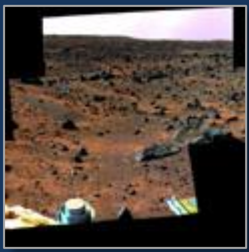
Further Geological Information for Scenes in the Mars Images

Lander Images:

Pathfinder, Ares Vallis, 1997:

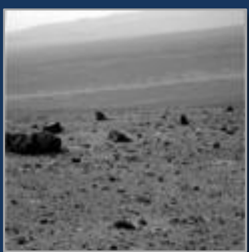


Ares Vallis, spanning about 1600 km, is one of the major outflow channels on Mars; running from the southern highlands in the region of Iani Chaos it opens into Chryse Planitia to the north-west and is commonly believed to have been formed from a massive release of ground-water about 2.5 billion years ago when Mars' atmosphere was likely thicker and its climate warmer. Many researches consider Iani Chaos to have been the source of the flood waters that formed Ares Vallis following the release of sub-surface ice or water. In addition, some authors argue that Ares Vallis formed not from a single catastrophic release of water from Iani Chaos, but multiple smaller outbursts spanning the Hesperian Period to the early Amazonian or about 3.6 to 2.5 billion years ago. (Image Credit: NASA/JPL-Caltech.)

Spirit Rover, Clovis Rock, Gusev Crater:

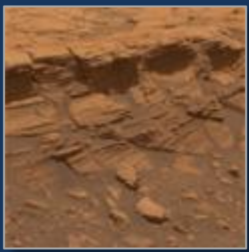
The altered Clovis rocks in the Columbia Hills are believed to date to the Noachian period about 4.1 – 3.8 billion years ago, a period of high rates of cratering, erosion, valley formation and the common presence of water. The Clovis outcrop is a clastic rock that has been interpreted as aqueously altered ejecta deposits formed by impacts into basaltic materials. Possibly significant is that in Clovis Spirit's Mossbauer Spectrometer detected the mineral goethite as this forms only in the presence of water. (Image Credit: NASA/JPL-Caltech.)

Opportunity Rover, Endeavour Crater, Aug. 2011:



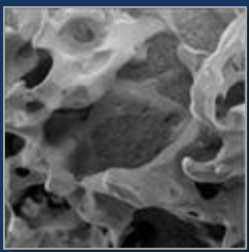
Endeavour is a middle to late Noachian-aged 20-km impact crater that has been largely in-filled and buried by sulphate-bearing sedimentary deposits. Its rim rises almost 100 meters above the plains and contains clay-bearing materials that form part of the early Noachian highlands crust. Clays are found in the plains, the rim and the interior of the Crater. Basaltic breccias produced by the impact form the rim deposits whilst gypsum-rich veins in sedimentary rock adjacent to the rim were precipitated by low-temperature aqueous fluids possibly creating, some believe, a temporary habitable zone. (Image Credit: NASA/JPL-Caltech.)

Opportunity Rover, 'Payson Outcrop' Erebus Crater:



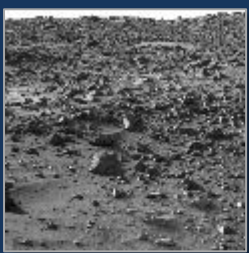
Payson outcrop, Erebus Crater, 11th April, 2006: The rock layers were likely formed from wind and water action. Erebus, which is 4 km south of Endurance crater, is about 300 meters in diameter and located on top of an older, 550 meter crater called Terra Nova; both Erebus and Terra Nova craters have been dated to the late Noachian Period. (Image Credit: NASA/JPL-Caltech.)

Spirit's Microscopic Imager study's the Rock GongGong:



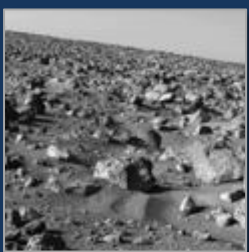
3cm view of GongGong, formed by volcanic and wind action over billions of years. The rock formed in a mass of molten lava and captured gas bubbles as they rose to the surface; when GongGong solidified it resembled a sponge. After being gradually worn down over billions of years by sand grains in the Martian winds, however, the thin layers of rock covering the gas bubbles were breached and the current spiny structure riddled with cavities emerged. For further information see http://photojournal.jpl.nasa.gov/catalog/PIA02157. (Image Credit: NASA/JPL-Caltech.)

Viking 1 Lander at Chryse Planitia, 1976:



Chryse Planitia is the focus of many of the major outflow channels on Mars, which, ending abruptly, has led to the hypothesis that they emptied into a body of water such as a large lake or even an ocean. Although a subject of debate there is also recent evidence (MARSIS) that the region may be the site of an underlying impact basin. (Image Credit: NASA.)

Viking 2 Lander at Utopia Planitia: Wide View, 1976:



Utopia Planitia is a major topographic depression measuring about 3,300 kilometres in diameter and situated in the northern plains of Mars whose impact cratering record is believed by some scientists to indicate the existence of an ice-rich sub-surface to great depths (km). (Image Credit: NASA.)

Phoenix Study's the Martian Arctic:

The location of the Phoenix Lander, the plains of Vastitas Borealis encircle Mars' Northern Pole and according to some scientists may have been the site of a former ocean. Arguing against this view, is the absence of evaporites, expected from an ocean, and the presence in low areas of meter-scale boulders rather than the fine-grained sediment that would be left behind by a standing body of water. Phoenix did confirm and examine, however, widespread underground deposits of water-ice and found signs of calcium carbonate, which forms in the presence of liquid water. It also witnessed falling snow.

