Regio
- The spacecraft’s color images and near-infrared spectra reveal that Pluto’s surface has a coating of red-tinged material
- Most likely this is a mixture of complex carbon rich organic compounds called tholins(1)
- Another aspect of the mission was an accurate measurement of Pluto’s size which is 2370km up from 2302km
- This makes Pluto the largest of the Kuiper belt objects by a small margin over Eris at 2336±12km

- The rugged peaks(left) of al-Idrisi Montes sit against the NW shore of Sputnik Plantia
- Chunks of water ice ~2-3km across are floating in a sea of nitrogen ice(2)
- They appear to be sliding down to the SP



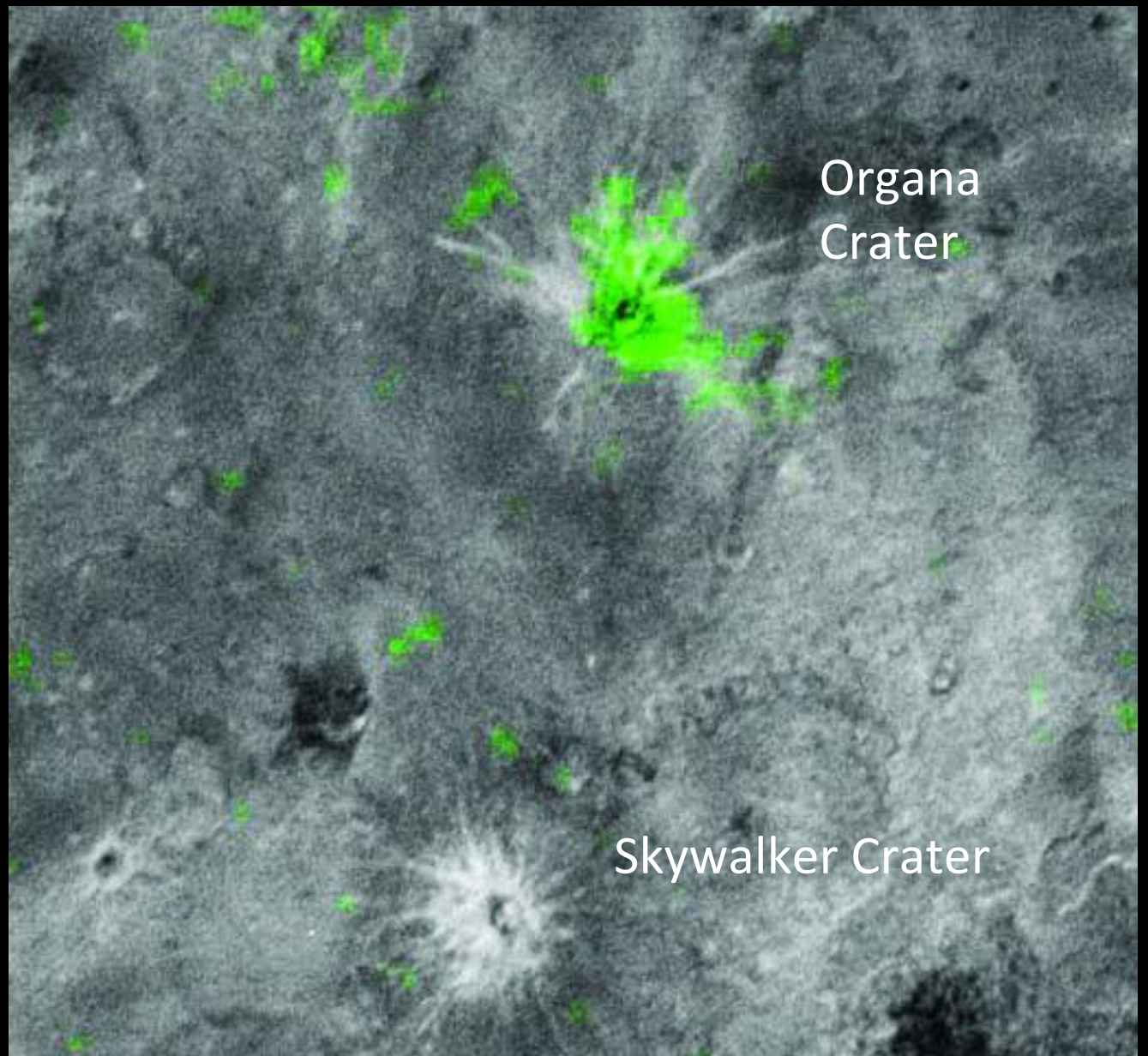
- Even though much of Pluto never gets warmer than 50 kelvin, evidence was spotted of massive, recent downslope glacial flow (arrowed) from eastern Tombaugh Regio, at right, into Sputnik Planitia.
- Altitudes span 6 km in this color-coded view and range from pink (low) to yellow (high)(1)



- In the flyby only one hemisphere of Charon was seen
- One observation was that of two broad areas with many impact scars
- In the north there was Oz Terra and the other was Vulcan Planum in the south
- Because of the icy, rock hard surface cratering history was maintained and both appear to be at least 4 billion years old
- Vulcan Planum has fewer craters and rows of furrows so it seems that some “refreshing” of the surface occurred possibly by cryovolcanism
- Also interesting are the isolated 3-4km high mountains surrounded by moats
- There is also an area in the NW that has an area of ammonia ice

Kubrick Mons-4km high water ice mountain surrounded by a moat

Organa crater with a deposit of ammonia ice



Charon

- Scientists originally expected that Charon would not be very interesting
- One of the first things that changed this opinion was the discovery of a dark red polar region that was named Mordor
- The inner zone is 170 miles across and the outer zone 280 miles
- The current thinking is that it is a deposit of methane gas escaping from Pluto's atmosphere that was deposited on Charon's very cold poles
- The methane then was converted by uv sunlight and cosmic radiation into long chained hydrocarbons called theolins that have the red color

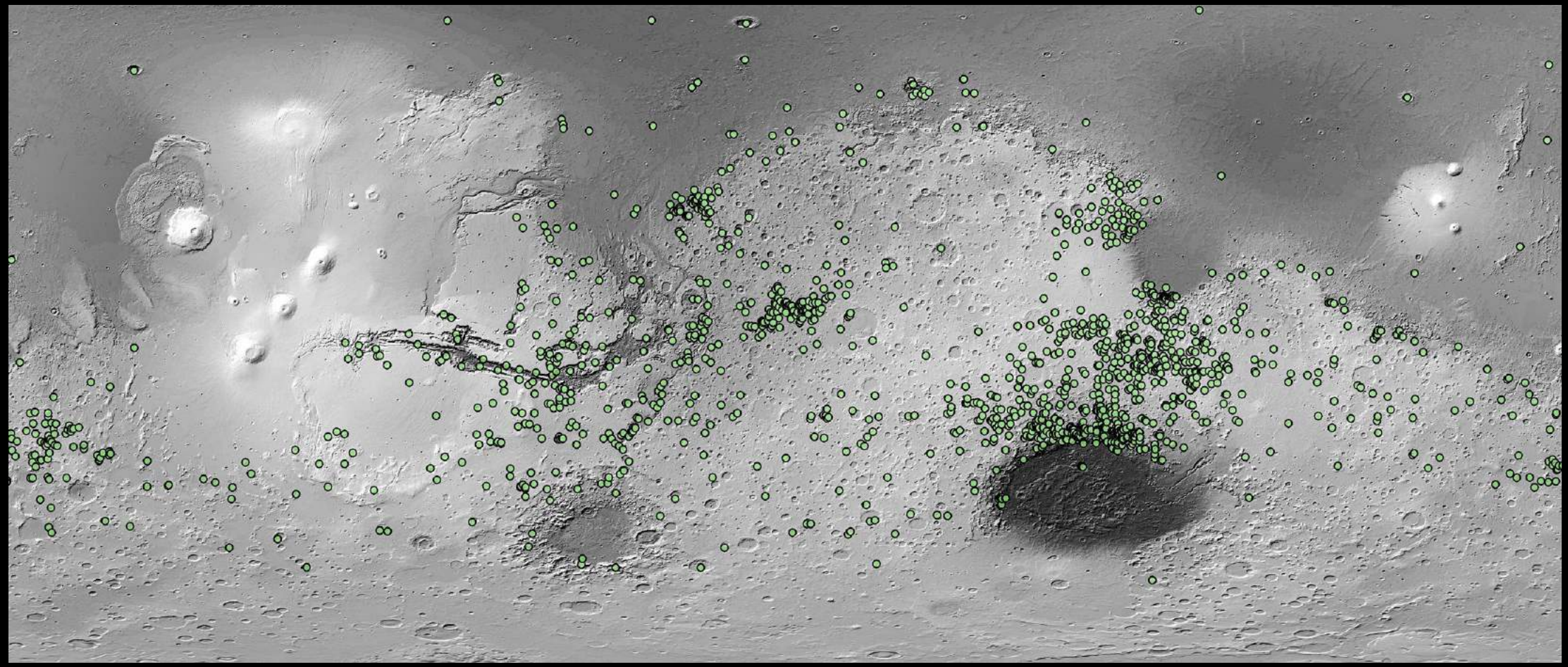
- The main area of interest was the huge fracture system across the midsection stretching for at least 1600km(1000mi)
- This system is 4X the length of the Grand Canyon and 2X its depth in spots
- The Serenity Chasma is 50km wide and 5km deep and the Mandjet Chasama reaches 7km in depth
- It appears like the entire crust of Charon has been split open

- The most logical explanation is that Charon once had an interior ocean of water that expanded as it slowly froze
- Estimates are that this resulted in a 1% increase in surface area and a 3km increase in radius
- To achieve this there had to be an outer shell of water 35km thick to freeze from top down

- The **Mars Express mission** is exploring the planet **Mars**, and is the first planetary **mission** attempted by the ESA.
- Launched June 2, 2003
- Arrival Dec 2003

