Was Mars terraformed

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This consists of a chapter from my book "Why We Must Go to Mars" and two unpublished papers. It examines the hypothesis that Mars was visited billions of years ago by aliens. They terraformed Mars by a series of oblique impacts aimed at the poles, these formed volcanoes on them including Tharsis, Olympus Mons, and Elysium Mons. The volcanoes outgassed thickening the atmosphere, they also sublimated the frozen atmosphere at the poles. The polar ice was also melted, this is traced in how it formed the Martian oceans. The rise of these volcanoes, particularly Tharsis, caused an imbalance of the planet inducing polar wander. The South Pole settled for a time a few hundred kilometres west of Hellas, the three main Martian faces (Cydonia Face, King Face, and Nefertiti) were on a great circle probably defining this former equator. Many possibly artificial formations follow this old equator. When the volcanoes cooled the atmosphere and oceans froze again at the poles, this moved them to their current positions. It also caused the extinction of the hypothesized alien colony. These papers are dated but indicate how the hypotheses of polar wander explain many of the fluvial and glacial formations on Mars.

Chapter Two

A theory of artificiality

The data so far is pointing towards a consistent theory of these anomalies, this will be fully explained over a series of future books but the basics can be outlined here. The most likely time frame for this alien visitation or evolved Martians is over a billion years ago. The reason for this early date is the Argyre impact[xxxii], a large meteor which hit Mars. This impact may have been done deliberately by alien visitors to warm up the planet, otherwise a random meteor impact may have caused a chain of events that warmed Mars for long enough to help sentient life to evolve there. Some uncertainty exists as to the actual date of this impact because if natural then it should have occurred in the Late Heavy Bombardment in the formation of the solar system several billion years ago, but there is no reason why it could not have happened later. If the impact was caused by aliens to terraform Mars then it might have happened much later than the early bombardment but it is no doubt far more ancient than our own civilization and probably predates any complex life on our own planet. I use the time of a billion years ago not to try and pinpoint any particular time accurately but to emphasize it was in the very remote past. It is probably impossible to work out how old these artifacts are, assuming some are artificial, until we eventually colonize Mars.

The reason this impact is interesting from the point of view of terraforming is that it may have been a shallow impact that hit the South Pole at the time, i.e. it came in at a very low angle rather than from directly overhead. This theory is more fully explained in the Appendix with a chapter called a History of Mars. It outlines the geological evidence for this being a shallow impact and how the shock waves would have warmed the planet by causing extensive volcanism and the subsequent moving of the Poles. Later in the book I discuss how this impact could be worth trying to emulate to terraform Mars. This is worth investigating even if the impact was a coincidence because of the effects it may have produced.

It would be logical to terraform a planet with meteor impacts, the same idea has been studied by the Mars Society[xxxiii] and in science fiction books. The idea is the impact produces heat which warms up the planet, in a shallow impact the shock wave moves for longer on the surface and this heats up much more of the surface to radiate heat into the atmosphere rather than just below ground. It also causes more fractures in the surface to allow volcanic magma to come up and form volcanoes such as Tharsis and Elysium Mons. Heat from underground also comes up to the surface heating the atmosphere, along with outgassing thickening the air with CO2 and sulfurous gasses. The longer this heat is concentrated on the Poles the more it prevents the air and water immediately refreezing back there, so aiming meteors at the poles would heat more of the frozen water and CO2. When the water ran off from the Poles it created a sea in the Northern Lowlands, this however needed a sufficient air pressure to stay as liquid water, a situation nearly impossible[xxxiv] currently on Mars. The idea then is the additional CO2 sublimated from the Poles thickens the atmosphere and stops the water in the seas from returning too quickly to the Poles. These seas would then create clouds, rain, snow, etc. which would be necessary for life to take root. Currently on Mars the air pressure is too low for liquid water to exist except fleetingly, this is a result of the triple point of water where with low enough air pressure it sublimates or boils directly into water vapor from ice without ever becoming water. So the additional air pressure from melting the CO2 at the Poles can allow more liquid water to survive on Mars.

This life introduced for terraforming would be tailored for such a harsh environment, the Mars Society and NASA have already considered doing the same to terraform Mars[xxxv]. The most likely source for this life would be from the alien home world; it may be that life from there was seeded onto Mars and the Earth. When the colony failed over a long period of time this life evolved, perhaps also because it was engineered to evolve more quickly, and eventually it produced animals and humans that look something like the Faces of the aliens. Because they also evolved from the same kind of basic life it is only necessary for this to produce animals with two eyes, a nose and a mouth like Earth animals for there to be a resemblance between the Faces and ourselves. Life elsewhere in the galaxy may also look similar to us because ours is extensively based on a simple mathematical sequence called Fibonacci numbers. These form for example the tree like shape of blood vessels in animal bodies, internal organs can look like plants such as cauliflowers looking like brains and kidneys shaped like beans. The dimensions of a face have been shown to relate to the Golden Mean and Fibonacci numbers, Leonardo da Vince used this in his paintings. If alien plant life also evolves based on Fibonacci numbers such as with roots and branches in plants then this may transfer to animals and lead to alien humanoids that look like us.

Of course there is no way to know if alien life was seeded on Mars and we evolved from it, but it shows there are plausible explanations for our resemblance to the Martian Faces. A good example of terraforming is the Mars trilogy science fiction books by Kim Stanley Robinson, one of the founders of the Mars Society where Mars is seeded with life. It is necessary for life to convert the CO2 atmosphere to more Oxygen because while CO2 will freeze in tiny amounts on our own Poles because of its relatively high freezing point, Oxygen freezes at a much lower temperature than would occur on Mars. If the air pressure is low on Mars however this reduces the amount of CO2 that will freeze even below its own freezing temperature[xxxvi]. The race would then be on to stabilize the atmosphere to retain heat before the effects from the impact and volcanoes wore off and caused Mars to freeze up again, initially however the high amounts of CO2 in the atmosphere should give a greenhouse effect. The theory here is that aliens may have done all this with meteors long ago to either try to colonize Mars or create enough atmosphere and heat for a short stay. Technically this would be much easier to do to Mars than the technology involved in travelling here from another star, the question is whether the impacts of Argyre and

Hellas, and perhaps Isidis and Chryse could have successfully terraformed Mars. There may also have been more water and air available on Mars then to work with, much has been lost because of the solar wind and a lack of a magnetic field[xxxvii].

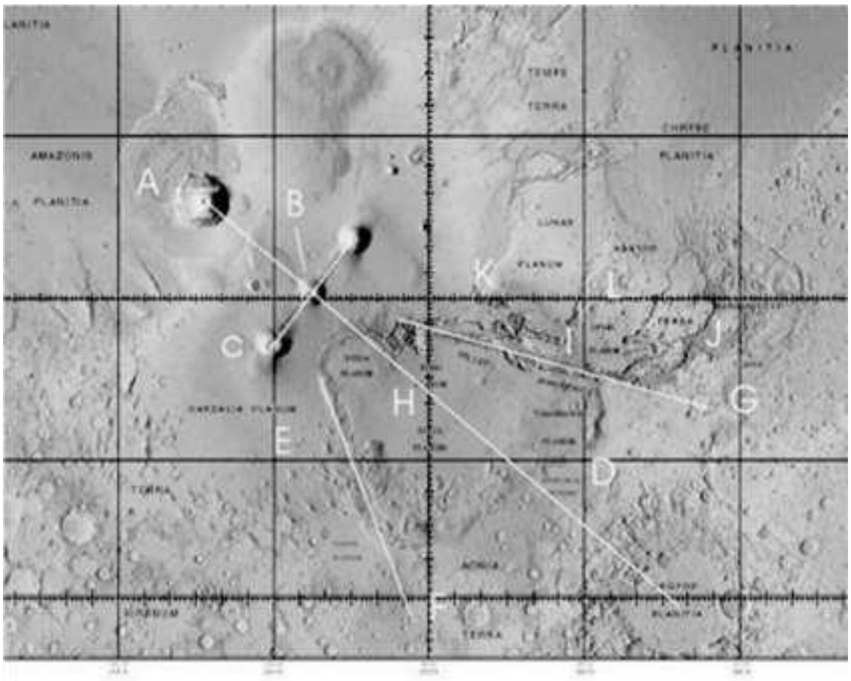

Figure 1

This is a section of the Martian surface. Argyre Planitia is seen on the bottom right, this was the impact crater. If it was a glancing impact then the shock wave would travel along the surface towards **H***, the heat from this would have created fractures in the ground such as Valles Marineris at* **G** *and caused volcanism to raise this area. The darker areas in the center denote a higher elevation and as can be seen the 4 large mountains at* **A**, **B**, *and* **C** *namely Olympus Mons and the three Tharsis Montes volcanoes line up with this crater. At* **I** *there would have formed a channel for water melting on the pole to flow outwards as well as through* **J**, **K**, *and* **L** *into Chryse Planitia.*

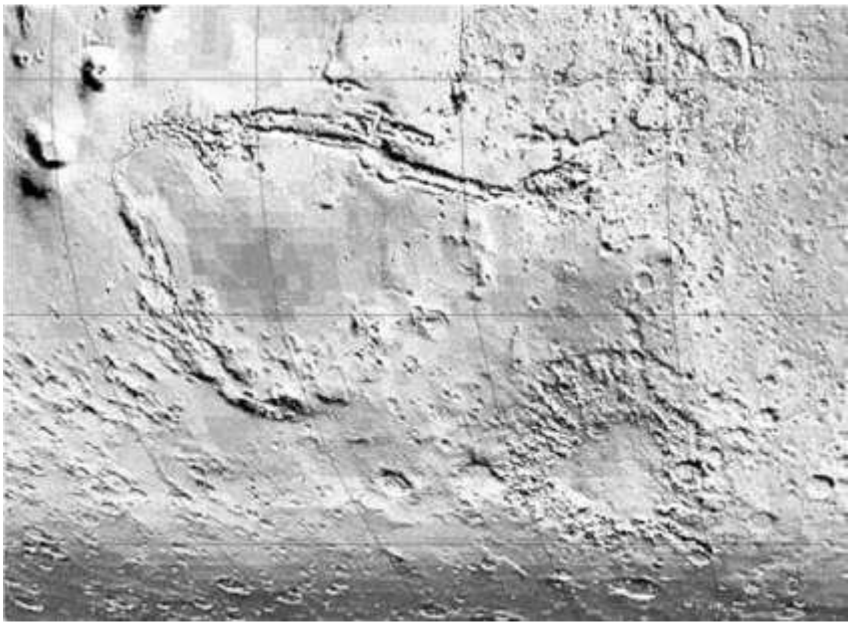

Figure 2

Argyre Planitia, the impact crater is shown again towards the bottom right. The darker areas are drier[xxxviii]*, they contain less water ice than the lighter areas while the dark area at the bottom is ice associated with the current South Pole. The image was originally color but needed to be converted to grey scale for this book, the link above takes you to the color image of this. The dark areas give an impression of radiating out from the crater towards the Tharsis volcanoes which can be seen in the top left. This would be caused by the shock wave heating the surface and creating the rifts and mountains shown. It can also be seen how these dry areas are on one side of the crater implying this shallow impact. By calculating the angle of this dark area radiating out from Argyre the approximate angle of impact could be estimated. We could do the same thing by aiming a meteor like this at the current North Pole of Mars letting the ice there melt and fill the Northern Lowlands, where the former Martian sea existed. At the same time this would sublimate much of the CO2 frozen at the Poles and give Mars a temporary increase in air pressure.*

To get all these benefits from a single impact would be a good result for these aliens, they would just have to nudge a large rock from the Asteroid Belt into a collision course with the Martian South Pole to give a glancing impact then wait for the planet wide effects like storms and Mars quakes to settle down enough to not be dangerous. This Pole was just to the East of Tharsis Montes at the time though of course these mountains did not exist as they would have been created by the impact. The heat from the impact melts the ice and CO2 at the South Pole and antipodal volcanism created another three volcanoes Elysium Mons, Hecates Tholus, and Albor Tholus next to the North Pole to heat up the ice and CO2 there. The Argyre impact would then produce polar wander, where the Pole moves to a different position because Mars would become unbalanced as large amounts of mass form on the Poles as these volcanoes grew. The Poles then tend to move so these volcanoes end up on the equator because of the centrifugal force, this causes water to be spread over large areas of Mars as the Pole melts when it moves over a warmer surface. The ice left behind is moved to lower latitudes because the Pole moves away from it and so it melts forming water runoffs, floods, rivers, rain, etc. A shallow meteor impact on one Pole combined with antipodal volcanism creating three other volcanoes on the opposite pole is a nearly ideal way to heat up Mars, the polar wander then is a good way to spread the water widely across it. Much of this water would go underground into an artesian system or freeze rather than return to the poles as rain or snow so if the temperature stays high long enough then higher oxygen levels could allow plants to survive and continue to terraform Mars. While there is no way of knowing for sure whether visiting aliens created this sequence of events it holds promise for our own efforts to terraform the planet. If we could duplicate these events with well-aimed meteor impacts then it may dramatically shorten the time it takes to make Mars habitable. More is explained on this later.

One problem with this idea is we don‟t know how long this terraforming would take, and hence whether the time scales involved would be practical for aliens. If they were colonizing Mars then presumably they having come all they to our solar system would be able to wait for however long it required. It is unlikely someone could come from another star with people being awake constantly so the likely alternatives to this are suspended animation or the colonists, flora and fauna would be frozen as seeds as the equivalent of our eggs and sperm to germinate in artificial incubators. It may have taken Mars hundreds of years or even thousands of years to settle down enough to colonize directly, we have no way of knowing this. Presumably the polar wander would take place over a long period of time, likely longer by millions of years than a probe or prospective colonists would be prepared to wait around but this polar wander could be occurring while they were actually on the ground with little effect on them. The other possibilities are that indigenous Martians evolved and there were no visiting aliens, or there were both, i.e. aliens visited indigenous Martians. In the case of Martians evolving this may have been accelerated by a chance shallow impact at Argyre and the resulting warm period on Mars allowed life there to rise to the level of sentience before becoming extinct when the planet cooled as the heat from the volcanoes ran out.

This also implies that the colonization lasted a long time, but this seems less likely because a colony that survived a million years for example should have left vast traces of its existence. For example our Earth civilization is arguably less than ten thousand years old and we have radically altered the planet in that time. It may be then that this polar wander occurred quickly or these aliens observed Mars from their home world as appearing more habitable after the Argyre impact and decided to come here after seeing this, much as we are now trying to do with extra solar planets by seeing if they are in a habitable zone and what their atmospheres are like. Aliens may have seen Mars on the edge of a habitable zone with a CO2 atmosphere and decided to come here to visit or colonize Mars or other planets[xxxix] of our solar system.

One problem with the polar wander theory is that the various anomalies found on Mars tend to be clustered around a great circle which may have been their Martian equator. If so then the Poles would have wandered a great distance according to the polar wander scenario, this would make it more likely the aliens came after the polar wander and Argyre impact had happened, that a first visit by a robot probe or other kind of ship started the terraforming and then a colony ship came much later, or a colony only built these formations after being on Mars for a long time. These 15 formations I believe may be artificial tend to cluster in a nonrandom pattern in a mainly temperate like zone near an old Martian equator. This was first noticed by the deceased Tom van Flandern who saw that the Cydonia Face was on the equator of a former Martian Pole position near the Hellas impact crater, but this Pole in the wander path[xl] would only occur as a last stage before the current Pole position and far from its original position prior to the Argyre impact. He also noticed that the face was aligned at right angles approximately to this equator.

A history of Mars

by Greg M. Orme.

Mars has a mysterious history. Many of the facts we know seem to be conflicting, for example it seems to have had a history of water flows which seems to contradict its current cold state. Valles Marineris is also hard to explain, a large rift valley with apparently no plates, which are needed on Earth to create them. There are many water flows from craters but there should be no water in those areas. Craters are unevenly distributed on Mars, covering only half the planet to a large degree and this coincides with a drop in height called the dichotomy boundary.

Here an attempted explanation is made based on large scale events, which may have driven most of the Martian changes and created the paradoxes we see today. It is a forced sequence of events so if the basic premises are accurate then it is quite likely something like this occurred, though perhaps in a different order.

The 4 largest outside influences we know about Mars are probably the last four big impact craters, Utopia, Isidis, Argyre, and Hellas. Since much of the confusion about Mars arises from the fact that we don’t perceive its evolution to be understandable compared to our own, this theory attempts to explain it by outside events driving the changes.

If a planet was perfectly round a pole might tend to wander over time. Usually planets are a spheroid, which means they are like a slightly flattened ball, and the wider parts tend to be at the equator. This is because the extra weight tends to go to the equator where it wields more force because it spins faster there.

The converse of this is that an absence of mass such as an impact crater or large valley like Valles Marineris would tend to go toward a pole since they become the equivalent of the flattened part of a spheroid. We also know that on Mars large impacts typically form a Mons or mountain on the other side of the planet, though sometimes not exactly opposite the crater. Logically this Mons would take a long time to form and we know that the Tharsis Montes for example probably continued to grow and restart through much of Martian history.

So at first with an impact there is an immediate tendency for the crater to move to the pole, and then as the Mons grows on the other side this weight fights to move to the equator and eventually may overcome the lack of mass in the crater. Also the crater may partially fill up over time as Utopia Basin appears to have[1]. It may then be that at first the crater moves to the pole and then after time moves toward the equator as the Mons grows. By having 4 impact craters and their associated Mons doing this it can make the resultant climate on Mars vary wildly, and make it much harder to decipher.

Also as a crater moves toward a pole its gravitational influence diminishes, so it will likely stop near but not exactly on the centre of the pole. It may also fill partially with ice and this addition of mass in it can further stop it moving closer to the pole. If the climate then changes for example with the heat added to the atmosphere by the volcanism of the Mons then this amount of ice can further fluctuate moving the pole as well. This would be because the warmer climate might move ice from the pole to the equatorial regions, and perhaps sublimate CO_2 from the poles.

While a Mons can be initiated by an impact it can also be altered or even restarted by additional impacts if the shock waves are strong enough. For example in here I will show that Isidis may have weakened the Tharsis area, which was further affected by an oblique impact from Argyre, and then from Hellas. This would have contributed to these volcanoes restarting many times until they reached their enormous size.

Generally it is believed that a large impact like Hellas would naturally make a large Mons on the other side of Mars, but the record from large impacts is not so clear. Utopia Basin and Isidis Basin have no large Mons opposite them, Argyre has Elysium Mons, and Hellas is hard to line up with the Tharsis Montes and Olympus Mons though it lines up well with Alba Patera. There is however enough of a correlation to think they are related.

The main theory is that when the impact occurs the core acts like a lens focussing the shock waves onto the crust on the other side of the planet, either exactly opposite or somewhat offset if the impact is oblique. This theory has several problems however. One is that a spherical core is not really the right shape to focus shock waves like this; such a shape should tend to defocus the waves. Also we don't know the relative densities of the materials involved so we can't say for sure what angle of deflections would be made by such a lens. As Mars became progressively deformed impacts happened from different elevations and so it would seem unlikely all of these would just happen to give such a precise focus to create a Mons.

The effect of shaping sound waves by a lens is well known, dolphins use it for example to direct their sonar.

A more likely explanation might be that as the shock wave spreads there is a small cone of the wave that goes directly through the centre of the core and other layers, and because over this area the surface of the core is relatively flat then this cone of the shock wave would tend to be not defocused. Outside of this cone the shock waves would tend to be defocused and perhaps distributed evenly over the opposite hemisphere to the impact crater.

People who need glasses can see a similar process. Squinting can improve eyesight because the light goes through a narrow aperture, which is similar to shock waves going through the centre of the core. The narrow beam that gets through the core without being defocused might by itself create only a very narrow circle of damage on the surface crating one small volcano, compared to a large area of devastation.

Other parts of the shock wave may even be reflected back so we may get bands of general volcanism as the force is distributed over a large area. For example the core and other layers should have an angle of reflection so that waves hitting at a shallow angle tend to bounce off it and waves at a steeper angle tend to refract into the core. Large enough impacts may even affect the magnetic field in the core and perhaps and stop the magnetic dynamo[2].

This general spreading of the shock waves could have induced a general increase in volcanism over the whole planet and perhaps in certain bands, so these may explain larger volcanic flows[3] [4]. As we will see later the two main areas of Noachian craters[5] may have been preserved by their having been under poles and thus have resisted volcanic resurfacing.

Some of the Martian names are shown on 2 maps[6] [7]. Also the polar wandering path of Sprenke et al[8] is referred to, these are adjusted to give a polar path more in line with impact craters and known deposits of ice found, which may correspond to old poles[9]. It is not possible to be exact with the positions of poles so long ago; also they may not have been circular. The current poles for example are not, which may be caused by the pole still moving.

The Utopia Impact

While previous impacts may have shaped Mars[10] [11] I begin here with the Utopia impact basin[12] [13]. Thomson and Head conclude this is an impact basin and also that it is very ancient, likely much older than Isidis, Argyre and Hellas since it is much shallower[14]. Isidis basin is on the edge of Utopia Basin, implying from its shape that it was formed later. There has long been controversy over whether this is an impact basin or an ancient sea. Thomson and Head argue the model of an impact basin as opposed to an ancient sea or ice sheet but the pole in the basin would perhaps make both indicators be seen together[15]. This area could have been a Northern ocean especially when the Utopia impact basin was still warm from the heat of the impact. I refer to the centre of

Utopia Basin as **North Pole 1** and subsequent poles are in numerical order. The current pole is **Pole 5**.

Interestingly similar lacustrine and volcanic arguments are made[16] in Valles Marineris which we will see later may have formed from the Isidis and Argyre impacts. If the pole had moved to the area of Valles Marineris in combination with the volcanic activity from the impacts tuyas may have been formed as well.

Smith et al[17] believe Valles Marineris may have formed after Argyre and Hellas, but this may also indicate those impacts helped to increase the rifting after it began with the Isidis impact. Valles Marineris is a large negative gravity anomaly[18] and so should tend to move to a pole as well. With the Isidis impact it was already near a pole, so this tendency was already realised.

As time progresses it moves further from the pole and as we will see towards the equator where it largely remained through further polar wandering. This implies it did not get much larger, or that if it did the negative gravity was compensated by the increased mass nearby of Tharsis Montes, Olympus Mons and the area around Solis Planum. If its rifting had have happened separate from an impact then we should expect to see the advance of the poles towards these impacts to be reversed at some stage when Valles Marineris was formed. This implies then that either it was never a significant negative gravity anomaly which seems unlikely or it formed in circumstances where its lack of mass were already compensated for and this did not change with a widening unrelated to the forming of further Mons from impacts. It is likely then that Valles Marineris was formed around the same time as the Tharsis Montes.

Sprenke et al[19] show no such change in the polar path heading back towards Valles Marineris or even seemingly being affected by it. Smith et al[20] also show how the current gravity of the Valles Marineris area is dominated by Tharsis Montes and Olympus Mons, and also by the area around Solis Planum, which also indicates the Utopia and Isidis impacts could have made that area heavier, slowly negating the negative mass of the Utopia and Isidis impact basins and allowing the pole to move on and this area to move towards its equator at the time. This area is shown in **Figure 1**[21].

Isidis Basin also has rootless cones, which according to Martel[22] may be formed by lava flows over water or ice. This would also be consistent with a pole here, and avoids the need to assume large amounts of ice all over Mars. Moore et al[23] believe fluvial erosion occurred in the Noachian to Hesperian.

The centre of this basin is 45 degrees North 248 degrees west, so directly opposite this is 45 degrees south and 68 degrees west. This is shown as **A** in **Figure 2**[24].

Interestingly this area has no Mons at all, though normally there should be one or more from the shock waves. The ground is raised around Solis Planum however and all the way to the Tharsis Montes. It may be then that the rifts around Solis and Syria Planum may have been partially formed from the Utopia Impact, where the whole area was raised rather than a narrow Mons.

The Argyre impact basin is very close to **South Pole 1**, and it may be that this hit the Mons opposite Utopia Basin, and removed all traces of it. The other possibility is that the Mons was in the area of Syria Planum and was either damaged in the Argyre impact or had eroded to a smaller size. This might account for the generally raised area around Solis and Syria Planum.

The Isidis Impact

The next oldest impact may have been Isidis[25]. If it has happened before the Utopia impact then likely it would show the effects and perhaps have been buried. It seems apparent that water flowed from the Isidis Basin into the Utopia Basin[26] [27]. Argyre also appears to be much younger.

When the impact occurred it would have moved closer to the pole, and the pole opposite would have also moved. The centre of the Isidis Basin is 12.7N 272.6W[28], giving the other pole as near 12.7S 92.6W, shown as **B** in **Figure 2**[29]. This would place it in Sinai Planum. So from one impact to another the pole may have moved from 45S 68W from the Utopia impact to 12.7S 92.6W. We cannot say where exactly **South Pole 2** was, though it is likely near a line between **A** and **B**.

Isidis is also the landing place for Beagle 2[30] [31] [32] [33]. Being very flat it is also more likely to be older than Argyre and Hellas. It also has signs of fluvial activity[34], which could be from when it was at or near a pole. Toon[35] says that large craters and river valleys appear to be the same age. This can be from impacts melting water, but also from impact craters moving to a pole which attracts ice and perhaps water if the craters retain some heat.

The elevated areas between Solis Planum, Icaria Planum, and Aonia then may have been caused by these two impacts. It also turns out that even though water signs were not picked up here by ODYSSEY[36] [37] the area is thought to contain ancient water deposits[38] [39] [40].

Barlow et al suggest the area has contained ice since the Hesperian[41], which fits in well with an ancient pole having been there. Interestingly they suggest the water table may have tilted here with the formation of Tharsis[42], which agrees with the time lines suggested in this paper. Instead of or in addition to the water accumulating here from Tharsis it could have accumulated from a pole forming here.

This agrees well with the proposed poles by Sprenke et al, who begin their polar wander at 45S 90W and then move to approximately 30S. It is more difficult to see signs of the opposing **North Pole 2** around Utopia Basin though ice signs are seen[43].

Not only does the area around **South Pole 2** in Syria Planum not show ice signs from ODYSSEY but they show the opposite, of being some of the driest parts of Mars. This conflicts with what is seen in Solis Planum, where fluidised ejecta from craters is known[44]. It may be then that there was ice here at one stage but events drove the water out. Since this area is opposite the Utopia and Isidis impact basins it implies that heating from those impacts may have removed the ice. Some ice may still be there[45].

After the Utopia impact this area would have become saturated with ice and perhaps water as it became a pole, and we know from the ejecta ice was there.

The pole may have extended into Solis and Sinai Planum in the middle of the raised ridges and rifts, though only the ones to the south may have been there then. Since this is opposite the Isidis impact and roughly follows the path of polar wandering by Sprenke and Baker it seems a reasonable possibility.

While the impact of Isidis may explain the lack of water signs opposite Utopia Basin it cannot explain the lack of water signs opposite Isidis itself. An additional event may have happened to make the further rifts around this pole, I call **Pole 2** (**Pole 1** would have been formed by the Utopia impact). Valles Marineris may have been formed from this further event.

Syria Planum is said by Webb[46] to be surrounded by a raised annulus as well. Stresses then are likely to have created the rifts such as Valles Marineris and allowed these Planum to subside. Instead however of Tharsis forming this strain this may have been done by the combined impacts of Utopia and Isidis, and that forming a pole of ice here restricted the volcanic effects to their perimeter. Scott[47] argues that Syria, Sinai, and Solis Plana were formed with a mantle plume, which is consistent with the idea of heat from the Isidis impact. The subsidence may have been partially formed by the weight of the polar ice. Also Scott[48] says this upwelling may have been enough to form Valles Marineris[49]. This area may also have escaped resurfacing from Tharsis because of this higher elevation according to Smith[50].

Hartmann[51] says Solis Planum also has well preserved craters, with larger craters more preserved. This may be because of the pole being there for a long time, having buried craters in ice.

Arsia Mons[52] [53]is roughly at 12S 120W, the same latitude as **South Pole 2**. It is also the largest of the 3 Tharsis Montes as well as being closest to the opposite of the Isidis Impact. Head says evidence of glaciation[54] [55] has been found also on Pavonis Mons and Ascraeus Mons, which is suggested to be from the late Hesperian. This may also have been from the time the pole was nearby. Few signs of water are seen, which would be consistent with polar ice. Head and Marchant[56] also say that Arsia Mons had volcanic outflows into the Hesperian, which is consistent with later impacts restarting the flows. Sprenke et al[57] say that the Tharsis Montes may have been formed after the Martian global magnetic field ceased, which might imply the Hellas and Isidis impacts had affected this field. It may also mean the volcanoes were reactivated later in subsequent impacts. Vast amounts of ice may be there even today[58].

Argyre Impact

Next the Argyre impact[59] may have occurred. Assuming **South Pole 2** was at Sinai Planum it would have been likely that this was an oblique impact. Argyre Planitia is shallower from the West to the North though it is deepest to the North West. Argyre is centred on approximately 50S 42W, and the Sinai Planum **South Pole 2** may have been at 12.7S 92.6W. Sprenke's[60] pole position would be 30S 90W so both give an oblique impact assuming the meteor came from within the ecliptic plane of the asteroid belt.

Looking at the higher elevations North West of Argyre Basin it seems these reach from Argyre all the way up to Valles Marineris and west to the northern edge of Icaria Planum, seen in **Figure 3**[61]. Illustrated in **Figure 4**[62] if you draw a line though Olympus Mons **A** and Pavonis Mons **B** then Arsia Mons and Ascraeus Mons **C** would be at close to right angles to this line as would the annulus **D** to the North West of Bosporos Planum. This also points at the centre of the Argyre Basin. The annulus west of Syria Planum and Solis Planum **E** would be approximately the same angle as Valles Marineris shown here as two lines **F** and **G**.

It may be then that while these features were partially formed by the Utopia and Isidis impacts the glancing blow of Argyre sent a shock wave in a shallow angle and created them. This would be the same mechanism as an impact on the other side of a planet except in this case the main shock wave comes from the side. The shock wave is always strongest in the path of the impact because the sound waves are most compressed along that line by the speed of the meteor and hence the frequency is most raised. So the strongest force in an oblique impact should be along the line of the impact trajectory.

This triangular shape can be approximated by shining a torch onto a circular bowl at an oblique angle, though the sides are more rounded. A shock wave would generally be cone shaped rather than cylindrical like a torch beam but the diffusion is unlikely to be great over this distance. As the beam goes through the pole at a shallow angle it would come out roughly in this triangular shape. The edges of the shock wave would tend to shear the ground creating an approximately triangular or egg shaped annulus and rifts. Rifting and faulting would tend to be in straighter lines making the shape more triangular.

The same thing may have created the triangular shape of Olympus Mons and the three Tharsis Montes, perhaps from a reflection from a subsurface layer. If a shock wave hits a denser layer below at an angle it may glance off like a light beam reflecting off a pane of glass at a shallow angle. The shape of this shock wave can be seen by shining a torch on a globe (representing the denser layer) at an oblique angle.

The shape is approximately the same, and faults would tend to be in straight lines to create the Tharsis Montes in a straight line. Here[63] Tharsis Montes and Olympus Mons are overlaid on this annulus shape together with Valles Marineris to show the similarity of the two shapes.

Another possibility is that the shock wave pointed directly at Tharsis and Olympus Mons, and a reflection made Valles Marineris and the rises. A geological layer would not reflect perfectly because of its rougher surface so some parts of the shock wave would go through and another part would reflect even when the angle of reflection favoured one or the other. A good analogy would be for light reflecting off frosted or roughened glass where some parts would reflect and others refract.

In this case then Valles Marineris would have been stressed but not rifted by the Isidis impact and upwelling and then sheared into a rift valley from the Argyre shock wave.

There are no signs of volcanic activity in any other direction from Argyre, which also implies a glancing impact. On the other side of Mars Elysium Mons would have been also formed from the impact. There are three Mons[64] opposite Argyre, Hecates Tholus, Elysium Mons, and Albor Tholus. This also connects the shape of Tharsis Montes plus Olympus Mons to the three opposite Argyre. The triangular shape of these three Mons may have occurred from a refraction of the somewhat triangular shock wave.

Hiesinger has out six scenarios for the evolution of the Argyre basin. Surious Valles has a delta shape, which may have been from water as **South Pole 2** melted. There is also evidence for a proglacial lake. Water signs are found there but too high for water to come in from the northern lowlands. A polar meltback[65] was proposed by Parker et al[66] though not in the **South Pole 2** position.

Elysium Mons is close to the Isidis basin which would have been the opposite **North Pole 2** at the time.

Such an oblique impact hitting the polar ice may have expelled large amounts of water and ice from Mars; indeed it is hard to imagine an event more likely to do so. Also if at this stage Mars had substantial amounts of frozen gases such as CO2 at the pole this could also have been ejected leaving the atmosphere much thinner. Much material from the crater may have also been removed from mars which could have subsequently made its negative mass more influential relative to the coming shift to **Pole 3**. Some ejecta may have added to the annulus to the west of Bosporos Planum **D** and even to the raised area further North West.

The subsequent heat would have melted much of the pole and raised the overall Martian temperature. If gases were frozen this would have raised the air pressure and allowed more liquid water, also floods from the ice melting were likely. Signs of these are probably shown in Valles Marineris which has an elevation sufficient to carry water into Margaritifer Terra and Chryse Planitia[67] which are also shown in **Figure 4**. In Lunae Planum there is also evidence of large scale flooding, also on Xanthe Terra, but little south of Solis Planum[68] and perhaps some into Argyre Basin which would be too hot at this time for water to channel into it. The water may also have gone North West[69] if Tharsis was not large at this time.

South Pole 2 would try to reform polar ice and water but the heat would drive it away. This then may explain why this area had evidence of water from ejecta in craters but this seems to have disappeared according to Odyssey[70], also shown in **Figure 5**[71]. As shown in **Figure 6**[72] one red section appears to radiate out of Argyre from the west **A** to the north **B**, and the second one sits in Solis Planum **C** where **South Pole 2** may have been. This indicates the Argyre impact may have dried out these areas, which is why they showed fluidised ejecta in the past but now show little ice. It may even have dried out east of Ascraeus Mons.

Later water would drain from the Argyre Basin as it cooled and water ran into it from **South Pole 2**. The raised annulus west of Bosporos Planum may also have prevented water going to the basin, as well as south to Aonia.

Thaumasia[73] shows deformational features radiating from the Argyre Basin which may show the impact had influence this far. While also radial to Tharsis here they may be more related to Argyre.

The large negative mass of the Argyre basin would have begun a pole shift. Also as the impact helped to grow Tharsis Montes and Olympus Mons they would have tended to move to an equator which would have also helped to shift the pole. As we will see according to the polar wander path of Sprenke and Baker Tharsis and Olympus Mons move directly closer to an equator westward, which in turn moves the pole eastward.

Sprenke et al show a movement of the pole to approximately 0S and 30W and then to 330W. This would take the pole to North of Argyre Basin into Margaritifer Terra and then east to Meridiani Planum. Since it is unlikely the pole stopped in Margaritifer Sinus this is not given the name **South Pole 3**, that is for when the effects of the Argyre impact stabilise a new pole. So the pole wanders from Sinai Planum **A** through Margaritifer Sinus **B** to Meridiani Terra **C** heading eastward, shown in **Figure 7**[74].

According to Grant[75] Margaritifer Sinus contains high valley densities, which would be consistent with the pole moving and subsequently ice melting. Also the area was resurfaced several times[76], perhaps from the subsequent volcanism from the Argyre impact. While Grant[77] believes some precipitation occurred most would have been from ground water, which is consistent to a water table associated with a forming pole. This discharge[78] lasted a long time according to Grant[79]. The Parana Valles[80] drainage system is particularly extensive.

Hynek et al[81] believe this time of fluvial resurfacing lasted several hundred million years. A combination of rainfall and sapping[82] appear likely, which may have formed a lake for a time[83]. A moving pole then may link the two main theories of precipitation and sapping to explain the valley networks[84], and that according to Nelson a large build up of ice which periodically melted. Philips et al[85] examined Margaritifer Sinus and concluded much of the Tharsis bulge was already in place before the drainage channels were formed, which is consistent with the general rise in elevation in the area of Tharsis and Sinai Planum from the Isidis impact. Further growth of Tharsis could happen later, though at the late Noachian it was large enough to direct the channels northward. Large amounts of material from this area were removed along these channels probably from water erosion as the pole melted, and moved into Margaritifer Sinus.

Valles Marineris[86] [87] [88] is then likely to have formed from the stresses of the Isidis and then the Argyre impacts, making its origin harder to see[89] [90]. By this time water and ice would have accumulated in it as the pole melted and moved, which may explain the paleolakes[91]. Carr[92] suggested that ground water flowed into Valles Marineris and then[93] into Chryse Planitia, forming lakes. Rossi et al[94] believe there is good evidence of ice and glaciers which would be consistent with a polar area.

Lunae Planum, also shown in **Figure 7**[95] would also have received water from the moving and melting pole. Greeley and Kuzmin[96] show how Shalbatana Valles originates in the chaos on Lunae Planum. Interestingly it comes from a probable impact basin that formed a catastrophic outflow. This impact may have occurred before or at the same time as Argyre, though its shape (not mentioned by the authors) would likely be elliptical if from the time of **South Pole 2**. While it is suggested the impact breached an aquifer this would be unusual for Mars. It does link the area with large amounts of water and probably ice triggered from an impact, something not seen elsewhere. A pole here would supply the water, and once it carved a channel keep it going with more water. A nearby elliptical formation, Orcus Patera[97] may also have come from an impact, its shape implying a pole was near here.

Xanthe Terra also shows evidence of water flows. Nelson and Greeley[98] discuss 3 major fluvial events here. The first is a broad sheetwash from the Valles Marineris area perhaps coinciding with the Argyre impact. Then there was more extensive water forming Shalbatana, Ravi Simud, Tiu, and Areas Valles which might coincide with the pole moving to Margaritifer Sinus. Most of this water came from chaos areas[99] which would link to the Argyre impact. Subsequent flooding would be as the pole continued to move, and when further enough away the water would cease.

In the new Odyssey results of subsurface ice[100] there is a large deposit on the equator in Babaea Terra shown in **Figure 8**[101] and centred at 330 degrees west. Another one can be seen on the left edge of the map just below the equator shown in **Figure 9**[102]. This would correspond to the opposite pole. According to Sprenke et al the pole moves in a curve through this ice rich area to 0S 330W, almost the centre of the ice rich area. I call this area **South Pole 3**. Having icy areas opposite each other like this makes it likely they were poles.

This can be explained from the effects of the Argyre impact. As the Tharsis and Olympus Montes grow they accumulate more mass which seeks to go to the equator. The movement of the pole to this area allows these to get much closer to the equator. Tharsis and Olympus Montes are today on the equator at around 120W and the pole would have moved to 330W. This adds to 150 degrees so the Montes would have nearly reached the equator, which indicates their weight was dominating at this stage. The pole has assumed a position between the Argyre and Isidis impact basins as each would have had a tendency to be near the pole.

This would tend to be a stable configuration. The Montes have grown enough to get near the equator so little more can move them closer. Elysium Mons has probably also formed to some degree which reduces some of the negative mass tendency of the Argyre Basin. It is at 210W so there is more than 120 degrees between there and the pole. **Pole 3** then would be balanced with Olympus Mons and Tharsis Montes tending to go to the equator and Elysium Mons almost opposite them also near the equator, and Isidis, Utopia, and Argyre basins around **South Pole 3**.

This also implies the growth of these Montes is strongly linked to the Argyre impact as the pole moved from near the Argyre Basin to mid way between it and the Isidis basin. If the Argyre impact had not happened then, its happening now would scarcely move the pole. It would be unlikely an impact causing the Argyre basin happened then just at a time where it wouldn't move the pole. Also that Elysium Mons has moved towards an equator which it wouldn't have done if it hadn't formed yet. Logically then the Utopia, Isidis, and Argyre impacts had to happen in this order, forming their respective Mons in the order described for this polar wander path suggested by Sprenke.

Interestingly **South Pole 3** coincides with an area of heavy cratering[103] and the second cratered area corresponds well with the opposite **North Pole 3** in **Figure 9**[104]. One likely explanation is that the polar ice protected the craters[105] from erosion, and when they were exhumed from the ice they remained in more pristine condition. **Pole 3** probably lasted a long time to give this crater disparity. It also implies at this time that the surface was being altered severely and other craters were being buried or obliterated by lava flows.

This may be because of the shock wave effect of these impacts which may have sent shock waves over large parts of the surface initiating volcanism. This would explain how volcanoes have apparently restarted in Martian history and the surface being relatively young in parts. **Pole 3** likely remained here through this resurfacing. Since these crater areas are linked into what is termed the Noachian surface it may be that the time after the Argyre impact may be regarded as the Hesperian, obliterating much of the Noachian terrain except for these parts protected with polar ice. Some other areas with Noachian craters are also found around Margaritifer Sinus, implying the pole may have slowly moved and protected other areas for a time in its path.

In moving from **Pole 2** to **Pole 3**, the polar ice closely follows and may have formed the dichotomy boundary. The main boundary is seen between 180 degrees west and 90 degrees west, which is 270 degrees or ¾ of a total possible boundary. The rest is taken up by the land mass of Tharsis Montes, Syria Planum, etc. **South Pole 2** moved from 12.7S 92.6W eastward to approximately 0S 330W, which is approximately 122 degrees of longitudinal movement or approximately 1/3 of the total great circle. The opposite pole travels from 12.7N 272.6W to 0S 150W, which is where the dichotomy boundary ends against Olympus Mons, for a movement of 122 degrees. This makes then 244 degrees of movement over a dichotomy boundary of 270 degrees as a polar path. The rest can be explained by the width of **South Pole 3** at 330W, which makes it appear to extend further east. So of the total visible dichotomy boundary virtually all of it is on the same line as the movement of **Pole 2** to **Pole 3** which is unlikely to be a coincidence.

