A Theory of Terraforming Mars in Fifty Years

By Greg M. Orme and Peter K. Ness

Introduction

The main inspiration for this paper was research done on Polar Wander on Mars. This led to a theory which can be seen by going to http://www.harmakhis.org and reading the History of Mars, The Origins of Valles Marineris and The Origins of Solis Planum.

The theory of these papers is that the Argyre impact was at a very shallow impact and its shock wave travelled partially along the Martian surface onto the South Pole of Mars at the time. This led to the Pole melting and the formation of Tharsis Montes[1], Valles Marineris and Olympus Mons.

It may also be that the same kind of meteor impact could be used today to terraform Mars. The advantage of this method is (if the History of Mars theory is correct) we can see what the effects of a similar meteor had in the past. So by recreating this event at one of the current Martian poles we might expect a similar sequence of events as happened then. This might include melting both poles and forming a liquid water ocean, and increasing the atmospheric pressure by outgassing from volcanoes as well as sublimated CO2 from the Poles.

Discussion

The basis of this terraforming would be to duplicate a similar event to the Argyre impact on Mars. Normally when a meteor hits Mars the shock wave goes into the ground in the direction the meteor was travelling, and the heat from the impact warms deep down where the energy is wasted for terraforming. Also if the objective is to form volcanoes to heat Mars then the shock wave underground is not useful for this as the heat energy from the impact normally stays underground.

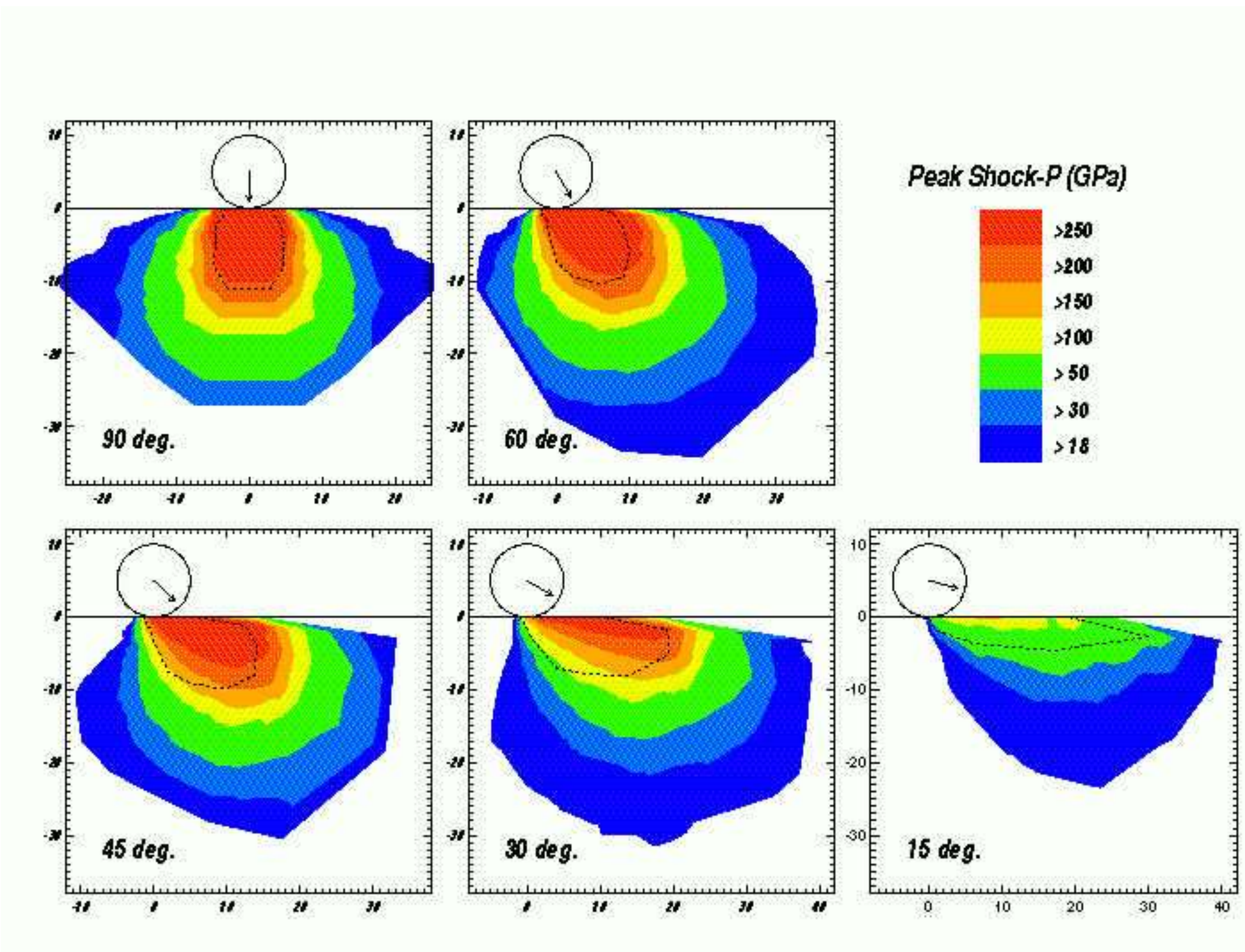
A shockwave is strongest in front of a moving object. For example if a moving car uses its horn the sound waves have more energy as well as being higher in frequency in the direction of motion of the car than behind it. The difference with a shallow impact is that the shock wave cone is strongest in the direction the meteor is moving and because the angle is so shallow on impact much of the shock wave cone doesn’t go into the ground but part of the shockwave is above ground and part is below ground[2], therefore part of the