The most important finding of Phoenix, however, has been its discovery of perchlorates in the Martian soil capable of destroying organics when heated to high temperatures, which has prompted a reconsideration of the lack of organics in the Viking Lander experiments, which involved such heating. Perchlorate can rest side-by-side with organics in the soil for billions of years, but if these are heated together in a soil sample the perchlorate quickly destroys the organics. It is not yet certain if this is what happened in the Viking Lander experiments, but this is the first in situ evidence to support this possibility. (Image Credit: NASA/JPL/Caltech/University of Arizona/Texas A&M University.)

Curiosity Rover in Gale Crater:

Gale Crater, 23rd August, 2012: The crater dates to the late Noachian/early Hesperian periods about 3.6 billion years ago. The crater is 150 km in diameter and filled with sedimentary deposits including a large mound called Aeolis Mons (informally Mt. Sharp) - Curiosity’s main target - that rises to about 5 km and spans 6000 square km. The origin of the mound remains unknown, but some scientists propose aeolian or wind action. One or more lakes have been hypothesized to have covered large portions of the crater, also cutting into Aeolis Mons. (Image Credit: NASA/JPL-Caltech.)

Curiosity at a Former Habitable Water Zone, Feb, 2013:

Here are two images each at the site of an ancient watery environment, but only one is considered to have been habitable, namely, the right-hand one belonging to the 'Sheepbed' group identified by Curiosity in Yellowknife Bay, Gale Crater. The left-hand rock, recorded by Opportunity in Meridiani Planum, was formed in a highly acidic, high saline environment. (Image Credit: NASA/JPL-Caltech.)

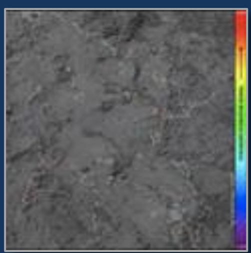
Spirit Rover, Husband Hill, Gusev Crater, 2006:

This is a wide-view of the slopes of Husband Hill in Gusev Crater taken by Spirit on April 17th, 2006. The image was taken late in the afternoon from the point called Low Ridge. As an indication of scale the sand ripples, called El Dorado, span about 500 feet. (Image Credit: NASA/JPL-Caltech.)

Curiosity, Hydrated Minerals, Knorr Outcrop:

The white veins and nodules shown in this image of the Knorr outcrop have been interpreted to be hydrated calcium sulphate, an indication that water once flowed through this rock (18th March, 2013). (Image Credit: NASA/JPL-Caltech.)

Hydration Map of Knorr Outcrop, December 2012:

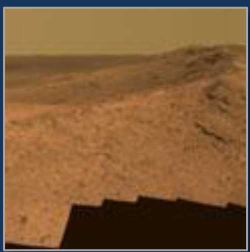


This image maps the distribution of hydration (water) in the rock, which Mastcam and ChemCam suggest is due to hydrated calcium sulphate. The colours indicating areas of hydration correspond only to the locations of the veins and nodules, not to the surrounding rock that is of different composition, suggesting that there was a second era of hydration; rocks already in place were fractured and as water flowed through them it was trapped in calcium sulphate minerals in the fractures. (Image Credit: NASA/JPL-Caltech.)

Curiosity, Yellowknife Bay, December 2012:

The Yellowknife Bay Formation records ancient stream and lake deposits believed to have once offered environmental conditions favourable for microbial life. This view is based upon the ability of *terrestrial* micro-organisms such as bacteria and archaea to withstand diverse and extreme conditions. Also, most or all of the ingredients required to support these organisms are present in the Sheepbed mudstone. The habitable environment existed during the Hesperian Era, when parts of the planet were becoming drier and more acidic, less than 4 billion years ago. For Curiosity's science team, the geography of the area suggests the Sheepbed mudstone extends beyond Yellowknife Bay to indicate the presence of an ancient lake covering at least 30 square km. For further information see http://www.seti-setr.org/SETL/solar_sys/Mars.html. (Image Credit: NASA/JPL-Caltech/MSSS.)

Pillinger Point, Endeavour Crater, May 2014:



It was evidence of a water-related mineral in this part of the crater's western rim, informally known as 'Pillinger Point', that drew the attention of researchers. The Mars Reconnaissance Orbiter detected a spectrum possibly belonging to montmorillonite, an aluminium-rich member of a class of clay minerals called smectites. The mineral, whose exposure extends for about 800 feet along the western rim, forms when basalt is altered under wet and slightly acidic conditions. ‘Pillinger Point’ was named after Colin Pillinger, principal investigator for the *Beagle 2* project. (Image Credit: NASA/JPL-Caltech/Cornell Univ./Arizona State Univ.)

Cape Verde, Victoria Crater, October 2007:

Victoria Crater is currently about 750 meters in diameter and 75 meters deep and formed in sulphate-rich sedimentary rocks. Features such as crater morphology and ejecta thickness indicate, however, that at its formation Victoria was about 600 meters in diameter and 125 meters in depth; the increase in crater width is due to erosion whilst its depth has been reduced by the deposition of wind-blown sand and material released from the crater walls. Also, sedimentary layering in the crater walls is believed to preserve evidence of ancient wind-blown dunes: such layering is seen at the base of the Cape Verde promontory as a band of horizontally parallel ridges. The height of the promontory is approximately six meters, the upper two meters of which has been identified as a layer of impact breccia, a mixture of angular fragments of different types of rocks held together by a fine-grained material. (Image Credit: NASA/JPL-Caltech/Cornell.)