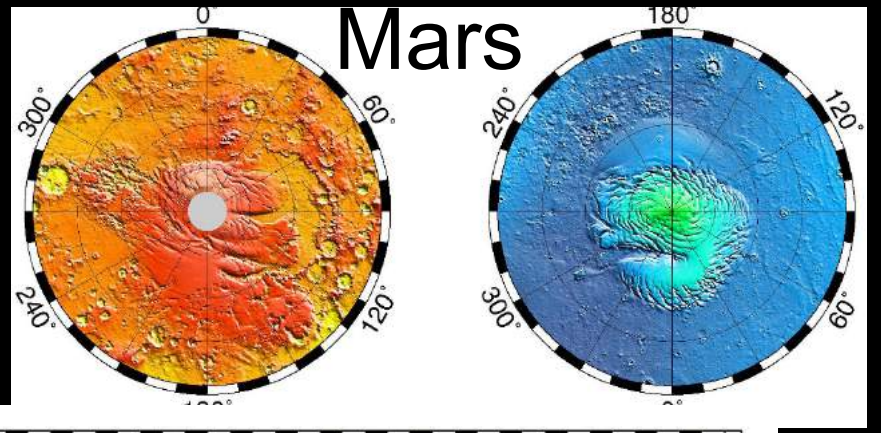
Mars Express Instruments

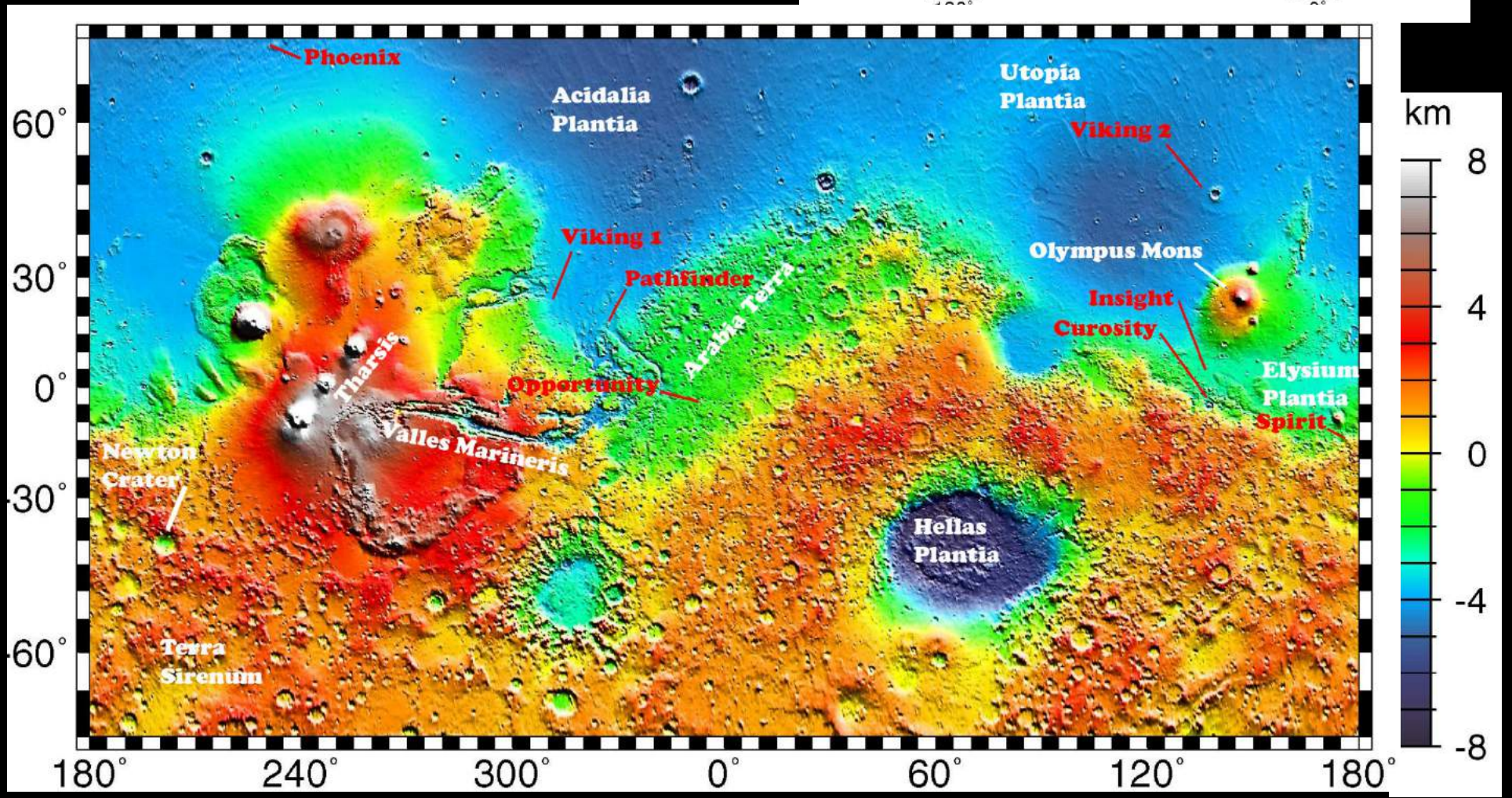
High Resolution (2m/pixel) Stereo Camera (HRSC);
Energetic Neutral Atoms Analyser (ASPERA);
Planetary Fourier Spectrometer (PFS);
Visible and Infra Red Mineralogical Mapping Spectrometer(OMEGA)
Sub-Surface Sounding Radar Altimeter (MARSIS);
Mars Radio Science Experiment (MaRS);
Ultraviolet and Infrared Atmospheric Spectrometer (SPICAM);

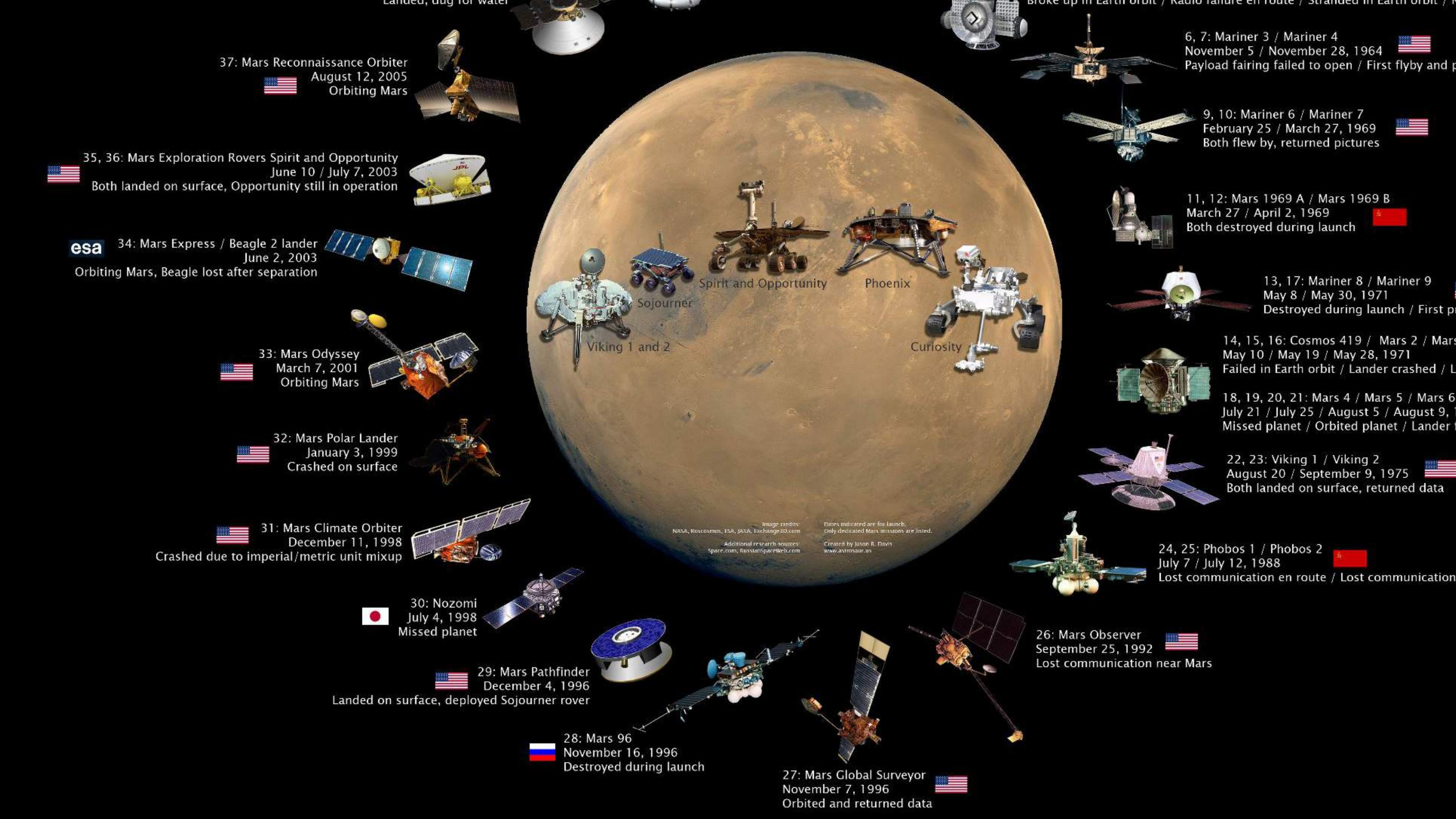


- During the last 10 years, the OMEGA visible and infrared mapping spectrometer has mapped almost the entire surface of the planet, at a resolution between one and five kilometres, with some areas at sub-kilometre resolution.
- OMEGA has detected phyllosilicates and hydrated sulphates over large, but isolated, areas on the surface. Significantly, although both minerals are the result of a chemical alteration of rocks, their formation processes are very different.
- In particular, they point to two major climatic episodes: an early, moist environment in which phyllosilicates formed, followed by a more acidic environment in which the sulphates formed.