[1] http://en.wikipedia.org/wiki/Tharsis

[2] http://www.psi.edu/~betty/obliqmelt.html

shockwave travels on the surface. The outline of this shock wave might have been as shown in Figure 1. While the angle of impact is not known exactly it should be able to be worked out from geological data around the impact site, assuming this theory is correct. So an observer might have seen the Argyre meteor coming from low on the horizon and strike a glancing blow on impact.

Peak shock pressure contours in the plane of impact (i.e., the plane perpendicular to the target surface that includes the projectile's line of flight) for the various simulations. A projectile 10 km in diameter is drawn for scale. The vectors from the center of the projectile show the direction of impact for the various oblique impact simulations.



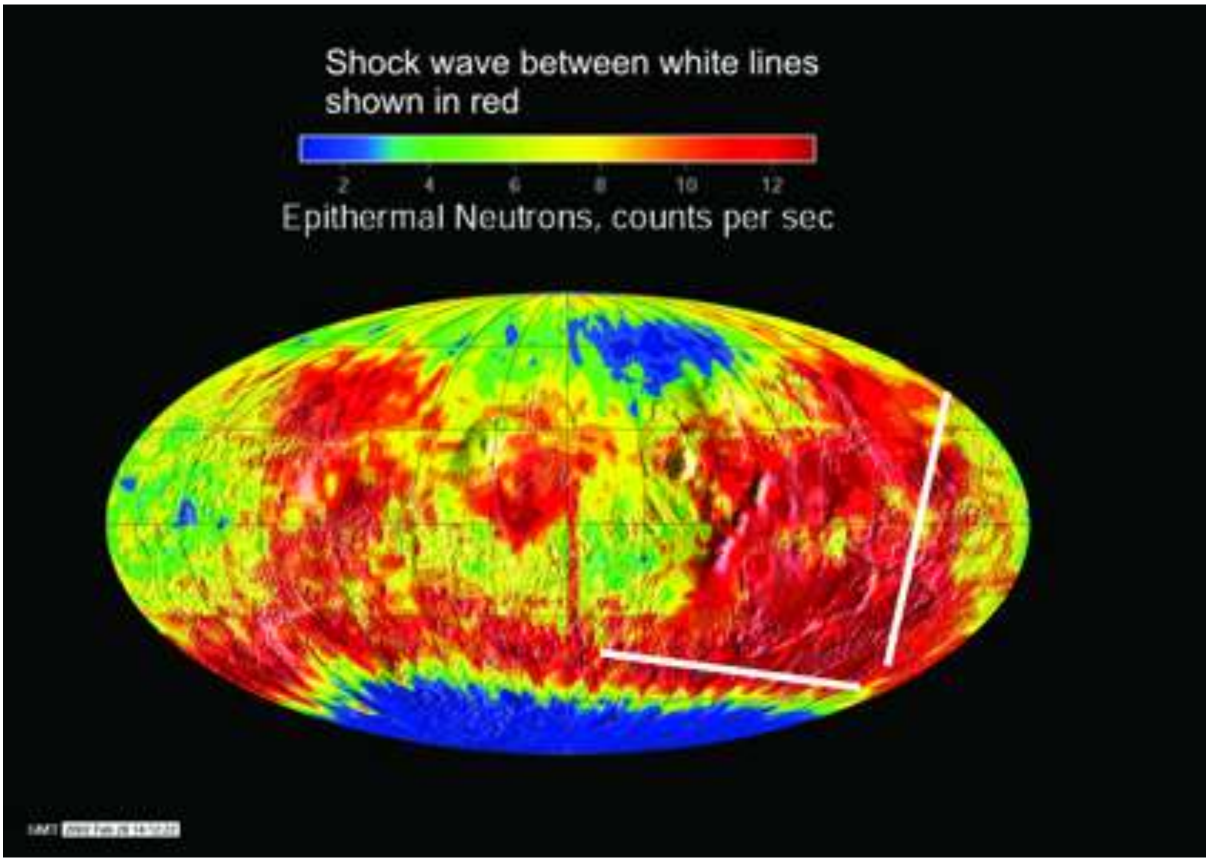
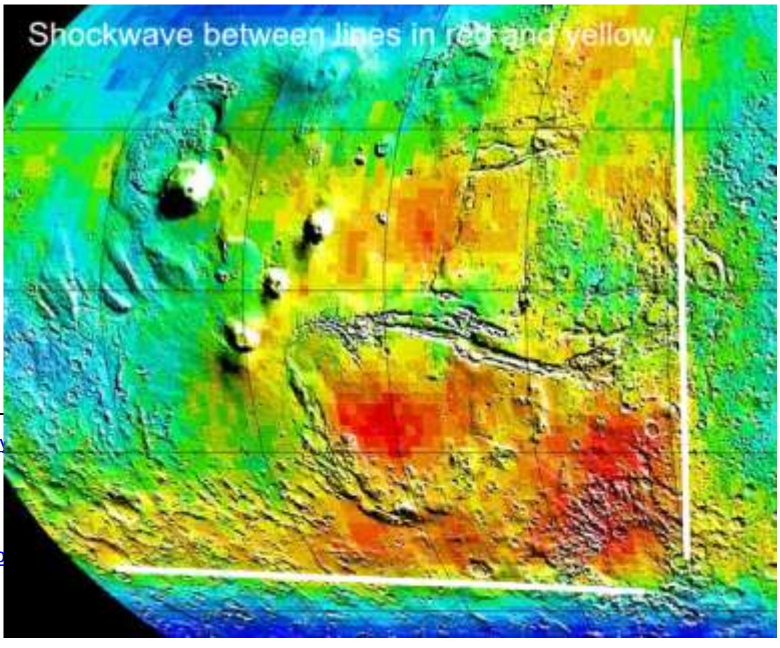


Figure 1[3]

The redder area indicates the ground contains less water ice. This radiates out from the Argyre impact crater and the length of this red boundary is more than the diameter of Mars. The blue area at the South Pole by contrast contains large amounts of ice. The shallow impact can also be seen in Figure 2 [4], where a reddish drier area again radiates out from Argyre crater.



[3]http://mars.jpl.nasa.gov/od

[4] http://www.lanl.gov/orgs/p

Figure 2

In Figure 3[5] the blue area is again drier, shown as radiating out from Argyre Crater.

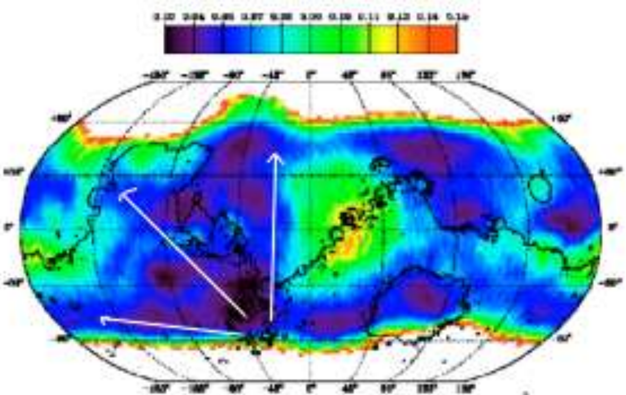


Fig. 4. Mid-latitude map of $\xi\Sigma_s$. The units are cm^2/g. A contour of topography at 0 km elevation is superimposed on the map.