Perseverance Valley, Endeavour Crater:

Perseverance Valley, targeted for the Opportunity rover's extended mission, cuts through Endeavour's western crater rim. How the valley was originally formed, however, remains unknown, although M.C. Bouchard and B.L. Joliff of Washington University, St. Louis, note that the hypothetical origins of the valley include, 1) wind abrasion, 2) ice wedging, 3) flowing water from a catchment basin and 4) mass wasting along a radial fracture or a some combination of these. Opportunity has itself, however, been silent since June 10th, 2017 due to a global dust storm and so no further in-situ studies will be possible until and unless it comes to life once again; at this point, August 2018, NASA engineers are hopeful. (Image Credit: NASA/JPL-Caltech/Cornell/Arizona State University.)

Vera Rubin Ridge, Aeolis Mons (Mt. Sharp), Gale Crater, September 2017:

Curiosity has been searching Vera Rubin Ridge for changes in composition and in the depositional environment recorded in exposed strata on the north-west slope of Aeolis Mons (informally Mt. Sharp). The ridge was targeted for study prior to Curiosity's landing in Gale crater on the basis of orbital spectroscopic data that identified haematite there. The Vera Rubin Ridge strata are collectively a part of the Murray Formation, which is interpreted as predominantly mudstones deposited in a lacustrine setting: that is, produced by or belonging to a lake. The Formation is a diverse collection of sedimentary depositional environments (facies). (Image Credit: NASA/JPL-Caltech/MSSS.)

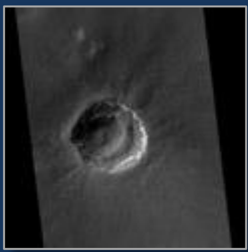
Orbiter Images:

Hellas Basin, MGS, September 30th, 2006:

Location: near 43.1^{o} S 307.3^{o} W (about 3 by 8 Km). Hellas Basin, about 2,300 Km in diameter, formed between 4.1 - 3.8 billion years ago and, many believe, may have once harboured lakes (possibly ice-covered) until the early

Amazonian Period (dating from about 3 billion years ago); a basin-wide sea in the Noachian has also been suspected. Eastern Hellas includes the highland volcanoes Hadriaca and Tyrrhena Paterae and the Harmarkhis, Dao and Reull Valles canyon systems. The Basin has also been noted as a source of Mars' global dust storms. (Image Credit: NASA/JPL/Malin Space Science Systems.)

Ada Crater, MRO (HiRISE), November 9th 2006:



Ada Crater is located in Meridiani Planum at 3.1° S, 356.8° E. It is 2.2 km in diameter and its formation has been dated by one researcher to about 50 thousand years ago (Golombek: 2012). The crater's off-set concentric rims have been explained by an impact angle of less than 45 degrees (from left of image) that also produced a predominately down-range ejecta blanket. The ragged 'scalloped' crater rim is due to erosion and the continued collapse of material from the crater wall, which is even more noticeable at Victoria Crater. (Image Credit: NASA/JPL/University of Arizona.)

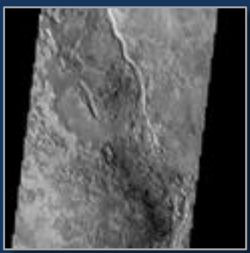
Amazonis Planitia, Mars Odyssey (THEMIS), 2006:

In this scene, spanning about 18 by 48 km, layer after layer has been first deposited, altered by impacts and other processes, and then been partly stripped away by erosion. The large circular feature is an old, mostly buried impact crater about 11 km wide and dating to the late Noachian or early Hesperian Period; the sediments that have all but buried it probably date to the later Amazonian Period. Debris ejected from a younger crater to the east (right) covers about half of the 11-km crater. The cluster of small hills southwest of the larger crater's rim show dark streaks; these mark dust avalanches that might have happened just days or months before the image was taken. The darkest streaks are the youngest.

The Broader Amazonis Planitia Context

Amazonis Planitia, often referred to as the smoothest plain on Mars, is located between Tharsis Montes and Elysium Planitia and to the west of Olympus Mons. Three features have had a major impact on the geological history of the region, forming barriers to sediment and subsequent lava flows: i) a 1300 km diameter Noachian-aged impact basin; ii) an approximately 100 meter-thick late-Hesperian lava flow unit from the pre-aureole Olympus Mons volcano, and iii) the formation of the Olympus Mons aureole. These three barriers caused further lava flows and outflow channel effluents (water) – mainly from the Elysium region – to pond in Amazonis Planitia smoothing the terrain there. At different times both lava and water are believed to have been carried from Elysium Planitia north-east through Marte Valles to Amazonis Planitia whilst probably in the late Hesperian considerable amounts of water and sediment were transported into the region through Mangala Valles to the south and its north-westerly off-shoot Labou Vallis, possibly feeding a slowly expanding ocean from the Vastitas Borealis Formation to the north of Amazonis Planitia. Note that the Medusae Fossae Formation that today stands in the path of the Mangala Valles system is a later, Amazonian feature and was not present to block water flow into Amazonis Planitia. (Image Credit: NASA/JPL/University of Arizona.)

Apsus Vallis, Mars Odyssey, Feb 2006:



Apsus Vallis, at 33^{o} N, 224^{o} W, is a channel of uncertain origin located to the north-west of the Elysium volcanic complex in Elysium Planitia. Hrad Vallis and Tinjar Vallis (out of image) run roughly parallel and to either side of Apsus Vallis. (Image Credit: NASA/JPL-Caltech.)