The pole then moves through Margaritifer Sinus and from here there is a green elevation path. This trail begins at east south east of **Pole 2** so the pole may have initially moved towards the Argyre crater, which is logical as its negative mass should move towards the pole. This implies the pole may have moved along this green area and lowered the terrain there.

The pole was probably moving on a slope, which may make the path easier to see than from **South Pole 3** to **South Pole 4** where the ground was not sloping. We already know the planet tends to slope towards the current North Pole, **North Pole 5**, and that this polar path is lower than the terrain south of it, and higher than the terrain north of it. This then implies the moving pole may have flattened part of a slope going into Acidalia Planitia and for the opposite Pole Elysium Planitia.

A pole moving on a slope like this would tend to have a runoff of water heading North through the journey. Depending on the temperatures and the air pressure at the time ice may have sublimated directly into water vapour and CO_2[106] may also have been a primary erosional force. On the sloping ground water, mud and perhaps CO_2 ice would tend to move like glaciers, with material in the ice moved north through avalanches and liquid CO_2 as described by Hoffman. Dust that formed on the pole through dust storms then would be moved north and perhaps create a very smooth surface in Acidalia Planitia, Utopia Basin and Elysium Planitia.

As the pole moved new ice would tend to form on the ground ahead and melt on the ground behind it as the temperatures changed. The ice in front would tend to freeze into the soil and create a similar situation to the current **Pole 5** where approximately half or more of the soil is ice. When this eventually melted or sublimated the soil in the ice should have moved down the slope and spread out. If there was a high enough air pressure this should have created a seasonal water flow into Acidalia Planitia and created the smooth surface. CO_2 might give the same movement at lower temperatures.

It is likely the temperatures of Mars were dropping from the Argyre impact, there are visible water channels in Lunae Planum, Xanthe Terra, and Margaritifer Sinus, but these are no longer seen as the pole moves eastwards. The edges of the green elevation may indicate the edges of the permanent ice cap.

This may mean then that the primary erosion was from ice and CO_2. Some channels are found north of **South Pole 3** in Arabia Terra, but these may be from the Hellas impact later when the pole moves again. If so then this would again imply the temperatures and air pressure were too low after Margaritifer Sinus for water erosion. More investigation of this polar route should confirm whether channels existed.

The ice deposit at **South Pole 3** abuts a cliff to the north, which is an extension of the dichotomy boundary. This ice then implies that it is connected to the creation of this cliff and by extension created the cliff of the dichotomy boundary as the pole moved. As water ran down the slope at **South Pole 3** it would have eroded the ground, but where the ground was permanently frozen the ground would have been protected. This should then give a boundary to the north of the moving pole where the ground slopes more.

The speed of the polar wander should be according to how quickly the Tharsis Montes and Olympus Mons grew, with their tendency to go to the equator. Also as the pole moved away from Argyre it may have been held back because the negative mass of the Argyre impact basin would tend to be near the pole. As it came closer to the Utopia and Isidis impact basins it may have accelerated, releasing more water. These basins would counteract to some degree the negative mass of Argyre as they too would seek to be near a pole. It may also be that with the polar movement the channels would be regularly changing and so did not form as large as in Margaritifer Sinus.

The Hellas Impact

The Hellas basin is centred at approximately 40S and 290 W. This would have made it about 40 degrees from **South Pole 3** and so would have been an oblique impact, though not as much as Argyre. Almost exactly opposite Hellas is Alba Patera, again probably formed from the shock waves. The resultant shock waves may again have gone around Mars stimulating volcanism, perhaps restarting Tharsis Montes and Olympus Mons which are also close to opposite Hellas. It may also have stopped Mars' magnetic field. Sprenke and Baker[107] point out that the rotational poles closely follow the movement of **Pole 2** to **Pole 3**, but this does not appear to extend to **Pole 4**. This may be because the Hellas impact stopped the magnetic dynamo with the shock waves.

Anderson et al[108] analysed Syria Planum in comparison to Alba Patera. They concluded Syria Planum is Noachian to late Hesperian with intense activity that declined later. This would be consistent with its initial formation from the Isidis impact and later from the Argyre impact. They consider Alba Patera to be similar, which is plausible if it was formed by the Hellas impact. This is considered to be extending from the early Hesperian into the Amazonian and so is later than the Syria Planum volcanism. They believe[109] that Syria Planum had a greater impact on Tharsis than Alba Patera which is again consistent with the impact sequence.

The large negative mass of Hellas would have tended to move the pole towards it, and Sprenke found from elliptical craters that the pole probably moved to 45S 345W. This places it on the edge of the Hellas Basin in the direction of the Argyre Basin, probably with the two negative mass craters tending to both be near the pole. This is the same as in **South Pole 3** where Argyre and Isidis basins were both near the pole. It is closer to Hellas probably because Hellas is much larger than the Argyre Basin, being younger. There are many large craters in this area as well; some may also have been preserved through burial under the polar ice. I call this **South Pole 4**.

In **Figure 10**[110] **A** is **South Pole 3** and **B** is **South Pole 4**. This is now relatively close to **Pole 1** at 45S 68W. There is approximately 83 degrees of longitude between **Pole 1** and **Pole 4**, and they are on the same latitude.

Also in this pole position Isidis is on the equator which means that **Pole 2,** Sinai Planum, and Tharsis Montes are also now on the equator. The pole then has moved to near Hellas while maintaining much of the weight of the Mons on the equator. This is consistent with the weight of Olympus Mons and Tharsis remaining on the equator, and the pole moving to the negative masses of impact craters.

Hellas is an oval shape approximately twice as long as it is wide[111], probably from the oblique impact. Since Hellas is approximately 45 degrees from **South Pole 3** this would imply an impact at 45N at the time, and the oval shape indicates an impact on the western side to give the oblique angle pointing mainly at right angles to **South Pole 3**. This is likely as to the west of Hellas there is a reddish area[112] with much less ice, shown in **Figure 11**[113]. The icy area of **South Pole 3** is elongated pointing along the path of the polar wander to **South Pole 4**. The section west of Hellas basin much drier is shown as from **C** to **D**. Since this is in a direct line with the longest part of Hellas it is likely this was formed from ejecta or shock waves making this area hotter for a long time, and eventually drying the area when **South Pole 4** moved. This is the same mechanism as might have happened with the Argyre impact drying west and north of it in **Figure 6**[114].

The icy blue area of the current South Pole reaches to Hellas and implies the pole may have wandered east into Hellas and then south to the current position, as shown in **Figure 13**[115]. The lack of ice on **South Pole 3** may also indicate the climate was warmer from the heat of the impact and stopped large amounts of ice forming.

The corresponding North Pole would then have moved to the east of Alba Patera in Tempe Terra. There is a possible platform there similar to that south west of Alba Patera. The pole may have moved as the gravitational influence of Argyre lessened, with the basin filling up and Elysium Mons growing larger. This would move **South Pole 4** to the east away from Argyre, there may be another platform on the eastern side of Hellas Basin. This would also be consistent with water gullies, which in other parts of Mars are near former poles. If the pole moved to eastern Hellas Basin this would explain gullies in Dao Vallis and Tempe Terra. It may also be that the polar ice extended eastward to there.

This would also be consistent with the shape of the current poles. Chasma Australe points to 270W and may have been formed by water melting as the pole moved, the pole perhaps still moving. Promethei Planum would also have been formed from the pole moving away from **South Pole 4**. A hot spot creating basal melting may have formed Chasma Australe but the moving pole could have also supplied the heat, the leading edge becoming colder, and the trailing edge warmer.

Hellas seems to have contained ice covered lakes which would be consistent with being near a pole. It can be seen that the moving pole may have made a lot of different areas appear to be ice rich and often to have fluvial flows, even glaciers and hydro volcanism. This could solve the mystery of why Mars has so many water signs and apparently not enough ice available to cover them all. It also can explain that even though the temperature has likely been too low for liquid water, channels are widely seen. The moving pole would have moved water and ice with it affecting each area in turn, looking as if there should be perhaps 10 times as much water on Mars.

Chemically Mars resembles a dry planet[116] so outside of these poles there may have been little ice or water, and CO2 erosion may even have predominated at times[117]. Each impact would have temporarily heated up the planet giving perhaps brief times of liquid water and perhaps higher air pressure through sublimated gases.

The various Mons might have been periodically restarted from shock waves from the impacts and the resulting heat kept the planet warmer for a time, until eventually all volcanic activity ceased and Mars reverted to the cold planet we see today.

Thomson and Head[118] believe glacial features, moraines, drumlins, and eskers are to be found in Hellas, consistent with being near a pole. According to them this could have been part of an ice sheet[119] and a proglacial lake[120], possibly middle Amazonian[121]. The lake they believe would have held enormous amounts of water that has disappeared, consistent with water from a pole that moved on.

Jakupova et al[122] have laid out a distribution of craters 10 km and over. This boundary of heavy cratering closely follows the movement from **Pole 2** to **Pole 3** and indicates when the resurfacing of the north may have occurred at this time.

This is consistent with the poles moving water and sediments northwards, and burying craters. There is an area above Margaritifer Sinus which is nearly devoid of craters; this is likely to have been resurfaced in the floodwaters in the movement of **South Pole 2** to **South Pole 3**. Isidis is comparatively devoid of craters, and this continues in a line with the movement of **North Pole 2** to **North Pole 3**. This would again be from transporting sediments and water north and removing craters. The area north of the equator and 60 degrees west extends high into the northern hemisphere with heavy cratering. This area was found by Odyssey to be drier and indicates that a lack of water is associated in this area with cratering.

Layers are Mars are thought to have been formed by dust alternating with CO2 or water ice. As water and ice were moved north by the movement of **Pole 2** to **Pole 3** it would have deposited on these layers. With this pressure and with liquid water the tendency would be for the CO2 and ice to melt and move upwards, which would make the layers collapse and the ground to lower in elevation. The movement of water northwards then could have created a lowering of the ground forming the Northern lowlands. This lowering in turn would enable a large sea, ice sheet or mud ocean to form and the collapsing of layers to become more and more widespread. If so then the southern hemisphere may have substantial amounts of CO2 and ice still trapped in layers.

The northern hemisphere is seen as Amazonian and the Southern surface as Hesperian implying the southern hemisphere is older. This is however from crater counts and it is possible that the craters in the northern hemisphere may have been removed and buried in this process.

After the Argyre impact the formation of the volcanoes may have added a lot of ash into the atmosphere which would have tended to collect at the cold trap in the poles. This would have subsequently been moved northwards as the poles moved.

Permanent ice in the north[123] would tend to compress the ground leading to polygons when the ice was eventually removed. Dust and accretion from meteors would have built up on the northern ice as well as in the south. As meteors impacted in the north they would have fallen on ice and so not left a permanent mark. Head et al[124] show that the northern lowlands contain areas of polygons, craters with ejecta lobes, and potential coastlines.

Deviations in the Contact 2 coastline may be accounted for by changes in Tharsis and Elysium Mons which would be occurring as the pole moved, and later.

When eventually the planet became colder after the effects of Hellas and Tharsis wore off the air would have begun to freeze and go to the poles. Then the northern ice would also have sublimated, some may even still be buried as a frozen ocean. The material that had built up on the northern ice would have fallen down onto the craters that had been preserved under the ice, and buried some of them. This material would appear similar to that of the south, and likely not show signs of water as it came from the surface above the ice. Some of the northern ice sheet may have been liquid underneath around Tharsis Montes, Olympus Mons, Alba Patera and Elysium Mons because of their heat.

Some of these surfaces then may be smooth from having been sediments on an ocean floor in this way. Others areas may be smooth because as the ice sublimated the material fell smoothly.

In two areas ice seems to follow the dichotomy boundary, shown in **Figures 14**[125] and **15**[126]. This may be a residue from the movement of the polar ice from **Pole 2** to **Pole 3**.

Amazonis Planitia is thought to be flat from sedimentation or fluvial processes according to Head[127]. This is north of where **North Pole 3** stopped. Also the outflow channels may be partially from when **South Pole 2** in Syria Planum melted and began moving. Arsia Mons which is the most southern of the three Tharsis Mons may have been much smaller then. Some channels leading to Amazonis Planitia point north but to the east some point more to the North West.

Lucas Planum[128] is described by Cabrol et al[129] as an estuarine delta. If so then this may imply that the movement of **Pole 2** to **Pole 3** was accompanied by water flows as the pole melted. It may also have formed water locally from the heat of Apollinaris Patera[130], or from when the pole began to move north towards the future site of Alba Patera after the Hellas impact. Alba Patera has steep sides and may have formed in the polar ice of **North Pole 4**. Fuller et al[131] believe this area was resurfaced volcanically and with fluvial sediments. This could be for example from when the Hellas impact restarted some volcanism in Olympus Mons and started melting and moving **Pole 3**.

The Medusa Fossae Formation follows the path of **Pole 2** to **Pole 3**, and has formations similar to a pole according to Fuller et al[132].

McGill[133] refers to the younger material sitting on the older Noachian material, which is consistent with the dust layer settling. The buried materials are similar in age to the southern highland, which is consistent with the idea that this was buried under ice and then overlain with dust as the ice sublimated. In this case the air pressure would already be low so there would not be a liquid phase, hence no water to leave signs of the removal of the ice and chemical signs of water having been there.

Watters[134] shows lobate scarps are found south of the dichotomy boundary suggesting that compressional deformation was involved in the boundary's formation, which is consistent with the weight of polar ice. While he suggests that this occurred in the early Hesperian Anderson et al[135] believe Alba Patera was also formed in the early Hesperian to Amazonian, but the impact of Hellas may have defined the start of the Amazonian from the Hesperian. Since the Noachian, Hesperian, and Amazonian are calculated from crater records the impact of Hellas here may have changed these same crater records of the Hesperian to Amazonian at least around Alba Patera.

Head et al[136] believe much of the northern lowlands were resurfaced volcanically and in some areas as sublimation residue from frozen ponded bodies of water[137]. This may have occurred by the diffusion of shock waves from the Hellas impact over the northern hemisphere of **Pole 4**.

Tanaka et al[138] believe the northern lowlands were smoothed by glaciation. This would be consistent along the dichotomy boundary while it was forming, if there was a larger icy area north of the moving pole that was melting and reforming. If the air pressure was too low then this could have been from ice sublimating.

Hoffman et al[139] believe flood channels from Cerberus Rupes may be from CO2. This area is to the north as the pole moved southwards from **North Pole 2** in Isidis Basin to the **North Pole 3** position. This then may give CO2 through this area, in combination with flood water from the melting pole. The actual flooding depends on the temperatures but this area is equivalent to Margaritifer Sinus. **South Pole 2** had begun moving and released water into Lunae Planum, Xanthe Terra, and Margaritifer Sinus, so the opposite pole would likely be releasing water at the same time as it moved.

Since CO2 typically sublimates on the current poles in summer this same mechanism would presumably be operating as the pole passed this area. It is not known at this stage whether CO2 can account for these effects, but it is likely that it was available.

Burr et al[140] believe flood water originates to the north of the Elysium Basin and Marte Vallis[141]. A lake in Marte Vallis may have been fed from Medusae Fossae to the south. Ice from the pole moving to the **North Pole 3** position may have been heated by Elysium Mons which would be forming from the Argyre impact, and so may have provided heat to the area. They also conclude[142] precipitation was unlikely to form the channels because nearby areas show no erosion from rain. Groundwater is likely to form from a nearby pole, and the heat from Elysium Mons should turn this to water when the pole got close to the area.

Burr et al[143] see rootless cones though Athabasca Valles, which can from lava on wet ground. This can be from the volcanic activity from the Elysium Mons area caused by the Argyre impact, and water from the passing pole. The carrying of sediments[144] is consistent with the idea the moving pole may have carved out the dichotomy boundary, and floods moving the sediment north. Ice from north of Elysium Mons[145] may also have been melted by volcanism[146] giving flood water.

Elysium Mons[147] according to Bowling[148] had two periods of activity, which may correspond to the original formation from the Argyre impact, and being reactivated by the Hellas impact.

The ice on the edge of **South Pole 3[149]** cuts off on the dichotomy boundary as shown in **Figure 16[150]** which may indicate the pole helped form the boundary.

While the pole was here each summer, water or ice may have fallen down the slope of the dichotomy boundary off the northern edge of the pole, and the dichotomy boundary here could have been the edge of the permanent polar cap. The edge would form here because each summer water or perhaps ice or CO2[151] avalanches would fall down the slope, eroding it away till it abutted the permanently frozen cap. In **figure 17** at **A** an ice trail, possibly from this water connects to higher ice areas. With higher ground to the south water may have tended to go north.

As the pole moved from **North Pole 3** to **North Pole 4** it moves close to Olympus Mons and the Tharsis Montes, which may have restarted from the shock waves of the Hellas impact. If so then the movement of the pole near such hot areas should sublimate frozen CO2, so this time was probably one of higher air pressure. As Alba Patera formed from the Hellas impact at **Pole 4** the heat would also have kept CO2 from freezing there and raised the air pressure. Since this would keep one pole from having as much frozen CO2 the overall air pressure should have been substantially higher for a long time.

This places the **North Pole 4** just to the north and North West of Olympus Mons shown in **Figure 19**[152]**.** Milkovith et al[153] interpret this area to the North West of Olympus Mons to be glacial, but much large than terrestrial glaciers. This would be consistent with polar ice. Each of the Tharsis Montes according to Head[154] also shows glacial signs, perhaps from as the pole was passing. Since a pole should slow as it nears its resting point there may have been a pole on the Western edge of the Tharsis Montes for some time.

Pole 5

This is the current Martian pole. As time progressed Alba Patera became larger, perhaps cancelling out the negative mass of the Hellas basin. The current poles have the major Mons all near the equator just as they did at **Pole 3** and **Pole 4.** This indicates that from the time of **Pole 3** the polar wander had to move so as to keep these large masses on the equator. Since **Pole 3**, **4**, and **5** are roughly in a straight line this would have been controlled by the Mons and indicates they are older than these three pole positions.

Pavonis Mons is on the equator and Arsia Mons the largest is at 10 degrees south. Olympus Mons is at 20 degrees North and Ascraeus Mons at 12 degrees north. Elysium Mons is at 25 degrees north.

Once the ice in the northern hemisphere started to sublimated and move to the poles this would have created a large negative mass that would have acted like a crater. The pole would have tended to move to the gravitational centre of this which would move it from Hellas Basin to the current position. Since most of the ice came from the north this may explain why[155] [156] the **North Pole 5** has more ice.

Since the shift to **Pole 5** temperatures may not have allowed this additional ice to sublimate and equalise the amount at both poles.

Chasma Boreale on the **North Pole 5** points to approximately the **North Pole 4**, and Chasma Australe on **South Pole 5** points approximately to **South Pole 4**. Both of these are the largest chasma on their respective poles. The poles may even still be moving which would explain why the South Pole is asymmetrical[157].

The North Pole seems similarly asymmetrical [158]. Both shapes seem to elongate at right angles to the previous pole positions. This would follow as the pole moved the forward edge would represent a line of temperature low enough to form a permanent CO2 cap. Clearly the elongation could not point into the movement of the pole as this would be against the temperature gradient.

Byrne et al[159] found evidence of short term change on the current Martian South Pole, in the “Swiss cheese” formations. This is consistent with the idea that **Pole 5** is still moving, though it seems unlikely such short term changes would be associated with the pole moving. Changes may occur in spurts as areas collapse with the changed temperatures. One analogy might be the changes in glaciers on the Earth’s pole which can change suddenly from the slower global warming.

These structures are found on the forward edge of **South Pole 5**, and the spider formations are found directly opposite this on the other side of the pole. It may be then that these "Swiss Cheese" formations may be older spider areas that have slowly been moved into colder areas and are now permanently frozen. In this way the similarity between the Swiss Cheese shapes and the spider bushes can be explained.

Some of the spider formations would then be left behind as the pole moved on its trailing edge, and we see this as spiders that merge into apparently inactive areas there.

Pathare et al[160] believe recent changes in the Polar Layered Deposits may have been caused by changing obliquity though these could also have been caused by the moving pole. Layering is seen along the path of **Pole 2** to **Pole 3**; implying layers may be formed as a pole moves.

Malin Space Science Systems[161] recently reported in Science more examples of changes on the South Pole. Hoffman[162] shows gullies on the current South Pole may be undergoing changes, again consistent with a moving pole. These pitted areas however are also significant in relation to **South Pole 4**, and the gullies may have been formed at that time. M1003736[163] mentioned by Hoffman is at 70.91S 358.7W, which is closest to **South Pole 4**. This would explain their pristine condition if they were moved into the polar area after the pole shift from **Pole 4** to **Pole 5**.

The Ages of Mars

The three ages of Mars, Noachian, Hesperian, and Amazonian are primarily based on craters counts. If the polar wander theory is correct then these time scales will be distorted by resurfacing after each of the four major impacts. The Argyre impact may have been so influential it might be said to have begun the Hesperian, forming Valles Marineris, Olympus Mons, the Tharsis Montes, the dichotomy boundary and Elysium Mons.

As an alternative guide the four impacts might themselves be defined as the start of an age. There would then be the ages of Utopia, Isidis, Argyre, and Hellas. This can be much easier to work out the ages of various formations as the beginning and end of each age is a fixed date. Ages could also be defined according to volcanoes, e.g. the Age of Tharsis, Olympus, Elysium, and Alba Patera.

An approximate age can be determined for each impact, and then a tree of cause and effect can be created following on from each impact. Then the age of each event that follows from an impact is determined and added to the tree. This in turn enables the age of each impact to be more precisely determined. Other events that were sufficiently independent could be portrayed as separate trees of cause and effect.

The age of Utopia may have begun to form some of the area around Solis and Bosporos Plana. There may also be areas to the north west of Elysium Mons that could be dated according to this impact. It may have formed a Mons that was destroyed by the Argyre impact, if so then signs around the Argyre Basin may be dated according to Utopia as a benchmark.

Many of the effects of each impact would happen relatively soon afterwards and there would be a long time between impacts dates. Many formations should then be able to be connected with an impact and more accurately determined. This is especially useful where each impact changes an area in turn. For example the area around Tharsis Montes may have been altered by all four impacts.

The age of Isidis could be initially estimated by comparing the relative age of the Isidis and utopia Basins. This in turn may date some of the changes to the Solis, Syria, and Sinai Plana, and perhaps earlier changes to the future Tharsis and Valles Marineris. Geologically it is easier to calculate the ages of these formations by showing how craters counts are changed by resurfacing.

The age of Argyre may have formed the Tharsis Montes and Olympus Mons. If so then craters on them may help date Argyre Basin. The beginnings of Valles Marineris, Candor, and Ophir Chasma could be dated to shortly after the Argyre impact. After this the water channels of Lunae Planum, Xanthe Terra and Margaritifer Terra could be estimated.

In turn this can be compared against the age of the dichotomy boundary which would be formed later. This may in turn allow the time of the formation of the northern lowlands to be determined, if much was formed after the Argyre impact.

The age of Hellas would move the pole from Lucus Planum northwards and begin the formation of Alba Patera. This may also date the restarting of Olympus Mons and Tharsis Montes from the shock waves of the impact. The combined heat from these volcanoes may have resurfaced the northern lowlands.

The current age may be dated from the time the existing poles were formed.

Narrow angle images

Previous poles have left many changes on the Martian surface. To examine smaller scale changes I have examined 730 MOC narrow angle images[164] out of a larger randomly acquired collection[165], separating them into various kinds of formations such as water signs, dunes, and layers. These were accumulated over several years, before the ideas in this paper were conceived so there is no relevant unconscious bias in their selection.

Fluid signs

The collection of fluid signs[166] was first examined in reference to **Pole 4**. This was done by converting the coordinates of each image to its latitude under **Pole 4**[167].
This gave a list of coordinates between 0, equal to 90 degrees old north and 180 which is 90 degrees old south.

Fluid signs gave an unusual distribution[168] with a large number clustering around the **Pole 4** equator. On further examination these were around 37 to 43S and 140 to 200W, and 39N 19W.

The first cluster is on the bottom edge of an ice ridge area identified by Odyssey[169], which abuts the old equator at these coordinates. This was previously identified as **Pole**

3. The second cluster abuts another ice rich area on the top, again on the old equator and also near the dichotomy boundary. This is at the opposite **Pole 3**.

The water could have several possible origins. Some ravines could have formed on this pole, but this is unlikely as it should be very ancient and the water flows are more recent[170]. The second possibility is these flows occurred on the equator of **Pole 4** because it was warm enough there for some water to melt from the remaining ice of **Pole 3**. In that case we may be seeing relics of this flow. The third possibility is we are seeing ice from **Pole 3** melting because the current latitudes are suitable for this. In all cases this implies the source of the water was ground water or ice in the soil from **Pole 3**.

Since the water only seems to have been flowing in small areas it seems likely that these areas started flowing on the equator in **Pole 4** in a restricted area close to the equator. Though the pole has shifted channels in the ground are still connected to this ice, and at certain mid latitudes this can still flow[171] [172]. As we will see the positions of gullies is also correlated with layering[173] relative to **Pole 4**. Hartmann et al[174] compare these gullies with Icelandic gullies, which is consistent with the idea of seepage from a former polar area.

Others seem to cluster around 35S 270W, and 29S 38W. The first cluster is on the north eastern edge of Hellas Basin and may represent an area on the eastern edge of the **South Pole 4** ice cap.

The second cluster is close to the south western edge of the **South Pole 3** ice cap and so is likely to have formed with the same mechanism. This then gives all 4 main clusters the same mechanism, of ice from an old pole now at mid latitudes suitable for a water flow.

Another cluster is at 37 to 53S 320 to 356W. This is close to **South Pole 4**. Again the mechanism seems to be a part of the ice from an old pole position which corresponds to the suitable latitude for water to flow now.

It would seem then the reason the craters with water signs are so rare is that old polar ice deposits and suitable current mid latitude temperatures only coincide at a few positions.

Schmidt[175] points out additional areas with craters, which are also examined.

Gorgonum Chaos[176] [177] is situated at[178] 37S 173W, which would be on the southern edge of **North Pole 3**. Wilson et al[179] believe these gullies are not so young and represent only a limited discharge. This would be consistent with the older position of **Pole 3**, which still had to move to **Pole 4** and on to the current **Pole 5**. One theory according to Moore et al[180] is that these knob fields were formed by water and near a lake, which would also be consistent with a previous **Pole 3** position.

Stewart et al[181] examine the idea that CO2 could have formed these channels, which is also consistent with a pole position. This would depend on the temperatures of **Pole 3** at the time. As seen earlier the pole may have cooled in its movement from **Pole 2**, as the number of channels may have diminished. The temperatures may have risen after the Hellas impact as the Pole moved northward to the **North Pole 4** position around then to be formed Alba Patera. Many of the objections to CO_2 arise from not having a mechanism to maintain enough of it long enough to create these formations, however a pole may be able to supply this reservoir. There may be then in some of these areas a mixture of the two kinds of erosion[182], without knowing the temperature at the time it is probably not possible to determine. Other ravines may be more recent[183].

Newton Crater[184] is situated at 41.1S 159.8W, also on the edge of the **North Pole 3** area. Cabrol et al[185] refer to the large amounts of water released into Newton Crater, which represents the dilemma of abundant water on such a dry planet. Being on the edge of a pole however could supply this water while non polar areas could remain dry.

Tempe Terra[186] [187] is found at approximately 42N 73W. This area would again have been on the edge of an ice cap, in this case **North Pole 4**. Volcanism[188] in the area may have come from the Hellas impact, like Alba Patera. Hauber et al[189] point out chaos similar to Gorganum Chaos, which is also on the edge of a former pole. Syria Planum, associated with **South Pole 2** also has these formations. Even though these three formations are relatively close to each other, each could have been formed from a different pole. They also show signs of glaciation, which is consistent with the edge of a pole.

Nirgal Vallis[190] [191] is approximately at[192] 27.5S 317W, on the edge of **South Pole 4** near Hellas Basin. This may account for its appearance of having water more recently. Lee and Rice[193] compare Nirgal Vallis to Devon Island, and find indications of the decay and retreat of an ice cover, consistent with the edge of a Martian **South Pole 4**.

Hale Crater[194] [195] is located at 36S 37W. This may have experienced outflows from Argyre basin when **South Pole 2** was moving eastward. Alternatively it could have received water from **South Pole 1** and the movement to **South Pole 2**. This could have been a slow movement and generated a lot of water in this area.

Maunder Crater is on the south western edge of **South Pole 4**.

Rabe crater is situated at 44S 325W, which is around the area of **South Pole 4**.

Dao Vallis is located at 33S 266W, on the north eastern edge of **South Pole 4**. Arfstrom[196] interprets the area as glacial, which is consistent with being on the edge of a pole. He believes[197] this may be part of a larger ice flow.

All these areas[198] referred to by Malin et al are on previous pole positions. This makes it likely groundwater rather than snow is the cause of these gullies and viscous flow features[199], though snow[200] [201] may also be forming more easily in shapes made by flowing water. In some cases CO_2[202] from previous poles may also have formed gullies.

Schorghofer et al[203] map locations of slope streaks, and one cluster is approximately on **South Pole 3**. This may imply they are indeed related to water. Other areas tend to follow the path of the opposite **North Pole 2** to **North Pole 3**, and then part of the movement to **North Pole 4** around Alba Patera. Residual ice in the soil may also make it conducive to landslides.

Palermo et al[204] believe these are more likely to be fluid flows. No actual gullies seem to be formed with streaks though a fluid reservoir implies they should flow over and over at least sometimes. The shapes probably represent the path to lower elevations water or dust would take.

Over time water should make some kind of mark or channel on the surface like we see in even in Russell Crater on sand. Moisture from underground ice deposits could cause landslides, and explain the link between old pole areas and the streaks. Sullivan et al[205] point out the streaks are similar to snow avalanches, which may be consistent with icy soil under a dusty surface layer. It may be fluid flows and dust avalanches both occur at times. Sullivan et al[206] refer to dust avalanches as the most likely explanation.

Another possibility is a small area of ice sublimates and the resulting vapour dislodges some dust and creates the landslide. If so then an example of this may have been imaged. MOC photo AB102003[207] shows a possible plume of vapour found by Spires, colloquially known as "Dan's smoker"[208]. There is a slope streak in this image pointing in the same direction, and other images in the area such as M2300332[209] contain slope streaks. The pale mark seems to go down one mound and then climb the other, which makes it unlikely to be a streak. If this was reimaged and the light streak was gone then it is more likely to have been vapour. E1103683[210] just misses this formation.

Hematite[211] has been found in the area of **South Pole 3**, which is consistent with the having water around a polar area. The area is believed to have been recently exhumed, by Lane et al[212] which is consistent with the pole moving and exposing this area. According to Hynek Aram Chaos and Valles Marineris[213] [214] also have hematite deposits, which is consistent with the path of the moving pole from **South Pole 2** to **South Pole 3** giving water to create hematite. Aram Chaos[215] is to the west of the **South Pole 3** position and is connected to the Areas Valles outflow channel. This would also be consistent with the pole depositing water as it moved.

Dunes

Images of dunes[216] were also compared to their **Pole 4** latitudes[217]. Dunes were generally found to be evenly spread around the current pole longitudinally and to be confined within 40 degrees north and south of the current equator. The distribution in regard to **Pole 4** was also even but generally from 50 degrees north to 50 degrees south. This is an usual correlation as **Pole 4** is at 45 degrees south, and so the distribution should be skewed. This implies that dunes formed in a band between 50 degrees old north and 50 degrees old south in relation to **Pole 4**. In turn this implies[218] a high enough air pressure for dunes to form at the time. After the pole shift the dunes would appear to be moving to the same kind of formation relative to **Pole 5**.

Dunes on the current **South Pole 5** were also examined[219]. These dunes were typically found between 75 to 85S and 100 westward to 350W. In relation to **South Pole 4** all of these dunes were found to be between 30 and 50 degrees old south (that is, south compared to **Pole 4**) which implies they were actually formed before the Pole shift of **Pole 4** to the current **Pole 5**. If so then these dunes may have been frozen in position since then. Malin et al[220] say there is no evidence dunes on Mars are presently mobile.

Layers

Layer images[221] were also examined[222] and mainly fell in the old southern hemisphere of **South Pole 4**, particularly from the equator to 50 degrees old south (old south is relative to **Pole 4**). This is surprising as it implies much of the layering shown was actually formed under **Pole 4** though earlier layers may be buried.

Layers found on the current South Pole, **Pole 5**, were typically at 85S and concentrated at 175 to 275W. This in relation to **South Pole 4** placed them between 30 and 50 degrees old south, also implying they were formed in the time of **Pole 4** rather than on the current pole. Malin et al[223] point out layers in Candor Chasma, which is near the equator of **Pole 4** seems relatively young compared to nearby Arsia Mons. The absence of craters may imply these layers were made in the time of **Pole 4**, or perhaps exhumed by processes in that time.

If so then much layering[224] has been a relatively recent occurrence associated with the Hellas impact, perhaps because older layering may have been buried. **Pole 4** may have existed for long enough for layers[225] under it to dominate.

Dunes and layers have a similar distribution in the southern hemisphere of **Pole 4**, while water signs seem to be related to different poles. It may be then that air rather than water is responsible for many of these layers. CO_2 may also have formed some layers, if the temperature dropped enough. The change from **Pole 4** to **Pole 5** may have occurred when the temperature dropped enough to freeze the air, so ice sublimated and went to the poles

If the air pressure dropping was enough to make the pole move to **Pole 5** then that implies it had not dropped to that level earlier, or the pole shift would have already happened. The dropping of the temperature then may have represented a final phase change, or the temperatures may have periodically risen with changing obliquity. If so then the pole may have wandered[226] to some degree between the positions of **Pole 4** and **Pole 5** depending on the level of ice depositions in the northern lowlands.

In this time CO_2 may have been involved in the formation of layers[227]. Odyssey thermal data[228] implies layers were not formed by water. Layers are found in the area of **Pole 3**[229], which may have formed in that time just as some layers form on the poles today. Layers could have formed under all the previous poles; it may be that **Pole 4** dominates because it is the most recent.

Some layers may have been formed in the movement of **Pole 2** to **Pole 3**, and because this is on the dichotomy boundary this will appear in the equatorial region of **Pole 4**. Also since Tharsis Montes, Olympus Mons, Hecates Tholus, Elysium Mons and Alba Tholus all are near the **Pole 4** equator in the time ash may form layers also appearing to be caused by **Pole 4**. Some layers may also have been formed along the equatorial region of **Pole 4** by water if the temperature was high enough.

In terms of astrobiology the impacts certainly warmed Mars, and depending on their timing may have created a climate that could have supported life for long periods.

In an ideal scenario the Utopia impact would have heated the planet for a long time, as ice and CO2 forming in the Utopia Basin would have been warmed. Since even now Mars is close to being warm enough to sublimate all the CO2 from the poles it is reasonable to believe that this impact basin at the pole would have made it warm enough to raise the air pressure, especially with higher obliquity[230].

If the Isidis impact occurred before the planet cooled then this would have added heat, as **Pole 2** forming on Isidis Basin would have sublimated CO2, as would the pole opposite it around Solis and Syria Planum.

Next the Argyre impact may have warmed the poles followed by the Hellas impact. If these were spaced at the right times then Mars may have had a long time of higher air pressure and occasional liquid water. These conditions would possibly have allowed microbial and even substantially more evolved life forms to survive, especially since the higher air pressure would have offered some protection from radiation. An impact may have decimated life much like impacts did on earth[231] but subsequently kept the planet warm enough for the survivors to adapt. If the Hellas impact destroyed the Martian magnetic field then this could have led to the extinction of some life. Without sufficient life to create oxygen this may have led to the air freezing more as CO2 and ice sublimating to the poles.

Eventually the impacts and volcanoes ceased and life if it still or ever existed would have had to adapt to the much colder climates.

The more likely scenario is that life may have evolved somewhat during these times of higher temperatures only to die off or survive at a low level when the planet cooled and the air froze. With the next impact some life may have evolved again if the times were long enough, perhaps being reseeded with meteors from Earth.

Conclusions

Much of the Martian terrain is consistent with the idea of polar wander. This may have been controlled by 4 main impacts, Utopia, Isidis, Argyre, and Hellas.

The Isidis impact may have formed some of the deformations around Solis and Syria Planum.

The impact of Argyre may explain the formation of the Tharsis Montes, Olympus Mons, Elysium Mons, Hecates Tholes, and Alba Tholus.

The movement of **Pole 2** to **Pole 3** may explain the formation of the dichotomy boundary and all the fluid channels north of it. It may also have formed the Northern Lowlands.

The number of narrow angle images examined here is too small to give a definite conclusion, but they give a picture of **Pole 4** having a large influence on many current Martian features. This may be an artefact of the selection process but they were accumulated well before the ideas in this paper.

Fluid signs in craters and valleys are found on the edges of older poles, which are now at suitable latitudes for water ravines to form.

Some dunes are found to be evenly spread compared to **Pole 4**, even on the current **South Pole 5** and imply a time of higher air pressure, and perhaps that since then there has been insufficient air pressure to move them from this pattern.

Layering may have partially occurred in the time of **Pole 4**, and some layers on the current South Pole may be from before the pole shift to **Pole 5**.