This is a composite of images from the Mars Global Surveyor mission from 1997-2006
Dark blue is -27500 ft thru green, yellow and red(+13750 ft) to white(+27500 ft). The white peaks are volcanos







Landed, dug for water

37: Mars Reconnaissance Orbiter
August 12, 2005
Orbiting Mars

35, 36: Mars Exploration Rovers Spirit and Opportunity
June 10 / July 7, 2003
Both landed on surface, Opportunity still in operation

34: Mars Express / Beagle 2 lander
June 2, 2003
Orbiting Mars, Beagle lost after separation

33: Mars Odyssey
March 7, 2001
Orbiting Mars

32: Mars Polar Lander
January 3, 1999
Crashed on surface

31: Mars Climate Orbiter
December 11, 1998
Crashed due to imperial/metric unit mixup

30: Nozomi
July 4, 1998
Missed planet

29: Mars Pathfinder
December 4, 1996
Landed on surface, deployed Sojourner rover

28: Mars 96
November 16, 1996
Destroyed during launch

27: Mars Global Surveyor
November 7, 1996
Orbited and returned data

26: Mars Observer
September 25, 1992
Lost communication near Mars

24, 25: Phobos 1 / Phobos 2
July 7 / July 12, 1988
Lost communication en route / Lost communication

22, 23: Viking 1 / Viking 2
August 20 / September 9, 1975
Both landed on surface, returned data

18, 19, 20, 21: Mars 4 / Mars 5 / Mars 6
July 21 / July 25 / August 5 / August 9,
Missed planet / Orbited planet / Lander

14, 15, 16: Cosmos 419 / Mars 2 / Mars
May 10 / May 19 / May 28, 1971
Failed in Earth orbit / Lander crashed / L

13, 17: Mariner 8 / Mariner 9
May 8 / May 30, 1971
Destroyed during launch / First p

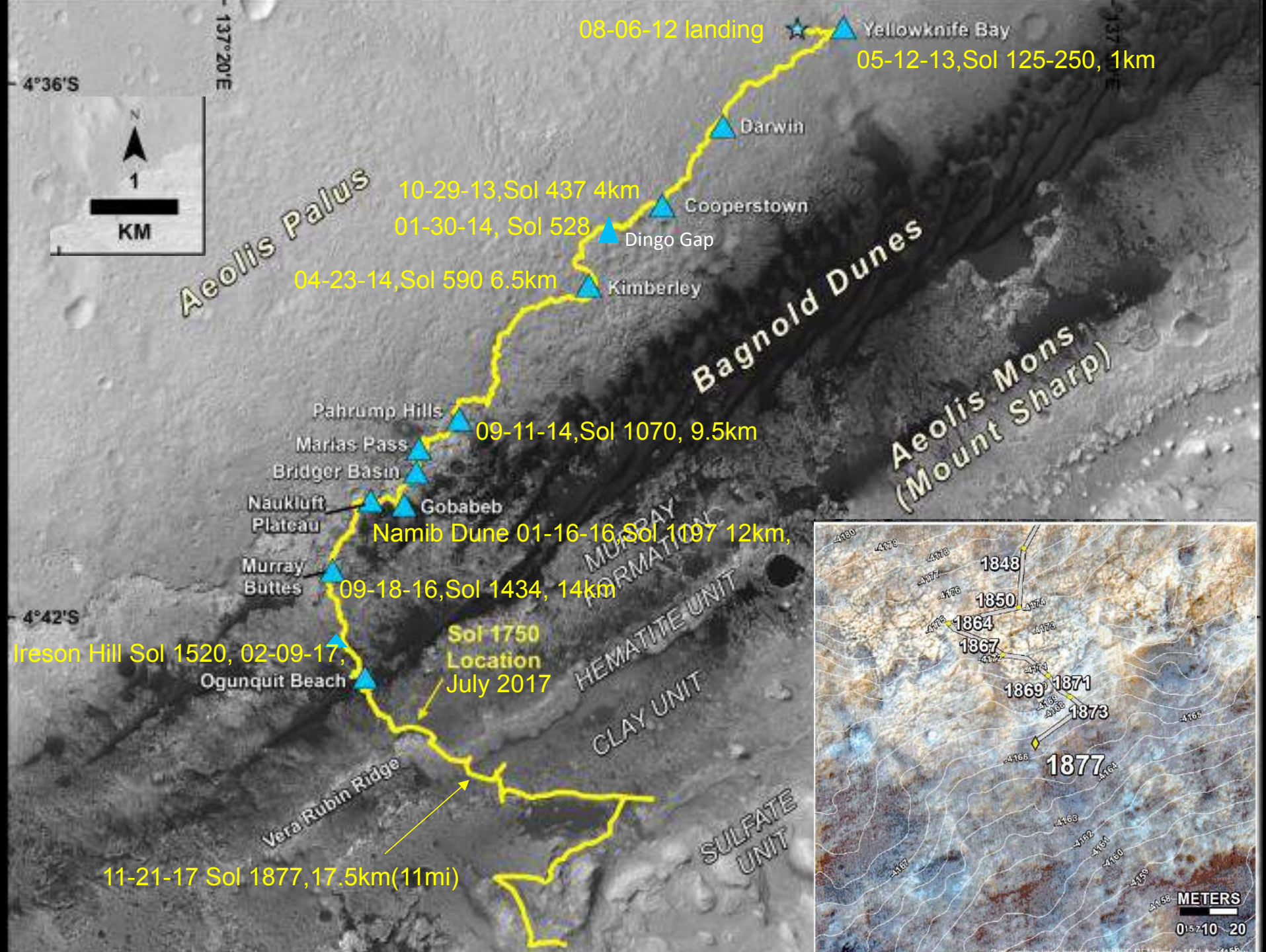
11, 12: Mars 1969 A / Mars 1969 B
March 27 / April 2, 1969
Both destroyed during launch

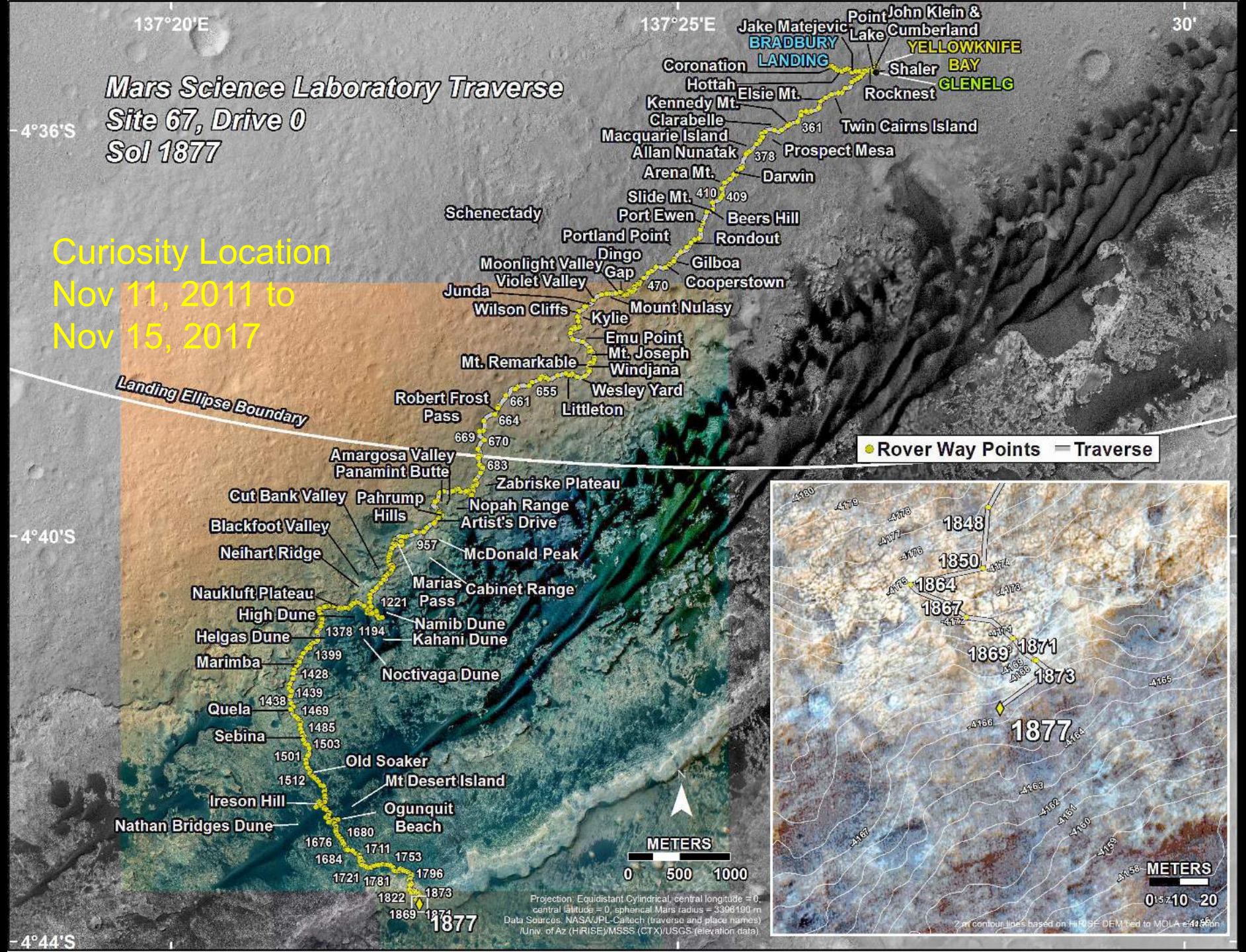
9, 10: Mariner 6 / Mariner 7
February 25 / March 27, 1969
Both flew by, returned pictures

6, 7: Mariner 3 / Mariner 4
November 5 / November 28, 1964
Payload fairing failed to open / First flyby and p