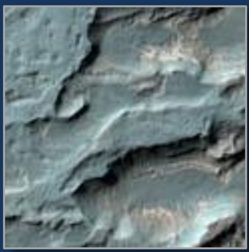
Ariadnes Colles, Mars Express, 16th April, 2007:

Ariadnes Colles is a basin exhibiting chaotic terrain and numerous light-toned hill-like knobs in Mars' southern highlands between Terra Cimmeria and Terra Sirenum. These knob-like deposits have been exposed from underneath a large volcanic deposit (the Noachian-aged "Electris" deposit). Ariadnes Colles and the other degraded basins Atlantis Chaos and Gorgonum Chaos may be the site of an ancient lake, named Eridania, which overflowed to create Ma'adim Vallis to the north. The knobs themselves, dating to the Hesperian or Amazonian Period, provide some evidence for the proposed lake as they consist mainly in magnesium-rich phyllosilicate clays that may form in an aqueous environment. (Image Credit: ESA/DLR/FU Berlin [G. Neukum].)

Eberswalde Delta, Mars Global Surveyor:

A delta or an alluvial fan? If a delta, as most believe, the structures in the image would represent ancient water channels that flowed into a body of water such as a lake; if an alluvial fan no such body of water would be required, the water instead flowing down from a steeper gradient onto a dry plain. The fan is a part of the Noachian-aged Eberswalde Crater, 65 km across, formed about 3.6 billion years ago whose southwest rim was later greatly modified by the impact that formed the 150 km diameter Holden Crater that may have been the source of the water that carried the fan-building sediment into Eberswalde Crater. In addition, if the fan is a delta and given the estimated timespan for its formation - perhaps 100,000 years – this would suggest the region to have been a favourable location for either the emergence of life or at least for its sustainability. This said, the fan-delta may have formed, according to some models, in as little as several years to hundreds of years, which may have been much less conducive to life. The fan is located in the western portion of Eberswalde Crater at 24.3°S, 33.5°W that is to the north-northeast of Holden Crater. (Image Credit: NASA/JPL/Malin Space Science Systems.)

Eberswalde Delta, HiRISE, November 8th, 2006:



This closer view of the proposed Eberswalde delta-fan shows one of many sinuous ridges that have been interpreted as inverted water channels. Known also on Earth, these form when the water channels have been filled in with a material that is more resistant to erosion than the surrounding terrain into which the channels were carved; consequently, the surrounding, less resistant material erodes leaving behind a raised or inverted channel (also described as a channel with positive relief). (Image Credit: NASA/JPL/University of Arizona.)

Kasei Valles and Sacra Fossae, Mars Express, 6th November, 2009:

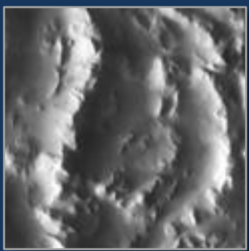
The image shows a 35-km impact crater whose south-western rim is highly eroded, due mainly to water, the source of which many believe to be Echus Chasma about 850 km to the south-west. The crater floor and north-western region, which are very flat, are formed from sediments and basaltic lava flows from the Tharsis region. Sacra Fossae, a fault system extending for about 1000 km and being several hundred meters deep, is believed to have possibly experienced tectonic stresses and subrosion - sub-surface rocks being dissolved and removed by water - causing overlying strata to partially collapse and form chaotic terrain. (See also ESA Mars Express page.)

Kasei Valles in the Broader Context:

Kasei Valles is about 2500 km in length, runs northwards from Echus Chasma and ends in Chryse Planitia; Echus Chasma itself is an approximately 175-km wide, 100-km long open-ended, flat-floored depression.

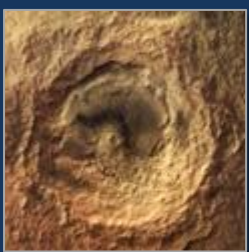
According to the majority of planetary scientists Kasei Valles formed as the result of a catastrophic flood that emerged from the sub-surface at Echus Chasma. Chapman, Mangold et. al. (2009) suggest that this event probably occurred in the early Amazonian Period. Subsequently, in the late Amazonian, a prolonged period of volcanic eruptions in both Tharsis Montes and Echus Chasma deposited a massive volume of lava in the valley. Mangold et. al. also found evidence of two earlier episodes of east-trending Tharsis-sourced Hesperian floods that occurred *only* in north Kasei Valles. Not all researchers, however, accept the fluvial origins of Kasei Valles, favouring instead a volcanic explanation not least because geological evidence indicates a cold, dry climate during the late Hesperian and Amazonian Periods, but also because, in the words of one researcher, "realistic mechanisms by which hypothesized aqueous outbursts might have taken place on Mars have not yet been confidently identified" (David Leverington, 44th Lunar and Planetary Science Conference, 2013, 1355.pdf). Image Credit: ESA/DLR/FU Berlin (G. Neukum).

Lycus Sulci, Mars Odyssey (THEMIS) 2003:



Part of the Olympus Mons aureole, Lycus Sulci is a region of roughly parallel hills and valleys (in geology 'sulci') surrounding the volcano on its northern and north-westerly sides and meeting Amazonis Planitia further to the west. Viking images of Lycus Sulci and Amazonis Planitia suggested to some researchers that the two met along a cliff face possibly formed by erosion due to wave action in a body of water: in short, a possible coastline. By late 1999, however, the higher resolution MGS MOC images of the region (1998) were interpreted as not supporting this hypothesis (see 'Mars Shoreline Tests', MSSS). The former presence of an ocean in Mars' northern lowlands remains, however, a subject of debate, some researchers seeing ice-rich sedimentary deposits where others see basalt. (Image Credit: NASA/JPL/University of Arizona.)