Figure 3

It is proposed that the strongest part of the shock wave from Argyre Crater was in the direction of its motion, probably towards Olympus Mons. This warmed and dried the ground in a fan shaped area comprising Solis Planum, Tharsis Montes and Olympus Mons enough to drive some water out of it, so it was likely hotter than the sublimation temperature of water for the air pressure at that time. A similar smaller dried area also radiates out from Hellas Crater indicating it may also have been a shallow impact, though not as great as Argyre.

For this kind of terraforming of Mars to be done by us the size of the asteroid and its speed would have to be selected carefully. As can be seen here an enormous amount of energy was added to this area of ground, and this would be needed to heat the ground without blowing off large pieces of Mars rubble which might threaten to hit Earth later. So the angle of impact would have to send this debris outwards in the solar system, which may have

[5] http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3253.pdf

been how some of the comets were formed in the past. For example rocks from the Argyre and Hellas impact may have reached escape velocity and have gone into an elliptical orbit out of the solar system like some comets. Since Argyre may have impacted near a Pole some of these rocks might contain large amounts of ice, as seen in some comets.

Heating such a large portion of the Martian surface hot enough to drive water out of it can translate to more heat in the atmosphere, which gives a window of opportunity for terraforming. Some of this heat comes from the kinetic energy of the meteor's momentum, as mass times velocity, but it also comes from opening up fractures and rifts and allowing hot magma from underground up to the surface. So a shallow impact if it creates enough fractures can release far more energy than just from the impact itself.

In the History of Mars there was theorized to be a Pole[6] in the area shown in Figure 4.

[6] http://www.aas.org/publications/baas/v31n4/dps99/40.htm

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. The area is located in the Solis Planum region (20S-30S, 50W-90W). An analysis of craters displaying the single lobe (SL) ejecta morphology found that the onset diameter for these craters is between 3 km and 5 km, compared to the 5 km to 6 km onset diameters found for this morphology throughout most of the martian equatorial region (i.e., within 30 degrees north and south of the equator). This is the largest area of smaller-than-normal onset diameters found in our study of the equatorial region. In addition, analysis of the distribution of multiple lobe (ML) ejecta morphologies also indicates a higher than normal abundance of craters with this morphology in the Solis Planum region. A global study by Barlow and Bradley (Icarus, v. 87, pp. 156-179, 1990) found a strong correlation among latitude, diameter, and ejecta morphology, which is consistent with the proposed distribution of subsurface volatiles based on geothermal and hydrologic models. Acording to the Barlow and Bradley model, SL morphologies result from impact into ice while ML morphologies result from excavation into liquid-rich reservoirs. 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.