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[1] Bradley J. Thomson and James W. Head III "Utopia Basin, Mars: Characterization of topography and morphology
and assessment of the origin and evolution of basin internal structure" JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. 0, PAGES 1–22, MONTH 2001
http://www.planetary.brown.edu/planetary/documents/2396.pdf
See Figure 1, comparing Utopia Basin with Hellas Basin.
[2]NASA, Jack Connerney, Mario Acuna, Carol Ladd "Martian Magnetic Map"
http://www.solarviews.com/cap/mgs/magmap.htm
[3] "The northern hemisphere is made up largely of rolling volcanic plains, not unlike the lunar maria. These extensive lava plains—much larger than those found on Earth or the Moon—were formed by eruptions involving enormous volumes of lava. They are strewn with blocks of volcanic rock as well as with boulders blasted out of impact areas by infalling meteoroids (the Martian atmosphere is too thin to offer much resistance to incoming debris). The southern hemisphere consists of heavily cratered highlands lying several kilometers above the level of the lowland north."
"On the basis of arguments presented in Chapter 8, this smoother surface suggests that the northern surface is younger. (Sec. 8.4) Its age is perhaps 3 billion years, compared with 4 billion in the south. In places, the boundary between the southern highlands and the northern plains is quite sharp. The surface level can drop by as much as 4 km in a distance of 100 km or so. Most scientists assume that the southern terrain is the original crust of the planet. How most of the northern hemisphere could have been lowered in elevation and flooded with lava remains a mystery."
Nanjing University Syllabus "The Surface of Mars available online at

http://astronomy.nju.edu.cn/astron/AT3/AT31004.HTM

[4] "Major features of topography. The dominant feature of the topography is the striking difference (;5 km) in elevation between the low northern hemisphere and high southern hemisphere that represents one of the outstanding issues of martian evolution. This hemispheric dichotomy also has a distinctive expression in the surface geology of Mars. The surface of the crust in the southern hemisphere is old and heavily cratered,
whereas that in the north is younger and more lightly cratered and was probably volcanically resurfaced early in Mars' history (17). The
hemispheric difference is also manifest in surface roughness (Fig. 3) calculated from the MOLA topographic profile data (18). Most of the northern lowlands is composed of the Late Hesperian–aged (19) Vastitas Borealis Formation, which is flat and smooth (Fig 2), even at a scale as short as 300 m (Fig. 3). The Amazonian-aged (19) Arcadia Formation, which overlies the Vastitas Borealis Formation, is also smooth at large and small scales, consistent with either a sedimentary (4, 20) or volcanic (21) origin for these plains. In the southern hemisphere Noachian aged (19) ridged plains form locally flat intercrater deposits, whereas younger Hesperian- aged ridged plains dominate in some regions. All are characterized by a rougher topography than the northern plains. The boundary between the smooth northern hemisphere and the rough southern hemisphere is characterized by mesas, knobs, and intervening plains (22), as well as regional elevation changes of up to 4 km over distances of 300 to 1300 km (23). Where the regional elevation change is relatively steep, it is referred to as the dichotomy boundary scarp (compare Fig. 1)." Smith, D.E. et al "The global topography of Mars and implications for surface evolution" Science, 284, 1495-1503, 1999 available online at
http://ltpwww.gsfc.nasa.gov/tharsis/global_paper.html

[5] "Very roughly speaking, this is a map of the ages of the surfaces on Mars. The red surfaces were formed in period 1, the green surfaces were formed in period 2, and the blue surfaces were formed in period 3. These three periods correspond roughly to the three Martian periods Noachian, Hesperian, and Amazonian (named after regions that approximate those ages.)" Mike Caplinger" Determining the age of surfaces on Mars" Malin Space Science Systems February 1994 available online at
http://www.msss.com/http/ps/age2.html [16/8/03]

[6] Jarmo Korteniemi "Main albedo features and full nomenclature" available online at
http://www.student.oulu.fi/~jkorteni/space/mars/maps/ [16/8/03]

[7] USGS Astrogeology Research program Regional MOLA map available online at
http://planetarynames.wr.usgs.gov/images/mola_regional.pdf

[8] K. F. Sprenke and L. L. Baker "POLAR WANDERING ON MARS?" Lunar and Planetary Science XXXI 1930.pdf
http://www.lpi.usra.edu/meetings/lpsc2000/pdf/1930.pdf

[9] Aviation Now "Water Find Will Shape Mars Exploration Plan" available online at
http://www.aviationnow.com/content/publication/awst/20020603/aw32.htm

[10] "Gravity over the north polar region (Fig. 4A) reveals several positive anomalies that have no obvious correlation with topography (16). A combination of ice and crustal material has been proposed (17) to account for anomalies situated in the immediate vicinity of the north polar layered terrains. In contrast, the south polar region (Fig. 4B) shows a positive anomaly of ;200 mgal immediately over the pole, which could represent the load associated with the permanent ice cap. The lack of a comparable anomaly over the northern cap could indicate that the southern cap is younger and has not yet had sufficient time to adjust isostatically, or that the southern layered deposits contain a larger
fraction of dust, thus constituting a greater gravitational load than in the north (12).
A possible explanation for the high-latitude northern hemisphere gravity anomalies, adjacent to and remote from the residual ice cap, is that they represent moderate-diameter (100 km) impact basins buried beneath the resurfaced northern hemisphere (18). The mass excesses implied by these positive anomalies may represent a combination of volcanic and sedimentary fill within the basin cavity and thinning of the northern hemisphere crust beneath the basin (19) that have not relaxed to an isostatic state (20)." David E. Smith et al "The Gravity Field of Mars:
Results from Mars Global Surveyor" available online at
http://ltpwww.gsfc.nasa.gov/tharsis/smith.mgs.grav.pdf

[11] “We find evidence for several probable buried basins in the lowlands and at least one in the highlands that are similar to Hellas, Argyre, Isidis, Chryse and Utopia in size. All of these buried features must be extremely old because smaller likely buried basins are superimposed on them. We previously used this relationship to suggest Utopia was "Earliest" Noachian in age.” FREY, Herbert V “LARGE BURIED AND VISIBLE BASINS ON MARS: TOTAL POPULATION AGES OF THE HIGHLANDS AND LOWLANDS” http://gsa.confex.com/gsa/2002AM/finalprogram/abstract_44774.htm
[12] http://www.harmakhis.org/history/1.jpg
[13] “Abstract. Recently obtained Mars Orbiter Laser Altimeter (MOLA) topography has permitted a new assessment of the morphology, structure, and history of Utopia Planitia. The new topographic data convincingly demonstrate that the Utopia region is an impact basin, as originally proposed by McGill [1989], whose major topographic expression is a circular, 1–3 km deep depression _3200 km in diameter. Utopia Basin is the largest easily recognizable impact structure in the northern hemisphere of Mars and is the only portion of the northern lowlands that exhibits a distinct large-scale impact signature; its presence there and its ancient age verify that a significant part of the northern lowlands dates back to the Noachian period.” Bradley J. Thomson and James W. Head III “Utopia Basin, Mars: Characterization of topography and morphology
and assessment of the origin and evolution of basin internal structure” JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. 0, PAGES 1–22, MONTH 2001
http://www.planetary.brown.edu/planetary/documents/2396.pdf
[14] “After Isidis, the largest impact-associated gravity anomaly (Table 2) is Utopia (Fig 5A), which has been interpreted as an ancient basin on the basis of surface geology (24). Topographic data indicate that the basin is a quasi-circular depression;1500 km in diameter (25), a factor of about 2 greater than originally proposed. Utopia’s gravity anomaly
is diffuse, occupying an area of ;107 km2 with no clear centre. The Utopia structure is buried beneath the northern hemisphere resurfacing,
but the size of the depression and gravity anomaly suggest that the original basin could have been of a size comparable to that of Hellas (Fig. 5B) (16). However, these two massive structures appear in complete
contrast gravitationally. Both appear to have readjusted isostatically, but Utopia was subsequently filled with material, which contributes
to the gravitational mass excess. If the Utopia and Hellas structures were originally similar, the gravity field data may be able to shed light on the density of the material that has filled Utopia and by inference on the material of the northern plains.” David E. Smith et al “The Gravity Field of Mars: Results from Mars Global Surveyor” 1 OCTOBER 1999 VOL 286 SCIENCE www.sciencemag.org available online at http://ltpwww.gsfc.nasa.gov/tharsis/smith.mgs.grav.pdf
[15] “8.5. Open Water Features
Parker et al. [1989] presented evidence for as many as seven contacts between the northern plains and southern uplands, which were interpreted to be highstands of a former ocean. On Earth, wave-cut platforms and associated landforms result from direct coupling of wind and the open water surface [Duane et al., 1972; Swift et al., 1972, 1973; Stubblefield et al., 1975; Swift, 1975; Rice, 1994]”
“

8.6. Ice-Dominated Bodies of Water
A second possible analog for the circumferential features includes the extremely wide, near-horizontal platforms that are common in high-latitude regions on Earth. Known as strandflats, they are up to 50–60 km wide and have extremely low crossplatform gradients [e.g., Evers, 1962; Benn and Evans, 1998].
There have been many theories advanced for their formation, but many workers have highlighted the importance of frost shattering [Nansen, 1904, 1922; Larsen and Holtedahl, 1985; Guilcher et al., 1994]. Frost action resulting from recurrent freeze-thaw cycles is an effective geomorphologic agent and is considered to be a key component of rapid coastal cliff recession and platform extension in polar seas [Hansom, 1983; Matthews et al., 1986]. The most extensive strandflats are found in areas sheltered from wave erosion [e.g., Hansom, 1983]. An ice foot, or accumulation of

sea ice frozen onto the shoreline, inhibits erosion by wave action during freeze periods but may increase the potential for frost shattering at the base of coastal cliffs [Nansen, 1922; Feyling-Hanssen, 1953; Nielsen, 1979]. Exposure of the coastline to wave action during thaw periods may increase the rate of platform formation by facilitating the removal of debris [Matthews et al., 1986]. An idealized cross section of terrestrial strandflat generations is given in Figure 12. Note that the sequence of landforms shown is of similar scale to the circumferential features shown in Utopia [see also Rice, 2000]." Bradley J. Thomson and James W. Head III "Utopia Basin, Mars: Characterization of topography and morphology and assessment of the origin and evolution of basin internal structure" JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. 0, PAGES 1–22, MONTH 2001
http://www.planetary.brown.edu/planetary/documents/2396.pdf

[16] "Viking Orbiter and Mars Orbiter Camera images show mesas having horizontal to angled layers in many Valles Marineris chasmata. Several chasmata are filled nearly to the plateau rim with Late Hesperian to Early Amazonian [1] interior deposits, many of which are separated from the chasmata walls by a moat. A lacustrine origin was suggested because of their apparent horizontal continuity and similarity in connected troughs [2,3,4,5,6,7]. Others prefer a volcanic origin based on the volcano-tectonic setting, layer diversity, low albedo and high competence of some layers, tuff-like weathering, and location of dark materials [1,4,8,9]. The interior deposits of Gangis and Juventae Chasmata were suggested to be similar to the ideal tuya form (table-like) 10] and eroded flutes and variable albedo of Hebes Chasma deposits bear an uncanny resemblance to tuyas [11]. We note that Mars Orbiter Laser Altimeter data show interior deposits that locally (1) reach 4-km in height, (2) rise above sections of plateau, and (3) in the case of Hebes, have the distinctive tuya form. Their morphologies include local resistant caps [12], ridged forms, and possible deltas. Based on the dimensions, morphologies, and associated catastrophic floods and other geologic events (glacial, tectonic, and mass flows) we support the suggestion that the interior deposits are hyaloclastic ridges and tuyas." Page 15 Volcano/Ice Interaction Workshop August 13-15, 2000 ReykjavÍk, Iceland available online at
http://astrogeology.usgs.gov/Projects/VolcanoIceWorkshop/abstract_volume_rev5.pdf

[17] "Valles Marineris shows a strong negative anomaly congruent with the topography (Fig 6). The rift axis anomaly is the largest negative gravity feature on Mars and is due mostly to the mass deficit associated with the chasm (29), which has a depth of 11 km below the surrounding terrain at its lowest point (12). The canyons are flanked by gravity highs but the canyon system lacks a negative anomaly, broader than the rift, that is associated with upwelling of hot mantle material beneath active rifts on Earth (30). The deviation of the canyon from isostatic compensation is consistent with its formation subsequent to Argyre and Hellas (31) and suggests that the martian lithosphere has not yet adjusted to its presence." David E. Smith et al "The Gravity Field of Mars: Results from Mars Global Surveyor" available online at
http://ltpwww.gsfc.nasa.gov/tharsis/smith.mgs.grav.pdf

[18] Fig 6 David E. Smith et al "The Gravity Field of Mars:Results from Mars Global Surveyor" available online at http://ltpwww.gsfc.nasa.gov/tharsis/smith.mgs.grav.pdf

[19] K. F. Sprenke and L. L. Baker "POLAR WANDERING ON MARS?" Lunar and Planetary Science XXXI 1930.pdf
http://www.lpi.usra.edu/meetings/lpsc2000/pdf/1930.pdf

[20] Fig 1a David E. Smith et al "The Gravity Field of Mars: Results from Mars Global Surveyor" available online at
http://ltpwww.gsfc.nasa.gov/tharsis/smith.mgs.grav.pdf

[21]http://www.harmakhis.org/history/1.jpg

[22] "Clusters of small cones on the lava plains of Mars have caught the attention of planetary geologists for years for a simple and compelling reason: ground ice. These cones look like volcanic rootless cones found on Earth where hot lava flows over wet surfaces such as marshes, shallow lakes or shallow aquifers. Steam explosions fragment the lava into small pieces that fall into cone-shaped debris piles. Peter Lanagan, Alfred McEwen, Laszlo Keszthelyi (University of Arizona), and Thorvaldur Thordarson (University of Hawaii) recently identified groups of cones in the equatorial region of Mars using new high-

resolution Mars Orbiter Camera (MOC) images. They report that the Martian cones have the same appearance, size, and geologic setting as rootless cones found in Iceland. If the Martian and terrestrial cones formed in the same way, then the Martian cones mark places where ground ice or groundwater existed at the time the lavas surged across the surface, estimated to be less than 10 million years ago, and where ground ice may still be today." Linda M.V. Martel "If Lava Mingled with Ground Ice on Mars" PSR Discoveries [6/26/01] available online athttp://www.psrd.hawaii.edu/June01/lavaIceMars.html

[23] "The southern rim of the Isidis Basin has been strongly modified by erosional processes, including weathering, mass wasting, fluvial incision, and transport and deposition of sediment. Most of this erosion occurred during the Noachian, but a late stage of fluvial incision probably extended into the Hesperian." J.M. Moore (NASA Ames), A.D. Howard (UVa), P.M. Schenk (LPI) "[48.08] Geomorphic Analysis of the Isidis Region: Implications for Noachian Processes and Environments" DPS 2001 meeting, November 2001 Session 48. Mars Surface available online athttp://www.aas.org/publications/baas/v33n3/dps2001/221.htm

[24] http://www.harmakhis.org/history/2.jpg
[25] H. V. Frey, S. E. H. Sakimoto, and J. H. Roark "MOLA TOPOGRAPHY AND THE ISIDIS BASIN: CONSTRAINTS ON BASIN CENTER AND RING DIAMETERS" LPSC98 available online at http://mars.jpl.nasa.gov/mgs/sci/lpsc98/1631.pdf
[26] Figure 1a
[27] "3) a site at ~5°S and 264°W just south of the Isidis rim that is heavily dissected by channels. These regions were optimally imaged by Viking for the generation of DTMs, lie within the Mars 2001 landing constraints, and are potential locations for fluvial or lacustrine deposits. Our initial analysis of the later sites indicates that fluvial erosion for large solitary channels probably took the form of sapping, whereas denser networks of small channels may have formed at least in part from runoff, such as from surface ice-melt. Both sites show that channeling took place during a period in which fairly large craters will still forming. The tectonic fabric appears to largely predate the channeling. Aeolian deposition largely post dates the channeling."
J. M. Moore (NASA Ames), A. D. Howard (U. Va.), P. M. Schenk (LPI) "[43.04] The Topography and Basin Deposits of the Equatorial Highlands: A MGS–Viking Synergistic Study" 31st Annual Meeting of the DPS, October 1999
Session 43. Mars Surface: Structure available online at http://www.aas.org/publications/baas/v31n4/dps99/98.htm
[28] J.A.Iluhina and J.F.Rodionova "AUTOMATED MAKING THE MAP OF ISIDIS'S BASIN" Microsymposium 36, MS037, 2002 available online at http://www.planetary.brown.edu/planetary/documents/Micro_36/Abstracts/037_Iluhina_Rodionova.pdf
[29] http://www.harmakhis.org/history/2.jpg

[30]"Isidis is generally very flat with low average slope values calculated from MOLA data." The Natural History Museum "Missions to Mars" available online at http://www.nhm.ac.uk/mineralogy/mars/Marshtml/2missions.html

[31] http://www.space4case.com/mars/mars7/mars143.html
[32] http://www.space4case.com/mars/mars7/mars142.html
[33] "Beagle 2 has as its focus the goal of establishing whether evidence for life existed in the past on Mars at the Isidis Planitia site or at least establishing if the conditions were ever suitable." Page 4 J. D. Farmer "Exploring for Martian Life: Recent Results and Future Opportunities" Astrobiology Volume 1 Number 3 [2001] available online at http://216.239.57.104/search?q=cache:XenIThQGrU8J:cips.berkeley.edu/events/discussion_group_2003_spring/farmer_astrobiology_space_missions.pdf+farmer_astrobiology_space_missions.pdf&hl=en&ie=UTF-8
[34]First image Ames Research Centre available online at http://amesnews.arc.nasa.gov/releases/2002/02images/mars/mars.html

[35] "When the river valleys on Mars were confirmed in the 1970s, many scientists believed there once was an Earth-like period with warmth, rivers and oceans," said Owen Toon, a professor at the University of Colorado and a coauthor of the Science paper. "What sparked our interest was that the large craters and

river valleys appeared to be about the same age." Another piece of evidence arguing against a condition warm, wet period on Mars are images of river channels without any sign of tributaries flowing into the main channel. "We definitely see river valleys but not tributaries, indicating the rivers were not as mature as those on Earth," said Toon. Jeff Foust "New research explores past, present water on Mars" Spaceflight Now December 5th 2002 available online at http://spaceflightnow.com/news/n0212/05mars/

[36] Nancy Ambrosiano "Los Alamos releases new maps of Mars water" Los Alamos National Laboratory [2003] available online at
http://www.lanl.gov/orgs/pa/News/cover_epi.jpg

[37] M. L. Litvak "DISTRIBUTION OF CHEMICALLY BOUND WATER IN SURFACE LAYER OF MARS BASED ON DATA ACQUIRED BY HIGH ENERGY NEUTRON SPECTROMETER, MARS ODYSSEY" Microsymposium 36, MS062, 2002
http://www.planetary.brown.edu/planetary/documents/Micro_36/Abstracts/062_Litvak_etal.pdf

[38]"The Solis Planum region of Mars is a high-elevation volcanic plain which lies south of the Valles Marineris canyon system and east of the Tharsis volcanic complex. In the 1970s, Earth-based photometric observations of dust storms in this region suggested that H2O condensate clouds were produced from a volatile-rich source located in Solis Lacus, the low-albedo area of Solis Planum. High reflectivity radar returns of the Solis region in the 1980s were interpreted as resulting from a seasonal freeze-thaw cycle of H2O in the upper centimeter of regolith. These observations led to speculation that a water-rich "oasis" exists near the surface in Solis Planum. However, Viking Mars Atmospheric Water Detector (MAWD) measurements did not find significant differences in water vapor column abundances between Solis Planum and elsewhere, and the oasis hypothesis faded from debate by the end of the 1980s. Recent advances in the understanding of the geologic evolution of this region combined with new high-resolution observations of geologic features suggesting an extensive volatile reservoir underlying Solis Planum have led our group to revisit the oasis hypothesis. Ejecta formation simulation codes are being used to estimate the amounts of volatiles in the substrate and measurements from the Mars Odyssey instruments should help to confirm if H2O is concentrated in this region." Nadine Barlow "SOLIS PLANUM, MARS: THE "OASIS HYPOTHESIS" REVISITED "2001-2002 Colloquium Series NAU Liberal Arts (Bldg 18, Rm 135), Thursday, 24 January 2002 available online
at http://www.phy.nau.edu/EVENTS/colloquium/speakers0102/barlow.html

[39]" Koroshetz and Barlow [12], using Viking Orbiter imagery, found smaller onset diameters for SL morphology craters in the Solis Planum region south of Valles Marineris (20°S-30°S 50°W-90°W), one of the same
regions where [6] found a higher concentration of ML morphologies. Koroshetz and Barlow propose that the uplift of the Tharsis Bulge, directly west of this region, caused the water table in this area to tilt and the water flowed into a topographic depression south of
Valles Marineris." N. G. Barlow "SUBSURFACE VOLATILE RESERVOIRS: CLUES FROM MARTIAN IMPACT CRATER MORPHOLOGIES" Fifth Conference 1999 http://mars.jpl.nasa.gov/mgs/sci/fifthconf99/6082.pdf

[40] "A group of scientists claims to have found evidence of liquid water under the surface of Mars. The team, led by Nadine Barlow of the University of Central Florida's Robinson Observatory, believes the reservoir lies relatively close to the surface, at a depth of roughly 110 meters (360 feet)." Ames Research Centre "Mars Watering Hole Found, Scientists Say" available online at
http://astrobiology.arc.nasa.gov/news/expandnews.cfm?id=1009

[41] "Our current study suggests that the ice-rich layer producing the SL morphology lies closer to the surface (<300 to 500 m) in the Solis Planum region than elsewhere in the equatorial region (~520-572 m) and that an underlying liquid reservoir, which produces the ML morphologies, has been present since the region formed in the Hesperian." N. G. Barlow, C. B. Perez (U. Central Fl.), J. Koroshetz (U. Fl.) "[39.06] A Volatile-Rich Reservoir South of Valles Marineris, Mars" 31st Annual Meeting of the DPS, October 1999 Session 39. Mars Surface: Evidence of Change available online at
http://www.aas.org/publications/baas/v31n4/dps99/40.htm

[42] "We propose that the uplift of the Tharsis Bulge to the west of this region warped the area and tilted a pre-existing groundwater table. The tilting of the groundwater table caused the volatiles to accumulate in the slight depression where today the smaller onset diameters and abundance of ML morphologies are found." Ibid.

[43] "8.4. Glacial Features
Another possible explanation of the circumferential features is that they are related to morainal/ice-margin features. A glacial explanation has been advanced for the formation of thumbprint terrain [Lucchitta, 1981; Rossbacher, 1985; Lucchitta et al., 1987; Scott and Underwood, 1991; Scott et al., 1992; Kargel and Strom, 1992; Kargel et al., 1995]. As shown in Figure 10, there are areas of thumbprint terrain that are located in the middle of the zone of circumferential features in southern Utopia. On the basis of the morphology and distribution of thumbprint terrain and other structures, several workers have suggested the former presence of large ice sheets in the northern hemisphere of Mars [Lucchitta et al., 1986; Chapman, 1994; Kargel et al., 1995]. The lack of associated glacial flow features such as drumlins in the northern plains seems inconsistent with widespread glacial activity. Drumlins are streamlined mounds of glacial till that have elongated teardrop shapes in plan view [Benn and Evans, 1998]. The absence of drumlins does not rule out a glacial explanation, for a glacial body in the northern hemisphere may have been cold-based for much of its evolution [e.g., Kargel et al., 1995]. However, the lack of drumlins highlights the general lack of features related to mass ice movement and scour in the interior of the Northern Plains. In addition, because ice experiences a drop in plasticity with decreasing temperature [Glen, 1955; Goldsby et al., 2001], the current temperature regime on Mars would tend to inhibit glacial flow. This does not exclude the possibility of glacial activity at periods of high obliquity or more
temperate paleoclimatic conditions but highlights the need for a greater understanding of ice deformation mechanisms [Goldsby et al., 2001] under possible Martian paleoclimates before the viability of a glacial explanation can be verified." Bradley J. Thomson and James W. Head III "Utopia Basin, Mars: Characterization of topography and morphology and assessment of the origin and evolution of basin internal structure" JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. 0, PAGES 1–22, MONTH 2001 available online at
http://www.planetary.brown.edu/planetary/documents/2396.pdf

[44] "A study of martian impact craters with fluidized ejecta morphologies has revealed that the area south of the Valles Marineris canyon system may contain a large near-surface volatile reservoir." N. G. Barlow, C. B. Perez (U. Central Fl.), J. Koroshetz (U. Fl.) "[39.06] A Volatile-Rich Reservoir South of Valles Marineris, Mars" 31st Annual Meeting of the DPS, October 1999 Session 39. Mars Surface: Evidence of Change available online at http://www.aas.org/publications/baas/v31n4/dps99/40.htm

[45] "Evidence for a large ground water reservoir -- capped by a relatively shallow layer of ice -- exists within the Mars' Solis/Thaumasia Planum region, says a team of scientists. The site is south of the huge Martian canyon system, Valles Marineris." Leonard David "Mars Watering Hole Found, Scientists Say" Space.com posted: 03:00 pm ET
13 August 2001
http://space.com/scienceastronomy/solarsystem/mars_ice_010813.html

[46]" We propose that the strain from Syria Planum was transferred along proto-Valles Marineris forming a sinistral transtensional zone which provided tectonic control for later valles formation. At the east end of Valles Marineris, the Coprates Rise is a lithospheric buckle with a thrust fault along the eastern edge. We also interpret the southern edge of the Thaumasia Highlands as the surface exposure of a thrust fault. The compressional structures of the Coprates Rise appear to extend into the Thaumasia Highlands. The thrust faults likely cut deep into the crust and may represent the décollment for later wrinkle ridge faulting in Sinai and Solis Planum. In this hypothesis, Claritas Fossae represents a dextral transpressional zone and acts as a boundary between the eastern and western halves of the south-Tharsis ridge belt identified by Schultz and Tanaka (1994, JGR 99, p. 8371), which includes the Coprates Rise, Thaumasia Highlands, and ridges in Daedalia Planum. Compression in Daedalia Planum likely resulted from the same

forces affecting the Thaumasia Plateau in the Noachian, but was arrested at an earlier stage of development, perhaps due to the buttressing effect of early Tharsis Montes construction.” WEBB, Benjamin M. “NOACHIAN TECTONICS OF SYRIA PLANUM AND THE THAUMASIA PLATEAU” Paper No. 132-0 [2001] available online at http://gsa.confex.com/gsa/2001AM/finalprogram/abstract_28019.htm

[47] “Summary: It is argued that Syria, Sinai and Solis Plana were generated by the volcanic activity associated with a mantle plume. They formed a large lithospheric root which was removed in a convective downwelling initiating a buoyant rebound of the region, followed by later subsidence when this uplift could no longer be sustained. The sequence of faulting within the region [6] is consistent with this scenario.” Evelyn D. Scott “SUB-LITHOSPHERIC ‘SUBDUCTION’ ON MARS: CONVECTIVE REMOVAL OF A LITHOSPHERIC ROOT. III: SYRIA PLANUM REGION” Lunar and Planetary Science XXXI 1331.pdf http://www.lpi.usra.edu/meetings/lpsc2000/pdf/1331.pdf

[48] “This hypothesis easily combines the various hypotheses that Valles Marineris formed either as a thermal response to events in the Martian mantle or as a tectonic response to the loading of Tharsis. If it is argued that there is an asthenospheric upwelling below the Plana, then the Wernicke 'Simple Shear' model can be invoked to explain the opening of Valles Marineris. In this model the upwelling is lateral to the site of the rifting, whereas McKenzie's 'Pure Shear' model would locate the site of rifting immediately above the mantle decompression. The fact that the fissure system of Noctis Labyrinthus has not evolved to the same extent as that of Valles Marineris could be because it is not as close to the thermal influence of the upwelling or because it has formed simply as a response to the isostatic realignment and was not influenced to as great an extent by the growth of the Tharsis volcanic shields.” Ibid.

[49] http://www.space4case.com/mars/mars6/mars125.html

[50] “The new topographic data illuminate a long-standing debate over the dominant contributors to the high elevations of the Tharsis region. A prominent ridge (containing Claritas Fossae; Fig. 2) extends southward from the region of the Tharsis Montes, and then curves northeastward in a “scorpion tail” pattern. This arcuate ridge bounds Solis Planum, a plateau within the southern rise. The ridge contains an abundance of heavily cratered Noachian material that has presumably escaped resurfacing by younger Tharsis volcanic flows because of its high elevation. It has been suggested (25) that the termination of the ridge structure could have formed by lithospheric buckling, as could, by analogy, other ridge structures in the south Tharsis region. The southern rise (southward of ;35°S) also contains exposures of heavily cratered Noachian units. These elevated ancient terrains are consistent with the view that the broad expanse of the southern rise (elevations .;3 km; see Fig. 2) formed at least in part by structural uplift (26). David E. Smith “The Global Topography of Mars and Implications for Surface Evolution” www.sciencemag.org SCIENCE VOL 284 28 MAY 1999 available online at http://www.ciw.edu/library/solomon/sci_284_1495.pdf

[51] “Figure 3 shows crater counts from a younger area, Solis Planum, where there has not been as much time for infilling, and the larger-crater population is more completely preserved, falling closer to the lunar mare reference line (dashed).” William K. Hartmann “MARTIAN CRATER POPULATIONS AND OBLITERATION RATES: FIRST RESULTS FROM MARS GLOBAL SURVEYOR” 1998, LUNAR AND PLANETARY SCIENCE CONFERENCE 29 (HOUSTON) available online at

http://www.psi.edu/projects/mgs/lpsc.html

[52] MSSS “Wide Angle View of Arsia Mons Volcano” MGS MOC Release No. MOC2-179, 27 September 1999 http://mars.jpl.nasa.gov/mgs/msss/camera/images/9_27_99_arsia/

[53] Calvin J. Hamilton “Arsia Mons” 1997 available online at http://www.star.ucl.ac.uk/~apod/solarsys/cap/mars/arsia.htm

[54] “Surface environmental conditions on Mars are presently extremely cold and hyperarid, most equivalent to polar deserts on Earth. Coupling newly acquired Mars MOLA and MOC data with field-based observations regarding the flow, surface morphology, and depositional history of polar glaciers in Antarctica, we show that the multiple facies of an extensive fan-shaped deposit on the western flanks of Arsia Mons, Tharsis Rise are consistent with deposition from cold-based mountain glaciers. An outer ridged facies that consists of multiple laterally extensive, arcuate and parallel ridges, resting without disturbance on both well-preserved lava flows and an impact crater, is interpreted as drop moraines formed at the margin of an ablating and predominantly receding cold-based glacier. Inward of the ridges lies a knobby facies that consists of irregular and closely spaced equidimensional knobs, each up to several kilometers in diameter; this facies is interpreted as a sublimation till derived from in situ downwasting of ash-rich glacier ice. A third facies comprising

distinctive convex outward lobes with concentric parallel ridges and aspect ratios elongated downslope likely represents rock-glacier deposits, some of which may still be underlain by a core of glacier ice. Taken together, these surficial deposits show that the western flank of Arsia Mons was occupied by an extensive mountain glacial system accumulating on, and emerging from, the upper slopes of the volcano (above ˜7000 m) and spreading downslope to form a piedmont-like fan. Similar deposits exist on the other Tharsis Montes, suggesting at least one phase of late Hesperian aged glaciation in the equatorial Tharsis region." J. W. Head , D. R. Marchant "COLD-BASED MOUNTAIN GLACIERS ON MARS: WESTERN ARSIA MONS" Geophysical Research Abstracts, Vol. 5, 02770, 2003
c European Geophysical Society 2003 available online at
http://www.cosis.net/abstracts/EAE03/02770/EAE03-J-02770.pdf

[55] "Using new MGS data and Earth analogs appropriate for Mars, we explored the hypothesis that the deposit is the remnant of a mountain glacier formed on the western flank of Arsia Mons (e.g., [1]). Conditions during the recent geological history of Mars suggest that glacial ice should commonly be below the pressure melting point, and thus analogous to polar glaciers, which are frozen to underlying beds (cold-based), and move by internal deformation, producing no record of basal scour or extensive meltwater features. Glaciers in the Antarctic
Dry Valleys may be most appropriate terrestrial analogs, and we find many similarities between them and the western Arsia fan-shaped deposits. We interpret the outer parallel ridge zone to be distal
dump moraines formed from the lateral retreat of a coldbased
glacier, and the hummocky facies to be proximal hummocky moraines resulting from the sublimation, decay and downwasting of the ice sheet (a sublimation till). The arcuate structures in the proximal zone are interpreted to be rock glaciers, formed by lobate flow deformation of debris-covered ice surfaces; some rock glaciers may still be ice-cored. We find little evidence for melting features in association with the deposit, and thus conclude that it was predominantly cold-based throughout its history. In summary, we find abundant evidence to support the interpretation that the fanshaped western Arsia Mons deposit was formed by a cold-based mountain glacier. Similar deposits are seen
on Pavonis and Ascraeus Montes." James W. Head and David R. Marchant "MOUNTAIN GLACIERS ON MARS?: WESTERN ARSIA MONS FAN-SHAPED DEPOSIT SMOOTH FACIES AS ROCK GLACIERS:" Microsymposium 36, MS103, 2002
http://www.planetary.brown.edu/planetary/documents/Micro_36/Abstracts/103_Head_Marchant.pdf

[56] "Characterization: The basic units comprising Arsia Mons consist of lava flow members of the Tharsis Montes Formation [2; see also 3], and the oldest flows are Late Hesperian in age, and younger units span the Amazonian. Scott and Zimbelman [1] show that during the Amazonian, three lava flow members of the Tharsis Montes Formation and the three facies of the fan-shaped deposit were emplaced. The ridged facies of the fan deposit clearly overlies Member 5 and is thus considered to be Late Amazonian in age." James W. Head and David R. Marchant "MOUNTAIN GLACIERS ON MARS? CHARACTERIZATION OF WESTERN ARSIA MONS FANSHAPED DEPOSITS USING MGS DATA:" Microsymposium 36, MS105, 2002
http://www.planetary.brown.edu/planetary/documents/Micro_36/Abstracts/105_Head_Marchant.pdf

[57] "Introduction: Prominent magnetic anomalies are absent over the major volcanic edifices of Mars. Apparently the martian global magnetic field ceased to exist long before the volcanism north of the dichotomy
occurred [1]. However, Arsia Mons, the southernmost of the great shield volcanoes of Mars, is located adjacent to a large regional magnetic anomaly (Fig.1). This raises the question of whether the Arsia Mons lavas might have acquired a magnetization induced from the much older remnant magnetization in the adjacent crust. This magnetization, induced by local fields associated with magnetized regions of the crust, would have occurred in spite of the absence of a global field at the time of emplacement." And see Figure 1 K.F. Sprenke and L.L. Baker "Magnetization of Arsia Mons, Mars" Lunar and Planetary Science XXXIII (2002) 1070.pdf
http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1070.pdf

[58] "Recently, it was proposed, on the basis of a morphological interpretation of Viking Orbiter images, that a thick ice sheet covers the Arsia Mons volcano in the Tharsis province on Mars, i.e. almost on the equator (Geology, March 1999, v. 27; no. 3; p. 231-234)." This conclusion is reached by examining deep canyons that cut into the fan areas of Arsia Mons and almost reach into the caldera area. These canyons are interconnected to circular vent-like structures that are interpreted as openings where ice has been melted above eruptive volcanic sites.

These vent-like openings lack a collar of ash normally associated with eruptive vents. The close association of a fissure swarm, large scale canyons, numerous vent-like structures and a broad fan area concur with a genetic relationship between these features." Johann Helgason "Does Mars Hide Vast Water Deposits" MARSDAILY.COM SPECIAL REPORT Reykjavik - June 10, 2000 available online athttp://www.spacedaily.com/news/mars-water-00b.html

[59]"The Argyre Basin" http://ltpwww.gsfc.nasa.gov/tharsis/argyre_insight.html

[60] See Figure 1 K. F. Sprenke and L. L. Baker "POLAR WANDERING ON MARS?" Lunar and Planetary Science XXXI 1930.pdf
http://www.lpi.usra.edu/meetings/lpsc2000/pdf/1930.pdf
[61] http://www.harmakhis.org/history/3.jpg
[62] http://www.harmakhis.org/history/4.jpg
[63] http://www.harmakhis.org/history/shockwave.jpg

[64] http://www.space4case.com/mars/mars5/mars110.html
[65] "Based on volume estimates of [13] which are based on a 3 km thick ice cap that covered the entire area of the Dorsa Argentea Formation, ~6.63 x 106 km3 of water could have been released. However, taking into account that the ice thickness very likely decreased toward the margins of the ice cap, that the ice cap contained up to 50% sediments, that not all of the melt water ended in the Argyre basin, that large amounts of ice never underwent melting but sublimed, and that large amounts of water are still stored in the pore space of the Dorsa Argentea Formation, we calculated that there is probably not enough water to completely fill the Argyre basin due to meltback of a Hesperian polar cap. We argue that partly filling the Argyre basin with water derived from polar cap meltback is more likely and is also consistent with Hesperian channels cutting far down into the basin." H. Hiesinger, J.W. Head III
"GEOLOGY OF THE ARGYRE BASIN, MARS: NEW INSIGHTS FROM MOLA AND MOC" Lunar and Planetary Science XXXII (2001) 1799.pdf
http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1799.pdf
[66]"Catastrophic flooding out of Argyre: Uzboi Valles is a relatively large, Noachian outflow channel that cuts the northern rim of Argyre (Nereidum Montes) and drained northward toward Holden Crater, into Holden Basin [7]. Without good topography, however, Uzboi Valles is somewhat confusing. With both ends obliterated by large impact craters and the channel floor exhibiting few streamlined forms, it isn't even obvious which way the channel flowed. However, even the gridded MOLA topography clearly shows Uzboi probably linked the Argyre interior with Holden Basin and Ladon Valles prior to formation of the large craters (Fig. 1). Next in the system is Holden Basin [7], into which Uzboi Vallis flow continued prior to formation of Holden Crater [2]. The northeast rim of Holden Basin is "gone" even though this basin superposes Ladon Basin. Instead, a broad "ramp" was identified in Viking Orbiter stereo pairs [2]. Ladon and Arda Valles converge on this ramp and drain into the interior of Ladon Basin. Parker [2] inferred that the rim of Holden Basin failed catastrophically during flooding from Argyre to produce this ramp, which drained a temporary lake that had formed in Holden Basin. Continued flooding from Uzboi Vallis favored Ladon Valles' course, so Arda Valles was quickly abandoned. Channel morphology disappears just inside the inner rim of Ladon Basin, but resumes on the basin's northeast side, at Margaritifer Valles [8]."
http://www.lpi.usra.edu/meetings/lpsc2000/pdf/2033.pdf
Parker et al., [2000], LPSC XXXI, 2033.pdf
[67] "Most highland basins show evidence of some communication between higher basins and adjacent, lower basins. The high plateau of Solis Planum exhibits surface drainage eastward through Her Desher Vallis–Nirgal Vallis into the upper parts of the Chryse Basin [1] as well as discharge westward into Amazonis as proposed by Dohm et al. [10].
Likewise, the Argyre basin overflowed northward through Nirgal–Uzboi Valles [11] into the Ladon basin and Margaritifer Basin [12] and eventually into Chryse Planita. The various interconnected lowlands of Icaria Province probably spilled over the southern rim into Argyre [1] providing a continuous pathway from the southern polar region to the northern ocean." R.A. De Hon "MARTIAN SEDIMENTARY BASINS AND REGIONAL WATERSHEDS" Lunar and Planetary Science XXXIII (2002) 1915.pdf
http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1915.pdf
[68] See Figure 1 Lionel Wilson and James W. Head III "Tharsis-radial graben systems as the surface manifestation of plume-related dike intrusion complexes: Models and implications" JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. E8, 10.1029/2001JE001593, 2002
http://www.planetary.brown.edu/planetary/documents/2584.pdf
[69] "A system of gigantic ancient valleys -- some as much as 200 kilometers wide -- lies partly buried under a veneer of volcanic lava flows, ash fall and wind-blown dust in Mars' western hemisphere. New observations made with Mars Orbiter Laser Altimeter on the Mars Global Surveyor spacecraft reveal

northwestern slope valleys (NSVs) northwest of the huge martian volcano, Arsia Mons, and south of Amazonis Planitia, site of a postulated ocean." Lori Stiles "Scientists Find Largest Flood Channels in the Solar System" University of Arizona uanews.org [2001] available online at http://uanews.opi.arizona.edu/cgi-bin/WebObjects/UANews.woa/wa/SRStoryDetails?ArticleID=3995

[70] http://www.lanl.gov/orgs/pa/News/cover_epi.jpg

[71] http://www.harmakhis.org/history/5.jpg

[72] http://www.harmakhis.org/history/6.jpg

[73] "Especially prominent are the Nilae Fossae around the Isidis basin, but less distinct concentric graben and scarps are visible around the Argyre and Hellas basins." BY THE VIKING ORBITER IMAGING TEAM "Deformational features" NASA SP-441 http://history.nasa.gov/SP-441/ch6.htm

[74] http://www.harmakhis.org/history/7.jpg

[75] "Introduction: The Margaritifer Sinus region of Mars preserves some of the highest valley network densities on the planet [1-4]. Two large northwest draining valley systems, Samara and Parana-Loire Valles, whose associated basins cover an area exceeding 540,000 km2, dominate regional drainage. These valley systems converge on Margaritifer Basin, a confluence plain shared with the Uzboi-Holden-Ladon-Margaritifer Valles meso-outflow system (UHLM) that drains northward from Argyre. Detailed geologic and morphometric mapping of the Samara and Parana-Loire valley systems confirms the timing of incisement and permits evaluation of possible mechanisms for valley evolution [2, 5-8]." J. A. Grant "Valley Evolution in Margaritifer Sinus, Mars" Available online at http://www.nasm.si.edu/ceps/research/grant/grant_marg2.pdf

[76] "features in Margaritifer Sinus. Four resurfacing events that deposited materials interpreted to be of mostly volcanic origin on the basis of wrinkle ridges and occasionally lobate morphology followed formation of these basins. The first three resurfacing events were widespread and ended before evolution of the preserved valleys; the first two occurred during early Noachian heavy bombardment [11] and the second ended at an N5 age of 1400 (number of craters >5 km in diameter per 1,000,000 km2). By contrast, the third resurfacing event began during the middle Noachian (N5 of 500) and ceased during the late Noachian (N5 of 300) coincident with waning highland volcanism [11]. Formation of Samara and Parana-Loire Valles, the UHLM system, infilling of associated depositional sinks (e.g., Parana Basin at 12.50W, 22.50S), and initial collapse of Margaritifer Chaos all occurred from the late Noachian (N5 of 300) into the early Hesperian (N5 of 150). The last, more localized resurfacing event lasted into the early and middle Hesperian (N5 ages 200 to 70) and emplaced materials that embay valleys. Nearly all area surfaces have been subsequently modified to varying degree by eolian activity." Ibid. available online at http://www.nasm.si.edu/ceps/research/grant/grant_marg2.pdf

[77] "Model for Valley Evolution: A model for valley formation consistent with these results involves mostly localized ground-water discharge enabled by surface fed recharge. In this model, precipitation (rain or snow) would be largely relegated to subsurface entry by high surface-infiltration capacities. Discharge at exposed relief would be controlled by occurrence of layers/ aquitards. Valley evolution would have continued until draw-down of the water table following cessation of precipitation, thereby resulting in a strong sapping overprint.
Martian valley formation by this process may best explain observed morphometry. For example, the basin wide distribution of valleys (Fig. 1), low drainage density and ruggedness numbers, degree of integration, and sediment volume in along-valley sinks may be difficult to accommodate in a hypothesis involving ground-water discharge in the absence of surface recharge. With surface-fed recharge, valley distribution would be controlled mostly by the occurrence of layers/ aquitards." Ibid. Available online at http://www.nasm.si.edu/ceps/research/grant/grant_marg2.pdf

[78] "The crustal structure accounts for the elevation of the Martian northern lowlands, which controlled the northward flow of water early in Martian history, producing a network of valleys and outflow channels. The new gravity-field data suggest that the transport of water continued far into the northern plains. The gravity shows features interpreted as channels buried beneath the northern lowlands emanating from Valles Marineris and the Chryse and Kasei Valles outflow regions." Goddard Space Flight Centre "View inside Mars reveals rapid cooling and buried channels" March 9 2000 available online at http://www.gsfc.nasa.gov/topstory/20000309mars.html

[79] “Geologic mapping in Margaritifer Sinus, Mars, defines a complex history of water transport, storage, and release that began in the late Noachian and persisted into at least the mid-Hesperian. Collection, transport, and discharge of the water from widely dispersed surfaces were accomplished by systems of differing character flanking opposite sides of the Chryse Trough. Drainage on the western side of the trough was accommodated by the segmented Uzboi-Ladon-Margaritifer mesoscale outflow system that heads in Argyre basin, drains approximately 9% of the Martian surface, and alternately incises and fills as it crosses ancient multi-ringed impact basins.” John A. Grant “DRAINAGE EVOLUTION IN MARGARITIFER SINUS, MARS” Paper No. 132-0 GSA Annual Meeting, November 5-8, 2001 Boston, Massachusetts http://gsa.confex.com/gsa/2001AM/finalprogram/abstract_27669.htm

[80] Dave Williams “Parana Valles drainage system in Margaritifer Sinus, Mars” available online at http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/vo1_084a47.html

[81] “Using high-resolution topographic data from the Mars Orbiter laser altimeter (MOLA) instrument on the Mars Global Surveyor mission (Smith et al., 1999), we have gathered evidence for a major fluvial resurfacing event in the Martian highlands. We completed detailed geomorphic mapping for the Margaritifer Sinus region (08–308S, 08–308W), where resurfacing appears most evident. In addition, evidence from adjacent areas suggests that this was not a localized event, but one that affected at least 1 3 107 km2 (an area equivalent to the European continent) of the cratered uplands. The topographic information allows for the first time a separation of younger, low-standing fluvially reworked terrains from older, high-standing erosional remnants. The newly acquired MOLA data also allow the volume of eroded material to be sensibly determined and minimum erosion rates to be estimated. The erosional episode was limited in time to no more than several hundred million years, and occurred ca. 4 Ga. The scale of the processes involved strongly suggests, but does not demonstrate uniquely, that precipitation must have played a major role in landscape denudation in this region of Mars.” Brian M. Hynek and Roger J. Phillips “Evidence for extensive denudation of the Martian highlands” available online at http://ltpwww.gsfc.nasa.gov/tharsis/hynek.erosion.pdf

[82] Formation processes of valley networks are still controversial; the debate is largely focused on the relative roles of surface runoff and groundwater processes. In the mapped region, the morphology of the valleys and associated networks (v-shaped profile, sinuous, high density, and high valley order) and the observation that numerous valleys originate near the tops of crater rims or hilltops (Fig. 3) indicate that precipitation and surface runoff may have played a major role in their formation. Some valleys show morphologies more consistent with a groundwater-sapping origin (u-shaped profile, low density and order, and alcove-like terminations), suggesting that subsurface water was also important. Therefore, both precipitation and groundwater certainly contributed to degradation in the Margaritifer Sinus region, but the relative importance of each erosion mechanism is unclear. These results are consistent with previous work completed on the south-central part of our study area (Grant, 2000).” Ibid. available online at http://ltpwww.gsfc.nasa.gov/tharsis/hynek.erosion.pdf

[83] “There is evidence for a large paleolake in the region (Parana basin; 22.58S, 12.58W, area ;33 000 km2) (Goldspiel and Squyres, 1991). The depression contains hummocky interior deposits with interspersed smooth terrain (Ni) that were emplaced contemporaneously with the extensive denudation and valley network formation. A large number of valley systems terminating at the proposed shoreline of Parana basin are believed to have been sources for the paleolake (Goldspiel and Squyres, 1991). The unit HNl contains a hematite spectral signature and is interpreted to be sedimentary layers deposited from large-scale water interactions (Christensen et al., 2000).” Ibid. Available online at http://ltpwww.gsfc.nasa.gov/tharsis/hynek.erosion.pdf

[84] “J.A. Grant examined the valley networks in the Margaritifer Sinus region, the area on Mars where they are most concentrated, and concluded that they were indeed carved by "sapping" (tunneling by underground water flows) rather than surface runoff -- but also that the only way such a subsurface water supply could be adequately replenished was if "widespread precipitation" in the form of rain or snow occurred in the region and then seeped into Mars' porous ground.