Maunder Crater in Noachis Terra, Mars Express (HRSC):



Maunder Crater is located at 50° S, 2° E in Noachis Terra, half-way between Argyre Planitia and Hellas Planitia in Mars's southern highlands. The crater is 90 km in diameter and approximately 900 meters deep, though it was deeper in the past before being largely in-filled with material. On the crater floor and ranging from 500 to 2500 metres in length can be seen dark features called *Barchan Dunes*, one of the most abundant dune forms in arid environments. The *eastern* region of the crater floor is bounded by a trough, approximately 700 metres deep (top of crater in the image). The *west* of the crater has experienced a major slope failure, during which a large landslide transported loose material eastward to the inner parts of the crater.

Images were taken of the Noachis Terra region by HRSC on *Mars Express* on 29th November and 14th December, 2005, including of Maunder Crater. (See DLR Portal, 'Hummocky and Shallow Maunder crater', 16th October, 2007.) Image Credit: ESA/DLR/FU Berlin (G. Neukum).

Nirgal Vallis Wall, MGS, July 12th, 1999:

Nirgal Vallis is a valley long believed to have been carved by water. The region shown reveals at least fourteen channels of nearly one kilometre in length ending in fan-shaped aprons, likely formed by water: since some of these aprons appear to cover the dunes the channels and the aprons may have formed more recently than the dunes. Also, the absence of craters in the dunes, channels or fan-shaped deposits suggests a geologically young terrain, at most a few million years or as little as a few days at the time the image was taken. The image spans an area about 2.3 km wide by 2.8 km in height and is located near 29.7°S, 38.6°W. See MGS MOC Release No. MOC2-240, 22 June 2000, MSSS. (Image Credit: NASA/JPL/Malin Space Science Systems.)

Olympus Mons, Viking 1 Mosaic:

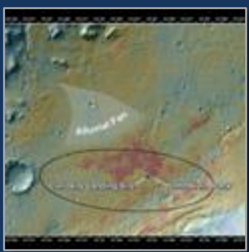
Olympus Mons (20°N, 135°W) is a shield volcano about 600 km across, 25 km high with an 87 km by 65 km caldera. The caldera, a depression at the top of a volcano, consists in at least 6 collapse craters, formed when large amounts of lava are emptied from underground conduits; without the support of the lava the conduit roof collapses. It is believed that the lava either erupted from vents on the volcano's side or temporarily drained deeper into the planet. Aureole deposits, the volcano's oldest deposits at over 3.8 billion years, surround the volcano extending 1000 km northwest of its centre and 600 km south-east of it. It is theorized that ancient clay sediments, perhaps hundreds of meters thick, emplaced beneath Olympus

Mons billions of years ago and before the volcano formed may be responsible for its asymmetric shape, the fluid-rich clay acting much like a lubricant for the spread of the volcanic material above it to such large proportions. (Image Credit: NASA.)

Mars, from Viking 1 Orbiter, Feb. 22nd, 1980:

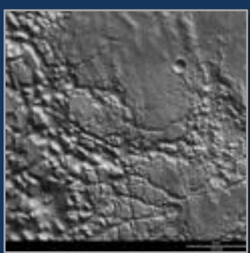
At the centre of this image is the Valles Marineris, a vast canyon spanning about 4000 km and with a depth of up to 8 km. To the left of the canyon is the Tharsis Montes, consisting in three enormous shield volcanoes (the three dark spots): from bottom to top these are, Arsia Mons, Pavonis Mons and Ascraeus Mons (Olympus Mons is just out of the image to the west). The dark area to the north of the Valles Marineris is Acidalia Planitia: features interpreted as dried up river valleys and former crater lakes testify that large amounts of water once existed here. (Image Credit: NASA.)

Alluvial Fan, Gale Crater, Mars Odyssey (THEMIS), March, 2013:



In this false-colour map is an alluvial fan where debris spread out downslope, which on Earth is often due to the flow of water. The John Klein outcrop is part of 'Sheepbed', a mudstone with abundant evidence for ancient aqueous processes. Possibly sediments were carried downhill from the eroding crater rim and became part of alluvial fan systems that accumulated water and sediments to form a habitable environment indicated by the Sheepbed mudstone. (Image Credit: NASA/JPL/University of Arizona.)

Iani Chaos, Mars Express (HRSC), October 14th, 2004:



This region of Iani Chaos lies at about 0.7° S, 340.6° E. The terrain is dominated by large-scale remnant massifs - massive structures of rock commonly more rigid than those of their surroundings - that have been moved and weathered as a block. These flat-topped hills or mountains bounded on at least one side by a steep cliff range in width from less than one kilometre to eight kilometres. Iani Chaos is also widely believed to have been the source of the water that carved out Ares Vallis; according to some researchers the evidence suggests that this water was released not in one great burst, but in multiple eruptions ranging from the

Hesperian to the mid-Amazonian Period. (Image Credit: ESA/DLR/FU Berlin - G. Neukum.)

Argyre Basin and Hooke Crater, Mars Express (HRSC), 8th June, 2012:

Seen here is part of the northern region of the 1800 km-wide Argyre Impact Basin and the 138 km-wide Hooke Crater inside of it (right of image/north). The white layer spanning much of the image and extending into the southern part of Hooke Crater is carbon-dioxide ice (dry-ice) that has condensed out of the winter air onto the surface. Hooke Crater lies just inside Nereidum Montes, a chain of mountains that forms part of Argyre's northern rim and spans more than 1100 km with some peaks rising to three or four thousand meters.