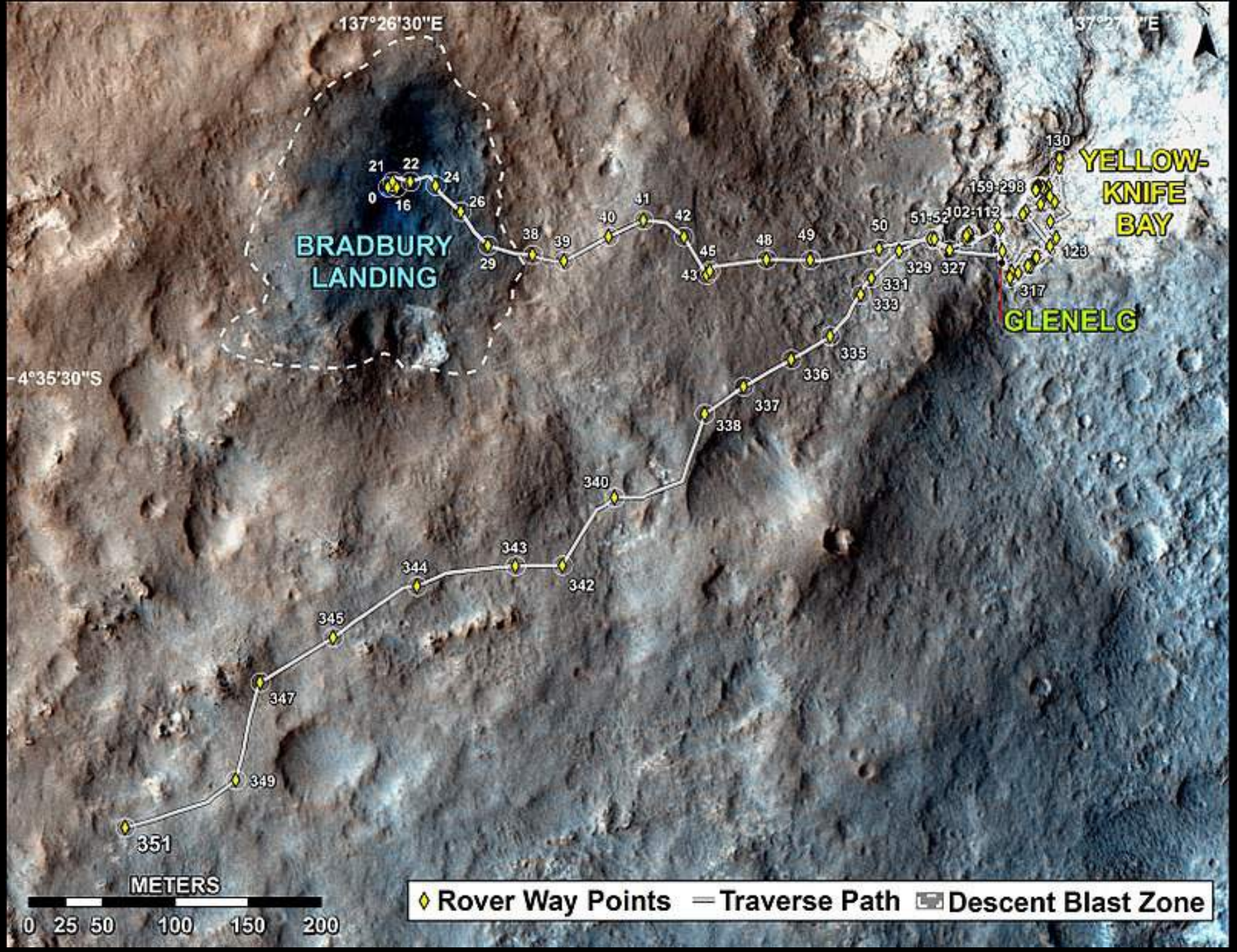
Broke up in Earth orbit / Radio failure en route / Stranded in Earth orbit /

- Picture taken by the MastCam on sol 703, Aug 4 2014 in Hidden Valley, Pahrump Hills.
- A variety of mudstone strata in the area indicate a lakebed deposit, with river- and stream-related deposits nearby.
- Decoding how these sedimentary rocks were formed and when is a key component in the determining the role of water and sedimentation in the formation of the floor of Gale Crater and Mount Sharp


08-06-12 landing
Yellowknife Bay
05-12-13,Sol 125-250, 1km
Darwin
10-29-13,Sol 437 4km
Cooperstown
01-30-14, Sol 528
Dingo Gap
04-23-14,Sol 590 6.5km
Kimberley
Aeolis Palus
Bagnold Dunes
Aeolis Mons
(Mount Sharp)
Pahrump Hills
09-11-14,Sol 1070, 9.5km
Marias Pass
Bridger Basin
Naukluft
Plateau
Gobabeb
Namib Dune 01-16-16,Sol 1097 12km,
Murray
Buttes
09-18-16,Sol 1434, 14km
MURRAY FORMATION
HEMATITE UNIT
CLAY UNIT
SULFATE UNIT
Sol 1750
Location
July 2017
Ireson Hill Sol 1520, 02-09-17,
Ogunquit Beach
Vera Rubin Ridge
11-21-17 Sol 1877,17.5km(11mi)
137°20'E
4°36'S
4°42'S
N
1
KM
1848
1850
1864
1867
1869
1871
1873
1877
METERS
0 5 10 20

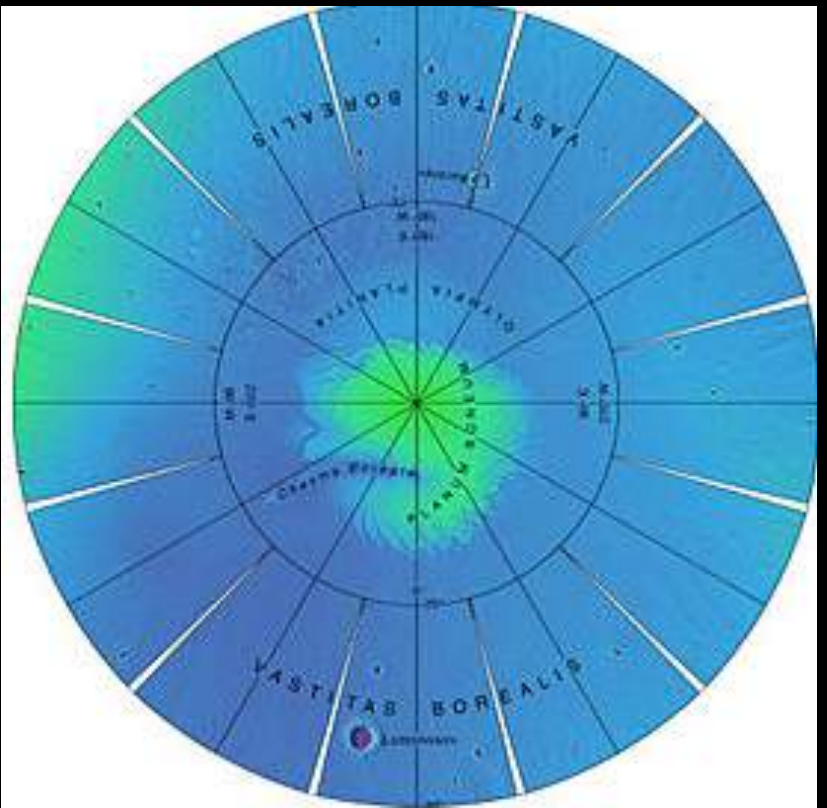

Mars Science Laboratory Traverse
Site 67, Drive 0
Sol 1877
Curiosity Location
Nov 11, 2011 to
Nov 15, 2017
137°20'E
137°25'E
30'
4°36'S
4°40'S
4°44'S
Landing Ellipse Boundary
Rover Way Points
Traverse
Jake Matejevic
Point Lake
John Klein & Cumberland
BRADBURY LANDING
YELLOWKNIFE BAY
GLENELG
Coronation
Shaler
Hottah
Elsie Mt.
Rocknest
Kennedy Mt.
Clarabelle
361
Twin Cairns Island
Macquarie Island
Allan Nunatak
378
Prospect Mesa
Arena Mt.
Darwin
Slide Mt.
410
409
Schenectady
Port Ewen
Beers Hill
Portland Point
Rondout
Dingo Gap
Gilboa
Moonlight Valley
Violet Valley
470
Cooperstown
Junda
Wilson Cliffs
Mount Nulasy
Kylie
Emu Point
Mt. Joseph
Mt. Remarkable
Windjana
Wesley Yard
655
661
Littleton
Robert Frost Pass
664
669
670
Amargosa Valley
Panamint Butte
683
Zabriske Plateau
Cut Bank Valley
Pahrump Hills
Nopah Range
Artist's Drive
Blackfoot Valley
957
McDonald Peak
Neihart Ridge
Marias Pass
Cabinet Range
Naukluft Plateau
1221
High Dune
Namib Dune
Helgas Dune
1378
1194
Kahani Dune
Marimba
1399
Noctivaga Dune
1428
1439
1438
Quela
1469
1485
Sebina
1503
1501
Old Soaker
1512
Mt Desert Island
Ireson Hill
Ogunquit Beach
Nathan Bridges Dune
1680
1676
1711
1753
1684
1796
1721
1781
1873
1822
1869
1874
1877
N
METERS
0
500
1000
Projection: Equidistant Cylindrical, central longitude = 0, central latitude = 0, spherical Mars radius = 3396190 m
Data Sources: NASA/JPL-Caltech (traverse and place names) /Univ. of Az (HiRISE/MSSS (CTX)/USGS (elevation data)
1848
1850
1864
1867
1869
1871
1873
1877
METERS
0
10
20
2 m contour lines based on HiRISE DEM tied to MOLA elevation

- Home Plate is a plateau of layered bedrock approximately
- It lies within the Inner Basin of the Columbia Hills, at the Spirit rover's landing site in Gusev Crater.
- The bedrock yielded the mission's first definite identification of deposits from explosive volcanic action.
- Indications are that hot basalt rock and briny water interacted here to create spectacular, landscape-changing explosions.