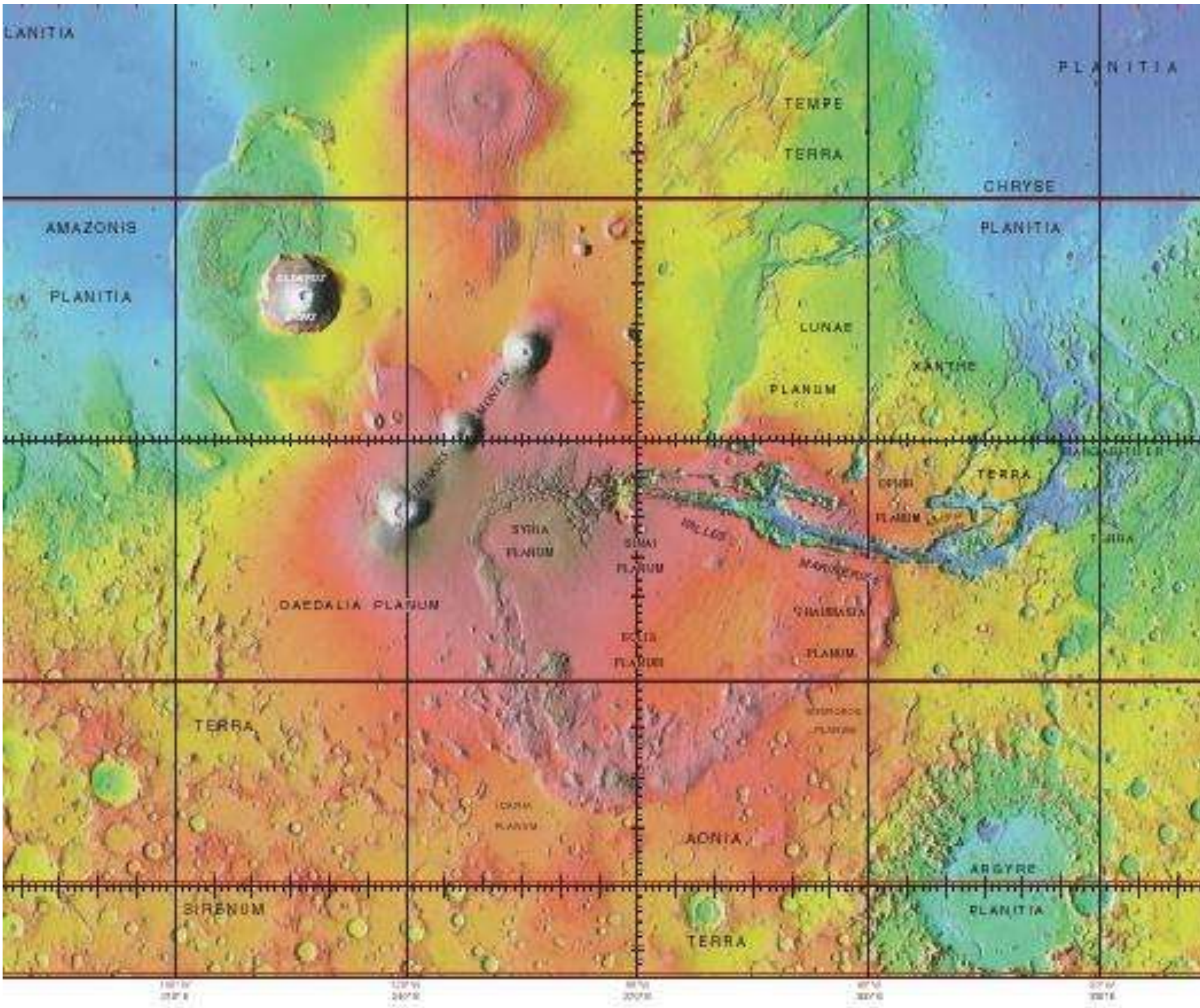


Figure 4

The shock wave was aimed at the South Pole of Mars at that time, so the redder higher areas shown in Figure 4 would have been caused by volcanic activity from the impact. As the History of Mars and other papers mentioned earlier propose, the Pole moved eastward to Meridiani Planum, then South to Hellas Crater and eventually to its current position. Thus this single impact may have caused the Pole to move over much of Mars. So this would also act to spread more water over the planet because the Pole changes the terrain as it moves and water from the Pole melts behind it. Using a similar impact to terraform Mars might also cause Polar Wander and spread more water around Mars.

The heat from the Argyre impact directed at the Pole would have melted the water and CO2 on it, and as proposed in the History of Mars paper much of this water ran into Chryse Planitia. We might then expect a similar amount of floodwater from a meteor impact aimed at the current Pole.

The North Pole might be preferable as a target for a meteor impact today because floodwater from the melting Pole would go into a depression called the Northern Lowlands. So if water can move away from the Pole into a depression then the hotter climate at lower latitudes will slow down its refreezing. The Pole is higher than the surrounding terrain because it is built up ice deposited there, so water that melts from the Pole would tend to sit around it or at lower latitudes.

The shock wave cone of the terraforming meteor impact would be similar to those in Figures 2 and 3 (the angles of the fan shape would depend on the angle of impact). The Pole would tend to retain heat for a long time after the impact and melt CO_2 and water ice that returned to the Polar cold trap. For example the melted water would create large seas and the sublimated CO_2 a thicker atmosphere and this would tend to create weather transporting water vapor back to the Poles. So the heat from the shock wave and crater there would prevent the Pole reforming for a time, as it may have done after the Argyre impact.

So to terraform Mars the idea would be to do something similar, to aim a meteor to impact at a shallow angle near the current North Pole on Mars so the impact should likely occur at round 70-80 degrees North. Ideally it may be better to aim this shock wave at Chasma Borealis.