Argyre Basin in the Broader Context:

Argyre Basin was formed by a large asteroid impact about 3.9 billion years ago and today is almost 5 kilometres deep. Large areas of Argyre Planitia - the Basin floor - have been modified by wind erosion and by water and ice. Whilst the presence of liquid water in the Basin at some point seems certain, when it entered the Basin - the Noachian or Hesperian Period - how much there was and for how long it persisted remains a matter for debate, some arguing that the entire Basin filled with water soon after the impact and overflowed into the Uzboi Vallis system to the north, whilst others consider that a much more modest lake formed later within the crater: in either case the liquid water would have soon iced-over producing glacial and periglacial environments. (Image Credit: ESA/DLR/FU Berlin - G. Neukum.)

Becquerel Crater (HRSC), Mosaic, 22nd July 2006- 7th March 2008:

This 167-kilometres crater located at 352.2 degrees E, 22.1 degrees N in the western Arabia Terra region marks the transition from the Martian highlands to the northern lowlands.

The dark areas consist of basaltic sands that appear blue-black due to an increase in the contrast of the camera's colour channels; in reality, they are grey-black and likely originate from volcanic ashes. The bright, layered sedimentary deposits within the crater consist of sulphurous rock that is hydrated in places, which is to say it contains water in its crystal structure. These sedimentary deposits have formed a mountain almost 1000 meters high with gently inclined slopes and a flat summit. The sediments may have formed through the interaction of emerging ground-water in low-lying regions - such as impact craters - and dust transported by the wind, possibly combined with ash deposits. Alternative explanations for the formation of the deposits include the similar ground-ice melting model, aeolian (wind-driven) deposition and so-called orbital forcing whereby the change in the tilt of a planet's axis affects its climate. (Image Credit: ESA/DLR/FU Berlin - G. Neukum.)

South-East Amenthes Planum, Wide-View, 13th January 2013:

To the left of the wide-view image and dominating the entire scene is an approximately 100-km crater with at least three smaller craters superimposed on its eastern edge, the topmost of these being about 35 km in diameter. The eroded southern (left) rim in particular of this crater exhibits distinct landslides. The 100-km crater, which extends westwards (top) beyond the image, has a third crater on top of it out of view. The floor of the large crater is chaotic, which is to say littered with broken rock due probably to the removal of sub-surface water ice. The channel at the bottom centre of the image meets Tinto Vallis as it breaches the southern rim of Palos Crater the western edge of which is seen here. To the far right of the image (north) and running from the breached northern rim of Palos Crater can be seen a channel that is the southernmost region of the Amenthes trough, which continues more extensively to the north-west.

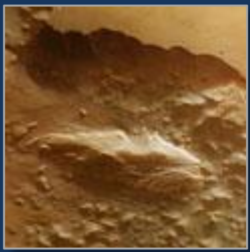
The Amenthes trough consists in lava plains and wind-blown (aeolian) deposits into which are cut numerous channels: as these are connected with Palos Crater and Tinto Vallis, which is interpreted as an open crater-lake system, the latter has been regarded as evidence that the channels in the Amenthes trough were formed by water. Some researchers estimate that the channels in the trough formed between about 2.7 and 3 billion years ago and indicate Late Hesperian to Early Amazonian fluvial (water) activity post-dating the formation of the Amenthes volcanic plains. (Image Credit: ESA/DLR/FU Berlin - G. Neukum.)

The Broader Context:

Formation of Tinto Vallis: Tinto Vallis, which is approximately 180 kilometres in length, is believed to have formed between about 3.5 and 3.6 billion years ago due to catastrophic flooding & steadier groundwater erosion.

Palos Crater: Palos Crater is approximately 53 kilometres in diameter and located at 2.7 degrees South, 110.8 degrees East in northern Tyrrhena Terra. Some researchers believe that the crater was once home to a lake that was fed by Tinto Vallis; the breach in the northern rim in turn served as a source for the 350 kilometre-long Palos outflow channel.

Juventae Chasma, Mars Express, 4th November, 2013:



Juventae Chasma is a 180-kilometre wide, 250-kilometre long north-south depression located north-east of the main interconnected chasmata of Valles Marineris; its most prominant characteristics are mounds of layered deposits and chaotic terrain. The largest of the mounds in the image rises 3.3 kilometres above its surroundings, is nearly 53 kilometres long and 20 kilometres wide.

Origin:

The chasma is linked to faulting resulting from volcanic activity more than 3 billion years ago, causing the chasma walls to collapse and slump inwards, so forming the broken, chaotic terrain seen to the right of the image. The faulting also opened cracks in the ground that released sub-surface water into the chasm: instruments on Mars Express (OMEGA) and Mars Reconnaissance Orbiter (CRISM) have shown that the mounds within the chasm consist in sulphate-rich minerals indicating that they were indeed altered by water. The upper layers are rich in gypsum (hydrated calcium sulphate) whilst the lower layers consist in kieserite (hydrated magnesium sulphate). (Image Credit: ESA/DLR/FU Berlin - G. Neukum.)

The Broader Context:

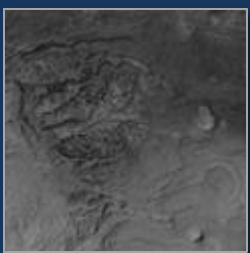
Maja Valles:

Maja Valles is a 50 to 150-kilometre wide channel extending 1600-kilometres northwards from Juventae Chasma and the highlands to the lowlands of Chryse Planitia. Whilst water from Juventae Chasma is understood to have sourced Maja Valles, the fact that the head of Maja Valles is over 3 kilometres above the floor of the Chasma requires an explanation for how water could have flowed out of the Chasma to form the channel system; one such explanation suggests that heat supplied by volcanic activity melted ice that in turn generated the floods necessary to overcome the 3-kilometre barrier (Chapman et. al. 2003).