B.M Hynek concluded from MGS' laser topography maps that the western Arabia Terra ("Arabia Highlands"), an area the size of Europe, was so eroded by surface rain that 3 million cubic km of its material was gradually washed into Mars' low-altitude northern plains.

K.P. Harrison and R.E. Grimm examined the fact that the areas on Mars where valley networks seem to be most concentrated are also those where MGS' magnetic sensors -- to everyone's surprise -- found local magnetic fields which seem to be areas where crustal iron minerals have been permanently magnetized by Mars' long-vanished early magnetic field.
Since this most easily occurs when molten rock is exposed to a magnetic field at the same time that it is rapidly cooled into solid form, the obvious possibility is that rising flows of underground magma may have collided in these areas with large amounts of groundwater kilometers below the surface, providing a flow of geothermal hot springs for the valley networks, and also cooling the magma quickly enough to "freeze" a copy of Mars' magnetic field into the resulting solid rock before Mars' magnetic field could reverse polarity (which, like Earth's, it probably did every million years or less) and thus scramble the permanently recorded "fossil" field.
D.M. Nelson examined the highlands south of the Elysium Basin -- through which three especially big channels seem to have carried fluid for a long period -- and concluded that the area showed signs of having undergone repeated cycles of geological peace that would have allowed a local layer of ground ice to build up, and episodes of moderate volcanism just right to melt the accumulated ice and produce large water flows into Elysium." Bruce Moomaw "Mars: A World of Varied Catastrophes" MARSDAILY May 1, 2001 available online at http://www.spacedaily.com/news/lunarplanet-2001-01a2.html
[85] "Valley networks were examined in detail (25) in Margaritifer Sinus, a region on the flank of the Arabia bulge and in the Tharsis
trough (Fig. 3B). Most formed on regions of relatively high topographic gradient on the flanks of the trough. The majority (;85%) of
observed valley networks here likely formed in Late Noachian time, between ;4.3 to 3.85 billion years ago (Ga) and ;3.8 to 3.50 Ga
(26), although the possibility exists that earlier valley networks in this region were destroyed by a high impact flux or alternative
erosion mechanisms. Because many of these valley network orientations are controlled by Tharsis-induced slopes, the Tharsis load must
be largely Noachian in age, which is consistent with inferences made earlier. Superposition and sequence relationships indicate that
the valley networks whose azimuths are not explained by the model are nevertheless contemporaneous with the Tharsis-controlled valley networks (27). The formation of valley networks in Margaritifer Sinus is intimately associated with a Late Noachian, large-scale erosion event on the flanks of the Tharsis trough that stripped at least 1.5 3 106 km3 of
material from this area, leaving behind numerous mesas of Early and Middle Noachian terrain (25)." Roger J. Phillips et al "Ancient Geodynamics and Global-Scale Hydrology on Mars" www.sciencemag.org SCIENCE VOL 291 30 MARCH 2001 available online at
http://ltpwww.gsfc.nasa.gov/tharsis/phillips.tharsis.pdf
[86] Goddard Space Flight Center Educational Programs [2002] image of Valles Marineris available online at http://education.gsfc.nasa.gov/experimental/all98invProject.Site/Pages/Vallis.Marineris.html
[87] Image of Valles Marineris
http://www.astronomija.co.yu/suncsist/planete/Mars/marindetalj.htm
[88] http://www.mmedia.is/~bjj/planet_rend/mars_vallesm.jpg
[89] "Figure 1 shows two recent magnetic maps of Mars derived using these techniques. The anomalies have a pattern strongly suggestive of faulting and perhaps offset along faults along a major tectonic structure. The Vallis Marineris on Mars is a series of large, fault-bounded canyons which have been compared with major rift structures on the Earth. The pattern in the magnetic maps, especially the abrupt truncation of the anomalies at the wall of the canyon, supports the idea that the Valles Marineris canyon is a tectonic graben. The maps also suggest that highly magnetic source rocks exist at the intersection of Coprates and Capri Chasmata, on the northeast corner of the canyons, and there is a good possibility that these magnetic rocks may be exposed along the fault wall." Herbert Frey Geodynamics 2001 The Year in Review available online at
http://denali.gsfc.nasa.gov/annual2001/mgg6
[90] M.E. Purucker et al "Interpretation of a magnetic map of the Valles Marineris region, Mars" available online at
http://denali.gsfc.nasa.gov/terr_mag/abstract_mars.pdf

[91] "Paleolake deposits have been mapped in Central
Valles Marineris since Mariner 9 and Viking
(McCauley, 1978; Nedell et al., 1988;Witbeck et al., 1991). Accordingly, the region has been proposed as a priority target for landed payloads intended to detect diagnostic mineral evidence of a permanent lake environment, and, especially, biogenic signatures that could have survived from such promising candidate Martian habitats. (eg, Murray, et al, 1996; Yen, et al, 1999, Murray, et al, 1999). Just-released MOLA data strongly buttress the hydrological case for longduration ice-covered lakes there during Hesperian times at least." Bruce Murray [1999] "PALEOLAKE DEPOSITS IN CENTRAL VALLES MARINERIS: A UNIQUE OPPORTUNITY FOR 2001" Second Mars Surveyor landing site Workshop available online at
http://web99.arc.nasa.gov/~vgulick/MSLS99_Wkshp/Murray_Paleolakes_VM_abs.pdf
[92] "Carr (1996) suggested that ground water flowed from the Tharsis uplands into the deep canyons of Valles Marineris before debouching onto Chryse Planitia in the northern plains. Such a flow may have persisted for billions of years, and is generally inferred to have maintained deep lakes beneath which lacustrine sediments accumulated. Remnants of these Hesperian Age lake deposits survive today as conspicuous layered
strata in Central Valles Marineris. Just published MOLA data (Smith, et al, 1999) confirm in detail this topographic trend and, most importantly, prove that deep, permanent lakes did indeed exist, especially in Central and Western Valles Marineris. Because the canyons in the Valles Marineris are deeper than the probable ground water table at that period, large portions of the canyons would have filled with water and formed ice-covered lakes." Ibid. available online at
http://web99.arc.nasa.gov/~vgulick/MSLS99_Wkshp/Murray_Paleolakes_VM_abs.pdf
[93] Valles Marineris Outflow Site (MER-A)
http://marsoweb.nas.nasa.gov/landingsites/mer2003/topsites/VMout/zoom.html

[94] "Recent high resolution MOC images have revealed the presence of deformed impact craters on flow-like features characterized by narrow bands of alternating light and dark material on the walls of Valles Marineris. The maximum crater elongations are consistent with the flow directions. Moreover the directions of these flows follow the topography downslope. In some cases, the flows emanate from cirque-like depressions, and the flows are divided by sharp ridges similar to arête. These landforms have resemblance to (1) alpine-type glacier morphology, including cirques, arêtes, and glaciers containing medial moraines; and (2) Grand Canyon-type sapping and mass wasting features. Certain aspects of the features in Valles Marineris seem more consistent with the first hypothesis involving a viscous rheology of the flows driven by ice-assisted creep processes. This hypothesis includes direct analogies to glaciers and rock glaciers. In the case of rock glaciers, flow is produced by freeze-thaw and by internal deformation of ice cores or lenses, whereas in the case of glaciers, movement occurs by internal deformation plus basal sliding in some cases where the glacier is melted at its bed. The amounts and roles of ice in the genesis of the Martian glacier-type landforms in Valles Marineris are not clear at this point. The population density of undeformed fresh impact craters on these flows appears to be low compared with the surrounding plateau areas. This may indicate relatively recent ages of the flow processes." A.P. Rossi, G. Komatsu, and J.S. Kargel "[46.03] Flow-like features in Valles Marineris, Mars: Possible ice-driven creep processes" 31st Annual Meeting of the DPS, October 1999
Session 46. Mars Surface: Evidence of Change Posters available online at
http://www.aas.org/publications/baas/v31n4/dps99/158.htm

[95] http://www.harmakhis.org/history/7.jpg
[96] "The channel is unusual because it appears to represent a single outflow initiated by a large impact. This impact could have excavated materials from the Martian crust from depths of several kilometers, apparently "tapping" the aquifer system leading to catastrophic
flooding to form the channel. Ejecta from the Noachian impact crater [6, 7] is preserved NW-W and SE from the source area. The width of Shalbatana Vallis near its source is about 50 km and then it continues 500 km NE as a sinuous, narrow channel of nearly constant width (10 -20 km cross) and depth (~2 km). The channel then becomes wider (40-50 km), bifurcates, and enters Simud Vallis [7]." Ronald Greeley and Ruslan Kuzmin "SHALBATANA VALLIS: A POTENTIAL SITE FOR ANCIENT GROUND WATER" MSL99 Workshop available online at
http://web99.arc.nasa.gov/~vgulick/MSLS99_Wkshp/Greeley_Kuzmin_Shalbat_abs%20.pdf
[97] "DISCUSSION The irregular shape and lack of significant downrange ejecta that surrounds Orcus Patera do not help support an impact origin; it is important to note that Orcus Patera and Schiller are very similar in shape, but the origin of Schiller is also poorly understood at present. The average flank slope

ETF value of –0.30 found for Orcus Patera is only barely within the –0.30 to –2.33 range for ETF exponents that were found for other Martian impact craters [6]. Cavity-wall slopes range from 4.33 to 9.65º and are more gradual than expected for degraded Martian impact craters. The floor of Orcus Patera is relatively flat, though this appears to be the result of post-formation lava flooding; the feature's cross sectional geometry is thus not typical of an impact crater of this size. MOLA colorstretched topographic grids around the depression reveal a shape that could be interpreted as the remnants of a butterfly ejecta pattern commonly emplaced by elliptical impact craters. However, taken together, these data provide insufficient grounds for interpreting Orcus Patera as an impact basin. Unfortunately, Orcus Patera's elliptical shape, interior resurfacing, and floor topography also fail to provide enough strong support for a solely volcanic origin. For instance, the plan view shape of the basin is similar to that of Long Valley caldera, one of the largest elongate calderas on Earth. Orcus Patera's depth below the surrounding plains and truncated asymmetric flanks, however, are similar to what is observed for small volcanic edifices in the Tharsis region on Mars, where subsequent deposits have flooded onto the flanks. Finally, if Orcus Patera is volcanic in origin, the difference in absolute age for Orcus Patera's interior and exterior deposits [9] (volcanic infilling in the interior is younger than the surrounding flanks) suggests that the feature had a prolonged volcanic history and multiple episodes of flooding. Further investigation of relative and absolute ages for smaller distinct units within this region is necessary to identify whether volcanism played a key role in the origin of Orcus Patera or simply modified it subsequent to formation." D.A. van der Kolk et al "ORCUS PATERA, MARS: IMPACT CRATER OR VOLCANIC CALDERA?" Lunar and Planetary Science XXXII (2001) 1085.pdf
http://www.geology.pomona.edu/Mars2000/1085.pdf

[98] "Summary. Geologic mapping of southern Chryse Planitia and the Xanthe Terra outflow channels has revealed a sequence of fluvial events which contributed sediment to the Mars Pathfinder landing site (MPLS). Three major outflow episodes are recognized: (1) broad sheetwash across Xanthe Terra during the Early Hesperian period, (2) Early to Late Hesperian channel formation of Shalbatana, Ravi, Simud, Tiu, and Ares Valles, and (3) subsequent flooding which deepened the channels to their current morphologies throughout the Late Hesperian. Materials from the most recent flooding, from Simud and Tiu Valles, and (to a lesser extent) materials from Ares Vallis, contributed the greatest amount of sediment to MPLS." D.M. Nelson, R. Greeley "XANTHE TERRA OUTFLOW CHANNEL GEOLOGY AT THE MARS PATHFINDER LANDING SITE" Lunar and Planetary Science XXIX 1158.pdf
http://mars.jpl.nasa.gov/MPF/science/lpsc98/1158.pdf

[99] "Following sheetwash, Mawrth Vallis was formed, possibly resulting from the discharge of floods from Margaritifer and Iani Chaos. A broad area of subdued terrain east of Ares Vallis indicates buried and embayed
craters to the south of Mawrth Vallis. Floods could have passed over this surface before excavating Mawrth, then drained downslope into Acidalia Planitia. Alternatively, the subdued area could be a spill zone
formed during the early excavation of Ares Vallis. Channelization continued in the Late Hesperian with the development of Shalbatana, Ravi, Simud, Tiu, and Ares Valles. Shalbatana Vallis possibly formed by subterranean discharge from Ganges Chasmata [7], and Ravi was excavated by flooding from Aromatum Chaos. Simud and Tiu Valles then developed by floods from Hydraotes and Hydaspis Chaos, and Ares Vallis developed by flooding from Iani Chaos. Cross-cutting relationships in Ares and Tiu Valles suggest that multiple floods occurred within these channels." Ibid.
http://mars.jpl.nasa.gov/MPF/science/lpsc98/1158.pdf

[100]
http://www.lanl.gov/orgs/pa/News/cover_epi.jpg

[101] http://www.harmakhis.org/history/8.jpg

[102] http://www.harmakhis.org/history/9.jpg

[103] Mike Caplinger February 1994 "Determining the age of surfaces on Mars" available online at
http://www.msss.com/http/ps/age2.html

[104] http://www.harmakhis.org/history/9.jpg

[105] "Surfaces on Mars that date to the period of heavy bombardment are different from the Moon in that processes other than cratering have modified the surface both during and, to a lesser extent, subsequent to the cratering epoch. This image shows an area in Mars in the region "Terra Tyrrhena" at about 285 degrees west longitude and 5 degrees south latitude and shows an area about 500x500 kilometers. It is fairly typical of areas of the heavily cratered terrain that have been extensively modified during and immediately after the period of heavy bombardment. Most of the large craters have very smooth floors."

A.D. Howard “Features of Martian Cratered Terrain” GEOMORPHOLOGY HOME PAGE University of Virginia available online at
http://erode.evsc.virginia.edu/marscrat.htm
[106] “Scarp retreat: Large areas of Mars downslope of the present-day dichotomy scarp are littered with remnant knobs, and distinctive valleys – the fretted terrains, eat back into the scarp. Collectively they appear to represent ~ 1000 km of scarp retreat in a planet-encircling belt. Profile analysis suggests that the missing volume represents a wedge 4 km thick at the present day scarp and tapering to zero over the 1000km width of the belt of fretted and knobbed terrain. Extending this in a girdle planetwide, we come up with ~5 x 107 km3 –the volume of the sediments.
Scenario: As the dichotomy collapsed, the slurries would have poured into the northern lowlands, filling and covering pre-existing cratered terrain and emplacing thick deposits on a very rapid timescale. Outgassing from trapped volatile CO2 would produce mud volcanoes [8, 9] and phreatic cones [10] as CO2 escaped to surface and blasted loose debris upwards. The northern plains would have been an extensive,
mobile “sea” of fluidised debris – a “Mud Ocean” [1]. Its surface would have been wreathed in clouds of escaping CO2 from fumaroles, fissures, and vents. The margin of the Mud Ocean would have been like the flow front of an aa lava – advancing in a bulldozer-like carpet, burying and engulfing the surrounding terrain, and steaming from the escape of CO2. The speed of advance would have been, like lava flows, very variable and a function of fluid supply behind the flow front. Long stillstands and episodes of slow creep would alternate with short intervals of hundreds of metres per day, or more.” N. Hoffman et al “EMPLACEMENT OF A DEBRIS OCEAN ON MARS BY REGIONAL-SCALE COLLAPSE AND FLOW AT THE CRUSTAL DICHOTOMY” Lunar and Planetary Science XXXII (2001) 1584.pdf
http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1584.pdf

[107] K. F. Sprenke and L. L. Baker “POLAR WANDERING ON MARS?” Lunar and Planetary Science XXXI 1930.pdf
http://www.lpi.usra.edu/meetings/lpsc2000/pdf/1930.pdf
[108] “Syria Planum: Syria Planum is the site of long-lived (Noachian to Late Hesperian) magmatic-driven activity with distinct episodes of intensive early magmatic/tectonic activity that declined in tectonic intensity by an order of magnitude from the Late Noachian to Late Hesperian [2,25], transitioning mainly into a dominantly volcanic setting during the Late Hesperian [2]. Some of the dominant characteristics of Syria include: (1) local and regional uplifts, (2) extensional and contractional tectonism, (3) dike emplacement, including the formation of Late Hesperian and possibly younger pit crater chains, (4) volcanism including the formation of shield fields [26] and the emplacement of voluminous sheet lavas that may range in relative age from the Late Noachian to the Late Hesperian [2],”
http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1811.pdf
[109] “Preliminary results indicate that Syria had a greater impact on the evolution of the Tharsis magmatic complex than Alba.” R. C. Anderson et al “COMPARATIVE INVESTIGATION OF THE GEOLOGICAL HISTORIES AMONG ALBA PATERA AND SYRIA PLANUM, MARS” Lunar and Planetary Science XXXIII (2002) 1811.pdf
http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1811.pdf
[110] http://www.harmakhis.org/history/10.jpg
[111] “The Hellas Basin is an ancient impact structure on Mars, approximately 3000 km long by 1500 km wide” J. Richardon “Isostacy in the Hellas Basin on Mars” available online at
http://www.lpl.arizona.edu/~jrich/work/hellasslides.pdf
[112] http://www.lanl.gov/orgs/pa/News/cover_epi.jpg
[113] http://www.harmakhis.org/history/11.jpg
[114] http://www.harmakhis.org/history/6.jpg
[115] http://www.harmakhis.org/history/13.jpg

[116] “The mineral olivine, an iron-magnesium silicate that weathers easily by water, has been found in abundance on Mars. The presence of olivine implies that chemical erosion by water is low on the planet and that Mars has been cold and dry throughout most of its geologic history.” R. N. Clark and T. M. Hoefen “New Evidence Suggests Mars Has Been Cold and Dry "Red Planet" Abundant with Green Minerals” available online at http://speclab.cr.usgs.gov/mars.press.release.10.2000.html

[117] N. Hoffman “Water on mars? Who are they trying to kid?” School of Earth Sciences University of Melbourne available online at

http://www.earthsci.unimelb.edu.au/mars/

[118] "Glacial History: There are a variety of distinct landforms on Mars that are interpreted to be associated with the presence of ground ice/permafrost [9-11]. Today, the only visible surface ice occurs at the permanent polar caps, although water ice is physically stable poleward of 45° N and S latitude. Some investigators have suggested that the ice cover was once more extensive, particularly in the southern hemisphere. Kargel [5] mapped the occurrence of a suite of landforms in Hellas that may have had a common glacial origin. These features, which he interpreted to be glacial scour marks, moraines, drumlins, and eskers, are shown in Figure 1." B. J. Thomson and J. W. Head "THE ROLE OF WATER/ICE IN THE RESURFACING HISTORY OF HELLAS BASIN" Fifth International Conference on Mars 6200.pdf http://www.lpi.usra.edu/meetings/5thMars99/pdf/6200.pdf

[119] "It remains unclear whether the grooved terrain, if it is indeed glacial in origin, is indicative of a local, isolated glacier or whether it was part of a more extensive ice sheet in the southern hemisphere." Ibid. available online at http://www.lpi.usra.edu/meetings/5thMars99/pdf/6200.pdf

[120] "Channel and Lacustrine Deposits: Northwards of the proposed area of maximum glacial extent there is a region interpreted to be influenced by glacio-lacustrine processes. Kargel [5] mapped a portion of the shoreline of a possible proglacial lake. The MOLA data reveal that this mapped shoreline lies almost entirely at the -6000 m elevation level. Possible sources of input to this lake is water derived from retreating glaciers as well as outflow channels which empty to Hellas from the east. The esker field, in which the long axis of the features in oriented north-south, may represent subglacial flow of water into a proglacial lake. The eastern channels also might have contributed to this lake. These small channels resemble other outflow channels
in gross morphology, but are greatly reduced in size. Interestingly, channel cutting terminates abruptly on the basin floor in a manner that is very similar to the abrupt cessation of the circum-Chryse outflow channels. The paucity of tributaries along the length of these Hellas channels suggests a localized source region, possibly due to volcano/ground ice interactions." Ibid. available online at http://mars.jpl.nasa.gov/mgs/sci/fifthconf99/6200.pdf

[121] "Glacial Hypothesis: There are a variety of distinct landforms on Mars that have been attributed to the presence of ground ice/permafrost [7-9]. Today, although water ice is physically stable poleward of 45° N and S latitude, the only visible surface ice occurs at the permanent polar caps. Some investigators have suggested that the polar ice cover was once more extensive earlier in Mars's history [e.g. 10-12]. Kargel and Strom [6] mapped the occurrence of a suite of landforms in Hellas which they believed share a common glacial origin. These features, which include glacial scour marks, moraines, drumlins, and eskers, are proglacial lacustrine deposits, are shown in Figure 1. The proposed age of the latest episode of glaciation is middle Amazonian. Three predictions of the glacial hypothesis that we have investigated with MOLA data are 1) glacial scouring on the south rim, 2) a shoreline from a pro-glacial lake in the north, and 3) a suite of glacial depositional landforms on the basin floor." Bradley J. Thomson and James W. Head "HELLAS BASIN, MARS: EXAMINATION OF A GLACIAL HYPOTHEISIS WITH MOLA TOPOGRAPHY" 32-th Vernadsky-Brown Microsymposium / Abstracts available online at http://www.geokhi.ru/~planetology/Abstracts/Thompson%20et%20al.pdf

[122] Jakupova A. E. et al "PREPARATION OF AN ATLAS OF THE CRATERING OF MARS" 38th Vernadsky/Brown Microsymposium on Comparative Planetology available online at http://www.geokhi.ru/~planetology/Abstracts/Jakupova%20et%20al.pdf

[123] "In this topographic portrayal of Mars, above, the northern lowlands are occupied by an ocean (blue) whose shoreline is placed at the position of Contact 2, the line that Parker and co-workers interpreted as an ancient shoreline. Thus, this view shows Mars as it might have looked mid-way through its history according to the oceans hypothesis. The Tharsis region, with numerous very large shield volcanoes is seen in the central part of the globe. In the upper right, many channels flow into the northern lowlands at Chryse Planitia." NASA Mars Global Surveyor Project; MOLA Team "Possible configuration of ancient oceans on Mars: Topographic portrayal of the surface of Mars derived from Mars Orbiter Laser Altimeter (MOLA) data" available online at http://www.brown.edu/Administration/News_Bureau/1999-00/99-060g.html

[124] See Figure 2 for shorelines and Figures 3 A to F for polygons and craters with ejecta lobes. "Martian impact craters in the 2- to 50-kmdiameter range commonly have ejecta deposits with distinctive lobe and rampart morphology, interpreted to be due to the presence of groundwater or ground ice in the target area that mobilizes the ejecta material (22). Craters on Mars smaller than a few kilometers generally do not have unusual ejecta ramparts, and thus the onset diameter of ramparts may be an indication of the depth at which groundwater or ground ice is encountered during cavity excavation. On the basis of this concept, Kuzmin et al. (23) assessed the onset diameter globally. Using their map, we found a correlation between the lower range of onset diameters (,4 km) and the northern lowlands (Fig.

3B). The craters with the smallest diameters (,2 km) correlate with the position of the two large basins within the northern lowlands, a distribution consistent with an interpretation of groundwater or ground ice occurring preferentially near the surface in the northern lowlands and particularly in the interiors of the two basins (7, 8)." James W. Head III et al. "Possible Ancient Oceans on Mars: Evidence from Mars Orbiter Laser Altimeter Data" 10 DECEMBER 1999 VOL 286 SCIENCE www.sciencemag.org available online at
http://ltpwww.gsfc.nasa.gov/tharsis/mola.ocean.pdf
[125] http://www.harmakhis.org/history/14.jpg
[126] http://www.harmakhis.org/history/15.jpg
[127] "An initial step towards identifying the mechanism of formation of Amazonis Planitia is to compare its topographic properties to other smooth regions with potentially analogous origins. Shown in Figure 4 are pro_les of elevation collected by various altimeters over smooth surfaces from a variety of solar system bodies. At the top is MOLA Pass 31 over Amazonis Planitia, where the anomalously smooth region is observed to extend over 600 km, approximately centered in the plot (vertical point-to-point accuracy _z _ 0:4 m, horizontal resolution _x _ 0:3 km). Below is a Clementine pro_le of the Moon's Oceanus Procellarum (_z _ 40 m, _x _ 2 km for 1 Hz data and _ 0:2 km for 8 Hz data) [Smith et al., 1997], Magellan radar altimetry over Niobe Planitia (_z _ 4 m, _x _ 10 km) [Ford and Pettengill, 1992], Shuttle Laser Altimeter data collected over the Sahara desert (_z _ 1:5 m, _x _ 0:7 km) [Garvin et al., 1997], and shiptracks of Seabeam 2200 bathymetry over the south Atlantic abyssal plains (_z _ 2 m, _x _ 0:1 km) [Neumann et al., 1996]. The last two pro_les were extracted from the GTOPO data set (highly variable _z _ 20 m, _x _ 0:1 km) [Gesch and Larson, 1996], _rst over the Great Plains in the U.S., and second over the Indo-Gangedic Plains across over the Tibetan Plateau, down across the Tarim Basin and continuing northwards. Oceanus Procellarum consists of lava flows that have been broadly tilted by subsidence and locally steepened by tectonic deformation (wrinkle ridges); their small-scale roughness is dominated by impact regolith formation processes. Niobe Planitia on Venus consists of vast lava plains similarly tilted and steepened but not influenced by regolith formation. Comparison of these surfaces reveals that of these lowest, smoothest regions observed in the solar system, Amazonis Planitia closely resembles in its smoothness only the heavily sedimented surfaces on the Earth, i.e. oceanic abyssal plains and basins _lled by fluvial deposition processes. It is noteworthy that volcanically resurfaced terrain is markedly rougher on the Moon, on Venus, and on Mars, than the peculiar Amazonis deposits. Saharan sand sheets are rougher by a factor of about three. Other regions in the Martian northern hemisphere that exhibit evidence of dust deposition are rougher than Amazonis as well." Oded Aharonson, Maria T. Zuber and Gregory A. Neumann "Mars: Northern hemisphere slopes and slope distributions" GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 24, PAGES 4413-4416, DECEMBER 15, 1998 available online at
http://ltpwww.gsfc.nasa.gov/tharsis/grl98_slopes.pdf

[128] NASA/JPL/Arizona State University [2003] "Mars Odyssey THEMIS Image: Lucus Planum"
http://www.marstoday.com/viewsr.html?pid=8867

[129] "RATIONALE: The debouche of Ma'adim Vallis in the Elysium Basin generated a transitional transported sediment structure, which planimetric shape is controlled by the enclosing topography of a deep re-entrant gulf of the Basin into the highland. We defined it as an estuarine delta. The location and the importance of this estuarine delta is supported by the theoretical model of graded profile constructed for Ma'adim Vallis [1], and by two approaches: (i) the reconstruction of Ma'adim Vallis downstream course from Gusev to Elysium Basin (figure 1), and (ii) the survey of the sediment deposit in the alleged estuary. The longitudinal graded profile of Ma'adim Vallis finds its base-level in the Elysium Basin, at a -1000 m elevation [1], which is in agreement with the observed Basin shoreline [2]. This model is supported by observational evidence of flow between the northern rim of Gusev crater, and the Elysium Basin shoreline. This downstream course of Ma'adim Vallis can be divided into three hydro geologic regions. Cabrol et al "Duration of the Ma'adim Vallis/Gusev crater hydrogeologic system, Mars" *Icarus* 133, 98-108 [1998].

[130] http://www.space4case.com/mars/mars5/mars112.html

[131] "flowing around the aureole. These three barriers (degraded Noachian crater rim, proto- Olympus Mons flow unit, and Olympus Mons aureole) caused subsequent lava flows and outflow channel effluents, primarily from the Elysium region to the west, to pond on the floor of Amazonis Planitia, preferentially smoothing the terrain there. Mars Orbiter
Camera (MOC) images substantiate that at least two very fluid lava flows alternated with fluvial episodes from Elysium Planitia, flowing through Marte Valles onto the floor of the Amazonis Planitia basin. Within Amazonis Planitia, MOC images show flow-like textures heavily mantled by sediments, and radar data reveal the presence of rough lava flow surfaces underlying the sedimentary debris. These data thus suggest that the unique smoothness of Amazonis Planitia is the result of deposition of thin fluid lava flows and fluvial sediments in an enclosed basin. Crater counts suggest that the most recent resurfacing may have occurred in the latest Amazonian Period, in the last 1% of the history of Mars." Elizabeth R. Fuller and James W. Head III "Amazonis Planitia: The role of geologically recent volcanism and sedimentation in the formation of the smoothest plains on Mars" JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. E10, 5081, doi:10.1029/2002JE001842, 2002 available online at
http://www.planetary.brown.edu/planetary/documents/2682.pdf
[132] "Introduction: This study seeks to understand origin of the equatorial layered deposits (ELDs), including the Medusae Fossae Formation (MFF) the filled craters of Elysium and Arabia Planitiae (Gusev and Henry Craters). Several origin hypotheses have been proposed for the MFF [c.f. summary in most involving a pyroclastic origin but one proposing formation at the poles [2]. Previous work using MOLA to test the polar formation theory found there are both similarities and significant differences between the equatorial and polar layered deposits, concluded that the MFF may be volatile rich, but not form at the poles [3]. Another MOLA-based study similarly found that the deposits were not polar origin, and instead concluded that they were most consistent with a welded ashfall tuff [4]. [5] further showed that the ELDs could not be evidence of polar wander on the basis of the time scales necessary for polar wander to have occurred. Morphological evidence also indicates that while there are similarities between the poles and the ELDs, including extensive layering at multiple scales, unusual smoothness at several scales [see also discussion in steep slopes (~1-6° in the MFF, ~1-10° at the poles), and distal thinning of the materials, there are fundamental differences, notably the lateral extent the ELDs: the MFF itself reaches across 90 longitude (Figure 1), and filled craters are present around the globe. If the ELDs did form by mechanism similar to that of the poles, what were sources of the volatiles, and how did they reach equator?
Volatile sources: There are three Amazonian-aged volatile sources in the equatorial region: degassing from nearby volcanism, Elysium-region catastrophic outflow, and polar material migration during periods
high obliquity. 1) Degassing: The Tharsis Montes, Olympus Mons, and Elysium Mons were all active during the Amazonian. [7] showed that these eruptions were most likely plinian, with extensive magmatic degassing releasing CO2 and H2O. Regional outflow: [8] and [9] have shown that waterrich debris flowed down the northwestern flanks Elysium Mons in the mid-late Amazonian. Additionally, in the late Amazonian there was repeated catastrophic release of water in Elysium Planitia, through Marte Vallis, debouching into Amazonis Planitia [10]. 3) Migration of polar materials: periods of maximum obliquity, the poles receive more insolation than the equator. As the poles warm, ice becomes unstable and is forced to migrate to a new cold trap (see below) [11]." E. R. Fuller and J. W. Head, III "PROPOSING A HIGH VOLATILE CONTENT IN THE EQUATORIAL LAYERED DEPOSITS INCLUDING THE MEDUSAE FOSSAE FORMATION, MARS" Microsymposium 36, MS022, 2002 Available online at
http://www.planetary.brown.edu/planetary/documents/Micro_36/Abstracts/022_Fuller_Head.pdf

[133] "Probably the most important question concerning the global-scale tectonic history of Mars is the origin of the crustal dichotomy. The northern lowland is not only several kilometers lower than the southern highland, it also is surfaced by materials that are significantly younger than surface materials in the southern highland (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka and Scott, 1987). The young surface materials in the lowland rest unconformably on basement material having an age comparable to the exposed ancient highland terrane to the south (Scott, 1978; Maxwell and McGill, 1987; McGill, 1989; McGill and Dimitriou, 1990; Schultz and Frey, 1990)." George E. McGill "Geologic Map Transecting the Highland/Lowland Boundary Zone, Arabia Terra, Mars: Quadrangles 30332, 35332, 40332, AND 45332" available online at

http://geopubs.wr.usgs.gov/i-map/i2746/

[134] "Tectonics: In the highlands of Amenthes-northern Terra Cimmeria and northern Arabia Terra, lobate scarps are found between approximately 200 to 600 km south of the dichotomy boundary. These lobate scarps, interpreted to be the surface expression of thrust faults, are oriented roughly parallel to the dichotomy boundary (Figure 1). The proximity and parallel orientation of thrust faults to the dichotomy boundary suggests that compressional deformation was involved in its formation
[2]. Extension along the boundary is thought to have occurred during the Late Noachian to Early Hesperian [3]. Thrust faulting of the highlands near the boundary appears to have occurred during roughly the same period [2, 4]. Thus the fractures and thrust faults may reflect a tectonic event that was associated with the dichotomy boundary (Figure 1). The deformation along the boundary suggests that the dichotomy formed in the Late Noachian to Early Hesperian [2, 3]. If the dichotomy formed earlier, this deformational event may have been responsible for shaping the present-day dichotomy boundary in the eastern hemisphere."
T. R. Watters "THE TECTONICS AND TOPOGRAPHY OF THE DICHOTOMY BOUNDARY IN THE EASTERN HEMISPHERE OF MARS" Lunar and Planetary Science XXXIII (2002) 1692.pdf
http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1692.pdf
[135] "Distinctions include: (1) magmatic-driven activity from at least the
Early Hesperian extending into the Amazonian [1,7-8]" R. C. Anderson et al. "COMPARATIVE INVESTIGATION OF THE GEOLOGICAL HISTORIES AMONG ALBA PATERA AND SYRIA PLANUM, MARS" Lunar and Planetary Science XXXIII (2002) 1811.pdf
http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1811.pdf
[136] "4. Conclusions
[93] Detrended MOLA altimetry data have provided a new picture of the Martian northern lowland basin topography, morphology, evolution, and relation to the history of Mars. We interpret our results to indicate that the northern lowlands are underlain by a regional unit containing a basin-wide system of subparallel wrinkle ridges and arches. This unit is laterally contiguous with Hesperian-aged ridged plains in the southern uplands and contains highly modified craters, the number of which suggests an Early Hesperian age. The orientation and location of the
wrinkle ridges in the North Polar Basin completes a global circum-
Tharsis ridge system forming a band approximately 7000 km wide and extending over the whole circum-Tharsis region. Several subareas of the northern lowlands show individual patterns (e.g., basin-like areas of Isidis and Utopia). The present spacing and height of wrinkle ridges and geometry of buried craters in the northern lowlands suggest that the Late Hesperian Vastitas Borealis Formation is a sedimentary unit superposed on Hr (regional plains). Hesperian-aged channels entering Chryse Planitia are controlled by the orientation and topography of wrinkle ridges deep into the basin, indicating that wrinkle ridges had largely formed by Late Hesperian. These channels are among the strongest
candidates for providing the material of the Vastitas Borealis Formation. Amazonian-aged smooth plains units of volcanic origin, particularly in Amazonis Planitia, further bury and obscure the underlying wrinkle ridges and the Vastitas Borealis Formation. [94] Recognition of these units and their stratigraphic relationships provides a new perspective on the history of the northern lowlands (Figure 17). In this scenario, in the Early Hesperian the majority of the northern lowlands was filled with volcanic plains similar to those presently exposed in the southern uplands (Hr). As with those deposits in the southern uplands, evidence for volcanic vents was scant or subdued in topography. The Hesperian-aged plains in the northern lowlands were pervasively deformed soon thereafter by Tharsis-circumferential and basin-related wrinkle ridges. Circum-Chryse outflow
channels formed in the Late Hesperian following courses largely controlled by wrinkle ridge orientation and height and deposited material in the basin to form a major contribution to the Vastitas Borealis Formation.
[95] Widespread emplacement of the Hesperian-aged ridged
plains of apparent volcanic origin is interpreted to mean that the
volcanic phase represented by this unit was global in nature and resurfaced the northern lowlands, in addition to the _10% of the
planet previously known, for a total resurfacing of about 30% of
Mars. This remarkable event increases by a factor of 2 the amount
of volatiles that might have been degassed into the atmosphere
during this time period of peak volcanic flux." James W. Head III et al. "Northern lowlands of Mars: Evidence for widespread volcanic flooding and tectonic deformation in the Hesperian Period" JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. 0, 10.1029/2000JE001445, 2002 available online at
http://www.planetary.brown.edu/planetary/documents/2575.pdf