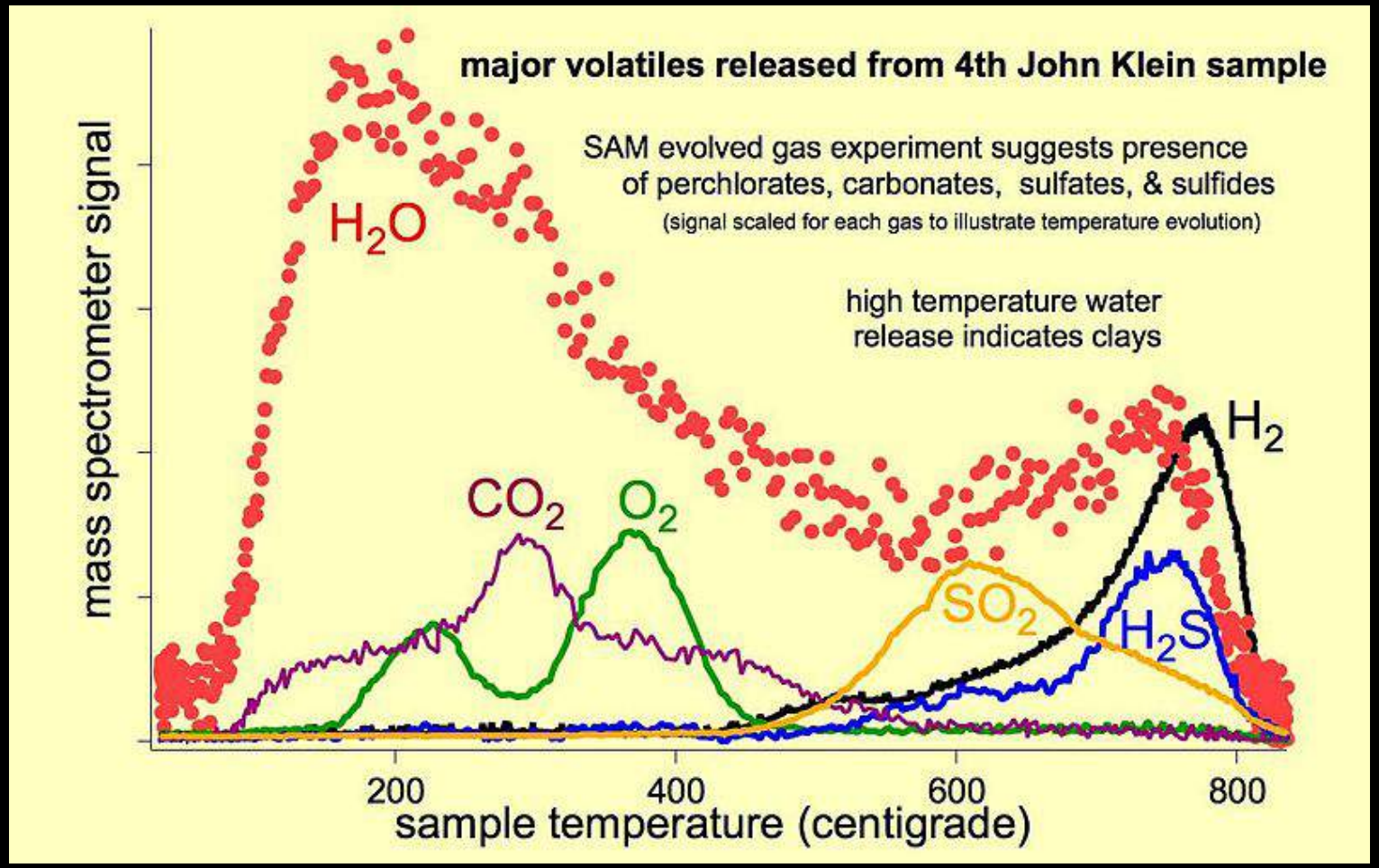

137°26'30"E
4°35'30"S
BRADBURY LANDING
YELLOW-KNIFE BAY
GLENELG
0
16
21
22
24
26
29
38
39
40
41
42
43
45
48
49
50
51-52
102-112
159-298
130
123
327
329
331
333
317
335
336
337
338
340
342
343
344
345
347
349
351
METERS
0 25 50 100 150 200
Rover Way Points
Traverse Path
Descent Blast Zone

Water on Ancient Mars

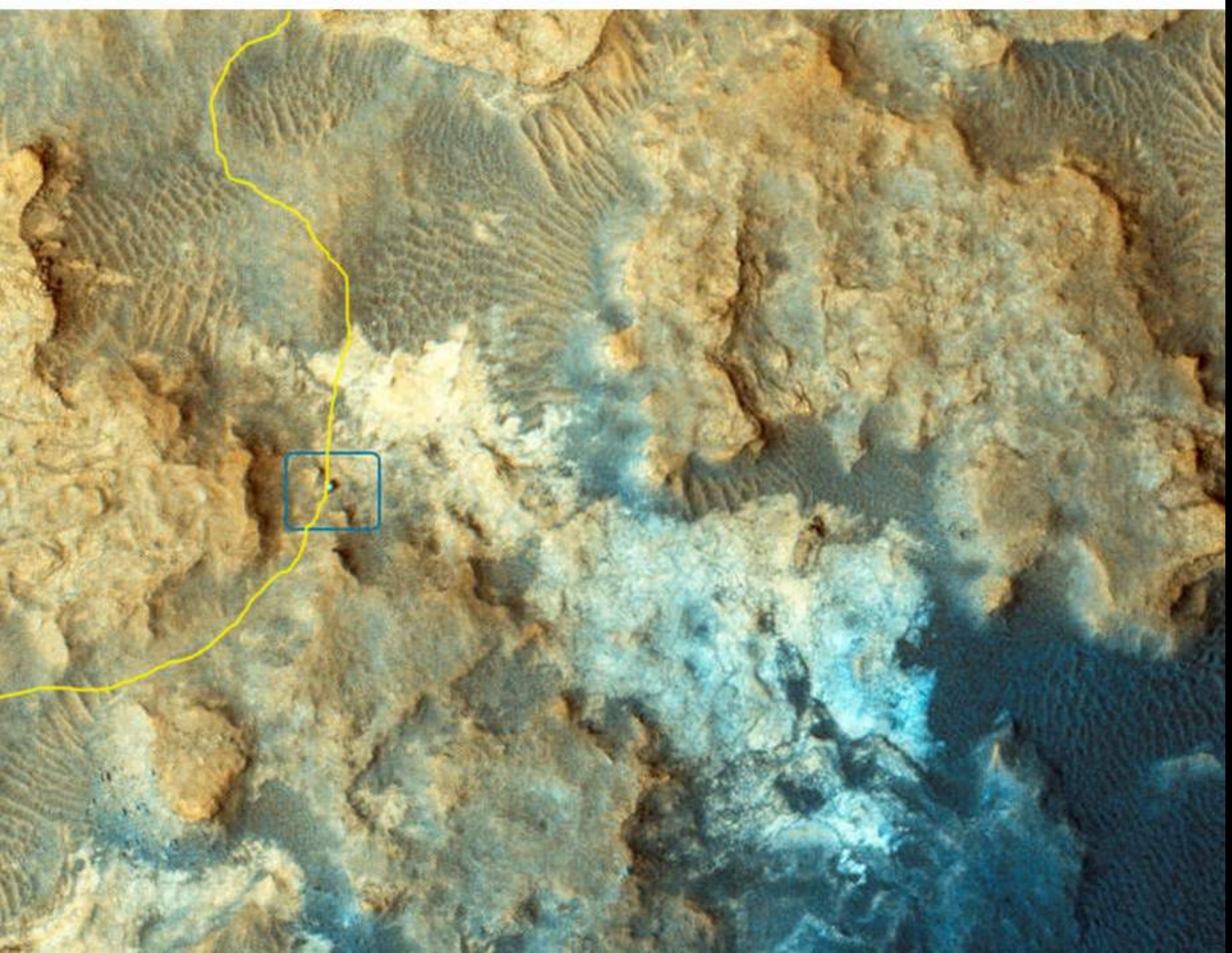
- Additional studies have also been done looking for ancients coastlines as well as rivers and deltas
- The image is of Eberswalde delta, 115 km^2 draining 4000 km^2(1) taken by the Mars Odyssey Orbiter



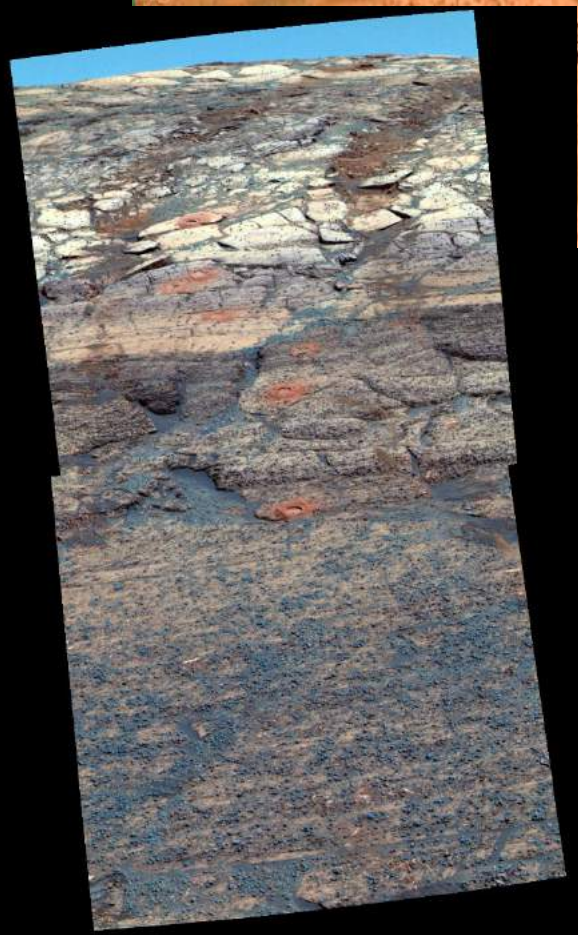
- **Vastitas Borealis** ('northern waste') is the largest lowland region of Mars. It is in the northerly latitudes and encircles the northern polar region.
- A 2003 study based on a shoreline using the Vastitas Borealis Formation(4) would result in 23 million km^3 of water or 156m GEL(4,6)