Valles Marineris, Viking Orbiters 1 & 2:

Valles Marineris, a system of canyons located just south of the Martian equator, is understood to have formed over a long period from the early to late Hesperian era. Long rectangular troughs, including Ius Chasma, formed as grabens that eventually connected with other chasmata. As seen in the image, Ius Chasma itself is divided by Geryon Montes into northern and southern sub-basins, a process occurring early in the chasma's history. Large outflow channels emerged from the eastern end of the valley during the middle Hesperian and ran northwards into Chryse Planitia and the northern lowlands. That water did flow through Valles Marineris is supported by the OMEGA instrument on Mars Express, which has revealed sulphate-rich deposits (gypsum, kieserite) that form in the presence of water. Valles Marineris is about 4000 kilometres long and in places 10 kilometres deep, whilst its central troughs merge into a depression up to 600 kilometres wide. Juventae Chasma is seen to the north-east. Noctis Labyrinthus, the 'Labyrinth of Night', is the broken, chaotic terrain visible at the far western edge of Valles Marineris. (Image Credit: NASA/JPL/USGS.)

Melas Chasma, Mars Reconnaissance Orbiter (MRO), HiRISE, 15th March, 2008:

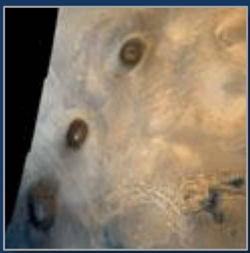


Melas Chasma is located in central Valles Marineris and centred at 287.46 degrees east, 10.52 degrees south; Coprates Chasma is to the east. Some researchers have suggested that a lake once resided in the Chasma, which finds support in the presence of depositional fans in a basin to the south-west. Dense, highly organized valley networks at higher elevations around the basin drain into a closed depression within it. Four fans have been identified: two in the western part of the basin (north and south fans, seen in the centre of the image), two in the eastern. The western fan complex consists in multiple lobes and structures that look almost leaf-like. Metz and colleagues estimate the timescale for the formation of the Melas fans to be between 100 - 10,000 years, thus requiring the presence of a stable body of water for at least this long.

Various origins for the fans have been considered, including alluvial, delta and gully deposits. Finally, however, the location of the Melas fans close to the centre of the basin in a topographic low, the fan slope angle and the sinuosities of the channels in the fans are considered by Metz and colleagues to be more consonant with a sublacustrine origin, so suggesting a lake; nevertheless, these features are not considered sufficient to conclusively eliminate a deltaic origin: for this an in-situ analysis at the centimetre to decimetre scale is believed to be required. (See J.M. Metz et. al. 'Sublacustrine depositional fans in southwest Melas Chasma', *J. Geophys. Res*., 114, 2009.)

Further evidence for the presence of water in some form comes from MRO CRISM data, which suggests the presence of opaline silica and hydronium-bearing (H_30+) jarosite within the Chasma, the latter most likely having formed in a low temperature, acidic environment; since these are hydrous (water-bearing) minerals this implies that liquid water was present when they formed. (Image Credit: NASA/JPL/University of Arizona.)

Noctis Labyrinthus & Eastern Tharsis, Viking 1 Orbiter, 22nd February, 1980:



Noctis Labyrinthus consists in a complex system of grabens; that is, blocks of rock that have dropped down between normal fault lines and are nested between raised blocks called horsts. This system formed due to extensional tectonics, a side-ways stretching of the crust, when intense volcanism in the Tharsis region led to the formation of a bulge, resulting in tectonic stress. This caused the crust to thin out and form the grabens.

The three shield volcanoes seen to the left of the image and collectively known as Tharsis Montes run along the crest of the Tharsis bulge and from top to bottom are called Ascraeus Mons, Pavonis Mons and Arsia Mons: the diameters of the volcanoes are respectively, 456.4 kilometres, 366.53 kilometres and 470 kilometres and each volcano rises about 15 kilometres above its surroundings. The distance between the Ascraeus and Pavonis calderas is about 800 kilometres. Olympus Mons, the largest shield volcano in the solar system, is about 1700 kilometres west of Ascraeus Mons. North is up. (Image Credit: NASA.)

Mars, Hubble Telescope, 2003:

The Hubble Space Telescope (ESA/NASA) took this image of Mars on August 26th, 2003, with its Wide Field and Planetary Camera 2 when the planet was just 34,648,840 miles (55,760,220 km) away. The image was taken 11 hours before the planet made its closest approach to Earth in 60,000 years. (Image Credit: ESA/NASA.)

Scientists had hoped to take advantage of this rare event to acquire information about the physical properties of the Martian surface and airborne dust, including particle size, shape, and possibly composition. (See *HubbleSite* - 'Mars: Closest Encounter', Background Info.)

Near the centre of the image is the 270-mile (450-km) diameter Huygens Crater, which is centred at 13.5 degrees south, 55.5 degrees east in the Noachian highlands between Tyrrhena Terra and Terra Sabaea. It has been estimated that the formation of the crater uplifted and excavated Noachian-aged materials from depths greater than 30 kilometres. The dark triangular shape to centre-right is Syrtis Major, whilst the Hellas Basin is the large circular area just below and to the right of centre. (See '**Hellas Basin, MGS, September 30th, 2006**'.)