[137] "[1] We analyze the fate of the Hesperian-aged outflow channel effluents emplaced into the northern lowlands of Mars. We have modeled the evolution of these effluents under the assumption that they were emplaced under a range of atmospheric conditions comparable to those of today and thought to have prevailed in the Hesperian. Under these conditions we find that the evolution of the sediment-loaded water after it left the channels includes three phases. Phase 1: Emplacement and intensive cooling: Violent emplacement of water followed by a short period of intensive evaporation from the surface and near-surface layer, and intensive convection. During this phase the water maintained and redistributed its large suspended sediment load. Water vapor strongly influenced the climate, at least for a geologically short time. When the temperature of the water reached the temperature of the maximum density or the freezing point, boiling and intensive convection ceased and the water deposited the sediments. Phase 2: Freezing solid: Geologically rapid freezing of the water body accompanied by weak convective water movement occurred over a period of the order of _104 years. Phase 3: Sublimation and loss: This period involved sublimation of the ice and lasted longer than the freezing phase. The rate and latitudinal dependence of the sublimation, as well as the location of water vapor condensation, crucially depend on the planetary obliquity, climate, and sedimentary veneering of the ice. Phase 3 would have been very short geologically (_105–106 years) if an insulating sedimentary layer did not build up rapidly. If such an insulating layer did form rapidly, sublimation could cease and residual ice hundreds of meters thick could remain below the surface today." Mikhail A. Kreslavsky and James W. Head "Fate of outflow channel effluents in the northern lowlands of Mars: The Vastitas Borealis Formation as a sublimation residue from frozen ponded bodies of water" JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. E12, 5121, doi:10.1029/2001JE001831, 2002 available online at
http://www.planetary.brown.edu/planetary/documents/2686.pdf
[138] "Resurfacing: We suggest that the latest resurfacing of the northern plains did not occur by sedimentation within an ocean or by widespread volcanism, but rather by the latest stages of long-term periglacial and thermokarst modification, with progressively reduced intensity occurring during the Hesperian through Early Amazonian. This activity obliterated or heavily modified earlier landforms, resulting in huge collapse structures, ghost craters, valley networks, highland/lowland fretted and knobby terrains, polar cavi terrains, and lowland thumbprint terrains. Such resurfacing likely involves erosion, ductile deformation, collapse, and effusive and violent eruptions of volatile charged material. The elevation dependence of the reworking may be related to gradual lowering of the threshold for near-surface volatile activity, as governed by the composition and distribution of subsurface volatiles and by the geothermal gradient. The difficulties to making Mars warm in the past and the lack of significant chemical weathering on Mars [14] seem to preclude substantial liquid water at the surface in the form of long-lived fluvial, lacustrine, and wet-based glacial activity. Instead, northern plains resurfacing may result mainly from the subsurface activities of both H_2O and CO_2 (CO_2 being more volatile), as well as from local discharges of sediment enriched with these volatiles."
K. L. Tanaka et al "RESURFACING OF THE NORTHERN PLAINS OF MARS BY SHALLOW SUBSURFACE, VOLATILEDRIVEN ACTIVITY" Lunar and Planetary Science XXXIII (2002) 1406.pdf
http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1406.pdf
[139] "CO_2 and Warm H_2O Models: The simplest and most self-consistent model for the morphologies we see in and Athabasca Vallis and nearby "flood" valleys is that a volatile-rich debris flow was deposited and sculptured by roller vortices to produce the flow parallel ridges which were impregnated with the flow volatiles (Figure 3a). Given likely flow velocities, thicknesses, and rheology, roller vortices actually are only stable for debris flows and density flows (and not for aqueous floods or lava flows) [1]. In the immediate aftermath of the flow, escape of highly volatile fluids from the ridges generated longitudinal chains of phreatic cones in a cryovolcanic process (Figure 3b). The most reasonable explanations for the Athabasca Vallis and its ridges of cones appears to be debris flows charged with warm water and/or CO_2 gas-. Implications For Local And Regional Geology:
Whilst Athabasca Vallis is currently targeted as a MER 2003 backup candidate landing site, due to the evidence for recent outburst floods, the terrain does not require aqueous action. Instead, massive CO_2-rich
gas-supported density flows may have resulted from outburst of subsurface liquid CO_2 reservoirs rather than liquid water reservoirs."
Nick Hoffman and Ken Tanaka "CO-EXISTING "FLOOD" AND "VOLCANIC" MORPHOLOGIES IN ELYSIUM AS EVIDENCE FOR
COLD CO_2 OR WARM H_2O OUTBURSTS" Lunar and Planetary Science XXXIII (2002) 1505.pdf
http://www.earthsci.unimelb.edu.au/mars/LPSC_2002_1505_Athabasca.pdf
[140] "Fluvial geomorphology. The fluvial nature of the Marte Vallis outflow channel appears to be confirmed by MOC images [10] that show streamlined islands of several hundred meters to a couple of

kilometers across, longitudinal grooves ten's of meters wide, and multi-level terraces on channel islands and margins. In conjunction with the anastomosing plan form of the channels, these features suggest channel formation by a high volume of low viscosity fluid that we hypothesize was sediment-laden water. Similar features also appear in MOC images to the north and west of the Elysium Basin, indicating the presence of some channels more substantial than previously supposed." D. M. Burr et al "RECENT FLUVIAL ACTIVITY IN AND NEAR MARTE VALLIS, MARS" Lunar and Planetary Science XXXI 1951.pdf
http://www.lpi.usra.edu/meetings/lpsc2000/pdf/1951.pdf
[141] See images in
http://webgis.wr.usgs.gov/mer/March_2002_presentations/Burr/Burr-Landingsite3.pdf
[142] "Discussion: MOC images have not shown many smaller networks as would be expected from precipitation. Malin and Carr [13] have suggested that the global lack of such dendritic channels may be due to modification by eolian and mass-wasting processes. However, the lava and channel morphologies of the Elysium Basin region appear pristine. The dendritic channels, then, are likely absent from MOC images of the Elysium Basin because they did not form there. In addition, the anastomosing form of the channels suggests formation by exceptionally large flow. Thus, we believe that the MOC data fails to support the idea that the channel flood water derived from precipitation." D. M. Burr "RECENT FLUVIAL ACTIVITY IN AND NEAR MARTE VALLIS, MARS" Lunar and Planetary Science XXXI 1951.pdf
http://www.lpi.usra.edu/meetings/lpsc2000/pdf/1951.pdf
[143] "Secondary geomorphic evidence: rootless cones. Rootless cones are seen throughout Athabasca Valles and the unnamed northern channel system, as well as in Amazonis Planitia, into which the Marte Vallis debouches [5]. Rootless cones form when lava flows over and intimately mixes with wet substrate, volatilizing the water which then erupts up through the overlying lava flow [5]. Rootless cone fields within
the channels, but not on the surrounding terrain, suggest that the water for their formation was emplaced by aqueous flow within the channels."
D. M. Burr et al "EXTENSIVE AQUEOUS FLOODING FROM THE CERBERUS FOSSAE, MARS, AND ITS IMPLICATIONS FOR THE MARTIAN HYDROSPHERE" Lunar and Planetary Science XXXIII (2002) 1047.pdf
http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1047.pdf
[144] "Source of the sediment: The sediment deposited in the streamlined forms was in transport by the floodwater. The floodwaters would have been carrying material entrained from the Martian surface during
the carving of Athabasca Vallis. Because they emanated from the Cerberus Fossae, the floodwaters may also have been carrying sediment from within the Fossae. Since the Fossae were a source for both water and lava, this sediment may have been hydrothermally altered. Athabasca Vallis was a candidate landing site for the Mars Exploration Rovers. If future landed missions target Athabasca Vallis, they may be able to collect sediment samples from the streamlined forms of such subsurface material." D. M. Burr "TEMPORARY PONDING OF FLOODWATER IN ATHABASCA VALLIS, MARS" Lunar and Planetary Science XXXIV (2003) 1066.pdf
http://www.lpi.usra.edu/meetings/lpsc2003/pdf/1066.pdf

[145] "[12] The Cerberus Fossae fissures (Figure 1C) have very sharp edges and steep slopes (>80° indicated by shadows and viewing geometry in M04-03770) and cut sparsely-cratered plains (e.g., M07-03839). Thus, although their structural trend is also observed in remnant ancient highland terrain [*Tanaka et al.*, 1992], we deduce the fissures to have been recently reactivated. That they appear to have been the source, not only of recent lava flows, but also of recent voluminous aqueous flooding, supports a causative relationship between the two types of flows, such as a scenario in which rising dikes melt ground ice [e.g., *McKenzie and Nimmo*, 1999] and open pathways to the surface. By analogy, the easternmost Cerberus Fossae could have been the main source for the larger aqueous floods down Marte Vallis [*Tanaka et al.*, 1992], although geomorphic and topographic evidence may now be largely buried beneath Cerberus Plains lavas. Burr, D. M "4. Source of the Flood Water" GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 1, 10.1029/2001GL013345, 2002

http://www.agu.org/pubs/sample_articles/sp/2001GL013345/4.shtml

[146] "Note the number of channels in this image. In places, these features look a lot like lunar sinuous rilles. They are all large flat-bottomed valleys. They begin abruptly in broad depressions. And their sources seem to form a ring centered on Elysium Mons. Like sinuous rilles on the Moon, these valleys might be lava channels. However, water is a more likely cause for their formation. Specifically, ground ice

appears to have been widespread in the Elysium region. Such ice is easily melted near hot magmas. Thus, melt water provides a ready source for erosion in the Elysium region. Further, the loss of a lot of ground ice can cause collapse depressions near the channel sources." S. De Silva "Elysium Mons" University of South Dakota available online at
http://volcano.und.nodak.edu/vwdocs/planet_volcano/mars/Shields/elysium.html
[147] Mars Odyssey and MGS Mars Orbital Laser Altimeter (MOLA) Science teams "Mars Odyssey Orbiter Watches a Frosty Mars" [2003] available online at
http://mars.jpl.nasa.gov/odyssey/newsroom/pressreleases/20030626a.html
[148] "Due to the presence of two distinct phases of volcanism of such differing characteristics, it is proposed that these phases were separated by a period of repose. During this time the magma chamber, which had supplied the Elysium Mons vent, cooled sufficiently to alter the regional stress fields and produce tectonic activity observed in the Elysium Mons area e.g. arcuate graben. It is suggested that the chamber cooled sufficiently to act as a regional "plug" thus preventing
magma from the second phase of volcanism following the same course to the surface as that of the first phase. A repose period of 10 Ma has been estimated as a period of time sufficient to allow a magma chamber of 1100 km." S.P. Bowling "Modelling the Effusion Rates and Activity Phases of the Elysium Volcanics" Lunar and Planetary Science XXX 1185.pdf
http://www.lpi.usra.edu/meetings/LPSC99/pdf/1185.pdf
[149] "The whole of north Terra Meridiani (centered at lat. 0°, long. 0°) contains an unusual and enigmatic terrain unit. On the equatorial geologic maps of Mars, this highland area was mapped as being surfaced by two units of Noachian age: a subdued crater unit and an etched unit [1,2]. The subdued crater unit is a plains unit marked by subdued and buried old crater rims and was interpreted to be thin, interbedded lava flows and eolian deposits that partly bury underlying rocks [1,2]. The etched unit was described as being deeply furrowed by grooves that produce an etched or sculptured surface and was interpreted to be ancient cratered material degraded by wind erosion, decay of ground ice, and minor fluvial erosion [1,2]." M. G. Chapman "2001 SITE IN NORTH TERRA MERIDIANI: THE TES CONCENTRATION AREA" MSL99 Workshop available online at
http://web99.arc.nasa.gov/~vgulick/MSLS99_Wkshp/Chapman_Hem_abs_pg1.pdf
[150] http://www.harmakhis.org/history/16.jpg
[151] N. Hoffman "Outburst floods as cold and dry avalanches" available online at
http://www.earthsci.unimelb.edu.au/mars/Outburst.html
[152] http://www.harmakhis.org/history/19.jpg

[153] "Interpretation: We interpret the fan shaped deposits found at the base of the Olympus Mons escarpment as remnants of glaciers, in agreement with Lucchitta [4]. It is important to consider what type of glacier. The con-tinuous, curvilinear ridges found on the surface of Unit C are very similar to rock glaciers. The source region, the basal escarpment, provides the topographic relief re-quired to provide the debris. The linear ridges found in the lower left region of the image are interpreted as the remnants of lateral moraines, which were deposited as the glacier retreated and then eroded again as the glacier advanced. This implies several episodes of advance and retreat.

However, there is no cirque-like source for the de-posits. Instead, they extend from somewhat linear seg-ments of the basal scarp. Additionally, the fan shaped deposits are much larger than terrestrial rock glaciers; they extend many tens of km rather than up to a few km. Thus, we interpret these features to be the remnants of debris-covered glaciers, which are morphologically simi-lar to rock glaciers but contain more ice and therefore flow more like valley glaciers and cover greater dis-tances.

We thus envision the following scenario: glacial ice builds up on the northwestern slope of the basal escarp-ment. Debris from the escarpment is deposited on top of the ice. As the glacier flows to the northwest, it spreads and develops a spatulate form. Several periods of ad-vance and retreat are recorded by the eroded lateral mo-raines. At the furthest extent of advance, the glacier de-posited a large terminal moraine. This moraine has now degraded, perhaps by sublimation of internal ice blocks or removal of debris through aeolian erosion. This has left the hummocky material in unit B.

Discussion: Lucchitta [4] also identified glacier-like features at the nearby Tharsis Montes. Recent analysis of MOLA topography data confirm this result and conclude that cold-based glaciers were once on the west-northwest flanks of Arsia Mons [16, 17] and Pavonis Mons [18, 19]. Cold-based glaciers are made up of ice that is entirely below the melting point; thus, it flows through internal deformation and there are no melting features associated with the glacier. It is likely that most mountain glaciers on Mars would be cold-based [17].

The glacial features found around the Tharsis Montes are far more extensive than those at Olympus Mons. This implies that a greater quantity of ice was available at the Tharsis Montes. Since all of these volcanoes are in the equatorial regions, it seems likely that they were glaciated at the same time. If water ice were stable at

one location, it should be stable at the others. However, the fact that Olympus Mons had smaller glaciers implies that the conditions there were not as favorable for surface ice.
One possibility is that Olympus Mons was more active at the time; a higher geothermal flux in this region could prevent large build-ups of ice." S. M. Milkovich and J. W. Head, III "OLYMPUS MONS FAN SHAPED DEPOSIT MORPHOLOGY: EVIDENCE FOR DEBRIS GLACIERS" Sixth International Conference on Mars (2003) 3149.pdf
http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3149.pdf
[154] See Figure 1, also
"Introduction: Tharsis Montes cap the broad Tharsis Rise (Fig. 1), a huge center of volcanism and tectonism spanning almost the entire history of Mars. Each of the Tharsis Montes, although largely constructed of effusive and explosive volcanic deposits, contains a distinctive and unusual lobe, or fan-shaped deposit on their western flanks. On the basis of their unusual nature and superposition relationships, they have attracted attention since they were first described from Mariner 9 and Viking data [1]. These deposits, as exemplified by those on Arsia Mons [e.g., 2,3], usually contain three facies: 1) An outermost ridged facies, consisting of a broad thin sheet characterized by numerous ridges, 1->10 km in length, and spaced a few hundred meters to several kilometers apart, that extend over topographic barriers without obvious deflection. 2) A knobby facies, which forms an extensive area of chaotic terrain that consists of surrounded several-kilometer-diameter hills; some hills are elongated downslope, and others form chains that are
parallel to subparallel to the ridges in the ridged facies. 3) A smooth facies, which contains arcuate lineations and
diffuse to lobate margins; the smooth facies appears to overlie areas of the knobby facies." J. W. Head "MOUNTAIN GLACIERS ON MARS? CHARACTERIZATION OF WESTERN THARSIS MONTES FAN SHAPED DEPOSITS USING MGS DATA" Mars atmosphere modeling and observations workshop [2002] available online at
http://www-mars.lmd.jussieu.fr/granada2003/abstract/head.pdf

[155] "In mid-October the frozen carbon dioxide, which seasonally caps Mars' north pole, evaporated enough to give Odyssey's scientists their first chance to look there for ice. "We are really excited about what we are seeing in the north polar region of Mars. With the seasonal carbon dioxide frost gone, we can see evidence of massive amounts of water ice in the soil, even more than we found in the south," said Dr. William Boynton, principal investigator for Odyssey's gamma-ray spectrometer suite at the University of Arizona, Tucson." "NASA's Revealing Odyssey" MEDIA RELATIONS OFFICE JET PROPULSION LABORATORY http://mars.jpl.nasa.gov/odyssey/newsroom/pressreleases/20021207a.html

[156] ""Once the carbon-dioxide layer disappears, we see even more water ice in northern latitudes than Odyssey found last year in southern latitudes," said Odyssey's Dr. Igor Mitrofanov of the Russian Space Research Institute (IKI), Moscow, lead author of a paper in the June 27 issue of the journal Science. "In some places, the water ice content is more than 90 percent by volume," he said. Mitrofanov and co-authors used the changing nature of the relief of these regions, measured more than 2 years ago by the Global Surveyor's laser altimeter science team, to explore the implications of the changes." Mars Odyssey and MGS Mars Orbital Laser Altimeter (MOLA) Science teams "Mars Odyssey Orbiter Watches a Frosty Mars" available online at http://mars.jpl.nasa.gov/odyssey/newsroom/pressreleases/20030626a.html

[157] T. N. Titus (Oak Ridge Associated Universities), H. H. Kieffer, K. F. Mullins (U.S. Geological Survey) "TES Observations of the South Pole" available online at http://www.mars-ice.org/crocus.html

[158] Timothy N. Titus, Hugh H. Kieffer, Kevin F. Mullins, Phillip Christensen "Slab Ice and Snow Flurries in the Mars Northern Polar Night" available online at
http://www.mars-ice.org/cold.html
[159] "Discussion: The narrowness of the size distribution combined with the size cutoff at smaller and larger sizes points toward a period in the history of this area of the residual cap where Swiss-cheese features were forming. It is hard to imagine what may be varying on timescales of centuries to control whether environmental conditions are suitable for Swiss-cheese formation or not. Orbital change cannot be playing a significant role over such short timescales and the atmosphere generally has no memory from one year to the next. One possibility is perhaps the slow redistribution of dust on a planet wide scale into preferred areas, which changes the albedo pattern with respect to the (by comparison) invariable elevation pattern. This could possibly switch the climate and circulation patterns into some other mode

leading to differing conditions on the residual cap and a reseting of dust to its original configuration. This dust redistribution action may also act on more regional or local scales, changing the environment only in the near polar areas." S. Byrne et al "Martian Climactic Events Inferred from South Polar Geomorphology on Timescales of Centuries" Lunar and Planetary Science XXXIV (2003) 3112.pdf
http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3112.pdf
[160] "Introduction: The origin of the layering characteristic of the Polar Layered Deposits (PLD) of Mars is generally not thought to arise from the flow of the water ice presumed (along with dust) to comprise these layers, since rheological modeling indicates that Mars is presently too cold to permit substantial ice flow in the polar regions. However, Martian obliquity deviates chaotically from its current Earth-like value of 25º, surpassing 45º within the last several Myr. Not only will the polar regions receive additional insolation at these high obliquities, but the resulting increase in H2O sublimation from the ice caps will initiate a water vapor greenhouse heating effect. Hence, surface and subsurface temperatures will be elevated at high obliquity, leading to dramatic increases in ice flow velocities." Asmin V. Pathare and David A. Paige "Enhanced Ice Flow at High Martian Obliquity: A Rheological Model of the Polar Layered Deposits" Lunar and Planetary Science XXXI 1571.pdf
http://www.lpi.usra.edu/meetings/lpsc2000/pdf/1571.pdf
[161] "The observation of these changes and the rate at which they are occurring is akin to the observations of the "ozone hole" over Antarctica, or the steady increase in atmospheric CO_2 in the Earth's atmosphere. Although the implications of these observations is often hotly debated (with most scientists convinced that they represent evidence for the impact of humans on the terrestrial climate), everyone agrees that they are evidence of contemporary climate change. Mars, too, is experiencing climate change today. We don't know what it means, or how extensive the changes may be, but we can now propose tests for future observations that can begin to address these questions." Malin Space Science Systems Team "Evidence for Recent Climate Change on Mars" available online at
http://mars.jpl.nasa.gov/mgs/msss/camera/images/CO2_Science_rel/malin_etal.html
[162] "Introduction: Recent work has shown, surprisingly, that active channel systems exist in widespread but specific locations on Mars [1]. Although conventionally interpreted as evidence for water flow, their context more firmly argues for the involvement of CO2 at cryogenic temperatures, and argues against liquid water. Channels within the South polar cap at 71o South are fresh and presumably carry annual flows as the pole cap ablates each spring. These are the freshest evidence for channels anywhere on Mars, with activity within the last Martian year. The temperature at this location has an annual mean around 200K making liquid water a very difficult proposition, in sufficient quantity to carry sediment 1.5 km downslope." N. Hoffman LPSC [2001] available online at
http://www.earthsci.unimelb.edu.au/mars/LPSC2001_Hoffman_Polar.pdf
[163] http://www.msss.com/moc_gallery/m07_m12/images/M10/M1003736.html
[164] http://www.harmakhis.org/paper/
[165] They can all be seen online at
http://www.harmakhis.org/
[166] http://www.harmakhis.org/paper/water/
[167] A spreadsheet using this formula is illustrated here. By inserting coordinates of other images their Pole 4 latitude can be calculated.
http://www.harmakhis.org/history/example.xls
[168] http://www.harmakhis.org/paper/water/craterchanneldata.htm
[169] http://www.lanl.gov/orgs/pa/News/cover_epi.jpg
specifically
http://www.harmakhis.org/history/9.jpg
[170] "Gullies seen on martian cliffs and crater walls in a small number of high-resolution images from the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) suggest that liquid water has seeped onto the surface in the geologically recent past. The gully landforms are usually found on slopes facing away from mid-day sunlight, and most occur between latitudes 30° and 70° in both martian hemispheres. The relationship to sunlight and latitude may indicate that ice plays a role in protecting the liquid water from evaporation until enough pressure builds for it to be released catastrophically down a slope. The relative freshness of these features might indicate that some of them are still active today--meaning that liquid water may presently exist in some areas at depths of less than 500 meters (1640 feet) beneath the surface of Mars." "MOC Images Suggest Recent Sources of Liquid Water on Mars"

MGS MOC Releases MOC2-234 to MOC2-245, 22 June 2000 available online athttp://mars.jpl.nasa.gov/mgs/msss/camera/images/june2000/

[171] "2. Occurrence in Regional Clusters. This observation was stated in the original paper [1], and is amplified by > 2 Mars years' worth of data. Gullies occur in regional clusters. Gaps, in which no gullies occur between clusters, are observed. More gullies occur in the
southern hemisphere than the north." K. S. Edgett et al "POLAR- AND MIDDLE-LATITUDE MARTIAN GULLIES: A VIEW FROM MGS MOC AFTER 2 MARS YEARS IN THE MAPPING ORBIT" Lunar and Planetary Science XXXIV (2003) 1038.pdf
http://www.lpi.usra.edu/meetings/lpsc2003/pdf/1038.pdf
[172] "Debris flows in French Alps: Best analogs to Martian gullies are debris flows from Greenland [4] and Canada [7] which occur over a permafrost. Debris flows in the Alps sometimes occur over a permafrost but this is not the case usually. They nevertheless consist of good analogs for the properties of the flow and the geometry. The two examples shown fit the association of alcove at the gully head and channel with levees. They have been triggered by snow melting in the springtime or strong showers in summer, thus external processes only. The debris flows of the Izoard do not show any springs at the head (Fig. 1). One spring has been observed in the valley 400m in elevation under the gully head and no debris flows alcove is observed at this location. The debris flows of Izoard formed in 1985 and they have overflow the road located at mid-slope. They are typically 10 m large with 2 m high levees." N. Mangold et al "FORMATION OF GULLIES ON MARS: WHAT DO WE LEARN FROM EARTH?" Sixth International Conference on Mars (2003) 3048.pdf
http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3048.pdf
[173] "3. Association with Layers. This observation was also stated in the original paper [1]. We reiterate it here after examining ~1300 images. Any model for the origin of gullies must explain the relationship with layers. Gully channels typically head at a specific layer exposed on a given slope (e.g., Fig. 1). Within a given regional cluster, gullies may all head at the same layer where it is exposed in different crater and trough walls." K.S. Edgett et al "POLAR- AND MIDDLE-LATITUDE MARTIAN GULLIES: A VIEW FROM MGS MOC AFTER 2 MARS
YEARS IN THE MAPPING ORBIT" Lunar and Planetary Science XXXIV (2003) 1038.pdf
http://www.lpi.usra.edu/meetings/lpsc2003/pdf/1038.pdf
[174] "Martian gullies discovered by Malin and Edgett [1] are widely regarded as evidence of recent hillside erosion by liquid water on Mars [2,3]. As reported earlier [3,4], Icelandic basaltic talus slopes of hillsides contain gullies that include virtually exact duplicates of
Martian gullies in terms of size, morphology, and placement with respect to blocky outcrops. At the 2001 LPSC, Costard et al. [5] and Lee et al. [6] also presented evidence of similar gullies in Greenland and Canada,
respectively." William K. Hartmann et al "COMPARISON OF ICELANDIC AND MARTIAN HILLSIDE GULLIES" Lunar and Planetary Science XXXIII (2002) 1904.pdf
http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1904.pdf
[175] "Global distribution of observed gully landforms" diagram in "True Colors of Mars by Schmidt [2001] available online at
http://silver.neep.wisc.edu/~neep533/FALL2001/lecture19.pdf
http://www.harmakhis.org/history/gullies.jpg

[176] "Evidence for Recent Liquid Water on Mars:
Gullies in Gorgonum Chaos" MGS MOC Release No. MOC2-236, 22 June 2000 available online at
http://www.msss.com/mars_images/moc/june2000/gorgonum/

[177] "Mars Odyssey THEMIS Image: Gullies of Gorgonus Chaos" Mars Odyssey THEMIS Tuesday, June 11, 2002 available online at http://www.marstoday.com/viewsr.html?pid=5736

[178] "Gorgonum Chaos: The Gorgonum Chaos basin is an ancient, highly degraded 220-km diameter basin centered at about 37ºS and 173ºW. The basin itself lacks a well-defined rim, and probably was created through erosional integration of at least three impact basins that were subsequently mantled by thick air fall deposits during or prior to the earliest Noachian [1,2]. This basin, together with the nearby Atlantis, Newton, and Ariadnes basins have been suggested to have hosted deep lakes during part or most of the Noahian [3], and it has been suggested that at least once the lakes were deep enough to have formed an integrated basin overflowing to form Ma'adim Valles [4]. The edges of these basins exhibit linear features that have been interpreted as possible shorelines [3]. The present abstract focuses, however, on bench-like features at the bottom of the Gorgonum Chaos basin that appear to have been formed in association with a post- Noachian lake. The Gorgonum Basin is shown in Figure 1, with the general location of the

post-Noachian lake outlined in cyan." A. D. Howard and J. M. Moore "THE CURIOUS SHORELINES OF GORGONUM CHAOS" Sixth International Conference on Mars (2003) 3190.pdf
http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3190.pdf

[179] "Image analysis: A thorough analysis of the MOC images coupled with a few simple climatic considerations suggest that these gullies are not so young. The gullies are not deeply incised and many of them are even filled up with detritus or dust-covered as can be seen in the upper part of Fig. 1 thus showing that the generating process acted only intermittently and was limited in time because no aquifer recharge has been available after their first formation." G. Leone "GORGONUM CHAOS: ARE THE SEEPAGE-RUNOFF FEATURES REALLY RECENT?" Lunar and Planetary Science XXXII (2001) 1649.pdf
http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1649.pdf

[180] "More speculative is our thinking on knob material origin. We note that the knob fields largely occur within five adjacent basins and within a restricted elevation range. Thus knob-material's restricted occurrence implies that it was emplaced in a (or as a) medium that was limited in areal extent and possibly under a strong gravity-control, such as a fluid. If this material is volcanic then its susceptibility to modern wind erosion tends to disfavor emplacement by molten lava flows but doesn't entirely rule out a subaerial pyroclastic density flow that didn't significantly weld after emplacement. However, this argument is weakened by the absence of evidence for volcanic activity in the region. If the knob material was deposited in water, then its composition could either be fine-grained clastic lacustrine material or precipitates (evaporites). Such materials on Earth are relatively unindurated. All
but one very small knob field occurs within and below the 1100 m high-stand of a lake proposed by Irwin et al [1]. The single exception is located in an isolated crater floor just SE of this putative lake and at a few 100 m above its reported high-stand." J. M. Moore and A. D. Howard "ARIADNES-GORGONUM KNOB FIELDS OF NORTH-WESTERN TERRA SIRENUM, MARS" Lunar and Planetary Science XXXIV (2003) 1402.pdf
http://www.lpi.usra.edu/meetings/lpsc2003/pdf/1402.pdf

[181] "3. Gully Formation
[32] Recently, several groups have proposed that the young gullies [Musselwhite et al., 2001; Hoffman, 2001, 2000b; Draper et al., 2000] and many larger-scale features on Mars [Hoffman, 2000a; Hoffman et al., 2001; Jo¨ns, 2001; Parsons, 2001] may have formed from slope collapse
related to the presence of subsurface liquid or solid CO2 and
subsequent CO2 vapor-supported flow." Sarah T. Stewart and Francis Nimmo "Surface runoff features on Mars:Testing the carbon dioxide formation hypothesis" JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. E9, 5069, doi:10.1029/2000JE001465, 2002
http://bullard.esc.cam.ac.uk/~nimmo/paper16.pdf

[182] "A clathrate mixture of CO2 and water ice, as long as it's under a fair amount of pressure, can actually exist in a solid form even if the ground is somewhat warmer than the melting point of ordinary water ice. If such a buried clathrate deposit was suddenly exposed by a landslide, the result would be a blast of liquid water -- squirted outward by the pressure of the vaporizing CO2 -- which could pour down the slope for some distance before vaporizing in the thin Martian air. [Since a rise in buried clathrate's temperature -- produced by geothermal warmth or a change in Mars' long-term climate -- could cause it to erupt in the same way, this is actually a variant on the "soda-water fountain" theory I described in Part 1 of my report -- except that the eruption of soda water would be released by "uncapping the bottle" through a landslide, rather than by through a temperature rise.] The obvious problem here is that, for the water part of the released clathrate to turn into liquid water rather than remaining a shower of ice fragments, the eruption would have to occur where the ground temperature was above 0 deg C. -- and the gullies are all in much colder areas. A possible way out of this problem, however, would be for the water part of the clathrate to be highly salty. As I mentioned in Part 1, some brines made out salts that are thought to be very common in Mars' soil -- such as magnesium sulfate and calcium sulfate -- have melting points dozens of degrees below that of pure water. And such "briny clathrates" might exist in solid form in these cold regions, but still be warm enough to turn into a short-lived torrent of liquid brine when a landslide released the pressure on them. There is also, perhaps, one more long-shot possibility. Carbon dioxide can't exist in liquid form under the 1-bar pressure of Earth's atmosphere (thus, frozen CO2 is known as "dry ice" because it sublimates directly from solid into gas). However, liquid CO2 can exist if the pressure is more than 5 bars -- and so there's a real possibility that large amounts of it may also exist underground in some regions of Mars. If a landslide released such a deposit, it just might remain liquid long enough to pour down a slope in the same manner as liquid water before boiling into gas. This, however, is unlikely -- Tanaka points out that such high-pressure liquid CO2 would explode into gas almost immediately on exposure to Mars' near-vacuum, and he thinks that - unlike released liquid water - it would have almost no time to pour down a slope in still-liquid form. Carr, however, disagrees, and that

this theory cannot be completely ruled out.) Another problem is that for CO2 to be under enough pressure to exist in liquid form, it must be much more deeply buried than a water ice-CO2 clathrate -- under at least 30 meters of Martian soil and rock -- and landslides big enough to suddenly unearth such a deposit would have to be a lot larger. However, it's possible that a smaller landslide could make the covering layer of rock and soil over such a deposit shallow enough that the underlying pressure of the liquid CO2 could cause it to burst out into the open." Bruce Moomaw "The Case For Outgassing" July 5, 2000 MARSDAILY.COM available online at http://www.spacedaily.com/news/mars-water-science-00g2.html

[183] Michael C. Malin and Kenneth S. Edgett "Evidence for Recent Groundwater Seepage and Surface Runoff on Mars" 30 JUNE 2000 VOL 288 SCIENCE www.sciencemag.org available online at http://geoinfo.nmt.edu/penguins/pdfs/se260002330p.pdf

[184] Malin Space Science Systems, MGS, JPL, NASA "Newton Crater: Evidence for Recent Water on Mars" Astronomy Picture of the Day available online at

http://antwrp.gsfc.nasa.gov/apod/ap000626.html

[185] "Evidence of drainage- The gullies in the CNewton crater have been discussed by Malin and Edgett (2000) who performed speculative scaling calculations to estimate the volume of water involving the discharge event. They concluded that about 2.5x106 liters of water were involved in each event, with nearly 100 channels active in the crater, giving a total of nearly 0.25 km3 of water that must have been discharged into the crater basin in a short period of time." N. A. Cabrol et al "PROLONGED PONDING EPISODE IN C-NEWTON CRATER IN RECENT GEOLOGICAL TIMES ON MARS" Lunar and Planetary Science XXXII (2001) 1255.pdf
http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1255.pdf

[186] "… approach in the Tempe Terra region. Geologic Setting: Tempe Terra is located on the northeastern flank of the Tharsis volcano tectonic province. It is an ancient terrain of Noachian age which has been cratered and heavily fractured. The western margin is embayed by volcanic flows originating from Tharsis and Alba Patera while the eastern margin is buried under probable alluvium from Kasei Valles and other outflow channels." B.W. Harrington et al "EXTENSION ACROSS TEMPE TERRA, MARS FROM MOLA TOPOGRAPHIC MEASUREMENTS" 5th Conference [1999]
http://mars.jpl.nasa.gov/mgs/sci/fifthconf99/6130.pdf

[187] http://www.space4case.com/mars/mars5/mars131.html

[188] "Introduction: Numerous small volcanic edifices have been previously identified in the Tempe Terra [1] and Ceraunius Fossae regions of Mars [2, 3]. Low shield
volcanoes dominate Ceraunius Fossae, while Tempe Terra has both low shields and steeper, possibly explosively erupted cones [1]. These features are an interesting example of plains volcanism, and several comparisons have been made with terrestrial volcanic features.
From Viking images, Hodges and Moore [3] used crater diameter/basal diameter (C/b) ratios for the Tempe volcanoes [C/b of 0.06-0.17] to suggest they may be similar to Mauna Ulu shield,
Hawaii and low shields in the Snake River Plain, Idaho. Additional photoclinometric measurements made by Davis and Tanaka [4] of five volcanoes in Tempe Terra indicated
morphological similarities to terrestrial cratered basaltic lava shields and tuff rings. Volcanoes in Ceraunius Fossae are less well studied, but previous work suggested they are similar to shields in Tempe Terra [3]." M. P. Wong et al
"MOLA TOPOGRAPHY OF SMALL VOLCANOES IN TEMPE TERRA AND CERAUNIUS
FOSSAE, MARS: IMPLICATIONS FOR ERUPTIVE STYLE" Lunar and Planetary Science XXXII (2001) 1563.pdf
http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1563.pdf

[189] See Figure 1, E. Hauber et al "MORPHOLOGY AND TOPOGRAPHY OF FRETTED TERRAIN AT THE DICHOTOMY BOUNDARY
IN TEMPE TERRA, MARS: GENERAL CHARACTERISTICS" Lunar and Planetary Science XXXIII (2002) 1658.pdf
http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1658.pdf

[190] "Nirgal Vallis is an ancient valley thought for nearly 3 decades to have been carved, in part, by running water at some time far back in the Martian past. Today the valley is, like the rest of Mars, quite dry. However, some of the high resolution Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) images reveal small gullies on the walls of this valley system. An example is shown here (above, left), in which more than 14 channels nearly 1 kilometer (0.6 miles) long run down the south-facing slope of the Nirgal Vallis wall. Each narrow channel starts at about the same position below the top of the valley wall, indicating that there is a layer along which a liquid--most likely, water--has percolated until it reached the cliff, then ran down hill to form the channels and the fan-shaped aprons at the bottom of the slope. Some

of the apron deposits seem to cover the dunes on the floor of the valley (lower 1/3 of the image), suggesting that the channels and aprons formed more recently than the dunes. The fact that neither the dunes nor the aprons and channels have impact craters on them suggests that these features are all geologically young, meaning a few million years at most, a few days or weeks at least."

"Evidence for Recent Liquid Water on Mars: South-facing Walls of Nirgal Vallis" MGS MOC Release No. MOC2-240, 22 June 2000" http://www.msss.com/mars_images/moc/june2000/nirgal/

[191] NASA/JPL/Arizona State University "Nirgal Vallis (Released 27 March 2002)" http://themis.la.asu.edu/zoom-20020327a.html

[192] J. R. Zimbelman "DECAMETER-SCALE RIPPLE-LIKE FEATURES IN NIRGAL VALLIS AS REVEALED IN THEMIS
AND MOC IMAGING DATA" Sixth International Conference on Mars (2003) 3028.pdf
http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3028.pdf

[193] "Small valley networks on Mars: Two alternative modes of formation for the small valley networks on Mars are generally considered: a) the valleys resulted from surface runoff following precipitation or b) they
resulted from the release of groundwater, with or without the involvement of hydrothermalism [e.g., 2]. In some instances, a case for the possible role of sapping has been made (such valleys would belong to "b"). For instance, Lee et al. [1] have reported ground ice sapping valleys within the distinctive impact breccia formation at Haughton crater, Devon Island, Canada, that are possible analogs to martian small valleys such as Nirgal Vallis.
...
We interpret the Devon valley networks to be glacial meltwater channel networks: they formed as a result of the decay and retreat of an ice cover, possibly with intervals of glacial reoccupation. The proposed
mode of formation is supported by our observation that similar networks can been seen actively emerging at the margin of the ice cap in the eastern part of Devon Island. Both subglacial and ice-marginal streams, and in some instances supraglacial streams and their icemarginal
falls, were seen to present significant discharges and contribute to valley formation at several sites along the receding edge of the cap. The interpretation of valley networks on Devon Island as meltwater channel networks is consistent with the island's overall landscape of glacial selective linear erosion, which suggests extensive former glacial occupation (mostly static ice) [5]." Pascal Lee and James W. Rice Jnr. "SMALL VALLEYS NETWORKS ON MARS: THE GLACIAL MELTWATER CHANNEL NETWORKS OF DEVON ISLAND, NUNAVUT TERRITORY, ARCTIC CANADA, AS POSSIBLE ANALOGS" Fifth International Conference on Mars 6237.pdf http://www.lpi.usra.edu/meetings/5thMars99/pdf/6237.pdf

[194] "Autumn Afternoon in Hale Crater"MGS MOC Release No. MOC2-257, 17 November 2000 http://www.msss.com/mars_images/moc/nov_00_hale/

[195] Figure 6 Nature Insight: Review article Hale Crater
http://www.nature.com/nature/journal/v412/n6843/fig_tab/412228a0_F6.html

[196] "Interpretations: I interpret the viscous-flow features as ice, glaciers, and rock glaciers derived from seepage and eroded valley wall material associated with gully and alcove formation [1 and 2]. I suggest that ice formation and accumulation have occurred on the NW wall of the valley under conditions of relatively low sublimation due to reduced insolation on pole-facing slopes [3]. Ice and ice-rich debris built up over time and began to flow under the influence of gravity in the form of glaciers and rock glaciers. These eventually reached the floor of the valley and continued to flow until areas of higher insolation were encountered. In these areas, the sublimation rates were high enough to ablate the glaciers to the point that they could advance no further."
J. D. Arfstrom "UPPER DAO VALLIS: A BASIN DOMINATED BY ICE-RICH VISCOUS MATERIALS" Lunar and Planetary Science XXXIV (2003) 1208.pdf
http://www.lpi.usra.edu/meetings/lpsc2003/pdf/1208.pdf

[197] "Observations: The ice formations on the slopes of Dao Vallis appear to be tributaries of an even more extensive ice formation on the floor of the valley (Figure 1). The ice formations of the slopes merge with the ice formation at the bottom of Dao Vallis in a way that suggests mutual flow, closely resembling the way terrestrial tributary glaciers merge with main valley glaciers (Figure 2). The ice formations on the

slopes and floor of Dao Vallis possess distinct structural morphologies that are characteristic of terrestrial alpine glaciers (Figure 3)."
J. D. Arfstrom "PROPOSED MARTIAN GLACIERS OF RECENT AGE AND A MODEL OF THEIR FORMATION" Lunar and Planetary Science XXXIII (2002) 1092.pdf
http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1092.pdf
[198] http://www.harmakhis.org/history/gullies.jpg
[199] "Cosmetic alterations A dirty ice sheet that once extended over Mars's mid-latitudes would explain several
enigmatic features there. Some of these have puzzled planetary scientists ever since the two Viking orbiters returned images in the late 1970s that looked for all the world like ice-related surface features on Earth. Most suggestive of ice, perhaps, were places where the surface seemed to be sloughing off the land and oozing downhill. Generically termed "viscous flow features," they looked like the work of Earth's rock glaciers, streams of flowing rock-laden ice. Many more have since turned up in close association with the dissected mantling spotted by Mars Global Surveyor. In the 13,000 MOC images they have inspected, Milliken and his Brown colleagues reported at the workshop, viscous flow features are restricted to the same 30° to 60° mid-latitude bands as the dissected mantling. The flows peak in abundance at the same 40° latitude as the dissected mantling.
Furthermore, the mysterious gullies—where liquid water seems to have flowed down steep slopes in the recent past—follow the same latitudinal distribution as viscous flow features and dissected terrain; they even tend to cluster in the same three or four places as the viscous flow features do. The currently favored explanation for gullies is that lingering patches of dirty snow melted there (Science, 28 February, p. 1294). Taken together, the Brown researchers say, these features could be explained by the warming of an ice-rich mantling. That could have produced meltwater that formed gullies, ice softening that gave rise to viscous flow, and ice loss through sublimation that weakened the mantling and allowed dissection. "That's consistent with what I've seen" in images, says planetary geologist James Zimbleman of the Smithsonian Institution's National Air and Space Museum in Washington, D.C. "I'd call it a working hypothesis." "Iceball mars?" 11 APRIL 2003 VOL 300 SCIENCE www.sciencemag.org available online at http://www.planetary.brown.edu/planetary/international/write_up.pdf
[200] "At a press conference and in a paper published online by Nature on Wednesday, planetary scientist Phil Christensen of Arizona State University proposed a new idea to explain the creation of the martian gullies. He suggests they could have been carved by water melting from snow banks." Vanessa Thomas "Snow May Have Carved Martian Gullies" Astronomy.com available online at
http://www.astronomy.com/Content/Dynamic/Articles/000/000/001/215vpcsq.asp
[201] "4. Occurrence of levees: Levees on each sides of the channels are typical of a particular kind of flows with a yield strength [12]. The yield strength corresponds to the minimal shear strength the material needs to reach before to flow. They are typically associated to flows containing 50 to 90% of solid particles (silt to pebble size) [12]. In Izoard, levees are 2 m high for a 10 m large channel, a size comparable to gullies observed on several MOC images. The existence of levees implies the incorporation of meltwater in the debris over a significant thickness of material. This is possible only if thawing of the ground occurs over a significant thickness (several tens of cm), on the contrary to the model of snowmelt proposed by Christensen [5] under present conditions. The ratio of water to sediment of 10:1 proposed by Christensen (so 10% of rock) is also not in the range of debris flows with levees which are characterized by a proportion of more than 50% of rock [12]. Nevertheless, if existing during high obliquity periods, the presence of snowpacks would favor the process of debris flows because snowmelt can efficiently fill the porosity of debris as observed in cold regions in Greenland [4] or North Canada [7]." N. Mangold et al "FORMATION OF GULLIES ON MARS: WHAT DO WE LEARN FROM EARTH?" Sixth International Conference on Mars (2003) 3048.pdf
http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3048.pdf

[202] "Now UA researchers propose an alternative explanation involving carbon dioxide erosion. They point to several reasons why CO2 is a better candidate than water in gully formation. One reason is that most gullies are found in the southern highlands, the oldest and coldest part of the planet, a place where liquid water is least likely to be stable.