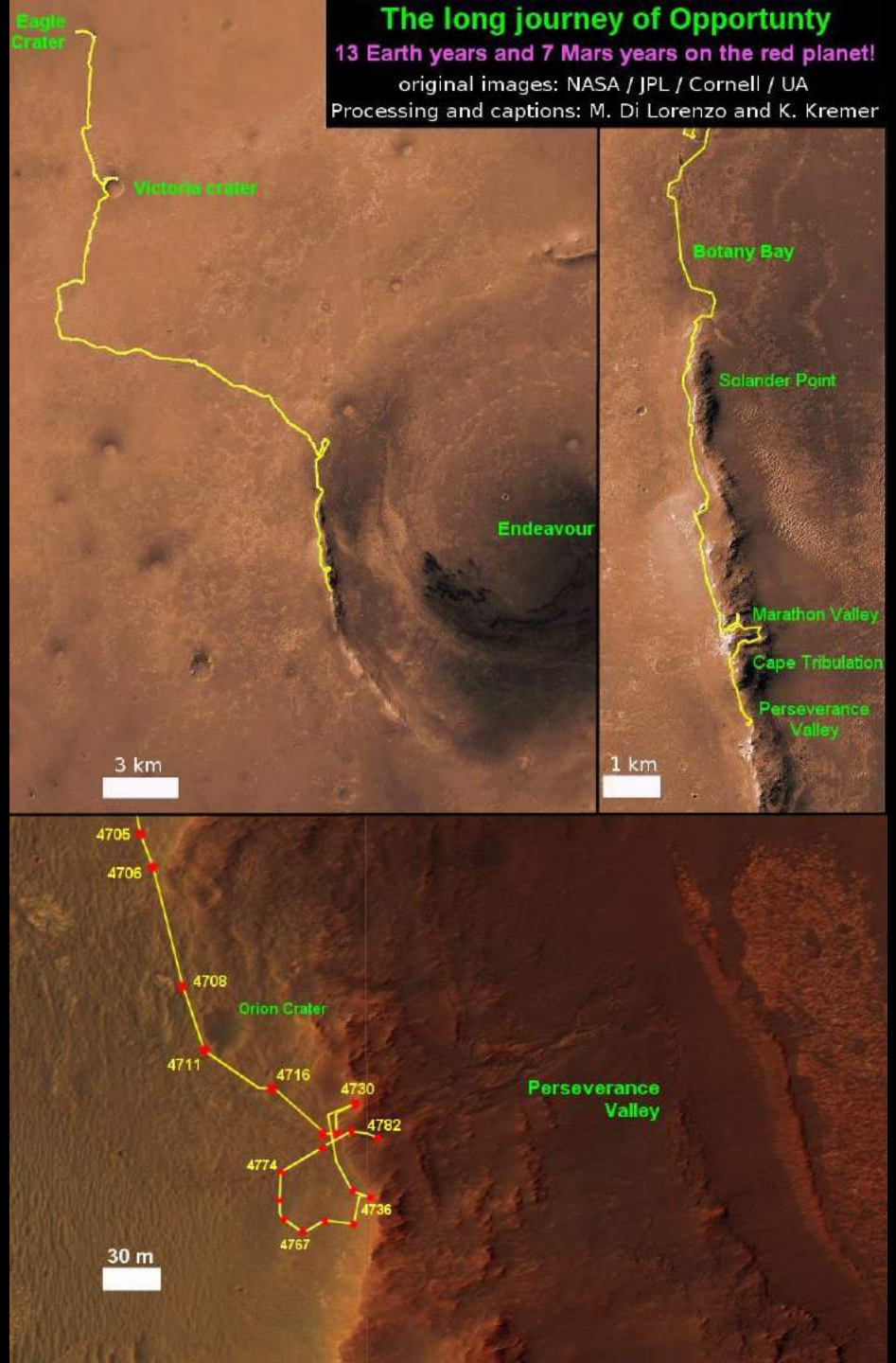
- The results analyzing the high temperature water release are consistent with smectite clay minerals.
- These evolved gases and the temperatures at which they evolved suggest the presence of hydrated minerals, carbonates, perchlorates, sulfates and sulfides, and clays in the rock-powder sample, some of the key ingredients for life

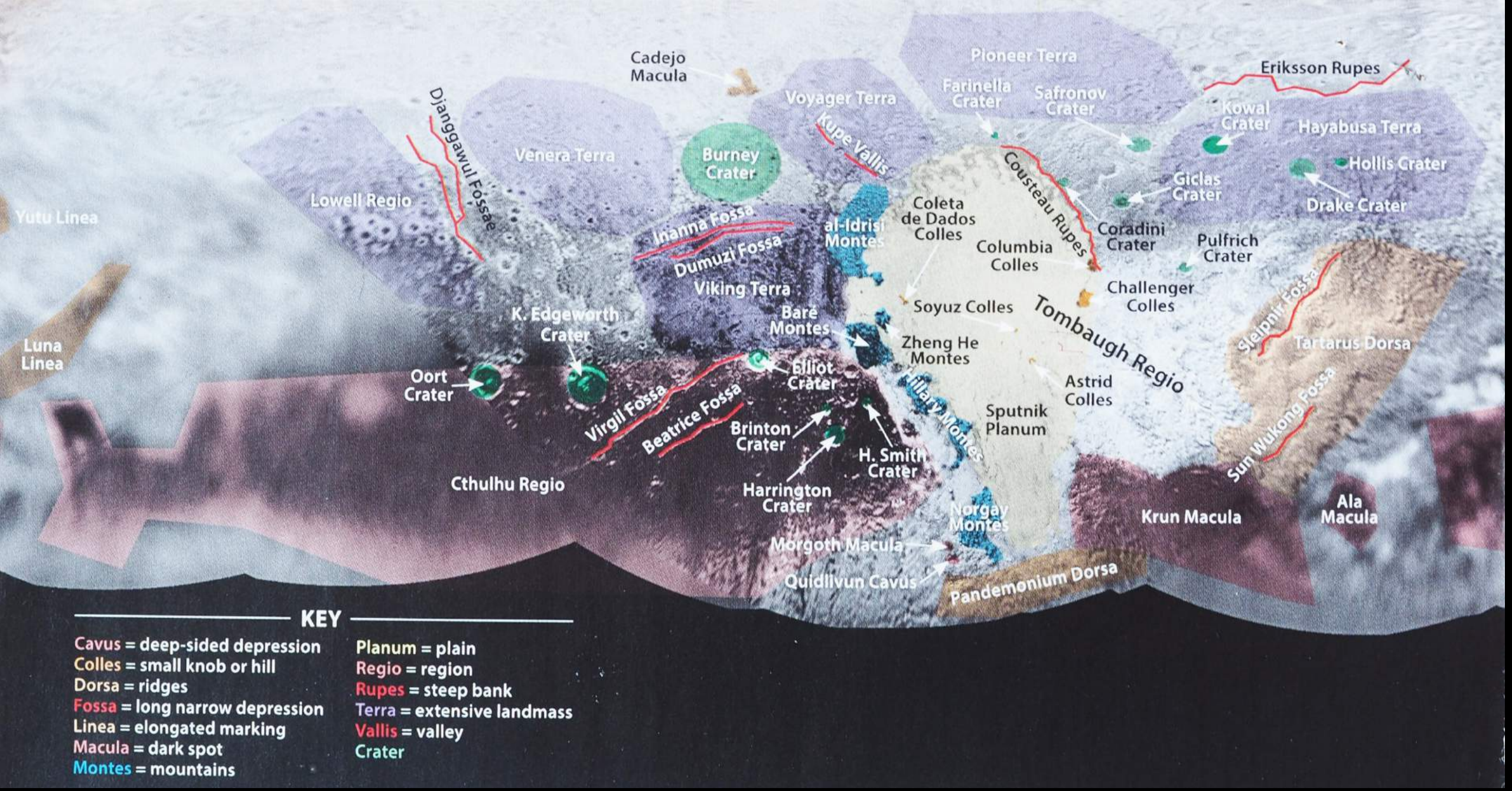


A image of Curiosity in the Pahrump Hills taken by the Mars Reconnaissance Orbiter on or near Sol 923



- In June of 2004, working overtime after its three month-long primary mission ended, Opportunity began carefully inching into a stadium-size impact crater called Endurance.
- The six months that Opportunity spent studying rock layers in Endurance rewrote our understanding of the history of water at Meridiani Planum.
- As Opportunity carefully crept some 30 feet (10 meters) into the crater, the distinct rock layers it studied showed subtle variations in chemistry, texture, and color that suggested the past presence of water.
- Analysis showed these and other minerals settled to the bottom of a salty body of water to form “rock salt” deposits similar to those seen in salt flats in desert regions on Earth.