Mars Hubble Composite, Aug. 26th-27th, 2003:

The left-hand view was captured by Hubble on August 26th, 2003, using its Wide Field and Planetary Camera 2 about 11 hours prior to Mars' closest approach to Earth in 60,000 years: at this point Mars was 34,648,840 miles away (see previous image for details). The right-hand view was captured on August 27th when Mars was only minutes away from closest approach: it was now 34,647,420 miles (55,757,930 km) from Earth. To the north-north-west (top) the circular feature is Olympus Mons rising to about 25 km. To its south-east in the Tharsis Montes can be seen in a line the three smaller volcanoes Ascraeus, Pavonis and Arsia Mons and to the east Valles Marineris, the 'Mariner Valley', stretching for 4000 km. The dark region to the south-west of the valley is Terra Sirenum and the southern pole is the white region at the bottom: though consisting in carbon-dioxide and water-ice only the former is currently visible. (Image Credit: ESA/NASA.)

Nili Fossae, Mars Express, 16th October 2014:

Nili Fossae, centred at 22.02 degrees north, 76.69 degrees east, is located to the north-east of Syrtis Major and on the north-western edge of Isidis Planitia. OMEGA data (Mars Express) has revealed Nili Fossae to possess a rich diversity of minerals, including magnesium and iron (mafic) minerals, such as olivine and pyroxenes, phyllosilicates - these being mainly iron-rich smectites, a type of clay mineral - carbonates and opaline silica. The phyllosilicates are present only in the Noachian crust (the Noachian being a period ranging from about 4.1 - 3.8 billion years ago). These diverse minerals indicate the former presence of widespread liquid water activity. Nili Fossae is a system of troughs that appear to have formed as a consequence of the formation of Isidis Planitia, whilst the floor of the trough system is understood to be covered in lava originating in lava flows from Syrtis Major. (Image Credit: ESA/DLR/FU Berlin - G. Neukum.)

The Broader Context:

Further evidence for the presence of water in the region has been found in the 45-km Jezero Crater (77.67 degrees East, 18.42 degrees North) to the south-east of the Nili Fossae trough where two sedimentary fan deposits are believed to have formed as lacustrine deltas (Head, J.W., Fassett, C.I., 2005). Mangold, N., Fassett, C.I., Head, J.W. et. al. 2007 have suggested that the crater was filled by a lake for at least thousands of years, although the origin of the water is unknown. Iron/magnesium-smectites and carbonate have been identified in the crater, the latter composing the majority of the northern delta; it is also believed that the carbonate has been transported to the crater from elsewhere as is common in terrestrial lakes. The western delta appears to be different in composition, indicating the presence of iron/magnesium-smectites (Head, J.W., Fassett, C.I. Mustard, J.F. Goudge, T.A., 2013).

Acidalia Planitia Mud Volcanoes, MRO, 2nd October, 2010:

Part of the northern lowlands of Mars and spanning nearly 3000 kilometres in an east-west direction Acidalia Planitia is centred at about 55 degrees North, 338 degrees East and lies between and to the north of Chryse Planitia and Arabia Terra. The region displayed in this MRO HiRISE image is about six kilometres wide.

It has been suggested that the lowlands were formed, in part, by several large impacts in the early history of Mars about four billion years ago (Frey 2006, 2008); remnants of these partially buried impact basins have been mapped by Frey as quasi-circular depressions (QCD's), Chryse Planitia and Acidalia Planita each being considered to be impact basins of this type. Others have proposed instead a giant impact even earlier in Mars' history that produced the crustal dichotomy boundary that distinguishes the northern lowlands from the southern highlands. On this view the Chryse and Acidalia basins may have been produced after the formation of the lowlands by the first impact.

Some researchers have suggested that due to the outflow channels that emptied into Chryse Planitia that Chryse, Acidalia and perhaps the entire northern lowlands were at some time under water either in the form of an ocean or of lakes.

Across Acidalia Planitia can be seen numerous circular mounds - over 18,000 - that have been interpreted by some researches as mud volcanoes; on Earth these typically emit during their formation a mixture of gas (hydrocarbons), water and solid sediments, although on Mars, and in Acidalia in particular, the triggering of mud volcanism by hydrocarbon generation (or by tectonic compression) is not suspected. The mounds range in size from hundreds of meters to several kilometres in diameter whilst the period of their formation has been dated to the early Amazonian between about 3 billion and 1.75 billion years ago (Oehler and Allen: 2010). It has been suggested that upwelling ground waters may have been channelled to the surface through the conduits created by the extensive mud volcanism and that the sub-surface accumulation of these waters and dissolved organics might have established microhabitats in Acidalia capable of supporting microbial populations, possibly even today. (Image Credit: NASA/JPL-Caltech/University of Arizona.)

Hydraotes Chaos, Mars Express:

This view shows a valley a little over 2 km deep in which mesas, buttes and hills, having been subjected to intense erosion, are seemingly chaotically arranged. No comparable structure is found on Earth. Hydraotes Chaos is located between Xanthe Terra and Margaritifer Terra in a major outflow channel, with Simud Vallis and Tiu Valles flowing out of it into Chryse Planitia. Aurorae Chaos flows into it. Whilst its formation remains uncertain, it is widely believed to have been the result of the interaction of magma and sub-surface water or water-ice, which when heated was released explosively through vents, possibly rupturing aquifers. The overlying rock then collapsed. The formation of the terraces associated with many of the existing blocks of rock have been interpreted as due to water action of some kind, including the interaction of waves and ice in a frozen lacustrine basin, or the result of ponding in catastrophic floods. Evidence is believed to exist, however, to support the view that the final collapse of the terrain to present day elevations post-dated the flooding that apparently formed the terraces. (Image Credit: ESA/DLR/FU Berlin, CC BY-SA 3.0 IGO.)