"That's high altitude in a region of low geological activity. It is difficult to invoke some hydrothermal action there," Musselwhite said. "The surface is old but the gullies are new."
Another reason is that the southern hemisphere has more extreme temperature variations throughout the year than does the northern hemisphere, a result of the fact that Mars is closer to the sun during southern summer and farther away during southern winter, Musselwhite said.

The gullies are generally on pole-facing slopes where they receive very little or no sunlight for most of the year.
However, Musselwhite said, the most compelling fact is that gullies always start about 100 meters below the top of the cliff. At that depth, the pressure of the rock overhead is just enough for liquid CO2 to be stable, if the temperature is low enough." Agnieszka Przychodzen "Exotic CO2 Process May Have Carved Martian Gullies" MARSDAILY April 2, 2001 available online at http://www.spacedaily.com/news/mars-water-science-01f.html
[203] See Figure 3
"3. The Role of Water
[11] The observed geographic (Figure 4), temporal (Figure 5), and azimuthal (Figure 6) correlations provide evidence for a connection between slope streaks and a surface temperature near the triple point of water, suggesting that the formation of streaks involves a phase transition of water. For instance, melting could provide lubrication of avalanches, or mass movements could be triggered by sublimation at the solid-gas transition. The analysis presented does not pinpoint a specific mechanism for slope streak formation, and hence we do not elaborate on any particular one, but consider the potential role of water generically.
(See also Ferris et al. [2002].) While alternative explanations not involving water, such as patterns in atmospheric dust transport, can be envisioned, the observations are simply accounted for if water plays a role, either in triggering the mass movements or in controlling dust deposition." Norbert Schorghofer et al "Slope streaks on Mars: Correlations with surface properties and the potential role of water" GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 23, 2126, doi:10.1029/2002GL015889, 2002 available online at
http://www.gps.caltech.edu/~oa/publications/schorghofer2002_grl.pdf
[204] "When examined in detail individually and as a group it appears that the seep features have far more characteristics associated with liquid flows than with flows of dry dust or slurries. The equatorial location of the seepages, clustering in the Tharsis region (and 180 degrees away north of the Hellas Basin) plus physical flow attributes, indicate that water (or possibly some other liquid) may be involved in their genesis. As we have demonstrated, these features are currently being formed on the Martian surface. These circumstances together imply that it is highly likely that water is now present on the surface of Mars." Efrain Palermo, Jill England and Harry Moore "A Study of
Mars Global Surveyor (MGS)Mars Orbital Camera (MOC) Images
Showing Probable Water Seepages. Are They Dust Slides as NASA Claims or Proof of Water on Mars?" available online at
http://www.eskimo.com/~jill/seeps_paper.pdf
[205] See Figure 3 R. Sullivan et al "MASS-WASTING SLOPE STREAKS IMAGED BY THE MARS ORBITER CAMERA" Lunar and Planetary Science XXXI 1911.pdf
http://www.lpi.usra.edu/meetings/lpsc2000/pdf/1911.pdf
[206] "Summary. We conclude that dark streak formation on Martian slopes is fundamentally similar to small mass-movements that have occurred on debris-covered steep slopes elsewhere on Mars; distinctive dark streak features result where small mass-movements occur in the presence of a thin, potentially mobile dust mantle. They cannot be easily interpreted as a dark fluid stain or float moving downslope from a point source."
R. Sullivan et al "MASS-MOVEMENT CONSIDERATIONS FOR DARK SLOPE STREAKS IMAGED BY THE MARS ORBITER CAMERA " Lunar and Planetary Science XXX 1809.pdf
http://www.lpi.usra.edu/meetings/LPSC99/pdf/1809.pdf
[207] http://ida.wr.usgs.gov/html/ab1020/ab102003.html
[208] http://www.harmakhis.org/ab102003dspires.jpg.htm
[209] http://www.msss.com/moc_gallery/m19_m23/images/M23/M2300332.html
[210] http://www.msss.com/moc_gallery/e07_e12/images/E11/E1103683.html
[211] "Crystalline hematite has been mapped over an area in Sinus Meridiani approximately 500 km in longitude extending approximately 200 km in latitude [3]. The extent of this deposit very closely matches the geomorphic boundary of a smooth, layered, friable unit that is interpreted to be sedimentary sedimentary in origin [3, 9]. This material may be the uppermost surface in the region, indicating that it might be a later-stage sedimentary unit, or alternatively a layered portion of the heavily cratered plains units. A second accumulation of hematite approximately 60 x 60 km in size is observed in Aram Chaos (2° N, 21° W). This site is also associated with layered materials and a water-rich environment." P.R. Christensen et al "THE DISTRIBUTION OF CRYSTALLINE HEMATITE ON MARS FROM THE THERMAL EMISSION
SPECTROMETER: EVIDENCE FOR LIQUID WATER" Lunar and Planetary Science XXXI 1627.pdf

http://www.lpi.usra.edu/meetings/lpsc2000/pdf/1627.pdf
[212] "Figure 4. Crater count diagram and isochrons for the Terra Meridiani hematite-rich area. Filled symbols show the population of "fossil craters" lying near the saturation equilibrium limit (upper straight line), indicating a very ancient surface. Open symbols show the fresh, recent craters created since the modern surface formed, indicating that the area has been exposed for as little as a few million years. Our interpretation is that an ancient (paleolake bed?) was covered by sediments and exhumed only a few million years ago." Melissa D. Lane et al "UPDATE ON STUDIES OF THE MARTIAN HEMATITE-RICH AREAS" Lunar and Planetary Science XXXII (2001) 1984.pdf
http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1984.pdf
[213] "Mineral abundance maps (Fig. 5) show basaltic lithologies for much of the VM interior, in the form of high- and low-Ca pyroxenes (up to 24% total) and plagioclase minerals (up to 28%) in layered deposits in the walls and interior, as well as in dark materials at the base of canyon walls. Note that the presence of surface dust in parts of Ophir and east Candor Chasmata appears to decrease the apparent abundance of minerals in these areas. The distribution of gray hematite agrees well with previous results [18], but we see only (~8%) a small enrichment of red hematite in the possible hydrothermal site in west Candor [14] (Fig. 6)." L.R. Gaddis et al "MINERAL MAPPING IN VALLES MARINERIS, MARS: A NEW APPROACH TO SPECTRAL DEMIXING OF TES DATA" Lunar and Planetary Science XXXIV (2003) 1956.pdf
http://www.lpi.usra.edu/meetings/lpsc2003/pdf/1956.pdf
[214] "Our observations of hematite in the VM are similar to those seen by Christensen et al., [37]." F. S. Anderson et al "MINERALOGY OF THE VALLES MARINERIS FROM TES AND THEMIS" Sixth International Conference on Mars (2003) 3280.pdf
http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3280.pdf
[215] "Aram Chaos is a 280 km diameter crater centered at 2.5N, 338.5 E. Like other nearby craters, it has been filled with a large amount of material since its formation [2]. It is connected to the Ares Vallis outflow channel by a small, 15 km wide channel that flowed outward, from Aram Chaos to Ares Vallis. The association of Aram Chaos with the outflow channels, as well as its obvious basin morphology, indicates a possible connection to past surface and subsurface water in the region." Timothy D. Glotch and Philip R. Christensen "The Geology of Aram Chaos" Lunar and Planetary Science XXXIV (2003) 2046.pdf
http://www.lpi.usra.edu/meetings/lpsc2003/pdf/2046.pdf
[216] http://www.harmakhis.org/paper/dunes/dunes.htm
[217] http://www.harmakhis.org/paper/dunes/dunesdata.htm
[218] "There are a number of reasons to proceed with numerical modeling of sand transport at this time. Most importantly, the wind regime near the surface is strongly influenced by topography, and the first accurate map of global topography from MGS MOLA has only recently become available. Mars GCM's now appear to adequately simulate the circulations during dust storm periods, which produce some of the strongest surface winds [8]. Finally, Mars GCM's now have the flexibility to examine wind regimes from different epochs. We have used surface wind output from the GDFL Mars GCM to build a global sand transport model for Mars. Several parameters have the same values used by Anderson et al. [1] in order to directly compare the Ames GCM output with that of the GDFL GCM. We compare the resulting sand distribution with the known sand dunes on the Martian surface. We also compare our results with those of Anderson
et al. [1]. The RDP/DP is also calculated along with the sand transport, and these values are compared with known dune forms and orientations as well as to the results found by Lee and Thomas [7] with the Ames GCM." L. K. Fenton and M. I. Richardson "GLOBAL MARTIAN SAND TRANSPORT AS PREDICTED BY THE GDFL MARS GCM" Lunar and Planetary Science XXXI 2072.pdf
http://www.lpi.usra.edu/meetings/lpsc2000/pdf/2072.pdf
[219] http://www.harmakhis.org/paper/newsouth/spoledunes/spoledunesdata.htm
[220] "Sand dunes are representative of these types of landforms. With nearly three years of high resolution observations of relatively small dunes, no evidence whatsoever has been found to support the contention that any dunes on Mars are presently mobile. Yet their dune crests appear to be quite sharp (inactive dunes still shed sand from their
crests and become rounded with age), and subtle markings on their slip faces suggest that a small amount of avalanche sand may move under the added weight of winter snow. Occasionally, dunes exhibit striations that suggest that their surfaces may be cemented or crusted, but for the most part their inactivity in the presence of winds likely to be able to move sand (we see dust-devil tracks on some dunes) suggests that their inactivity may be related to some environmental factor, such as the absence of locally sustained winds." M. Malin and B. A. Cantor "MARS ORBITER CAMERA CLIMATE OBSERVATIONS" available online at http://www-mars.lmd.jussieu.fr/granada2003/abstract/malin.pdf
[221] http://www.harmakhis.org/paper/layers/layers.htm

[222] http://www.harmakhis.org/paper/layers/layersdata.htm
[223] "Exposures of layered materials in western Candor Chasma illustrates yet another incongruent relationship: these layered outcrops display very few impact craters on their surface. Indeed, they show crater densities two to three orders of magnitude lower than those seen within the summit caldera of Arsia Mons (Figure 3). Since the evidence is very good that these materials are ancient and being exhumed, the absence of craters means that the layers have been recently exhumed, or that their surfaces have been recently eroded (if the Arsia Mons caldera is of the
order of hundreds of millions of years old, then the surfaces in Candor are only hundreds of thousands to millions of years old, and in cases where there are no craters at all, even younger). We see no evidence of the process that has exposed these materials, and no evidence for where the materials have gone. There is certainly nothing acting today that could create what we see. This landscape, too, is not representative of the present-day suite of processes." Ibid. available online at
http://www-mars.lmd.jussieu.fr/granada2003/abstract/malin.pdf

[224] "Two basic processes are portrayed: deposition of sediment as dust settling out of the atmosphere, and deposition in bodies of water such as crater lakes and shallow seas.

The chief source for sediment in both cases may be a combination of materials produced by explosive volcanism and meteorite impact, as well as weathering and erosion, researchers said.

Malin and Kenneth Edgett have suggested that the some of the layers may have formed underwater in lakes or perhaps shallow seas inside craters.

If the sediment fell from the air, then some recurring phenomenon would have had to create thin layers of regular thickness and properties -- the type of deposition that occurs in bodies of water.

Malin and Edgett explained how deposition from the air might have occurred. The atmosphere's pressure might have varied on a regular basis from something that is hundreds of times thicker than it is at present to something that is perhaps only tens of times (or less) thicker than it is today. As the atmospheric pressure went up, it could have carried more dust to be deposited; as it went down, there would have been less.

It is also possible, the researchers say, that the layers were created by a combination of deposition from the air and from water.

"Ultimately, geologists will have to go to Mars," Malin said, "to investigate the changes in ancient Martian environments recorded in these rocks."

Jack Farmer, director of the astrobiology program at Arizona State University, said standing water is the most likely explanation for the layering.

"This truly is exciting stuff," Farmer told SPACE.com. "If true, it indicates that water-lain sediments could be much more widespread than we thought previously." Senior Science Writer "MORE IMAGES: Martian Sediment Layers Explained" 05 December 2000 available online at
http://www.space.com/scienceastronomy/solarsystem/mars_sediment_pics_001205.html

[225] Science@NASA "Layers of Mars" available online at
http://science.nasa.gov/headlines/y2001/ast23jan_1.htm
[226] "HOUSTON,TEXAS—Planetary scientists poring over the latest data returned by Mars orbiting spacecraft have reached a startling conclusion: Half the Red Planet appears to have been encrusted with ice in the relatively recent past. A layer of dirty ice still covers Mars poleward of latitudes that, on Earth, would encompass Anchorage, Moscow, and South America's tip. But several lines of evidence suggest that, within the past million years or so, a now-vanished ice layer cloaked Mars down to the latitudes of Buenos Aires, New Orleans, and Baghdad. This icy coating would not have been the first to cover large areas of Mars, according to new climate modeling reported last month at a workshop here.* Mars has a tendency to wobble back and forth on its axis, and the new modeling suggests that this instability would have triggered a succession of ice ages throughout the planet's history. The tilting would have shifted

polar climes to lower latitudes, vaporizing the polar ice caps and layering dirty ice toward the equator. That would help explain much geology that has puzzled researchers for as long as 30 years: swaths of "softened" martian terrain that look like they're made of ice cream scooped on a hot day, slopes that ooze like wet paint dripping down a wall, and even the enigmatic gullies where water seems to have flowed on a frozen planet. More speculatively—and farther back in Mars history— extreme tilting of the planet may have repeatedly driven ice sheets right down to the equator. If so, that ice is gone now, but the dust left behind could have formed the mysterious layered sediments of the equatorial region." "Iceball Mars?" 11 APRIL 2003 VOL 300 SCIENCE www.sciencemag.org available online at http://www.planetary.brown.edu/planetary/international/write_up.pdf

[227] "Recent research has confirmed the observation that extensive areas of Mars are dominated by layered terrain. Layers exist everywhere - even within craters. This poses two main problems, depending on the interpretation of the origin of the layers.

If the layers are sedimentary, then it implies an active early sedimentary history for Mars, involving a far stronger hydrological cycle than we have evidence for. If early Mars were this active, then all the early craters should have been wiped away, yet they are largely unaffected. In addition, layering exists within many unbroken craters, without sign of an entry or exit channel. It is as if the layers had fallen from the skies.

If the layers are lavas, then it implies a much greater early volcanic history than we see evidence for. Again, many of the large early craters should have been destroyed or buried, and we should see evidence for many more volcanic vents and fissures than we do in fact see. In one way, the volcanic model can explain the layers in enclosed craters. Massive volcanic eruptions could have formed ash clouds that rained down into the craters, yet we don't see the vents.

Here are the seeds of yet another Mars paradox. The evidence is internally contradictory. We see layers, yet no sign of the processes that caused them or the likely side effects of those processes." N. Hoffman "Origin of Layering on Mars" available online at http://www.earthsci.unimelb.edu.au/mars/Layer.html

[228] "Analysing the spectra from the ten different bands of infrared light the instrument can detect, the THEMIS team has begun to identify specific mineral deposits, including a significant layer of the mineral olivine near the bottom of a four-and-a-half kilometer deep canyon known as Ganges Chasma. Olivine, Christensen notes, is significant because it decomposes rapidly in the presence of water. "This gives us an interesting perspective of water on Mars" he says. "There can't have been much water – ever – in this place. If there was groundwater present when it was deep within the surface, the olivine would have disappeared. And since the canyon has opened up, if there had ever been water at the surface it would be gone too. This is a very dry place, because it's been exposed for hundreds of millions of years. We know that some places on Mars have water, but here we see that some really don't." "Olivine points to dry Mars" June 6, 2003 available online at http://www.geolsoc.org.uk/template.cfm?name=THEMIS

[229] "However, there are a few places exhibiting large regional exposures. The largest is in north Terra Meridiani (8°N–5°S, 8°W–9°E). These layers are laterally continuous over hundreds of kilometers. Some can be traced west and northwestward until they disappear amid craters of ancient, heavily cratered terrain. The layers are interbedded with craters that also contain layers. Beds are nearly horizontal and form cliffs. In some places they form buttes and mesas of a scale similar to those of Monument Valley in Arizona/Utah. The bedding properties, buttes, and cliffs indicate the material is indurated and is sedimentary. Observations from the Viking Infrared Thermal Mapper and MGS Thermal Emission Spectrometer suggest the outcrop surfaces have effective particle sizes of very coarse sand (or coarser); this might indicate that a thin regolith has developed on the outcrops. A Phobos 2 Termoskan image shows that different layers (or groups of layers) exhibit different thermal properties, indicating differing physical properties of the overlying, thin regolith. The Termoskan and MOC images, together, also show that eolian mantles obscure formerly-exposed outcrops in adjacent intercrater plains. True lithostratigraphic geologic mapping of the layers is underway. Determination of processes that exposed the layers is difficult. There are no streambeds to indicate fluvial, nor yardangs to indicate eolian, erosion. Likewise, the depositional environments and sediment provenance cannot be uniquely determined. Colleagues have proposed a tremendous range of origins, but all are speculative, at best: the geology and relation to surrounding terrain is very complex." EDGETT, Kenneth S "SEDIMENTARY ROCK OUTCROPS

OF NORTHERN TERRA MERIDIANI, MARS" Paper No. 26-7 2002 Denver Annual Meeting (October 27-30, 2002)
Denver, CO available online at http://gsa.confex.com/gsa/2002AM/finalprogram/abstract_42548.htm

[230] Jenkins, Gregory S. 2001 "High-obliquity simulations for the Archean Earth: Implications for climatic conditions on early Mars" Journal of Geophysical Research - Planets - Vol. 106, No. E12 http://www.agu.org/pubs/toc/je/old/je106_12.html

[231] For a good novel based on life surviving these impacts that may have killed the dinosaurs there is "Evolution" by Steven Baxter.

The Spirit and Opportunity landing sites as former Martian Poles

Abstract:

Mars has many enigmatic features, such as Tharsis, Olympus Mons, Valles Marineris, and Alba Patera. The volcanoes and Valles Marineris are huge compared to the size of Mars with no apparent explanation for what made them. In the theory outlined here the poles of Mars wandered through history in response to 4 major impacts, Utopia, Isidis, Argyre, and Hellas. As each impact occurred the large negative mass of the crater tended to attract a rotational pole to it, and then later as large volcanoes formed the mass of these tended to move to the Equator. The combination of these events caused the poles to move over much of Mars spreading water and ice signs along its path, and often leaving the rest of Mars dry by comparison. This would account for how Mars shows so many water and ice signs in some areas and appears so dry chemically in others. In this paper only part of the polar path is shown, from south of Valles Marineris the pole moved to Meridiani Planum where the Opportunity rover is now. The opposite pole, which eventually became the current North Pole moved from the area of the Isidis Crater to the area around Gusev where the Spirit Rover is. We show how these areas are geologically consistent with former poles, and how this polar path implies a watery zone, possibly habitable for hundreds of millions of years. This would be sufficient for life to possibly evolve substantially if it existed at this time.

Keywords: astrobiology, crinoid, Gusev, Mars, Meridiani,, Opportunity, polar, Spirit, water.

This theory originally came about from reading a paper by Sprenke and Baker[1] on a proposed polar wander path on Mars. In the process of examining this we accumulated published papers referring to features along this path, and looked at whether features there were consistent with having been on a pole.

Typically such features would be formed by water or ice, and the terrain would be similar to known geology we see on the current poles. This was contrasted with areas off this polar path, which typically were much drier and ice free. Because the proposed polar path went back to before Tharsis, Olympus Mons and Valles Marineris it became possible this path was directed by the same forces that made these formations, and much of the current Martian landscape. We found that virtually every single paper published on Martian geology is consistent with this polar wander path.

Because these large volcanoes have so much mass they tend to move to the Equator, and so these could only form at certain times in the polar wander. The polar path if correct then implies when these Mons formed and also when large craters formed as their negative mass would tend to attract the pole to them. Once the correct polar path is known, then every other Martian feature with a significant impact on the gravitational balance of Mars should only occur at certain points along that path.

Because of space limitations and the serendipitous landing of the Rovers on two former poles opposite each other, we have reproduced here the middle part of the polar path. In the next paper we will show the possible events before this section that formed Tharsis Montes, Olympus Mons, Elysium Mons, and Valles Marineris. A following paper will carry on after this one, with the Hellas impact attenuating the Martian magnetic field and moving the pole to Hellas Crater, and then its current position.

While it is not known if life exists on Mars the polar path strongly implies a habitable zone existed around these poles as they wandered across Mars, for hundreds of millions of years or more. The large volcanoes of Tharsis, Elysium Mons, and Elysium Mons may have heated the planet, as they are associated with parts of the polar path that appeared to generate huge amounts of water.

In the three papers we will refer to 5 pole positions as being stable for a time, and the polar movement between these positions. The current pole positions we call Pole 5, and the polar movement from Pole 2 to Pole 3 is discussed here, Pole 4 is near Hellas Crater. To follow this path a good map of Mars is essential as many of the names are obscure. If you Google and download "mola_regional.pdf"[2] this map shows all the place names referred to here. For any image numbers, placing the image number in a search engine and selecting the link from msss.com is the fastest way to find them.

In this paper we concentrate on the movement from what we call the South Polar Cap 2 position near Solis Planum (south of Valles Marineris) to South Polar Cap 3 position at Meridiani Planum, shown in Figure 1. The associated North Pole moved from the North Polar Cap 2 position around Isidis Planitia eastward to near Lucus Planum as the corresponding North Polar Cap 3. We call this North Polar Cap 3 because eventually it will go to the current North Pole position. In this theory the Argyre impact starts the polar wander from the second to the third position.

The path begins when the Pole is moving eastwards from the South Polar Cap 2 position around Solis Planum, to north of Argyre Basin into Margaritifer Terra and then east to Meridiani Planum, the site of South Polar Cap 3. One should remember that a pole is very large in its influence, so the exact position of the centre is often not significant. For example the current poles are quite asymmetric in shape compared to the rotational pole itself.

There is no direct evidence for the Polar Cap stabilizing or remaining in Margaritifer Sinus for any great length in time along this route. Figure 1 shows this path, South Polar Cap 2 to 3 is from Solis Planum to Meridiani Planum.

Figure 1: The proposed polar wander path from Pole 2 to 3.

The large river networks in the Xanthe Terra and Margaritifer Sinus areas imply the atmosphere at the time was much thicker, since water would need a much higher air pressure than found today. A higher polar obliquity may have also contributed to this. The axial tilt of Mars is believed to change periodically over time, and when the angle is greater the ice around the poles is thought to melt or sublimate much more.

This gives a possible habitable environment at this time, with abundant water, heat from the Argyre impact, and higher air pressure. These water signs persist all the way along the polar path to Meridiani Planum.

According to Grant[3] Margaritifer Sinus contains remnant high valley densities, which is consistent with a moving pole and ice melting. This area was resurfaced several times[4], perhaps from the subsequent volcanism related to the Argyre impact. Therefore, ice may have partially vaporized, sublimed or melted, either due to impacts, and/or due to subsurface heat from associated geothermal activity. While Grant[5] believes some precipitation occurred, most ground water would be consistent with a water table associated with either a forming or sublimation/melting of an existing pole. The Parana Valles[6] drainage system is particularly extensive. Therefore, according to Grant[7], groundwater discharge[8] must have continued for some considerable time. The length of time referred to would likely be sufficient for life, if present to evolve substantially.

Lewis and Aharonson[9] examine Holden Crater and the distributary fan discovered in it. This area is near Argyre Crater and implies liquid water was discharged from the Polar Cap nearby. Pondrelli et al[10] also examine the area and how it connects the Argyre Basin to the northern channels. Williams et al[11] report on fans in Xanthe Terra, along the path of the Polar Cap.

Hynek et al[12] suggest that the fluvial resurfacing in this area lasted for a period of some several hundred million years. A combination of rainfall and sapping[13] appear likely, so lakes may well have formed[14]. Polar wander may link the two main theories of precipitation and sapping, hence explaining the extensive valley networks[15].

According to Nelson ice may have periodically melted. An examination of Margaritifer Sinus, by Philips et al[16] concluded that much of the Tharsis bulge was already in place before the drainage channels formed. This is consistent with the general rise in elevation in the area of Tharsis and Sinai Planum from the Argyre impact. At this time Tharsis and Olympus Mons would have been growing after the Argyre impact, and their extra weight would tend to move to the Equator. This would have the effect of forcing South polar Cap 3 to move eastwards to Meridiani Planum. This part of the polar path (and its antipodes, the future North Pole) shows abundant evidence of water and ice. The area around Margaritifer Sinus was plausibly a habitable zone and the Rover

Opportunity has now shown Meridiani Planum was a habitable zone. In between these two there are enough water signs to imply this was a long period of Martian history in which a habitable zone existed. It is not known however if there was life there to take advantage of this.

During the late Noachian, Tharsis Rise was large enough to direct the channels northward. Large amounts of material eroded from this area were transported along these channels, most probably as a direct result of basal water erosion during melting (and sublimation) as the Pole moved north east of Valles Marineris[17] [18] towards Margaritifer Sinus.

By the time the Polar Cap had moved north east of Valles Marineris water and ice would have accumulated in it as the Polar Cap melted and moved from the Argyre impact event, which may explain the paleolakes[19] there. Carr[20] suggested that ground water flowed into Valles Marineris and then into Chryse Planitia, forming lakes. Rossi et al[21] believe there is good evidence of ice and glaciation, consistent with a polar area adjacent to and south of the Valles Marineris at that time. Glacial features in the area support this interpretation.

Lunae Planum would also have received water from the moving and melting of the pole. Shalbatana Valles originates in the chaos on Lunae Planum (Greeley and Kuzmin[22]). Interestingly this would have resulted from a probable impact basin that formed a catastrophic outflow.

Nelson and Greeley[23] discuss three major fluvial events in Xanthe Terra, with indications of surface water flow. The first is a broad sheetwash from the Valles Marineris area, perhaps coinciding with the Argyre impact. Following this more extensive flooding occurred, forming Shalbatana, Ravi, Simud, Tiu, and Areas Valles. This may coincide with the pole migrating to Margaritifer Sinus. The majority of surface

water was sourced from chaos areas[24]. This gives a direct link to the Argyre area and perhaps to that impact.
As we follow the polar wander, the fluvial-features seem to overprint other terrain, so flooding may have continued as the Polar Cap migrated.

At the antipodes North Polar Cap 2 near the growing Elysium Mons started to move eastward. This area has many signs of ice and water, for example M0901921, M0905888, M0906366, M1001498, M1900226, M1902068, M2000840, and M2000907. Again these photos from the MOC can be seen by placing the image numbers in a search engine and selecting the link from msss.com. Further signs can be seen in Martei Valles in M2001192, M2200885, and SP238804. Lanagan et al[25] see evidence of fluvial flows associated with Elysium Mons and lava flows in the area, and rootless cones[26] also indicate ice in the area.

The new Odyssey results of subsurface ice[27] indicate a large deposit on the equator in Babaea Terra. A second area of ice occurs on the left edge of the map, just below the equator. This corresponds to the location of the opposite North Polar Cap 3. According to Sprenke et al the South Polar Cap moved in a curve to 0S 330W, almost into the centre of the ice rich area at Meridiani Planum. We call this area South Polar Cap 3. The geology and the geophysical data indicate icy areas on opposite sides of the planet. When we calculate the radius of the planet and adjust for any faulting, the result suggests that these areas were almost certainly a polar pair. For each Polar Cap pair we back-calculated the polar separations. The differences in diameters are almost perfectly offset by the thickness of rift-like valleys and fault movement and by assuming earth-like passive fault movement the polar age relationships could be back calculated.

We believe the poles stabilised in these ice rich areas for a long time, also with ample evidence of water signs. Thus the possible habitable zone extends to the results we see from the Rovers and implies similar chemistry and water signs may be found along this whole polar path from Solis Planum.

Rift-like faults, glaciation, evidence of surface water, and even volcanic activity tend to track the polar movement. The movement of Pole 2 to Pole 3 adds to approximately 150 degrees of longitudinal movement so this is consistent with Tharsis forming near South Polar Cap 2 and then moving nearly 180 degrees to the Equator, which pushed the poles about 150 degrees eastward.

In this time Tharsis had to be growing so it would have been adding a lot of heat to the atmosphere, and initially along with the newly formed Argyre Crater parts of South Polar Cap 2 would have overlaid these hot areas, melting water and CO2 if frozen. This would thicken the atmosphere and perhaps create snow or precipitation away from the heat. Tharsis and Argyre, with Elysium Mons then could have supplied the heat for this potentially habitable zone to last so long. This would also explain why Mars has so many water signs when it should have been too cold for most of its history. The overall temperature of Mars probably remained low, inhibiting the destruction of olivine even in the presence of water.

South Polar Cap 3 assumed a position between the Argyre and Isidis impact basins as each, being low gravity (low mass) would tend to be close to this pole. When this occurred the Pole 3 positions would attain a stable configuration. Tharsis was by this time near the Equator and South Polar Cap 3 was near the two main negative masses of the Argyre Crater and Isidis Crater, with Utopia Crater a lesser influence.

Interestingly, South Pole 3 coincides with an area of heavy Noachian cratering[28] and the second cratered area corresponds well with the opposite North Pole 3. One likely explanation is that the polar ice protected the craters from erosion, and when they were exhumed from the ice they remained in more pristine condition. Pole 3 seems to have been stable for a long enough time for crater disparity. It also implies at this time that the surface was being altered severely and other craters were being buried or obliterated by lava flows.

Volcanism seems to follow the polar wander, so is either related to the shock waves from impacts or is a late stage effect, occurring in relation to degassing (geothermal activity) during faulting of polar valleys. This would explain how volcanoes have apparently restarted in Martian history and the surface is relatively young in parts.

Rift-like, passive, or strike-slip valleys would be thus be overprinted by basal melting of icecaps and related sublimation. Most large catastrophic flood (outburst) features occur adjacent to these poles so may be triggered by increased geothermal heat. Pole 3 likely remained in a stable location through this resurfacing.

These crater areas are linked into what is termed the Noachian age. Thus, after the Argyre impact may be regarded as the Hesperian, obliterating much of the Noachian terrain except for these parts protected with polar ice. Some other areas with Noachian craters are also found around Margaritifer Sinus, implying the Polar Cap may have slowly moved and protected other areas for a time in its path. In a later paper we will show a large northern ice sheet or ocean would have sublimated after the Hellas impact, exposing the terrain referred to as Amazonian. The two impacts then may have caused the features known as Hesperian and Amazonian to form. This makes it difficult to estimates times for these events as the polar path would have obscured and altered crater counts.

In moving from Pole 2 to Pole 3, the polar ice closely follows and may have formed or modified the dichotomy boundary. The main dichotomy boundary is seen between 180 degrees west and 90 degrees west, which is 270 degrees or ¾ of a total possible boundary. The rest is taken up by the land mass of Tharsis Montes, Syria Planum, etc.

South Polar Cap 2 moved from 12.7S 92.6W eastward to around 0S 330W, which is approximately 122 degrees of longitudinal movement or approximately 1/3 of the total great circle. The opposite pole migrated from 12.7N 272.6W to 0S 150W, which is where the dichotomy boundary ends against Olympus Mons, for a movement of 122 degrees. This makes 244 degrees of movement over a dichotomy boundary of 270 degrees as a polar wander path. The rest can be explained by the width of the edge of South Polar Cap 3 at 330W in Meridiani Planum, which makes it appear to extend further east. Thus virtually the entire visible dichotomy boundary falls on the same line as the movement of Pole 2 to Pole 3.

The Northern Lowlands represents a paradox. It is so large a negative mass that it would likely prevent the Polar Caps moving along the path proposed by Sprenke and Baker. Smith and Zuber[29] say that Hellas Crater for example is only 10% of the volume of the Northern plains. Thus its gravitational influence would be greater than either Argyre or Hellas.

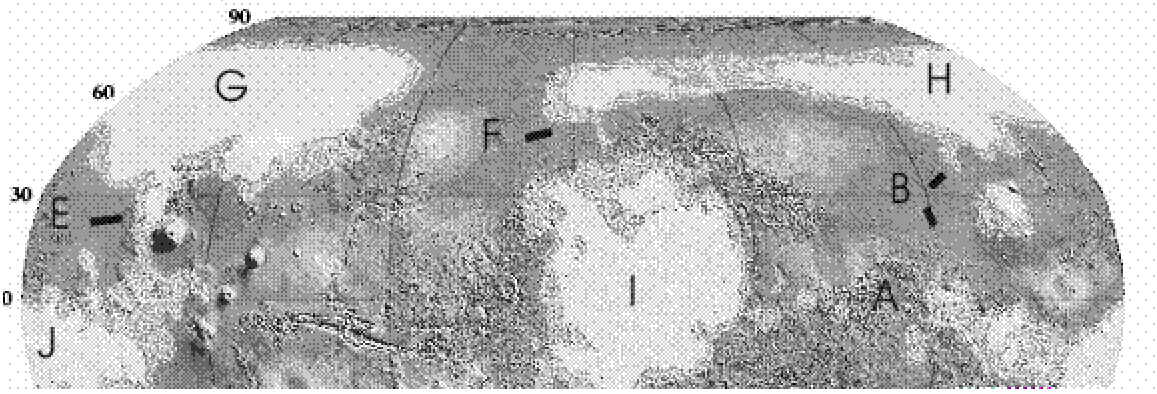
Therefore if this polar path is correct the Northern Lowlands was partially covered in water or ice early in Martian history, neutralising its negative mass. Oner et al[30] make some estimates of its size. This would make the planet more balanced and not impede polar wander. Indeed this ice or ocean had to exist for this polar wander to occur, so proving polar wander proves the northern ice sheet existed. The Northern Lowlands is so large a negative mass that the poles could never have moved from their current position without water or ice to fill in the low areas. Hence polar wander implies this water or ice existed, and the shape of the ice rich areas at 60N shown by THEMIS implies at least parts contained more ice at some point.

Early in the history of Mars the Northern Lowlands may have had other impacts such as a Borealis impact lowering this area. Water and ice just as on Earth would have migrated to the lower areas balancing the planet. Over time the water would have smoothed out these ancient craters, as it may have also done with Utopia Crater.

The polar wander path along the dichotomy boundary may have been on a pre existing slope, altering its shape with ice and water erosion. A Polar Cap moving on a slope like this would tend to have a runoff of water heading north, accounting for the smoother surfaces in Acidalia, Arcadis, Amazonis, and Elysium Planitia.

THEMIS[31] shows some evidence of such a runoff. Blue ice rich areas extend from the polar path south west of Elysium Mons and north to a huge ice deposit encircling the planet at 60N. This may have been part of the ancient northern ice sheet or ocean. The heat from Elysium Mons here would have been melting part of the moving polar cap and the water flowed north to the main ocean or ice sheet. This THEMIS map should be looked at in conjunction with the previously mentioned mola_regional.pdf.

Figure 2 shows a map of these ice rich areas. To make them clearer in monochrome we have made the blue areas on the original appear white.



A is the approximate position of North polar Cap 2, where white ice deposits can be seen. This trail moves to the right down to C, and on the left edge of the map at J which would be North Polar Cap 3. North east of A there is a trail of ice (more clear in the original map) shown by B. This connects to the large ice deposit at H. In the center of the ice trail at B is Elysium Mons. This implies that the heat from Elysium Mons melted water here to make the runoff to H, and therefore that Elysium Mons was hot when the pole was at A. On the northern end of this trail is where Viking 2 landed, and also the best example of Martian spider ravines[32] [33]outside of the current South Pole. The large ice deposit at South Polar Cap 3 in Meridiani Planum is shown at I, and F an ice trail linking it to a northern ice sheet.

This is consistent with the motion of the pole described here. At E we see a large ice trail again, this time next to Olympus Mons and also east towards Pavonis Mons[34]. This implies some of the ice of North polar Cap 3 was melted by Olympus Mons and moved north to the large ice area at G. E is also the location of Amazonis and Arcadia Planitia which show signs of having been made smooth by water[35]. Photos M1900946 and M1901546 show many volcanoes. These probably formed partially or wholly in water. While this water may have come from melting ice it may indicate the area was covered with ice or water. Olympus Mons and Tharsis would have been still hot at this time, which helps to date these events.

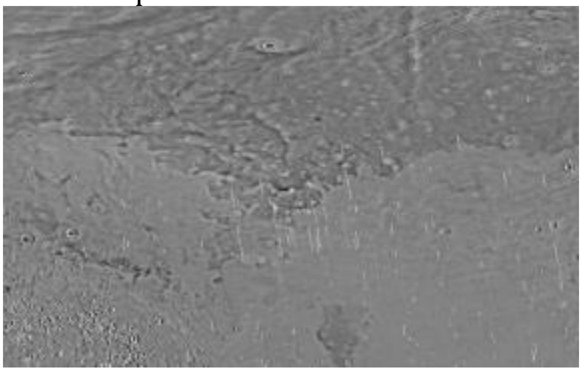


Figure 3: the Northern lowlands

Figure 3 shows dark areas on the Martian surface around the area of H in Figure 2. This implies these dark areas may be associated with higher amounts of ice. The trails of ice leading to these dark areas imply there was liquid water, which implies some parts may have been a liquid ocean at this time.

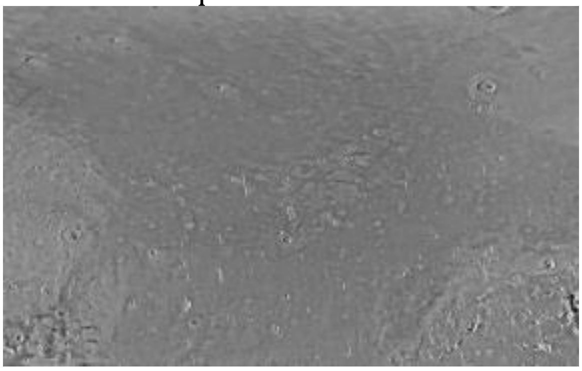


Figure 4: Amazonis and Arcadia Planitia.

Figure 4 shows the dark areas coinciding with Amazonis and Arcadia Planitia.

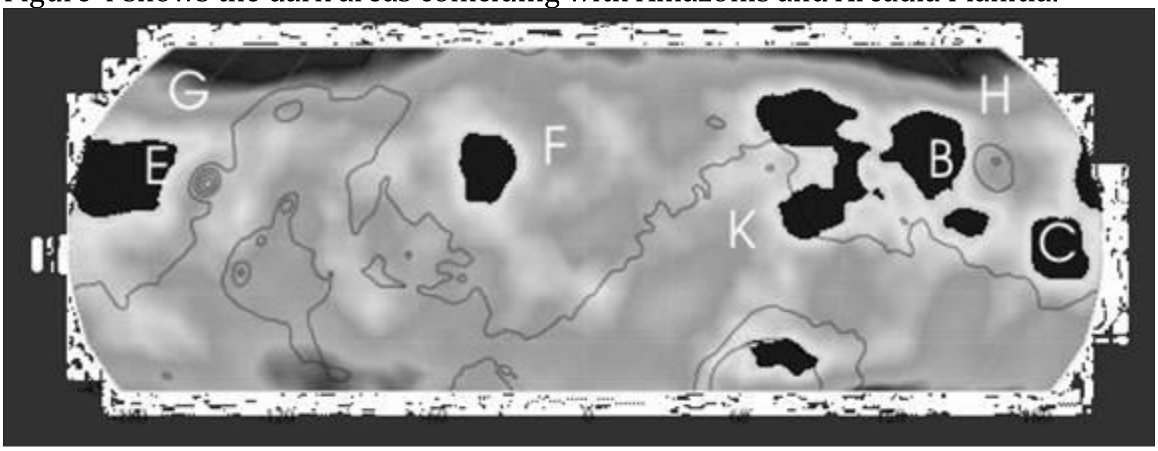


Figure 5: Map of Martian Iron at mid-latitudes.

In Figure 5 a map of Iron on mars from the Odyssey Gamma Ray Spectrometer[36] is shown. Here we have made the red, high iron areas on the original map black to be seen more clearly. E corresponds to Amazonis Planitia as a high Iron area. This is also associated with darker soil, has many water and ice signs, and is associated with the ice trail going northwards. So it is likely then some of the Iron may have been leached from the ground by water melted by Olympus Mons from North polar Cap 2. G shows the northern ice sheet is also Iron rich and connected by water or ice trails.

F shows an iron rich area coinciding with an ice rich area. Between K and B there is a trail of Iron from Meridiani Planum, or South polar Cap 3 up to Elysium Mons. This implies again that water from the pole moved north and north east to the large ice areas at H. C shows a large Iron deposit at North polar Cap 3.

It would be difficult for this Iron to occur in these areas due to glaciation alone, so it is likely has some association with water. This then implies a long-term northern ocean and ice sheet at the time Olympus Mons, with heat provided along the major north-south faults by Elysium and other Mons, at the same time the Pole moved from Position 2 to 3. The Opportunity area also has high iron (Fe). We know this is due to pisolite. Hence, pisolite may have formed in at least some of these regions.

As the Polar Cap moved along the dichotomy boundary from 2 to 3, new ice would tend to form on the ground ahead and melt on the ground behind it as the temperatures changed. The ice in front would tend to freeze into the soil and create a similar situation to the current Pole 5 where approximately half or more of the soil is ice. When this eventually melted or sublimated the soil in the ice should have moved down the slope and spread out. If there was a high enough air pressure this should have created a seasonal water flow into Acidalia Planitia and created the smooth surface. Amazonis Planitia is thought to be flat from sedimentation or fluvial processes according to Head[37]. Fuller et al[38] believe the Alba Patera area was resurfaced volcanically and with fluvial sediments. A periodically higher obliquity may have also created a water flow.