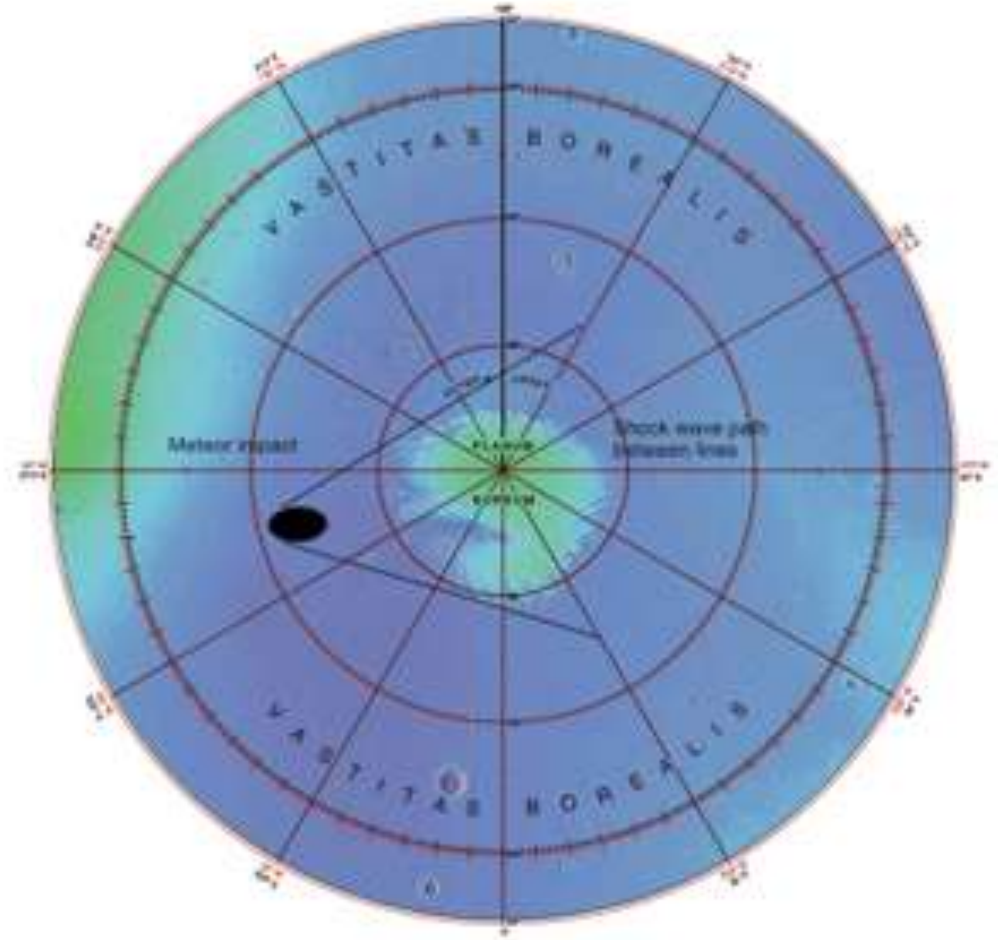


Figure 5

In Figure 5 the dark ellipse is a suggested location for the meteor impact site, and the dark lines show an estimated shock wave aimed at the North Pole around Chasma Borealis[7] [8]. Melting floodwaters from the Polar ice should flow back down this Chasma onto the hotter impact site. So this floodwater would hit the impact crater and this heat would convert much more of it into steam. Ideally there would be a flood of water into the Northern

---

[7] http://www.lpi.usra.edu/meetings/lpsc2003/pdf/1854.pdf

We note that the build up of CO_2 frost occurs first at the deepest portion of the Vastitas Borealis forma-tion where the atmosphere is thickest. It then pro-ceeds poleward through Chasma Boreale (also corre-sponding to the thickest atmosphere at that latitude) eastward to its head before proceeding northward to the pole. This behavior can be explained by the higher CO_2 frost point temperatures (the temperature at which CO_2 vapor will begin to condense) at the higher pressures that exist within, and just beyond the mouth of Chasma Boreale.

[8] http://www.lpi.usra.edu/meetings/lpsc2006/pdf/1363.pdf

Introduction: Chasma Boreale, a large reentrant in the martian North Pole, is distinct from other polar troughs by its large size and counterclockwise orientation [5]. The ~ 1300 m deep chasma extends for ~ 500 km from its proposed origin at 85□ N, 2º E and is on average ~ 60 km wide.

Lowlands in this area and the impact crater would continue to boil this water into clouds and create rain elsewhere on Mars. Because the Pole is higher than the surrounding terrain, from its ice sheet, then part of the shock wave above ground would impact the side of this ice and tend to fragment and melt it.