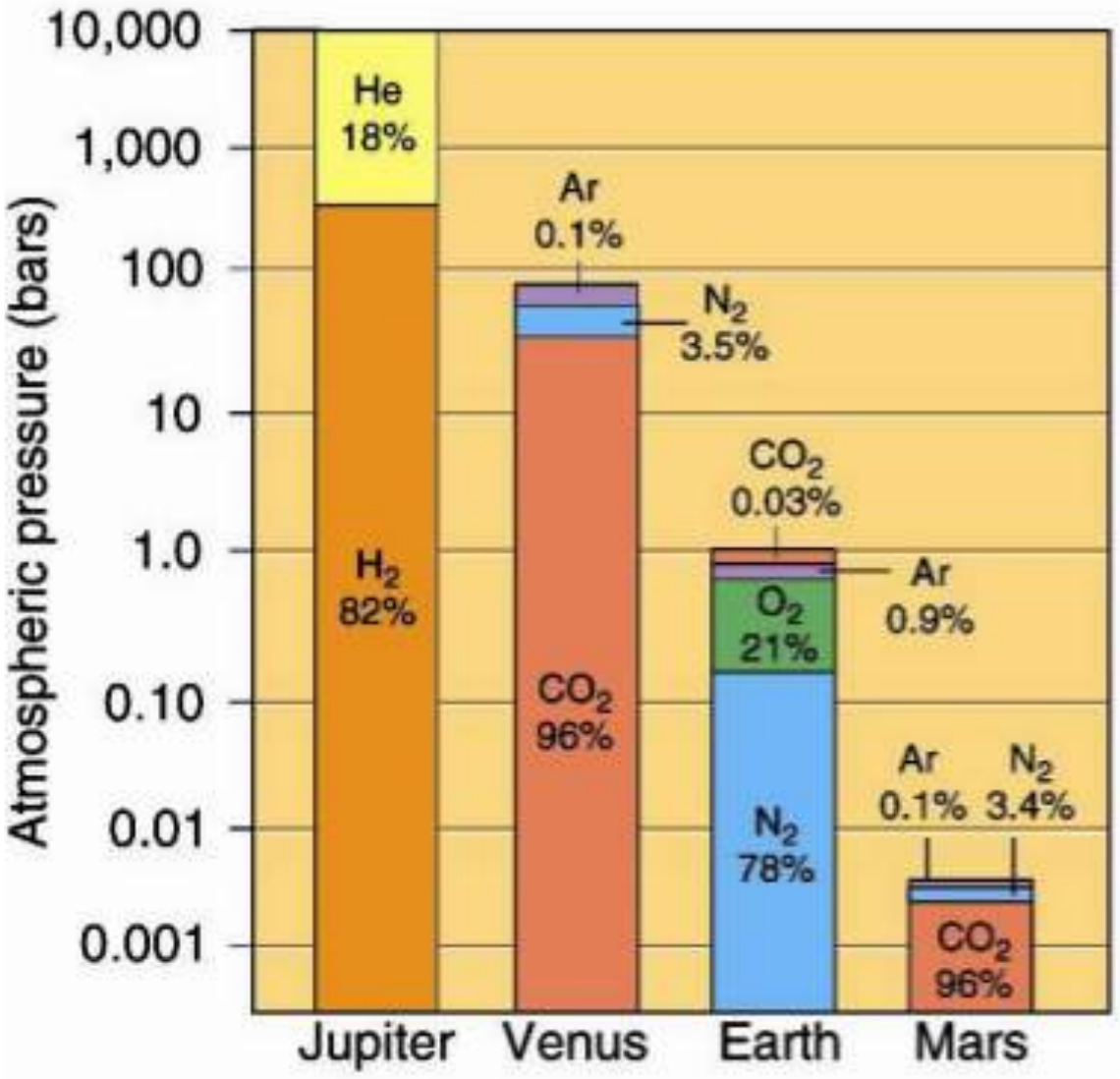

The long journey of Opportunty
13 Earth years and 7 Mars years on the red planet!
original images: NASA / JPL / Cornell / UA
Processing and captions: M. Di Lorenzo and K. Kremer
Eagle Crater
Victoria crater
Endeavour
3 km
Botany Bay
Solander Point
Marathon Valley
Cape Tribulation
Perseverance Valley
1 km
4705
4706
4708
Orion Crater
4711
4716
4730
4782
4774
4736
4767
Perseverance Valley
30 m



KEY

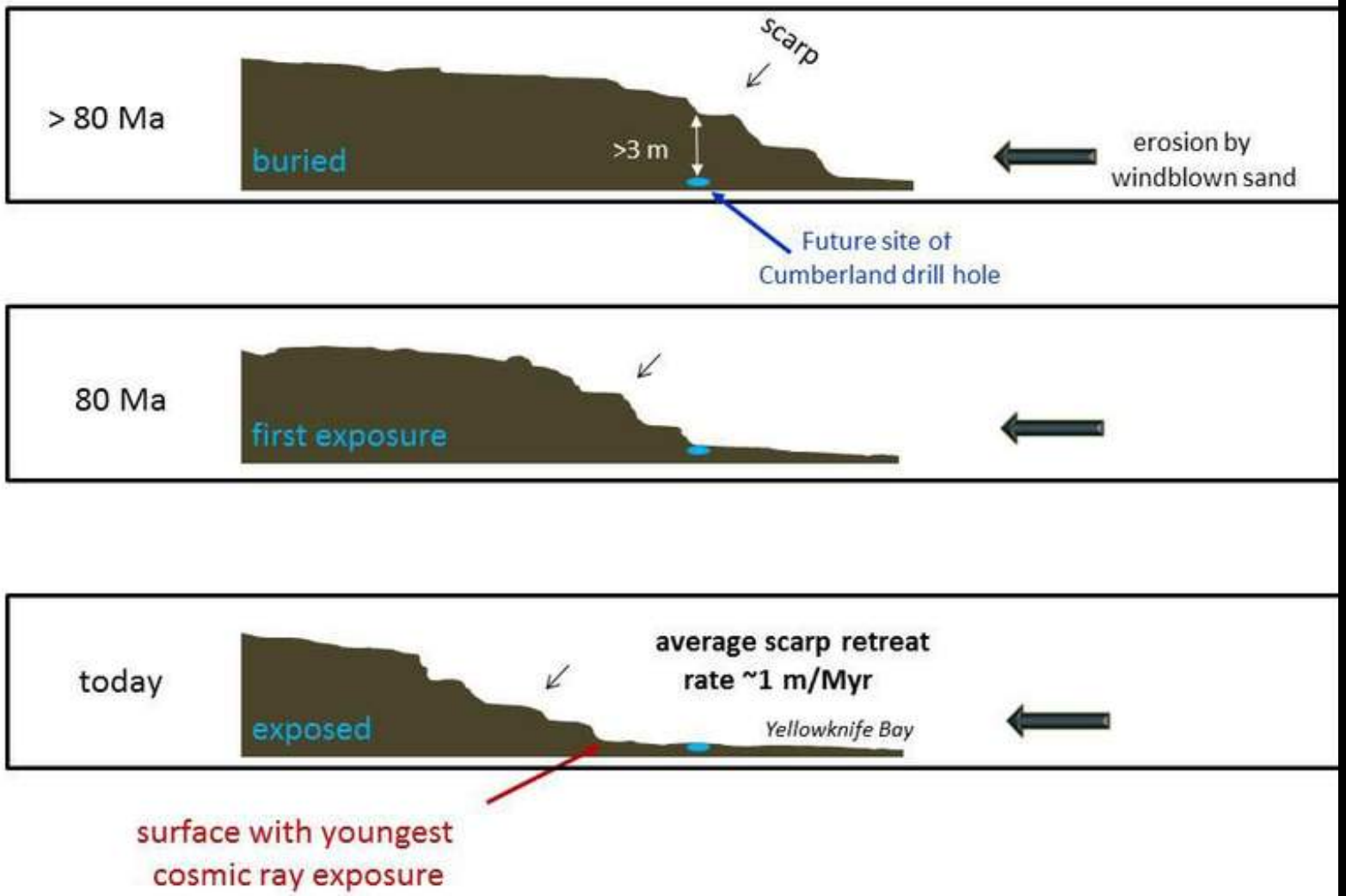
Cavus = deep-sided depression
Colles = small knob or hill
Dorsa = ridges
Fossa = long narrow depression
Linea = elongated marking
Macula = dark spot
Montes = mountains
Planum = plain
Regio = region
Rupes = steep bank
Terra = extensive landmass
Vallis = valley
Crater

Atmospheric Compositions



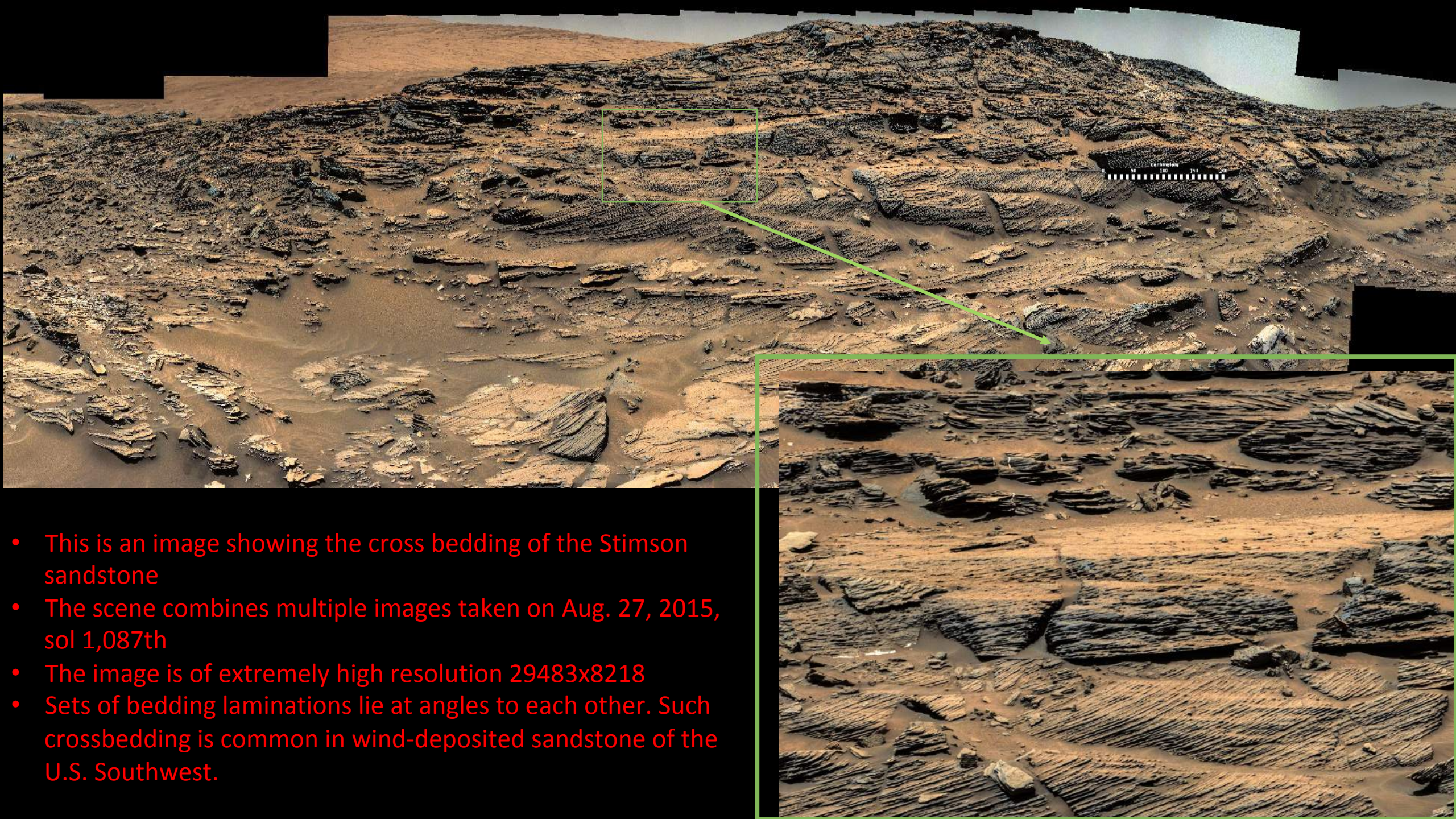
Earth's present atmosphere is distinctly different from that of its nearest neighbors, Venus and Mars. Although, it is believed that at one time, the atmospheres of these three planets were much more alike.