There are visible water channels in Lunae Planum, Xanthe Terra, and Margaritifer Sinus, but these became less common as the Polar Cap moved eastwards. The edges of the (green) elevation in MOLA maps[39] along this path may indicate the edges of the permanent ice cap cutting a flat platform. The primary erosion may have been caused by ice. Thus, at this stage Martian temperatures and air pressure were possibly dropping after the Argyre impact.

The ice deposit at South Polar Cap 3 abuts a cliff to the north, which is an extension of the dichotomy boundary. This ice then implies that it is connected to the creation of this cliff and by extension created the cliff of the dichotomy boundary as the Polar Cap moved. As water ran down the slope at South Pole 3 it would have eroded the ground, but where the ground was permanently frozen the ground would have been protected. This should then give a boundary to the north of the moving Polar Cap where the ground slopes more. Note also how South Polar Cap 3 also has an ice path at approximately 345W connecting to the northern ice sheet or ocean. Water and ice signs can be seen in narrow angle images from Malin Space Science Systems, such as E0101857, E0300317, E0401351, E0401589, E0503396, E1600085, E1801705, E2001051, E2100663, and E2301402.

These ice paths imply the terrain at the time was conducive for water to flow into the ice rich areas at 60N, which implies these ice rich areas were formed substantially from water runoff themselves. If they were solely formed from ice deposition there would be no need for them to connect in apparent water paths. Much of this water may have moved in subsurface aquifers, which would explain a lack of rivers connecting to the ice rich area. Much of the water or ice had to previously exist there for polar wander to occur. This can easily be tested by simulating different depths of ice to these lower areas, and seeing if it balances the planet sufficiently for the polar path shown here to occur.

North Polar Cap 3 includes the area around Gusev Crater and the Spirit Rover site. Pablo et al[40] examined Atlantis Basin on this previous Polar Cap and believe this contained an ancient paleolake. This is consistent with the idea of a Polar Cap here, the area becoming desiccated when the Polar Cap moved on. The heat sources may have been from Olympus Mons, which would have been active at the time from the Argyre impact.

Spirit has found indications of repeated exposure to water[41] [42]as well as more hematite concretions.

Irwin et al[43] describe Ma'adim Vallis as one of the largest valleys on Mars, believed to have been carved from a large flood. This amount of water on North Polar Cap 3 fits in well with the water signs at South Polar Cap 3. Water from North polar Cap 3 may have moved northwards into Arcadia Planitia.

Thomas-Keptra et al[44] propose carbonate disks in ALH84001 may have formed in an area similar to conditions found by the Rover Opportunity, which would link possible life signs to these former poles.

This is also consistent with the idea of the water at the Rover Opportunity site being from polar ice. Leask et al[45] examine the Ravi Vallis and Aromatum Chaos areas and calculate the amount of water that would have been involved. This would be the western edge of South Polar Cap 3 and also represent an area the Polar Cap moved over.

Coleman[46] also examined this area and believes an ice covered lake in Ganges Chasma recharged the aquifer source. This is also consistent with the ice and water coming from South Polar Cap 3. Woodworth-Lynas and Guigne[47] examine the Kasei Valles area and believe water here was covered by ice floes. This is on the western edge of South Polar Cap 3 and again implies large amounts of water connected with the areas examined by Opportunity. The results of Holden Crater, Aromatum Chaos and Kasei Valles imply the climate was warmer at one stage for South Polar Cap 3, perhaps from increased obliquity[48].

Barlow and Dohm[49] examine Arabia Terra which is also on the edge of South Polar Cap 3 and conclude a subsurface reservoir of ice and liquid water existed here. Dohm et al[50] also indicate the magnetic field may have been waning, consistent with the idea of the Hellas impact later attenuating the magnetic field of Mars.

Arkani-Hamed and Boutin[51] plotted magnetic poles which agree reasonably well with the movement of the Polar Cap along the dichotomy boundary. The movement is roughly cycloidal, and from this it may be possible to calculate how long it took the Polar Cap to move from South Polar Cap 2 to 3. This assumes the magnetic Polar Cap may tend to move around a given rotational Polar Cap position.

South Polar Cap 3 contains an area called the “Arabian Water-Rich Spot” with 16% water (Mitrofanov et al[52]). Dalton et al[53] also found evidence of water accumulation in the Flaugergues drainage divide, which is also on South Polar Cap 3.

In each case, rift-like fault systems and hence lakes were all adjacent to old polar caps. The valleys were then modified due to sublimation of the icecaps and fluvial activity obscuring much of the faulting (as with Chasma Australe).

If the degassing has a volcanic relationship as implied by the polar-fault relationships, then SO2 may the major gas released with the CO2 component being minor, related only to initial defrosting. This seasonal defrosting would open pathways allowing degassing to occur.

The high iron and the sulfur content would thus result from volcanic degassing. The Opportunity area is bounded by rift-like faults both sides, and these look like they controlled the lake. The same Fe and Sulfur relationships occur at Viking 2 (Utopia Planitia). In each case, rift-fault systems and hence lakes were all adjacent to old polar caps.

In the Opportunity region, the pisolites (blue berries) form in two ways. The first is by in situ replacement, possibly of titanium-rich minerals by a lateralization-like process due to surface water. Other pisolite overlay the Opportunity lake sediments. This may have formed by shedding from an old iron deposit or may have formed like a bog iron ore, after the polar cap moved. There is strong evidence[54] at Opportunity that Meridiani Planum was wet and hospitable for life. The water would likely be from the polar cap and implying an environment hospitable to life along the whole polar path.

Siltstones may have formed in lakes and oceans adjacent to polar caps. Some of these may have been carbonate rich (perhaps varves) at the time. Thus, the icecap formed, then the rift valleys formed, degassing and volcanism followed. The lakes may have existed in equilibrium with the icecaps so a stable hydrological system must have existed, at least near this polar pair.

Many of the rifts and major normal and strike slip faults of mars occur adjacent to the polar caps. Thus, the crust has preferentially fractured in polar regions. Degassing would occur due to increased geothermal activity near hot spots or fractures in the mars crust.

The gases given off would be: CH_4, SO_2, SO_3, CO, CO_2, H_2O.
Some of the minerals formed due to hydrothermal activity would be: FeS, CuFeS, $CuSO_4$.
$SO_2 + 2H_2O \Rightarrow H_2SO_4 + H_2$

H_2SO_4 (sulfur) + $CaCO_3$ (Limestone/calcium-rich silts) => $CaSO_4$ (gypsum) + H_2O + CO_2
The rocks at the Opportunity site indicate that the water then eroded the gypsum crystals. The pisolites overlay the lake sediments, and either formed during or most probably after the degassing event . The gypsum in the lake sediment must therefore either be due to the lakes/oceans drying up, or since the crystals crosscut the bedding may well even be related to the degassing.

$CaSO_4$ (gypsum) + SiO_2 + H_2O => Mud

In arctic conditions mud may not always form. The result may be very fine silt, which would mix with or cover any near surface ice. If the temperature were to increase the ice just below the surface melt and the material would flow to create the mud-like surface features we see at Opportunity. Even olivine would erode to fine dust particles. In addition, any original pyrite related to hydrothermal activity would eventually weather due to the existence of water.

2FeS (pyrite) + $3H_2O$ => Fe_2O_3 (pisolite) + $2H_2S$ (rotten egg gas) + $1/2H_2$

The water would most likely then react to form sulfates or revert to ice and be covered by or mixed with dust.

Astrobiology

It has been openly speculated at the recent Rover Press Conferences about fossils[55] possibly being found at the Rover sites, particularly at Meridiani. Also there have been some objects found which some believe look like fossils. We will then examine the astrobiological implications of this polar path.

The polar movement from Pole 2 to pole 3 as shown is accompanied by regular discharges or water, flooding, and hematite deposits. Hematite[56] has been found in the area of Pole 3, which is consistent with the having water around a polar area. The area is believed to have been recently exhumed, by Lane et al[57] which is consistent with the Polar Cap moving and exposing this area. According to Hynek Aram Chaos and Valles Marineris[58] [59] also have hematite deposits, which is consistent with the path of the moving Polar Cap from South Polar Cap 2 to 3 giving water to create hematite. Hematite has been found by Spirit at Gusev Crater on North Polar Cap 3. Catling and McKay[60] discuss possible biological aspects of hematite deposits. Cockell[61] shows that life could survive under snow, which would protect from UV rays and still allow photosynthesis.

Hynek et al[62] say the erosion from water in Margaritifer Sinus lasted up to several hundred million years. If the whole polar wander path from Margaritifer Sinus to Meridiani Planum lasted only this long then it implies a habitable area may then have existed on Mars for long enough for life forms to have evolved in comparable time scales and environments as on Earth. Even in Margaritifer Sinus it may have been wet enough for long enough for life to evolve substantially. Life could have stayed close enough to the volcanoes for warmth, and the polar path implies at least Tharsis was hot for several hundred million years or more.

Opportunity[63] has found a volcanic rock almost identical spectrographically to the Shergotty meteorite found on Earth. If transfers of material were happening when Meridiani was a pole then it implies life from Earth (or vice versa) may have been introduced by the same mechanism along this polar wander path.

Several objects in particular seen at the Opportunity site seem to have a resemblance to fossil shapes, such as crinoids. The fossil shapes may be also explained by vughs forming during lateritization - but since even skeptics agree they look like fossils, more work is required to test this hypothesis.

Ausich et al[64] in their Figure 5 shows some shapes which can be compared to Figures 6 and 7 in this paper. Aronson and Blake[65] show similar shapes in Polychaetes. Radwanska and Radwanski[66] show more similar examples.

Figure 6[67]:

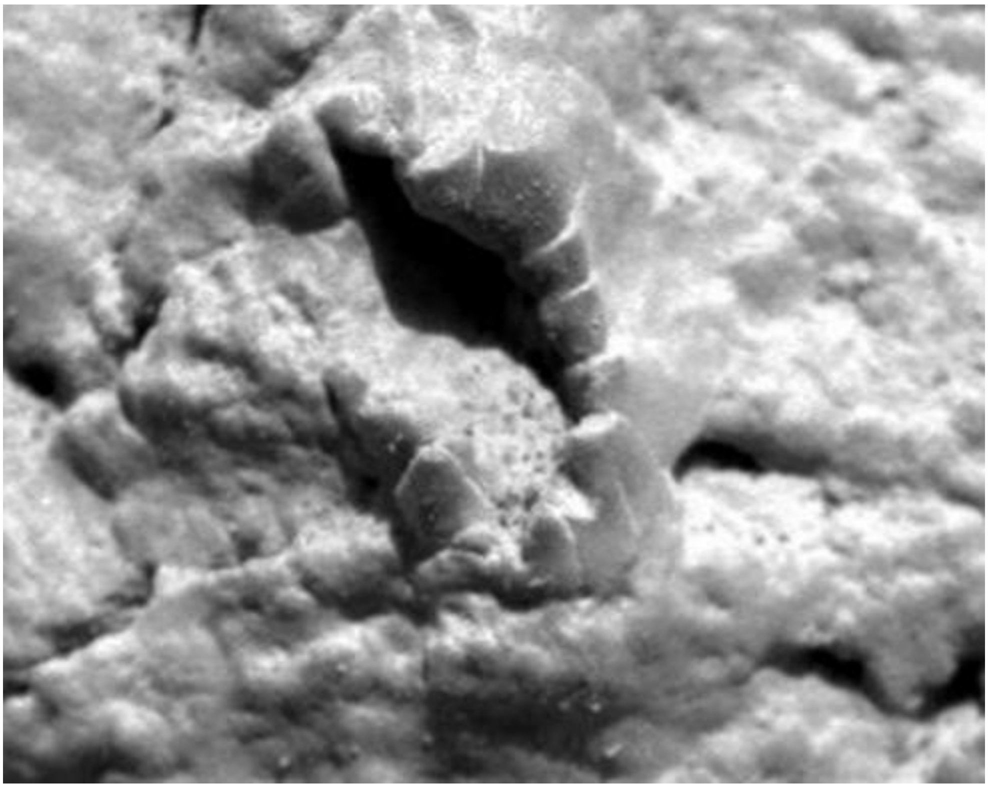


Figure 7[68]: The top of the fossil like shape appears to be beginning to branch in two. There appears to also be a tail like shape.

Schelble et al[69] discuss biological material often found associated with hematite, similar to shapes seen by the Opportunity Rover. Figure 8[70] shows a tubular shape reminiscent of a fossil or cryptobiotic soil crusts.

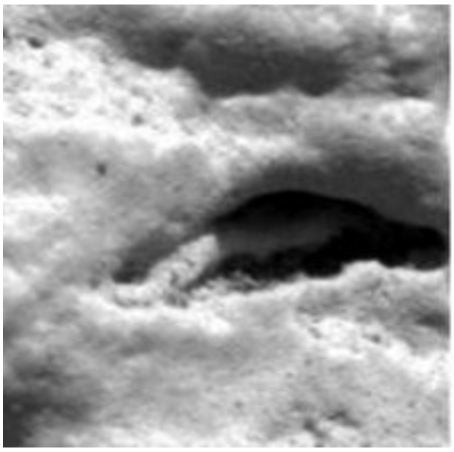


Figure 8

Krasnopolsky et al[71] have detected methane in the Martian atmosphere which they believe is coming from the equatorial regions, which is consistent with this polar wander path. Vittorio Formisano[72] has also found methane, at 10.5 parts per billion. Mumma et al[73] also found methane. On Earth methane is usually associated with biological activity.

Conclusions

Geology along the polar path suggested by Sprenke and Baker is consistent with polar ice and water. This section of the polar path would have been initiated by the rise of Tharsis, and as Tharsis moved to the Equator it forced the eventual South Pole eastward from Solis Planum to Meridiani Planum.

Signs of water, ice erosion, and hematite follow the polar wander path. Since the Opportunity Rover detected a potentially habitable environment, this may have persisted during the entire polar wander from Solis Planum and perhaps even earlier.

Estimates of the time taken to make this polar path are consistent with the time needed for substantial evolution to have taken place in Earth's early history. If life existed on

Mars at the start of this path, then it is possible a habitable zone existed for most of not all of this time.

Earlier than this an ice sheet and ocean would have occupied parts of the Northern Lowlands, in a shape consistent with water flows from the heat around Olympus Mons and Elysium Mons. Water near the heat from these volcanoes would be another potentially habitable zone for as long as they supplied a heat source.

Objects have been found at the Opportunity site with shapes similar to fossils. Methane emissions from the equatorial regions could be signs of past or present life. The polar wander path links a large volume of geological data suggesting that liquid water and the prerequisites for life did exist on Mars and over a substantial period in time. Thus, if life is not detected it may be a function of the measurement methods used rather than life not having existed. Future missions to mars need to be designed to help answer this more substantively.

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[1] K. F. Sprenke and L. L. Baker (2000) "POLAR WANDERING ON MARS?" LPSC XXXI 1930.pdf
[2] Such as :
http://planetarynames.wr.usgs.gov/images/mola_regional.pdf
[3] J. A. Grant (2001) "Valley Evolution in Margaritifer Sinus, Mars" LPSC XXXII 1226.pdf.
"Introduction: The Margaritifer Sinus region of Mars preserves some of the highest valley network densities on the planet [1-4]. Two large northwest draining valley systems, Samara and Parana-Loire Valles, whose associated basins cover an area exceeding 540,000 km2, dominate regional drainage. These valley systems converge on Margaritifer Basin, a confluence plain shared with the Uzboi-Holden-Ladon-Margaritifer Valles meso-outflow system (UHLM) that drains northward from Argyre. Detailed geologic and morphometric mapping of the Samara and Parana-Loire valley systems confirms the timing of incisement and permits evaluation of possible mechanisms for valley evolution [2, 5-8]."
[4] Ibid.
"features in Margaritifer Sinus. Four resurfacing events that deposited materials interpreted to be of mostly volcanic origin on the basis of wrinkle ridges and occasionally lobate morphology followed formation of these basins. The first three resurfacing events were
widespread and ended before evolution of the preserved valleys; the first two occurred during early Noachian heavy bombardment [11] and the second ended at an N5 age of 1400 (number of craters >5 km in diameter

per 1,000,000 km2). By contrast, the third resurfacing event began during the middle Noachian (N5 of 500) and ceased during the late Noachian (N5 of 300) coincident with waning highland volcanism [11]. Formation of Samara and Parana-Loire Valles, the UHLM system, infilling of associated depositional sinks (e.g., Parana Basin at 12.50W, 22.50S), and initial collapse of Margaritifer Chaos all occurred from the late Noachian (N5 of 300) into the early Hesperian (N5 of 150). The last, more localized resurfacing event lasted into the early and middle Hesperian (N5 ages 200 to 70) and emplaced materials that embay valleys. Nearly all area surfaces have been subsequently modified to varying
degree by eolian activity."

[5] Ibid.

"Model for Valley Evolution: A model for valley formation consistent with these results involves mostly localized ground-water discharge enabled by surface fed recharge. In this model, precipitation (rain or snow) would be largely relegated to subsurface entry by high
surface-infiltration capacities. Discharge at exposed relief would be controlled by occurrence of layers/aquitards. Valley evolution would have continued until draw-down of the water table following cessation of precipitation, thereby resulting in a strong sapping overprint.

Martian valley formation by this process may best explain observed morphometry. For example, the basin wide distribution of valleys (Fig. 1), low drainage density and ruggedness numbers, degree of integration, and sediment volume in along-valley sinks may be difficult to accommodate in a hypothesis involving ground-water discharge in the absence of surface recharge. With surface-fed recharge, valley distribution would be controlled mostly by the occurrence of layers/
aquitards."

[6] D. Williams (2003) "Parana Valles drainage system in Margaritifer Sinus, Mars" NASA Goddard Space Flight Center. Image at:
http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/vo1_084a47.html

[7] John A. Grant (2001) "DRAINAGE EVOLUTION IN MARGARITIFER SINUS, MARS" Paper No. 132-0 GSA Annual Meeting, Boston, Massachusetts

"Geologic mapping in Margaritifer Sinus, Mars, defines a complex history of water transport, storage, and release that began in the late Noachian and persisted into at least the mid-Hesperian. Collection, transport, and discharge of the water from widely dispersed surfaces were accomplished by systems of differing character flanking opposite sides of the Chryse Trough. Drainage on the western side of the trough was accommodated by the segmented Uzboi-Ladon-Margaritifer mesoscale outflow system that heads in Argyre basin, drains approximately 9% of the Martian surface, and alternately incises and fills as it crosses ancient multi-ringed impact basins."

[8]March 9, 2000. Goddard Space Flight Centre "View inside Mars reveals rapid cooling and buried channels" Top Story. Available online at http://www.gsfc.nasa.gov/topstory/20000309mars.html

"The crustal structure accounts for the elevation of the Martian northern lowlands, which controlled the northward flow of water early in Martian history, producing a network of valleys and outflow channels. The new gravity-field data suggest that the transport of water continued far into the northern plains. The gravity shows features interpreted as channels buried beneath the northern lowlands emanating from Valles Marineris and the Chryse and Kasei Valles outflow regions."

[9] K. Lewis and O. Aharonson (2004) "Characterization of the distributory fan in Holden NE Crater using stereo analysis" LPSC XXXV 2083.pdf.

"**Introduction:** The recent discovery of a distributary fan in a large crater northeast of Holden by Malin and Edgett has been presented as evidence for persistent flow of water on Mars [1]. With at least three separate depositional lobes and a clearly layered structure, this feature is so far unique among sedimentary
structures on Mars. This fan has been deposited by fluvial processes, and then subsequently eroded back from its original extent. This process has left behind an inverted topography, with the floors of former channels standing above the surrounding terrain. Several of the remnant channels in this formation appear to display meandering curves, which is the strongest evidence for a steady supply of water at this location.

Further, persistent flow raises the possibility that this feature was, at one time, a lacustrine delta."

[10]M Pondrelli et al (2004) "Complex evolution of Paleolacustrine systems on Mars: an example from the Holden Crater" LPSC XXXV 1249.pdf
"**Introduction:** Lacustrine systems are extremely sensitive to environmental fluctuations and, thus, they represent an ideal geological setting to investigate for climatic changes. Among the putative Martian paleolakes, the Holden crater (26S/326E) (Fig. 1) shows a richness of fluvio-lacustrine features. The Holden crater is 130 km wide and lies on Noachian rocks of the southern-cratered terrains [1]. The crater appears to interrupt a fluvial system of Hesperian age [1] which likely connected the Argyre basin to the northern chaos-outflow channels system. The main valley, Uzboi Vallis, cuts the southern rim and debouches into the crater. The Uzboi Vallis and Holden crater floors have been previously mapped as same units of fluviolacustrine deposits origin reworked by wind activity [2]. These deposits show a variety of sedimentary and morphological differences at MOC and THEMIS scale."
[11] R.M.E. Williams et al (2004) "Young fans in an equatorial crater in Xanthe Terra, Mars" LPSC XXXV 1415.pdf.
"**Introduction:** In recent years, the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) investigation has largely focused on NASA's Mars Exploration Program "Follow the Water" theme. We report here on MOC narrow angle (NA) images obtained in 2003 following observations from 1999 that show a specific, un-named, ~60 km-diameter impact crater at an equatorial latitude (7.6oN, 33.0oW) that exhibits well-preserved landforms similar in planimetric form and morphology to alluvial fans of arid environments such as the Mojave Desert of southern California. The principal question is whether these fans represent the products of water and gravity-driven alluvial sedimentation. The landforms in the Xanthe Terra crater are unique
among MOC images of martian impact craters, with the exception of some features in middle latitude Hale Crater and its central peak (35.9°S, 36.6°W). The purpose of this paper is to present an initial, brief description of these landforms and explore their implications.
…
Some of the channels display branching networks proximal to the fan (Fig. 3). The channel networks display a third-order topology using Horton's ordering scheme. First-order tributaries of the channels that feed the fans extend to the crest of local topographic highs. Locally, the density of channels (total channel length per area of network) is extremely high (preliminary value >500 km-1), comparable to terrestrial values for much larger scale rivers in humid environments with highly erodable substrates. In areas of high channel density, channels are visible to the resolution limit of the MOC NA images."

[12] B. M. Hynek and R. J. Phillips (2001) "Evidence for extensive denudation of the Martian highlands" Geology, 29, 407-410.
"Using high-resolution topographic data from the Mars Orbiter laser altimeter (MOLA) instrument on the Mars Global Surveyor mission (Smith et al., 1999), we have gathered evidence for a major fluvial resurfacing event in the Martian highlands. We completed detailed geomorphic mapping for the Margaritifer Sinus region (08–308S, 08–308W), where resurfacing appears most evident. In addition, evidence from adjacent areas suggests that this was not a localized event, but one that affected at least 1 3 107 km2 (an area equivalent to the European continent) of the cratered uplands. The topographic information allows for the first time a separation of younger, low-standing fluvially reworked terrains from older, high-standing erosional remnants. The newly acquired MOLA data also allow the volume of eroded material to be sensibly determined and minimum erosion rates to be estimated. The erosional episode was limited in time to no more than several hundred million years, and occurred ca. 4 Ga. The scale of the processes involved strongly suggests, but does not demonstrate uniquely, that precipitation must have played a major role in landscape denudation in this region of Mars."
[13] Ibid.
[13] "Formation processes of valley networks are still controversial; the debate is largely focused on the relative roles of surface runoff and groundwater processes. In the mapped region, the morphology of the valleys and associated networks (v-shaped profile, sinuous, high density, and high valley order) and the observation that numerous valleys originate near the tops of crater rims or hilltops (Fig. 3) indicate that precipitation and surface runoff may have played a major role in their formation. Some valleys show morphologies more consistent with a groundwater-sapping origin (u-shaped profile, low density and order, and alcove-like terminations), suggesting that subsurface water was also important. Therefore,

both precipitation and groundwater certainly contributed to degradation in the Margaritifer Sinus region, but the relative importance of each erosion mechanism is unclear. These results are consistent with previous work completed on the south-central part of our study area (Grant, 2000)."
http://ltpwww.gsfc.nasa.gov/tharsis/hynek.erosion.pdf
[14] Ibid.
[14] "There is evidence for a large paleolake in the region (Parana basin;
22.58S, 12.58W, area ;33 000 km2) (Goldspiel and Squyres, 1991). The
depression contains hummocky interior deposits with interspersed smooth terrain (Ni) that were emplaced contemporaneously with the extensive denudation and valley network formation. A large number of valley systems terminating at the proposed shoreline of Parana basin are believed to have been sources for the paleolake (Goldspiel and
Squyres, 1991). The unit HNl contains a hematite spectral signature
and is interpreted to be sedimentary layers deposited from large-scale
water interactions (Christensen et al., 2000)."

[15]B. Moomaw (2001) "Mars: A World of Varied Catastrophes" MARSDAILY May 1, 2001 available online at http://www.spacedaily.com/news/lunarplanet-2001-01a2.html

"J.A. Grant examined the valley networks in the Margaritifer Sinus region, the area on Mars where they are most concentrated, and concluded that they were indeed carved by "sapping" (tunneling by underground water flows) rather than surface runoff -- but also that the only way such a subsurface water supply could be adequately replenished was if "widespread precipitation" in the form of rain or snow occurred in the region and then seeped into Mars' porous ground.

B.M Hynek concluded from MGS' laser topography maps that the western Arabia Terra ("Arabia Highlands"), an area the size of Europe, was so eroded by surface rain that 3 million cubic km of its material was gradually washed into Mars' low-altitude northern plains.

K.P. Harrison and R.E. Grimm examined the fact that the areas on Mars where valley networks seem to be most concentrated are also those where MGS' magnetic sensors -- to everyone's surprise -- found local magnetic fields which seem to be areas where crustal iron minerals have been permanently magnetized by Mars' long-vanished early magnetic field.
Since this most easily occurs when molten rock is exposed to a magnetic field at the same time that it is rapidly cooled into solid form, the obvious possibility is that rising flows of underground magma may have collided in these areas with large amounts of groundwater kilometers below the surface, providing a flow of geothermal hot springs for the valley networks, and also cooling the magma quickly enough to "freeze" a copy of Mars' magnetic field into the resulting solid rock before Mars' magnetic field could reverse polarity (which, like Earth's, it probably did every million years or less) and thus scramble the permanently recorded "fossil" field.

D.M. Nelson examined the highlands south of the Elysium Basin -- through which three especially big channels seem to have carried fluid for a long period -- and concluded that the area showed signs of having undergone repeated cycles of geological peace that would have allowed a local layer of ground ice to build up, and episodes of moderate volcanism just right to melt the accumulated ice and produce large water flows into Elysium." Bruce Moomaw "Mars: A World of Varied Catastrophes"

[16]R. J. Phillips et al (2001) "Ancient Geodynamics and Global-Scale Hydrology on Mars" SCIENCE VOL 291 30 MARCH 2001
"Valley networks were examined in detail (25) in Margaritifer Sinus, a region on the flank of the Arabia bulge and in the Tharsis trough (Fig. 3B). Most formed on regions of relatively high topographic gradient on the flanks of the trough. The majority (;85%) of
observed valley networks here likely formed in Late Noachian time, between ;4.3 to 3.85 billion years ago (Ga) and ;3.8 to 3.50 Ga (26), although the possibility exists that earlier valley networks in this region were destroyed by a high impact flux or alternative erosion mechanisms. Because many of these valley network orientations are controlled by Tharsis-induced slopes, the Tharsis load must be largely Noachian in age, which is consistent with inferences made earlier. Superposition and sequence relationships indicate that

the valley networks whose azimuths are not explained by the model are nevertheless contemporaneous with the Tharsis-controlled valley networks (27). The formation of valley networks in Margaritifer Sinus is intimately associated with a Late Noachian, large-scale erosion event on the flanks of the Tharsis trough that stripped at least 1.5 3 106 km3 of material from this area, leaving behind numerous mesas of Early and Middle Noachian terrain (25)."

[17] H. Frey (2001) Geodynamics "2001 The Year in Review" Annual Report of the Geodynamics Branch, Goddard Space Flight Center.
"Figure 1 shows two recent magnetic maps of Mars derived using these techniques. The anomalies have a pattern strongly suggestive of faulting and perhaps offset along faults along a major tectonic structure. The Vallis Marineris on Mars is a series of large, fault-bounded canyons which have been compared with major rift structures on the Earth. The pattern in the magnetic maps, especially the abrupt truncation of the anomalies at the wall of the canyon, supports the idea that the Valles Marineris canyon is a tectonic graben. The maps also suggest that highly magnetic source rocks exist at the intersection of Coprates and Capri Chasmata, on the northeast corner of the canyons, and there is a good possibility that these magnetic rocks may be exposed along the fault wall."
[18] M.E. Purucker et al (2001) LPSC XXXII 1865.pdf "Interpretation of a magnetic map of the Valles Marineris region, Mars". available online at http://denali.gsfc.nasa.gov/terr_mag/abstract_mars.pdf

[19] B. Murray [1999] "PALEOLAKE DEPOSITS IN CENTRAL VALLES MARINERIS: A UNIQUE OPPORTUNITY FOR 2001" Second Mars Surveyor landing site Workshop.
"Paleolake deposits have been mapped in Central Valles Marineris since Mariner 9 and Viking (McCauley, 1978; Nedell et al., 1988;Witbeck et al., 1991). Accordingly, the region has been proposed as a priority target for landed payloads intended to detect diagnostic mineral evidence of a permanent lake environment, and, especially, biogenic signatures that could have survived from such promising candidate Martian habitats. (eg, Murray, et al, 1996; Yen, et al, 1999, Murray, et al, 1999). Just-released MOLA data strongly buttress the hydrological case for longduration ice-covered lakes there during Hesperian times at least."
[20] Ibid
"Carr (1996) suggested that ground water flowed from the Tharsis uplands into the deep canyons of Valles Marineris before debouching onto Chryse Planitia in the northern plains. Such a flow may have persisted for billions of years, and is generally inferred to have maintained deep lakes beneath which lacustrine sediments accumulated. Remnants of these Hesperian Age lake deposits survive today as conspicuous layered strata in Central Valles Marineris. Just published MOLA data (Smith, et al, 1999) confirm in detail this topographic trend and, most importantly, prove that deep, permanent lakes did indeed exist, especially in Central and Western Valles Marineris. Because the canyons in the Valles Marineris are deeper than the probable ground water table at that period, large portions of the canyons would have filled with water and formed ice-covered lakes."

[21] A.P. Rossi et al (1999) "[46.03] Flow-like features in Valles Marineris, Mars: Possible ice-driven creep processes" 31st Annual Meeting of the DPS, October 1999 Session 46. Mars Surface: Evidence of Change Posters .

"Recent high resolution MOC images have revealed the presence of deformed impact craters on flow-like features characterized by narrow bands of alternating light and dark material on the walls of Valles Marineris. The maximum crater elongations are consistent with the flow directions. Moreover the directions of these flows follow the topography downslope. In some cases, the flows emanate from cirque-like depressions, and the flows are divided by sharp ridges similar to arête. These landforms have resemblance to (1) alpine-type glacier morphology, including cirques, arêtes, and glaciers containing medial moraines; and (2) Grand Canyon-type sapping and mass wasting features. Certain aspects of the features in Valles Marineris seem more consistent with the first hypothesis involving a viscous rheology of the flows driven by ice-assisted creep processes. This hypothesis includes direct analogies to glaciers and rock glaciers. In the case of rock glaciers, flow is produced by freeze-thaw and by internal deformation of ice cores or lenses, whereas in the case of glaciers, movement occurs by internal deformation plus basal sliding in some cases where the glacier is melted at its bed. The amounts and roles of ice in the genesis of the Martian glacier-type landforms in Valles Marineris are not clear at this point. The population density of undeformed fresh impact craters on these flows appears to be low compared with the surrounding plateau areas. This may indicate relatively recent ages of the flow processes."

[22] R. Greeley and R. Kuzmin (1999) "SHALBATANA VALLIS: A POTENTIAL SITE FOR ANCIENT GROUND WATER" 2nd Mars Surveyor landing site workshop, SUNY/Buffalo, 43-44

available online at http://www.aas.org/publications/baas/v31n4/dps99/158.htm

"The channel is unusual because it appears to represent a single outflow initiated by a large impact. This impact could have excavated materials from the Martian crust from depths of several kilometers, apparently "tapping" the aquifer system leading to catastrophic

flooding to form the channel. Ejecta from the Noachian impact crater [6, 7] is preserved NW-W and SE from the source area. The width of Shalbatana Vallis near its source is about 50 km and then it continues 500 km NE as a sinuous, narrow channel of nearly constant width (10 -20 km cross) and depth (~2 km). The channel then becomes wider (40-50 km), bifurcates, and enters Simud Vallis [7]."

[23] D.M. Nelson and R. Greeley (1998) "XANTHE TERRA OUTFLOW CHANNEL GEOLOGY AT THE MARS PATHFINDER LANDING SITE" LPSC XXIX 1158.pdf.
"Summary. Geologic mapping of southern Chryse Planitia and the Xanthe Terra outflow channels has revealed a sequence of fluvial events which contributed sediment to the Mars Pathfinder landing site (MPLS). Three major outflow episodes are recognized: (1) broad sheetwash across Xanthe Terra during the Early Hesperian period, (2) Early to Late Hesperian channel formation of Shalbatana, Ravi, Simud, Tiu, and Ares Valles, and (3) subsequent flooding which deepened the channels to their current morphologies throughout the Late Hesperian. Materials from the most recent flooding, from Simud and Tiu Valles, and (to a lesser extent) materials from Ares Vallis, contributed the greatest amount of sediment to MPLS."
[24] Ibid.
"Following sheetwash, Mawrth Vallis was formed, possibly resulting from the discharge of floods from Margaritifer and Iani Chaos. A broad area of subdued terrain east of Ares Vallis indicates buried and embayed craters to the south of Mawrth Vallis. Floods could have passed over this surface before excavating Mawrth, then drained downslope into Acidalia Planitia. Alternatively, the subdued area could be a spill zone formed during the early excavation of Ares Vallis. Channelization continued in the Late Hesperian with the development of Shalbatana, Ravi, Simud, Tiu, and Ares Valles. Shalbatana Vallis possibly formed by subterranean discharge from Ganges Chasmata [7], and Ravi was excavated by flooding from Aromatum Chaos. Simud and Tiu Valles then developed by floods from Hydraotes and Hydaspis Chaos, and Ares Vallis developed by flooding from Iani Chaos. Cross-cutting relationships in Ares and Tiu Valles suggest that multiple floods occurred within these channels."
[25] P. D. Lanagan et al (2001) "GEOMORPHOLOGIC MAPPING OF CERBERUS PLAINS, MARS" LPSC XXXII 2077.pdf
"Fluvial features in the Cerberus plains cut into and are covered by lava flows [2]. MOC images, which show streamlined islands and longitudinal grooves, and MOLA topography suggest that water that carved the more recent of these channels originated from Cerberus Rupes or in regions of ground collapse highland rem-nants north of Cerberus Rupes, ran south into the Cer-berus plains, and finally emptied into Amazonis Plani-tia via the Marte Valles outflow channels [1]."
[26] Lanagan et al (2001) Rootless cones on Mars indicating the presence of shallow equatorial ground ice in recent times", *Geophysical Research Letters,* vol. 28, p. 2365-2368.

"**C**lusters of small cones on the lava plains of Mars have caught the attention of planetary geologists for years for a simple and compelling reason: ground ice. These cones look like volcanic rootless cones found on Earth where hot lava flows over wet surfaces such as marshes, shallow lakes or shallow aquifers. Steam explosions fragment the lava into small pieces that fall into cone-shaped debris piles. Peter Lanagan, Alfred McEwen, Laszlo Keszthelyi (University of Arizona), and Thorvaldur Thordarson (University of Hawai`i) recently identified groups of cones in the equatorial region of Mars using new high-resolution Mars Orbiter Camera (MOC) images. They report that the Martian cones have the same appearance, size, and geologic setting as rootless cones found in Iceland. If the Martian and terrestrial cones formed in the same way, then the Martian cones mark places where ground ice or groundwater existed at the time the lavas surged across the surface, estimated to be less than 10 million years ago, and where ground ice may still be today."

[27] (2003) Los Angeles National laboratory News and Public Affairs, News Releases, Photos. Available online at: http://www.lanl.gov/orgs/pa/News/cover_epi.jpg

[28] M. Caplinger February (1994) "Determining the age of surfaces on Mars" Malin Space Science Systems, Available online at:

http://www.msss.com/http/ps/age2.html

[29] D. E. Smith and M. T. Zuber (2004) "Gravitational effects of flooding and filling of impact basins on Mars" LPSC XXXV 1923.pdf.

"**Introduction.** The presence of large impact basins and the low northern plains that might have contained ice or liquid water at an earlier stage of Mars' evolution suggests that the global gravity field could have been different in the distant past than it is today. In addition, any significant change in the distribution of mass affects the moments of inertia and consequently and could conceivably change the position of the Polar Cap and the length of day. Similar effects could have been produced by large erosional processes, such as the removal of crustal material from the Arabia Terra region and subsequent re-depostion in the Chryse region of the northern plains [1]. We have endeavored to estimate the magnitudes of material that might have been involved in these processes and their possible effect on the gravity and dynamics of Mars. We have used present-day topography [2] and gravity field [3] as a starting point, recognizing that both the result of the processes that we are trying to study rather than the state at the times of interest.

Basin Volumes. The largest volume (arbitrarily defined below zero elevation) that could have been filled with H2O in the past is the northern plains (Fig. 1a) , which occupy about 47% of the surface of the planet [2]. Because of its location, which is approximately symmetrical about the Polar Cap, the additional mass associated with flooding contributes largely to the zonal gravity field, particularly degrees 1, 2 and 3, with small changes to the moments of inertia. (Note: we do not account for flexural effects.) Hellas (Fig. 1b) is the largest impact basin, and if filled to the zero elevation level would only hold about 10% of the volume of the northern plains. But because of its location at 30 to 50S, 50 to 90oE, it has the potential to have a larger effect on the moments. If suddenly filled today it would want to move toward the equator and because it is almost antipodal position to Tharsis it would move Tharsis southward [*cf.* 4]. The second largest impact basin was probably Utopia [5, 6] but today it is filled with sediments and volcanics [7], thus making the basin much shallower than it was originally. It appears to have been a Hellas sized basin and therefore might have been a significant contributor to global-scale mass re-distribution. Argyre, in comparison to Hellas, has only about 10% of the volume of Hellas as measured by today's topography, and has a relatively minor effect on the global mass redistribution."

[30] A. T. Oner et al (2004) "The volume of possible ancient ocean basins in the Northern Lowlands" LPSC XXXV 1319.pdf.

"**Discussion:** Our results for Arabia and Deu-teronilus shoreline present-day topography are some- what lower than those obtained previously [7,8]. the Meridiani shoreline our result is clearly lower than that in [8], fundamentally due to the fact that these authors use an excessively high value of 0 (with re-spect to the global datum) for the mean paleoshoreline elevation, whereas we use a mean elevation of −1.5 km [17]. Elevational range and geologic relations along Ara-bia shoreline, especially with respect to the Tharsis region, suggests that this is not a true paleoshoreline [7,8]. This implies that volumes obtained for the Ara-bia shoreline are likely not representative of any an-cient martian **ocean**. Otherwise, elevations in the puta-tive Meridiani shoreline are roughly similar to those of the Arabia shoreline in northeast Arabia, Utopia (not taken into account the Isidis basin), Elysium, and Amazonis regions. A paleoshoreline through these Arabia shoreline portions and the Meridiani shoreline would be a better candidate to represent a true **ancient** oceanic limit [5,18]: areas, volumes, mean depths and GELs obtained here for the Meridiani shoreline would be roughly valid for this **possible** paleoshoreline."

[31] (2003) Los Angeles National laboratory News and Public Affairs, News Releases, Photos. Available online at: http://www.lanl.gov/orgs/pa/News/cover_epi.jpg

Also JPL 2002 image releases, Global Map of Epithermal Neutrons, May 28 2002, PIA 3800. Available online at: http://www.jpl.nasa.gov/images/mars/pia3800_caption.html

[32] Greg M. Orme and Peter K. Ness (2003) "Martian Spiders" New Frontiers in Science, Fall 2003. *Viking Spiders.* Available online at: http://newfrontiersinscience.com/Members/v02n03/a/NFS0203a.shtml

"Oddly enough, Viking 2 [137] landed [138] nearly in the middle of a sub polar area that seems truly spider like [139]. Interestingly, some troughs were found near Viking 2 [140]. While other explanations have been suggested, the presence of the spiders nearby and their association with sometimes polygonal ravines makes these troughs possibly spider ravines. These "enigmatic troughs" [141] can be traced in a sequence of photos [142]. If they are spider ravines, it might indicate that when the spiders seasonally dissipate, they might leave ravines that are too shallow to see. There are also pits [143] in the area of unknown origin. In *The Martian Landscape* , Figures 195 [144],199[145], and 200 [146] may also be troughs. Figures 290, 210 and 211 [147] show paler areas devoid of rocks, which may be related to spiders. Of course, there are many other explanations but the proximity to the spiders makes these interesting. In imagery of the landing site [148], spider branches are 1-3 pixels wide where a pixel's width [149] is 9.46 meters [150]. Since spiders typically have a paler albedo and a comparable branch width to these pale patches, it is possible that they might be spider remnants."

[33]Peter K. Ness and Greg M. Orme, (2002). "Spider-Ravine Models and Plant-like Features on Mars - Possible Geophysical and Biogeophysical Modes of Origin" Journal of the British Interplanetary Society*, 8* February 2002. Vol 55 No 3/4, March-April Edition, Pp 85-108. available online at http://www.martianspiders.com

[34] D. E. Shean and J. W. Head (2003) "Pavonis Mons fan-shaped deposit- a cold based glacial model" 6th International Conference on Mars 3036.pdf

"Introduction: Each of the three Tharsis Montes volcanoes on Mars has unusual fan-shaped deposits located exclusively to the west-northwest of each shield. The fan-shaped deposits of the Tharsis Montes generally share three major facies: 1) a ridged facies, 2) a knobby facies, and 3) a smooth facies. Any ex-planation for the origin of the fan-shaped deposits must take into account both the similarities and differences in their morphologies, their approximately similar Amazonian age, and the fact that all three occur on the west-northwestern sides of the volcanoes [1]. Based on Viking Orbiter data, several models have been pro- posed for their formation, including massive landslides [2], glacial processes [3,4,5,6] and pyroclastic flows [6]. We support a glacial origin for the fan-shaped deposits and refine the previous models using new data from both the Earth and Mars. Based on Viking Or-biter data, Williams [3] and Lucchitta [4] suggested that the fan-shaped deposits were the result of the deposition of moraines due to recession of local ice caps that formed on the volcanoes from mixtures of emanated volatiles and erupted ash [4]. Scott et al. [6] suggest an explanation combining glacial and volcanic processes

…

We interpret these ridges as drop moraines formed at the margins of a retreating cold-based glacier [7]. The fact that these ridges can be seen in the proximal regions of the Pavonis fan-shaped deposit suggests that at least one major phase of retreat and deposition oc-curred. The ridges are superposed on underlying to-pography, including a lobate lava flow to the west, and are not deflected by obstacles. The fact that the ridged facies is observed up to elevations of 9.2 km above Mars datum on the northern flanks of Pavonis suggests that a large glacier would have covered a significant portion of the flanks of the shield."

[35] E.R. Fuller and J.W. Head III (2002) "GEOLOGIC HISTORY OF THE SMOOTHEST PLAINS ON MARS (AMAZONIS PLANITIA) AND ASTROBIOLOGICAL IMPLICATIONS" LPSCXXXIII 1539.pdf

"The cryosphere, a frozen layer of ice and regolith, has been acting as a global aquitard to the groundwater system below [e.g., 9]. Once the cryosphere is breached, the water, under hydrostatic pressure, emerges with very high flow rates, and continues flowing until pressure equilibrium is reached. This water flowed through Marte Vallis, eroding channels and debouching into Amazonis Planitia. This catastrophic outflow was shortly followed by lava outflow; the magma flowed through the fracture and released flood lavas onto the surface. This lava followed the path of the water, re-surfacing Marte Vallis and pouring into Amazonis Planitia. As it flowed over the water-saturated surface, the phreatomagmatic interactions created rootless cone structures [see also discussion in 10]. **Astrobiological implications:** The lava flows associated with the emplacement of these plains have been dated as extremely young geologically (less than 10 million years old [11]). If fossil or extant life existed at depth in the subsurface groundwater system at this time (a troglodytic fauna), it is highly likely that they would be among the material erupted to the surface, and washed down into Elysium Planitia and Amazonis Planitia. The fate of such effluents under current martian conditions has recently been modeled [12] and it has been shown that standing bodies of water at this scale would quickly freeze over and sublimate, leaving a sedimentary sublimation residue. Thus, Elysium and Amazonis Planitiae would be excellent locations to sample recently emplaced freeze- dried troglodytic faunal remains."

[36] JPL Planetary Photojournal PIA04253 "Map of Martian Iron at mid-latitudes". Available online at: http://photojournal.jpl.nasa.gov/catalog/PIA04253

[37] O. Aharonson et al (1998) "Mars: Northern hemisphere slopes and slope distributions" GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 24, PAGES 4413-4416, DECEMBER 15, 1998.
"Characterization of Martian surface slopes from the aerobreaking hiatus phase of the MGS mission provided several insights. Regional slopes across prominent canyons measured on a 10-km baseline range from 0 – 5_for regions which have undergone mass wasting and collapse, up to approximately 30_for less modi_ed scarps. The average slopes across the dichotomy boundary are small, < 1_, but on a local
scale can execed 20_. The northern lowlands are found to be unusually smooth and form a distinct statistical population. Other distinct populations correspond to the rough highlands and the extremely smooth Amazonis Planitia region. Amazonis is markedly smoother than any other large scale surface observed onMars, than volcanic plains on both the Moon and Venus, and than an example of desert terrain on the Earth. Its statistical properties resemble most closely certain terrestrial depositional environments including
oceanic abyssal plains and sedimentary basins. Given previously hypothesized scenarios for Mars' geological past [Carr, 1981], the evidence so far may be consistent with an origin for Amazonis in which extensive aeolian deposition follows a volcanic resurfacing event. Also possible is a modicational history in which water provides a sedimentary environment capable of efficiently smoothing meter scale topography."

[38] E. R. Fuller and J. W. Head III (2002) "Amazonis Planitia: The role of geologically recent volcanism and sedimentation in the formation of the smoothest plains on Mars" JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. E10, 5081, doi:10.1029/2002JE001842, 2002.
"[9] Parker et al. [1993] drew Contact 2, one of two interpreted shorelines for their proposed Hesperian northern ocean, near the margins of the central smooth unit of Amazonis Planitia. Head et al. [1999], using MOLA data, assessed the elevation of the two contacts, and found that Contact 1 deviated substantially from an equipotential line, but that Contact 2 was much closer to being level, with a mean elevation of 3760 m below the Martian datum. Figure 5e shows the trace of the _3760 m contour through the
Amazonis Planitia region.
…
[10] Morris and Tanaka [1994] mapped the eastern edge of Amazonis Planitia in their analysis of the Olympus Mons region. They identified two plains subunits of the Arcadia Formation (Figure 2): Aa_1 and Aa_2, both volcanic plains mantled by aeolian deposits. They also present evidence that the age of mapped volcanic units associated with Olympus Mons span the Middle to Late Amazonian, and that if the aureole deposits represent the collapse of a proto-Olympus Mons edifice, then extrusive activity must have extended back to the Late Hesperian. On the basis of their mapping, they favor a landsliding and gravity-spreading mechanism [see also Tanaka, 1985; Francis and Wadge, 1983], but point out that this requires a lubricant such as water or ice. They further point out a weakness of their hypothesis: ''if a huge, proto-Olympus Mons had formed (necessary for the landsliding and gravity-spreading mechanisms), extant lava flow fields beyond the aureoles might be expected, but they are absent'' [Morris and Tanaka, 1994, p. 15].
…
Its smoothness is comparable only with Earth regions shaped by long-term aqueous deposition, such as ocean floors and the North American Great Plains (the former location of an epeiric sea) [Aharonson et al., 1998]. Re-examination of Pass 31 shows that the smoothest region within the several thousand kilometer-long track corresponds precisely with the central smooth unit of Amazonis Planitia identified in this study (Figure 7)."
[39] Such as :
http://planetarynames.wr.usgs.gov/images/mola_regional.pdf

[40] M. A. de Pablo (2004) LPSC XXXV 1223.pdf.
"The subsequent evolution of Atlantis Basin is closely related to the evolution of Eridania Lake. The desiccation of Eridania Lake, probably during the Late Noachian [5], might have predated the existence of a series of reduced and interconnected lakes in the area, in which Atlantis might have been included. In this
work we propose the name *Atlantis Lake* for the lake formed inside this basin and originated in the decrease
of the water level of the Eridania Lake. Water probably flowed in the area from the South, initially draining to Southwest, but later forming an endorreic basin until its complete desiccation. In relation with this evolutionary sequence, the presence of 'mesas' in the basin edges (Fig. 1-f) have been interpreted as sedimentary materials deposited in the floor of the ancient Eridania Lake, and subsequently eroded. This interpretation, together with the presence of relatively recent collapse areas (Fig. 1-g) and mud-flow deposits (Fig. 1-h) around the Atlantis Chaos terrain, indicate the existence of liquid water in the recent

past. The appearance of linear structures in the interior of Atlantis basin has been interpreted as indicative of possible ancient dike systems [8], whose new activation would explain the existence of the subsidence zones and the mud-flow deposits by the fusion of the permafrost. Equally, the presence of gullies (Fig. 1-i) in several closed basins near to Atlantis Basin (as Gorgonum Chaos [9]), makes feasible the existence of recent liquid water under the surface [10] [11] [12] [13].
Astrobiological interest: The intense volcanic and tectonic activities, and the presence of possible dikes in the area, as well as the relation of Atlantis with the former wide Eridania Lake, the gullies, and the sedimentary deposits, all highlight the astrobiological interest of Atlantis. A heat source related to tectonovolcanic activity and flowing and ponded water are both hypothesized to have been present in the basin in different periods of the Martian history, perhaps until recent times (Late Amazonian)."

[41] Mars Exploration Rover Mission Press Releases (April 1, 2004). Available online at: http://marsrovers.jpl.nasa.gov/newsroom/pressreleases/20040401a.html
"Gusev is halfway around the planet from the Meridiani region where Spirit's twin, Opportunity, recently found evidence that water used to flow across the surface.

"This is not water that sloshed around on the surface like what appears to have happened at Meridiani. We're talking about small amounts of water, perhaps underground," said Dr. Hap McSween, a rover science team member from the University of Tennessee, Knoxville.

"The evidence is in the form of multiple coatings on the rock, as well as fractures that are filled with alteration material and perhaps little patches of alteration material," McSween said during a press conference at NASA's Jet Propulsion Laboratory, Pasadena, Calif."

[42]Mars Exploration Rover Mission Press Releases (March 5, 2004). Available online at: http://marsrovers.jpl.nasa.gov/newsroom/pressreleases/20040305a.html
"NASA's Spirit has found hints of a water history in a rock at Mars' Gusev Crater, but it is a very different type of rock than those in which NASA's Opportunity found clues to a wet past on the opposite side of the planet.

A dark volcanic rock dubbed "Humphrey," about 60 centimeters (2 feet) tall, shows bright material in interior crevices and cracks that looks like minerals crystallized out of water, Dr. Ray Arvidson of Washington University, St. Louis, reported at a NASA news briefing today at NASA's Jet Propulsion Laboratory, Pasadena, Calif. He is the deputy principal investigator for the rovers' science instruments.

"If we found this rock on Earth, we would say it is a volcanic rock that had a little fluid moving through it," Arvidson said. If this interpretation is correct, the fluid -- water with minerals dissolved in it -- may have been carried in the original magma that formed the rock or may have interacted with the rock later, he said."

[43] R. P. Irwin III and T. A. Maxwell (2004) LPSC XXXV 1852.pdf.
"**Introduction:** At 900 km long, 8–15 km wide and up to 2,100 m deep, Ma'adim Vallis is one of the largest valleys in the Martian highlands. The valley descends northward and terminates at the landing site for the Spirit Mars Exploration Rover at Gusev Crater, which acted as a detention pond or terminal basin for Ma'adim flows [1]. Previously we identified the valley head at the breached drainage divide of an enclosed basin in the mid-latitude highlands. Along with characteristics of the head basin, this feature suggested that the valley was carved primarily during a single paleolake overflow at the Noachian/Hesperian boundary [2] (~3.7 Ga [3]). Earlier work had suggested that Ma'adim Vallis was carved over a prolonged period up to 1.8 Ga by episodic groundwater-fed flows [4–10]. Here we investigate the valley's longevity using crater counting, topography, and flow hydraulics. These analyses provide quantitative support for development of the valley during a brief overflow, followed by a geologically brief period of tributary development."

[44] K. L. Thomas-Keptra et al (2004) "Determination if the three-dimensional morphology of ALH84001 and biogenic MV-1 magnetite: comparison of results from electron tomography and classical transmission electron microscopy" LPSC XXXV 2030.pdf.

“**Introduction** Dated at ~3.9 billion years of age, carbonate disks [1], found within fractures of the host rock of Martian meteorite ALH84001, have been interpreted as secondary minerals that formed at low temperature [e.g., 2] in an aqueous medium [e.g., 3]. Heterogeneously distributed within these disks are magnetite nanocrystals that are of Martian origin. Approximately one quarter of these magnetites have morphological and chemical similarities to magnetite particles produced by magnetotactic bacteria strain MV-1 [4], which are ubiquitous in aquatic habitats on Earth. Moreover, these types of magnetite particles are not known or expected to be produced by abiotic means either through geological processes or synthetically in the laboratory. The remaining three-quarters of the ALH84001 magnetites are likely products of multiple processes including, but not limited to, precipitation from a hydrothermal fluid, thermal decomposition of the carbonate matrix in which they are embedded, and extracellular formation by dissimilatory Fe-reducing bacteria. We have proposed that the origins of magnetites in ALH84001 can be best explained as the products of multiple processes, one of which is biological.

[45] H. J. Leask et al (2004) “The formation of Aromatum Chaos and the water discharge rate at Ravi Vallis” LPSC XXXV 1544.pdf.
“**Summary:** The Aromatum Chaos depression- Ravi Vallis outflow channel system is sufficiently simple that water flow rate and volume estimates can be made that throw light on processes operating to form the Aromatum and Ravi features. Typical discharge rates through Ravi Vallis are estimated at 3 x 106 m3 s-1. By assuming a high sediment load in the water we find a minimum duration of ~2 months. Too much water flowed in the channel to be explained by cryosphere melting alone, and drainage of a local aquifer system delineated by intrusions is clearly implicated.
Aromatum Chaos: The main Aromatum Chaos depression is a truncated triangle ~92 km long and an average of 30 km wide (Fig. 1). Its interior consists mainly of a mass of blocky-chaotic terrain, with blocks generally becoming progressively smaller towards its Eastern end. Some larger blocks at the Western end show some evidence of rotational slumping and also appear to be less eroded, having flat tops showing a rather angular connection between the flat top and the walls. The edges of Aromatum Chaos show strong evidence of local structural control and so, in an attempt to look for similar control of the interior, we examined all MOLA profiles crossing the interior, and found 30 profiles which collectively crossed the tops of 20 blocks. From these we measured the absolute heights (relative to Mars datum) of the tops of the blocks and their depths below the rim of the depression. The tops of blocks lie between 1,008 m and 2,361 m below the rim and show no systematic correlation with depth below rim or height above floor, suggesting piecemeal collapse rather than a structural control on their subsidence.”

[46] N. Coleman (2004) LPSC XXXV1299.pdf.
“**Floodwater Sources:** Confined groundwater was the apparent source for the initial outflows. If this were the only source the flow could not have been sustained because confined aquifers, once released, tend to depressurize rapidly. The unconfined dewatering of an aquifer takes much longer. In addition, the presence of an ice-covered lake in ancestral Ganges Chasma would have provided a substantial reservoir to recharge the aquifer source for both Ravi V. [7] and Shalbatana V. [7, 10], permitting outflows over an extended period. If the flows were concurrent, then the flooding occurred in mid- to upper-Hesperian because Shalbatana V. incised ridged plains material of lower Hesperian age [11].”

[47] C. Woodworth-Lynas and J. Guigne (2004) “Extent of floating ice in an ancient Echus Chasma/Kasei Valles valley system, Mars” LPSC XXXV 1571.pdf.
“**Introduction:** From images of the Echus Chasma/Kasei Valles valley system we present further, new observations of surficial Martian features that are interpreted to be the result of interactions between the keels of flat-bottomed floating ice floes with a submerged sediment [1,2]. These features are proxy indicators of three basic environmental conditions: the former presence of a water body; the water body was seasonally, or perhaps permanently, covered by ice floes; the water area was large enough for winds, currents or both to drive the floes forward during ice/lakebed interaction. We also present an analysis of shorelines. These observations are made from analyses of Mars Global Surveyor Mars Orbiter Camera (MOC) images. In places we have observed several, closely-spaced, terraces interpreted to be shorelines preserved at different elevations along the margins of the valley system. We use the geographic distribution of the floating ice-related features and shoreline terraces to define the limits of floating ice in the valley system. We compare the shoreline boundaries with equipotential (waterline) surfaces using Mars Orbital Laser Altimeter (MOLA) data, and estimate the volume of water and floating ice that occupied the valley system.”

[48] T. Nakamura and E. Tajika (2002) "Evolution of the climate system of Mars: effects of obliquity change" LPSC XXXII 1057.pdf.
"The obliquity change could cause a climate jump in the Martian climate system on short timescale. Figure 2 shows the annual mean atmospheric pressure as a function of the obliquity. The present solar constant and 2.0 bar of the total amount of CO_2 in the system are assumed for a nominal example. There are two branches of the solution. One is a "cold" residual-cap solution branch, and the other is a "warm" no-ice-cap solution branch. It is noted that the residual-cap solution branch disappears in higher obliquity region. On the other hand, the no-ice-cap solution branch does not exist in lower obliquity region. Therefore, climate jumps should occur at the ends of two branches. Assuming the state I in Figure 2 as an initial state, for example, when the obliquity increases, the state should change to be the state II. If the obliquity continues to increase, a climate jump will occur from the state II to III to reach the state IV. This climate jump results in a drastic increase in the atmospheric CO_2 pressure, thus warming. On the other hand, starting from the state is IV, if the obliquity decreases, the state changes from the state IV to I via a climate jump from the state V to VI. In this case, the climate jump results in a decrease in the atmospheric pressure, thus cooling. It is, therefore, suggested that the Martian climate could have dramatically changed repeatedly in short-term cycles during the Martian history."

[49] N. G. Barlow and J. M. Dohm (2004) "Impact craters in Arabia Terra, Mars" LPSC XXXV 1122.pdf.
"**Discussion**: Crater morphologic and central pit data suggest that Arabia hosts a subsurface volatile rich reservoir of ice and possibly liquid water. The crater data are just one indicator of the uniqueness of Arabia Terra. The combined stratigraphic, topographic, structural, crater, geomorphic, geophysical, elemental, and thermophysical signatures suggest that Arabia is unusual compared to other highlands regions [1]. GRS neutron spectrometer data reveal Arabia to be one of the most H2O-rich areas in the equatorial region of Mars [10, 11]. The correlation of this region with crater indicators of subsurface volatiles suggest that volatiles exist over a range of depths in this region, from less than a meter (GRS/NS analysis) to over 2 km depth (based on crater depth-diameter analysis). The existence of ejecta and central pit features over a range of crater preservation ages indicates that this volatile reservoir has existed for a substantial amount of Martian history, perhaps extending back into the Noachian based on the ages of ejecta craters [12]."

[50] J. M. Dohm et al (2004) "Ancient giant basin/aquifer system in the Arabia Region, Mars". LPSC XXXV 1209.pdf.
"Magnetic anomalies are observed in this region, although the magnitude is diminished relative to the anomalies in the Terra Cimmeria region [1,2]. The impact would have erased any preexisting magnetic anomalies in the crust as is seen with Hellas and Argyre. If, however, the impact occurred when the dynamo was active, the crust would have a chance to reacquire magnetization. The diminished intensity could indicate that the dynamo was active but in a waning stage. On the other hand, the reduction in magnetic signals may be the result of deep burial by basin infill. Although there is no geophysical manifestation of a large buried impact basin in the gravity or magnetic data (e.g., circular positive mascons as noted for Argyre, but subdued for Hellas), the extreme age of the event may preclude any detectable geophysical signature and may in fact explain the uniform appearance of the gravity."

[51] J. Arkani-Hamed and D. Boutin (2003) "Polar wander of Mars: Evidence from magnetic anomalies" Sixth International Conference on Mars. 3051.pdf.
"**Introduction:** The polar wander of Mars has been suggested by many investigators. The quasi-circular surface morphology of the deposits in the polar region detected by Mariner 9 mission led Murray and Malin [1973] to suggest that the Martian rotation axis has wandered by 10-20 degrees in the last ~100 Myr. Melosh [1980] gradually removed the mass of Tharsis bulge while diagonalizing the moment of inertia tensor of Mars, and showed that the Martian rotation axis has displaced by about 25 degrees due to the formation of the bulge. The similarity between the deposits on Mesogaea, south of Olympus, and those in the polar region led Schultz and Lutz [1988] to suggest a polar path with a total of 120 degree wandering. Long-term rotational dynamics of Mars was theoretically investigated by Spada et al. [1996] through modeling Olympus mountain as a point mass, initially located at 45 degree latitude on the surface, and allowing the mass to reach the equator. They considered a comprehensive suit of internal structure models of Mars with mantle viscosity ranging from 1021 to 1023 and imposed the Murray and Malin's constraint of 10-20 degree polar wander in the last 100 MYr. The authors concluded that the mass will reach the equator within less than 2 Gyr., in a much shorter time for low viscosity mantle models. It is also shown that a thick elastic lithosphere atop

a viscous mantle increases polar wander because of elastically supporting the surface mass and allowing its greater influence on the rotational dynamics of Mars [Willmann, 1984; Stiefelhagen, 2002]. The Mars Global Surveyor magnetic data have provided new evidence for the polar wander of Mars. Arkani-Hamed (2001a) estimated the paleomagnetic Polar Cap positions of Mars through modeling 10 small and isolated magnetic anomalies. Seven out of the 10 Polar Caps clustered within a radius of 30 degrees centered at 25N, 225E. Hood and Zakharian (2001) modeled the source bodies of two magnetic anomalies near the north Polar Cap. One of the anomalies was included in the 10 anomalies modeled by Arkani-Hamed, and the Polar Cap positions of this anomaly determined by the authors were very close. Assuming that the diPolar Cap core field axis coincided with the rotation axis, the clustering of the Polar Caps suggests that the rotation axis has wandered by about 65 degrees since the magnetic source bodies were magnetized. This critical assumption that links the diPolar Cap core field axis to the rotation axis presently holds for both terrestrial planets with active core dynamo, Earth and Mercury, and possibly for Earth throughout its history. We make the same assumption in this paper."

[52] I.G. Mitrofanov et al (2004) "Arabia and Memonia equatorial regions with high content of water: data from HEND/ODYSSEY" LPSC XXXV (2004) 1640.pdf.
"**Results.** The consistency of HM and DLM with observational data was tested for the samples of pixels for Arabia and Memnonia. It was shown that DLM model is better supported by the observational data for Arabia and Memnonia in comparison with HM. The best fitting values of parameters ∫down were used for estimation of water content at these regions. It was shown (see [7]) that North Arabia (0°-45°E, 0°-30°S) contains on average 9.0 wt% of water under a dry layer with thickness of 26 g/cm2; the South Arabia (0°-45°E, 0°-20°S) contains on average 10.0 wt% of water under a dry layer with thickness of 32 g/cm2; the Memnonia (180°-200°E, 0°-25°S) contains on average 9.0 wt% of water under a dry layer with thickness of 29 g/cm2. One particular surface element with coordinates (30°E, 10°N) has the smallest emission of epithermal neutrons in the equatorial belt (Figure 2).The best fitting subsurface parameters for this element correspond to 16 wt% water under a dry layer with thickness 29 g/cm2 [7]. This estimate for the dry layer is consistent with the average value found for the entire North Arabia. Therefore, this result showing a high content of water at this surface element is not produced by uncertainties in the model-dependent data deconvolution. The value of 16 wt% corresponds to a real minimum in epithermal neutron flux in Arabia. We name this spot "Arabian Water-Rich Spot", or AWRS. It lies around an old eroded crater between craters Cassini and Schiaparelli."

[53] J.B. Dalton et al (2004) "Search for evaporate minerals in Flaugergues Basin, Mars" LPSC XXXV 1869.pdf.
"the Flaugergues drainage divide in the Noachis region of Mars (16.8 S, 340.8 W; [4]) indicates areas of water accumulation (Fig. 1). Putative paleolakes residing in craters (e.g., Gusev Crater, Schiaparelli) have already been examined for evidence of aqueous minerals. However, basin flow models suggest that craters deeper than low-lying basins do not necessarily drain large areas. Raised crater rims often isolate craters from their surroundings. The model has identified areas of water accumulation fed by large geographic areas which could produce enhanced transport of aqueous materials. *MOLA* A shaded-relief map constructed from MOLA data was used to assess the geomorphology of putative paleolake basins. Many were found to exhibit smooth features suggestive of a lake bottom."

[54] Mars Exploration Rover Mission Press Releases (March 2, 2004). Available online at: http://marsrovers.jpl.nasa.gov/newsroom/pressreleases/20040302a.html
"Scientists have concluded the part of Mars that NASA's Opportunity rover is exploring was soaking wet in the past.

Evidence the rover found in a rock outcrop led scientists to the conclusion. Clues from the rocks' composition, such as the presence of sulfates, and the rocks' physical appearance, such as niches where crystals grew, helped make the case for a watery history.

"Liquid water once flowed through these rocks. It changed their texture, and it changed their chemistry," said Dr. Steve Squyres of Cornell University, Ithaca, N.Y., principal investigator for the science instruments on Opportunity and its twin, Spirit. "We've been able to read the tell-tale clues the water left behind, giving us confidence in that conclusion."

Dr. James Garvin, lead scientist for Mars and lunar exploration at NASA Headquarters, Washington, said, "NASA launched the Mars Exploration Rover mission specifically to check whether at least one part of Mars ever had a persistently wet environment that could possibly have been hospitable to life. Today we have strong evidence for an exciting answer: Yes."

[55] These and many other shapes were independently found by many researchers, we would like to acknowledge Michael Davidson and Francisco J. Oyarzun.
[56] P.R. Christensen et al (2000) "THE DISTRIBUTION OF CRYSTALLINE HEMATITE ON MARS FROM THE THERMAL EMISSION SPECTROMETER: EVIDENCE FOR LIQUID WATER" Lunar and Planetary Science XXXI 1627.pdf.
"Crystalline hematite has been mapped over an area in Sinus Meridiani approximately 500 km in longitude extending approximately 200 km in latitude [3]. The extent of this deposit very closely matches the geomorphic boundary of a smooth, layered, friable unit that is interpreted to be sedimentary sedimentary in origin [3, 9]. This material may be the uppermost surface in the region, indicating that it might be a later-stage sedimentary unit, or alternatively a layered portion of the heavily cratered plains units. A second accumulation of hematite approximately 60 x 60 km in size is observed in Aram Chaos (2° N, 21° W). This site is also associated with layered materials and a water-rich environment."
[57] M. D. Lane et al (2001) "UPDATE ON STUDIES OF THE MARTIAN HEMATITE-RICH AREAS" LPSC XXXII 1984.pdf.
"Figure 4. Crater count diagram and isochrons for the Terra Meridiani hematite-rich area. Filled symbols show the population of "fossil craters" lying near the saturation equilibrium limit (upper straight line), indicating a very ancient surface. Open symbols show the fresh, recent craters created since the modern surface formed, indicating that the area has been exposed for as little as a few million years. Our interpretation is that an ancient (paleolake bed?) was covered by sediments and exhumed only a few million years ago."
[58] L.R. Gaddis et al (2003) "MINERAL MAPPING IN VALLES MARINERIS, MARS: A NEW APPROACH TO SPECTRAL DEMIXING OF TES DATA" LPSC XXXIV 1956.pdf.
"Mineral abundance maps (Fig. 5) show basaltic lithologies for much of the VM interior, in the form of high- and low-Ca pyroxenes (up to 24% total) and plagioclase minerals (up to 28%) in layered deposits in the walls and interior, as well as in dark materials at the base of canyon walls. Note that the presence of surface dust in parts of Ophir and east Candor Chasmata appears to decrease the apparent abundance of minerals in these areas. The distribution of gray hematite agrees well with previous results [18], but we see only (~8%) a small enrichment of red hematite in the possible hydrothermal site in west Candor [14] (Fig. 6)."
[59] F. S. Anderson et al (2003) "MINERALOGY OF THE VALLES MARINERIS FROM TES AND THEMIS" Sixth International Conference on Mars (2003) 3280.pdf.
"Our observations of hematite in the VM are similar to those seen by Christensen et al., [37]."
[60] D. C. Catling and C. P. McKay (2000) "Aqueous Iron Chemistry on Early Mars: Was it Influenced by Life?" Journal of Conference Abstracts Volume 5(2), 291.
http://camb.demonhosting.co.uk/JConfAbs/5/291.pdf
"The Thermal Emission Spectrometer on NASA's Mars Global Surveyor has detected deposits of crystalline hematite [1] in Sinus Meridiani, Aram Chaos and Vallis Marineris. These appear to be similar to terrestrial iron formations that formed in the Earth's Pre-cambrian oceans. The Sinus Meridiani deposit exceeds ~$10^5 km^2$ in size, and consists of coarse-grained, grey, schistose hematite [2]. Its age is ~4Ga or older based on counts of exhumed fossil craters [3]. Terrestrial Banded Iron Formations (BIFs) are laminated sediments deposited directly from solution. Pathological cases of crystalline hematite are particularly characteristic of the Late Proterozoic. These are associated with glaciomarine deposits and possibly formed when oceanic ice cover retreated. Iron oxides were precipitated when ferrous iron reacted with dissolved O_2. There is no question that the oxygen in the late Proterozoic atmosphere originated
from photosynthetic organisms. Could iron formations that formed ~4 Ga ago on Mars also be related to oxygenic photosynthesis?
...
On early Mars several mechanisms could precipitate iron oxides from solution. However, these processes all stoichiometrically require oxygen. There are only two possibilities for an oxygen source: (1) Small quantities of oxygen were slowly produced as hydrogen escaped to space and ferrous iron acted as a sink for this oxygen over an extended timescale.
(2) Early Mars had an oxygenic photosynthetic biosphere. Simple calculations suggest that atmospheric oxygen was very scarce on a volcanically active early Mars. The exposed deposits of hematite, if they are deep, would require significant quantities of oxygen. Finally, although many of the findings

suggestive of life in the ALH84001 meteorite have been disputed, the strongest piece of evidence has always been magnetite crystals of biogenic shape. It is interesting to note that magneto-tactic bacteria use magnetite for a specific purpose: to move along a redox gradient away from a surface environment dominated by oxygen."

[61] C.S Cockell (2003) "LIFE IN MARTIAN SNOWS – MEASUREMENTS OF UV PROTECTION UNDER NATURAL ANTARCTIC SNOWS IN THE UVC (254 nm)" Third Mars Polar Science Conference 6125.pdf. "Convolved with a simple Mars radiative transfer model, the data suggests that under ~6 cm of Martian snow, DNA-damage would be reduced by an order of magnitude [2]. Under approximately 30 cm of snow, DNA damage would be no worse than that experienced at the surface of the Earth. Although we do not know the exact characteristics of Martian snows, these first-order data suggest that burial in even modest coverings of Martian snows could allow for the long-term survival (and if water if present, even growth) of contaminant microorganisms at the Martian polar caps even under the extreme UV fluxes of clear Martian skies. These coverings of snow will also allow for enhanced preservation of organics against UVdegradation. Intriguingly, at the depth at which DNA damage is reduced to similar levels as those found on the surface of present-day Earth, light levels in the photosynthetically active region (400 to 700 nm) are still two orders of magnitude higher than the minimum required for photosynthesis, showing that within snow-pack on planets lacking an ozone shield, including Mars, UV damage can be mitigated, but light levels are still high enough for organisms that have a requirement for exposure to light for their energy needs. Photosynthetic life is not expected at the Martian poles, but the data reveal the apparently favourable radiation environment for life within the polar caps."

[62] B. M. Hynek and R. J. Phillips (2001) "Evidence for extensive denudation of the Martian highlands" Geology, 29, 407-410.
"Using high-resolution topographic data from the Mars Orbiter laser altimeter (MOLA) instrument on the Mars Global Surveyor mission (Smith et al., 1999), we have gathered evidence for a major fluvial resurfacing event in the Martian highlands. We completed detailed geomorphic mapping for the Margaritifer Sinus region (08–308S, 08–308W), where resurfacing appears most evident. In addition, evidence from adjacent areas suggests that this was not a localized event, but one that affected at least 1 3 107 km2 (an area equivalent to the European continent) of the cratered uplands. The topographic information allows for the first time a separation of younger, low-standing fluvially reworked terrains from older, high-standing erosional remnants. The newly acquired MOLA data also allow the volume of eroded material to be sensibly determined and minimum erosion rates to be estimated. The erosional episode was limited in time to no more than several hundred million years, and occurred ca. 4 Ga. The scale of the processes involved strongly suggests, but does not demonstrate uniquely, that precipitation must have played a major role in landscape denudation in this region of Mars."
[63]Mars Exploration Rover Mission Press Releases (April 15, 2004). Available online at: http://marsrovers.jpl.nasa.gov/newsroom/pressreleases/20040415a.html
"NASA's Opportunity rover has examined an odd volcanic rock on the plains of Mars' Meridiani Planum region with a composition unlike anything seen on Mars before, but scientists have found similarities to meteorites that fell to Earth.

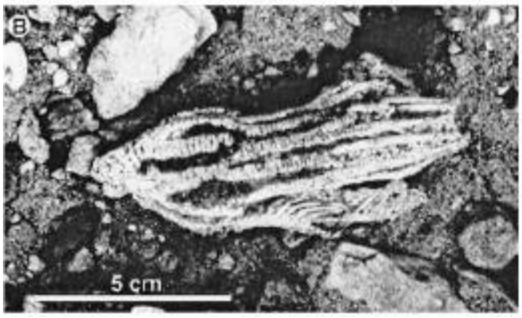
"We think we have a rock similar to something found on Earth," said Dr. Benton Clark of Lockheed Martin Space Systems, Denver, science-team member for the Opportunity and Spirit rovers on Mars. The similarity seen in data from Opportunity's alpha particle X-ray spectrometer "gives us a way of understanding 'Bounce Rock' better," he said. Bounce Rock is the name given to the odd, football-sized rock because Opportunity struck it while bouncing to a stop inside protective airbags on landing day.

The resemblance helps resolve a paradox about the meteorites, too. Bubbles of gas trapped in them match the recipe of martian atmosphere so closely that scientists have been confident for years that these rocks originated from Mars. But examination of rocks on Mars with orbiters and surface missions had never found anything like them, until now.

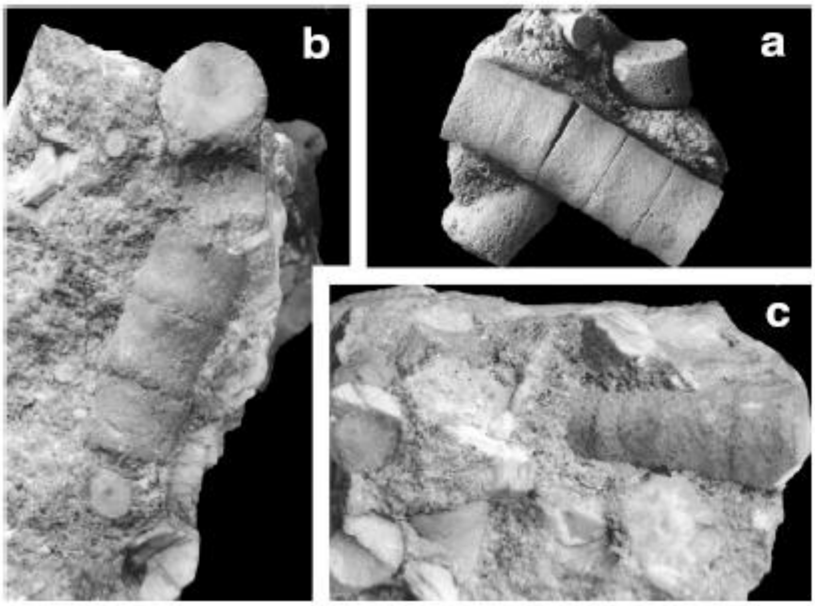
"There is a striking similarity in spectra," said Christian Schroeder, a rover science-team collaborator from the University of Mainz, Germany, which supplied both Mars rovers' Moessbauer spectrometer instruments for identifying iron-bearing minerals."
[64] WILLIAM I. AUSICH, et al. *J. Paleont.,* 76(6), 2002, pp. 975–992 Copyright q 2002, The Paleontological Society "0022-3360/02/0076-975 "ORDOVICIAN [DOBROTIVIAN (LLANDEILLIAN STAGE) TO ASHGILL]

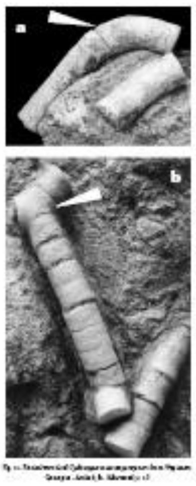
CRINOIDS (PHYLUM ECHINODERMATA) FROM THE MONTES DE TOLEDO AND SIERRA MORENA, SPAIN WITH IMPLICATIONS FOR PALEOGEOGRAPHY OF PERI-GONDWANA”

[65] R. B. ARONSON, AND D. B. BLAKE (2001) “Global Climate Change and the Origin of Modern Benthic Communities in Antarctica” AMER. ZOOL., 41:27–39, Figures 1 and 3b.



[66]U. RADWA¡SKA & A. RADWA¡SKI (2003) “The Jurassic crinoid genus *Cyclocrinus* D’ORBIGNY, 1850: still an enigma” *Acta Geologica Polonica,* Vol. 53 (2003), No. 4, pp. 301-320 Figures 3, 8, 9, 10, 11, 12, 13, and 14.
http://www.geo.uw.edu.pl/agp/table/pdf/53-4/radwanscy.pdf





[67] JPL (2004) Mars Exploration Rover Mission raw images. m/030/1M130846496EFF0454P2933M2M1
[68]JPL (2004) Mars Exploration Rover Mission raw images. m/034/1M131201699EFF0500P2933M2M1
[69] R. T. SCHELBLE et al (2001) "HEMATITE MINERALIZED BACTERIAL REMNANTS: IMPLICATIONS FOR MARTIAN HEMATITE DEPOSITS" LPSC XXXII 1438.pdf.
"by Fe-oxides for extended periods of time. Although banded iron formations have not so far been recognized on Mars, hematite deposits have been observed. Christensen, et al. [7] cite five possibilities for the origin of the hematite deposits:

- Direct precipitation from standing, oxygenated iron-rich water
- Precipitation from iron-rich hydrothermal fluid
- Low-temperature dissolution and precipitation through mobile groundwater leaching
- Surface weatherings and coatings
- Thermal oxidation of magnetite-rich lavas

If bacteria did exist on Mars, their preservation by Fe-oxides in any of these potential settings is possible. Thus, the Martian hematite deposits would be an excellent site to look for past life on Mars.

[70]JPL (2004) Mars Exploration Rover Mission raw images.
m/029/1M130761497EFF0454P2953M2M1.JPG

[71] A. Krasnopolsky et al. "DETECTION OF METHANE IN THE MARTIAN ATMOSPHERE: EVIDENCE FOR LIFE" V. European Geosciences Union 1st General Assembly, Nice, France, 25 - 30 April 2004. Available online at: http://www.cosis.net/abstracts/EGU04/06169/EGU04-A-06169.pdf

Using the Fourier Transform Spectrometer at the Canada-France-Hawaii Telescope, we observed a spectrum of Mars at the P-branch of the strongest CH_4 band at 3.3 μm with resolving power of 220,000. Summing up the spectral intervals at the expected positions of 18 strongest Doppler-shifted martian lines, we detected the absorption by martian methane at a 3.9 sigma level. The observed CH_4 mixing ratio is 11 ± 4 ppb. Total photochemical loss of CH_4 in the martian atmosphere is equal to 1.8×10^{5} cm^{-2} s^{-1}, and the CH_4 lifetime is 440 years. Heterogeneous loss of atmospheric methane is probably negligible, while the sink of CH_4 during its diffusion through the regolith may be significant. There are no processes of CH_4 formation in the atmosphere, so the photochemical loss must therefore be balanced by abiogenic and biogenic sources. The mantle outgassing of CH_4 is 4000 cm^{-2} s^{-1} on the Earth and smaller by an order of magnitude on Mars. The calculated production of CH_4 by cometary impacts is 2.3 per cent of the methane loss. Methane cannot originate from an extinct biosphere, as in the case of "natural gas" on Earth, given the exceedingly low limits on organic matter set by the Viking landers and the dry recent history which has been extremely hostile to the macroscopic life needed to generate the gas. Therefore, methanogenesis by living subterranean organisms is the most likely explanation for this discovery. Our estimates of the biomass and its production using the measured CH_4 abundance show that the martian biota may be extremely scarce and Mars may be generally sterile except for some oases.

[72] Kerr (2004) **"**Methane Means Martians?", *ScienceNOW* 2004: 1.

[73] M. J. Mumma et al (2003)"[14.18] A Sensitive Search for Methane on Mars." DPS 35th Meeting, 1-6 September 2003 Session 14. Mars Atmosphere II Poster, Highlighted on, Wednesday, September 3, 2003, 3:00-5:30pm, Sierra Ballroom I-II.

"CH_4 and its oxidation products (H_2CO, CH_3OH, C_2H_6) on Mars have received both observational (1) and theoretical attention (2, 3), but have not been firmly detected. Owing to its short photochemical lifetime (~ 300 years), the existence of significant methane would indicate \underline{recent} release from sub-surface reservoirs; a quantitative measure of the release rate could be inferred from its present atmospheric abundance. Sub-surface methane could be primordial (reduced cosmogonic carbon) (1) or biotic in origin (4); local enhancements are expected if methane is released from discrete regions. The presence of sub-surface hydrogen concentrations on Mars has been inferred from local-enhancements in epithermal neutron fluxes measured on Mars Odyssey (5), however, independent evidence is required to establish its likely chemical form (e.g., water vs. hydrocarbons) in low-latitude sites (Amazonia Planitia, and Schiaparelli-Cassini). We suggest that enhanced methane there could test whether sub-surface hydrogen is chemically bound in hydrocarbon moieties. In any case, a quantitative measure of methane production would provide a key for assessing models of biogenic vs. primordial origins. "