Scarp Retreat Model and Exposure History of Yellowknife Bay



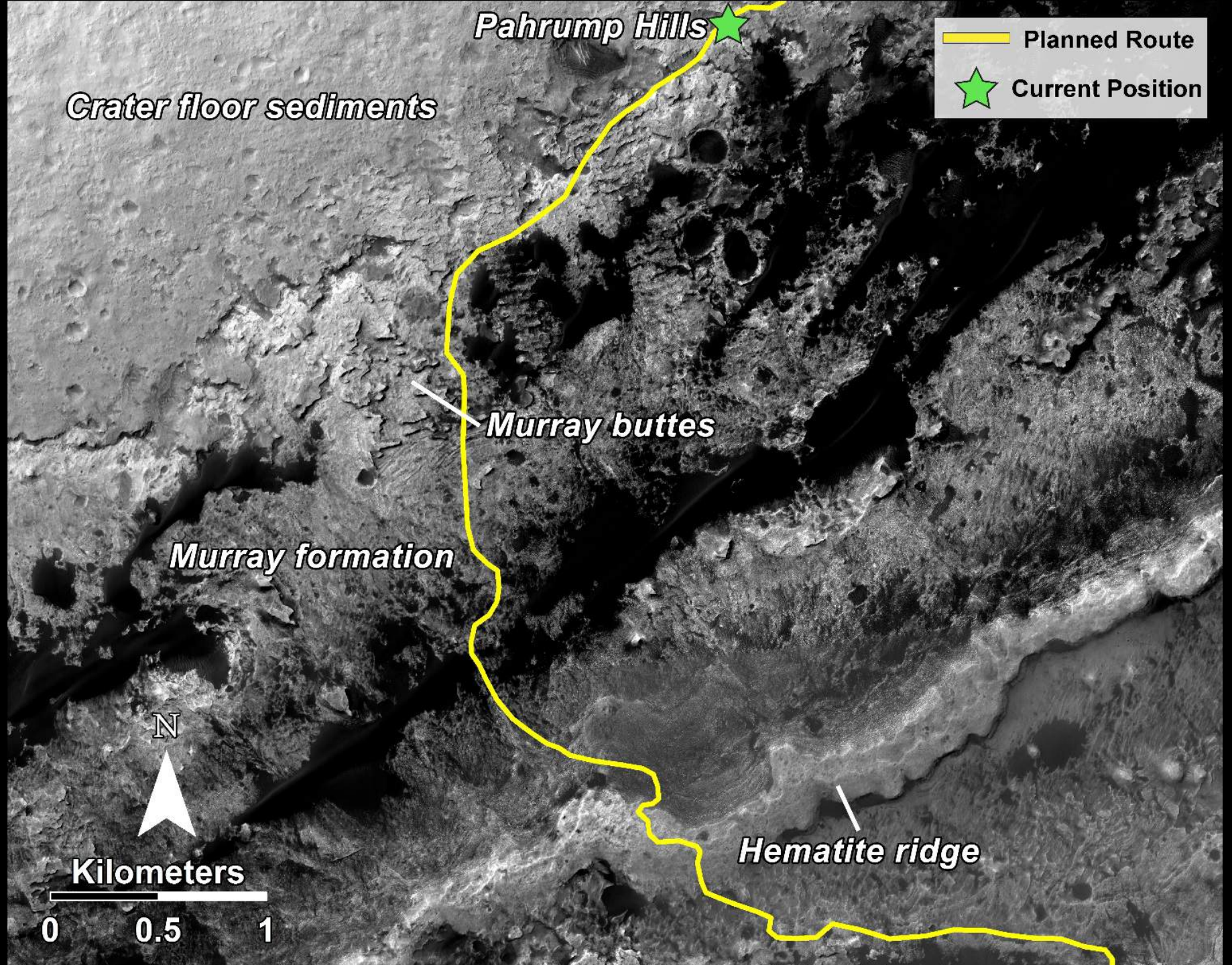
Argon-40 with the QMS, the SAM team determined that the rocks were between 3.86 to 4.56 Bya and thus were the oldest rock on the planet

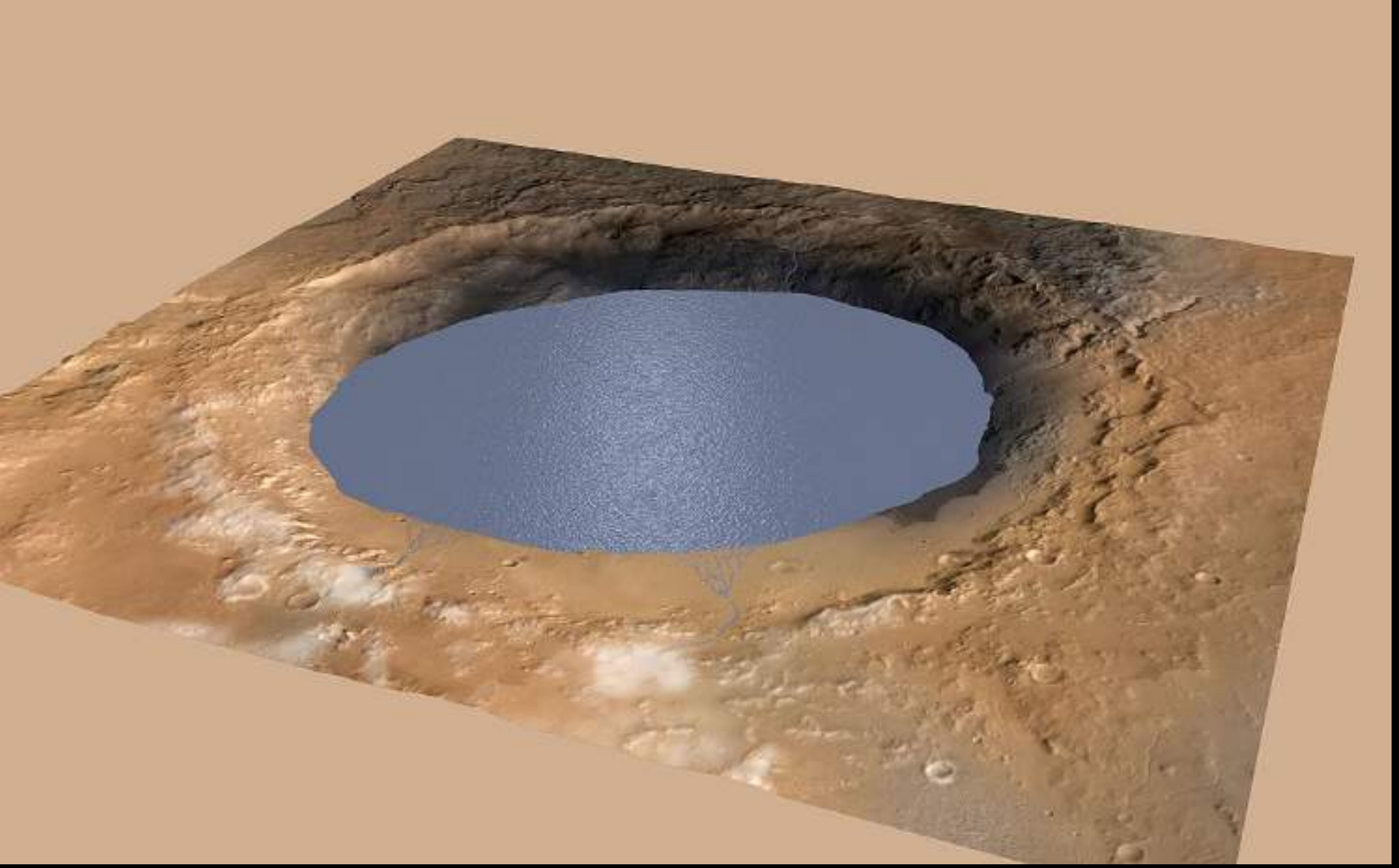
- Inaddition, by looking at the amount of helium, neon, & argon gas present it was determined that the rock had been exposed at the surface for only 80 My
- They likely were once on the highlands and were later deposited on Gale's floor and only recently exposed by the sandblasting winds



- This is an image showing the cross bedding of the Stimson sandstone
- The scene combines multiple images taken on Aug. 27, 2015, sol 1,087th
- The image is of extremely high resolution 29483x8218
- Sets of bedding laminations lie at angles to each other. Such crossbedding is common in wind-deposited sandstone of the U.S. Southwest.

- This image shows the transition between the "Murray Formation," in which layers are poorly expressed and difficult to trace from orbit, and the hematite ridge, which is made up of continuous layers that can be traced laterally for hundreds of meters.
- Orbital data shows that this change in bedding style between the Murray formation and the hematite ridge is also accompanied by a major change in layer composition.


Pahrump Hills
Planned Route
Current Position
Crater floor sediments
Murray buttes
Murray formation
Hematite ridge
N
Kilometers
0
0.5
1



- This illustration depicts a lake of water partially filling Mars' Gale Crater, receiving runoff from snow melting on the crater's northern rim.
- Evidence of ancient streams, deltas and lakes has been found in the patterns of sedimentary deposits in Gale Crater
- This suggests the crater held a lake such as this more than three billion years ago, filling and drying in multiple cycles over tens of millions years

When the crater first held a lake, it might have had central peak, formed as a rebound from the impact that excavated the crater. Such a peak might have appeared as an island in the lake.