Elysium Mons is one of 3 mountains directly on the opposite side of Mars to the Argyre impact, likely formed by antipodal volcanism [9]. One possible event is that, according to the History of Mars papers mentioned earlier, the shock wave from the Argyre impact travelled through the Martian core and created a fracture in the ground, releasing magma and forming these Mountains.

One reason to believe this occurred is that the drier areas from the shockwave radiating out from Argyre are longer than the diameter of Mars. So if a shock wave could travel this far on the surface it should be able to travel the same distance through Mars to the other side.

So in terraforming Mars a volcano might form near the South Pole opposite the Northern impact crater, and this would provide some warming on the South Pole, melting water and draining into the surrounding lowlands and perhaps Hellas Crater. This heat would also persist because magma from this volcano would continue to make it grow and add heat to the area. Also a volcano like this should release gases to thicken the atmosphere further. Elysium Mons and her two sister volcanoes are quite large and also illustrate the large amount of additional heating of Mars created by the Argyre impact. So using the same kind of impact antipodal heating might be substantial and melt much of the huge ice reserves of the South Pole, forming a sea in Prometheus Basin.

Meteors

The shallow impact directed at the Martian poles could also be done by several smaller meteors from different angles. One advantage of this is the effect of each meteor might be

[9] http://www.grc.nasa.gov/WWW/K-12/MarsV/rania.htm

We decided to further investigate the meteor relationship by calculating the impact energy and mass of Argyre and Elysium as for Helles and Tharsis. Again we found that the impact energy in this case was sufficient to produce the bulge mass. Therefore, if the meteor theory is correct for Helles-Tharsis then it is correct for Argyre-Elysium. If this is so, then crystal thickness of the area can be calculated.

We assumed a direct relationship between the diameter of a crater on Earth and the crustal thickness, using Vredefort in SA as our example.
Then we imposed this ratio on the crater diameter size on Mars to calculate the crustal thickness.

We calculated that for Argyre and Elysium the crustal thickness was about 60 km. For Helles and Tharsis it was 200 km. This further provided us with proof that the meteor theory was correct because of the multi-ring basin present for Argyre-Elysium, which was not present for Helles-Tharsis due to the thicker crust in the latter case.

Following these investigations we were able to conclude that the meteor theory for Mars could have a part to play in producing volcanoes on Mars.

checked and subsequent meteors deflected away if not needed or there was too much effect from previous impacts. Also smaller meteors might be easier to deflect onto the desired trajectory. Because the effects on Mars from Argyre may have lasted millions of years it may only be necessary to create a smaller terraforming effect. Also a smaller impact and subsequent volcanism might make the planet stable in a shorter time.

The asteroid belt is close to Mars and large asteroids move close to Mars and often impact on it. The theory requires altering the trajectory of one or more of these asteroids sufficiently, to create something similar to the Argyre impact. The Argyre meteor has been estimated[10] at around 900 kilometers in diameter but one much smaller may be all that is required for terraforming.

Basically then, asteroids that pass close to Mars would be surveyed, and at least one selected. Then it would need to have its orbit altered so it would hit Mars like the Argyre impact, at a shallow angle. Proposals including launching rock from such a meteor with rail guns, nuclear rockets, etc would be use to nudge the meteor into the right impact angle, perhaps over several orbits around the Sun.

So the trajectory of the asteroid would be moved, much as we ourselves propose to move asteroids including preventing one hitting Earth in the future. So again no more technology is required than we ourselves have proposed and planned for, though the cost of this is well beyond budgets available at this time.

However if the theory is correct Mars might become habitable in as little as 50 years. Assuming 20 years for changing the orbit of a meteor, in say 6 of its orbits around the sun, and 30 years for the effects of the impact to stabilize then people might begin living and terraforming on the ground in 50 years or less. Once the water and CO2 from the Poles had melted from the impact this should reach equilibrium with the hot rock of the impact site and water returning to the cold trap of the Poles. Over time volcanism would further heat Mars but settlements could be set far away from these. While some fallout from volcanoes might be dangerous the thicker atmosphere would cause more meteors to burn up in the atmosphere.

So the initial heat would come from the impact, allowing a window of opportunity to use plants and algae to create Oxygen from Carbon Dioxide. Because Oxygen would never freeze at the current Martian temperatures the air pressure on Mars would become permanently

---

[10] http://www.lpi.usra.edu/publications/books/CB-954/chapter1.pdf

Fig. 1.9. An ancient multiring (?) impact basin on Mars. The flat-floored Argyre Basin (upper left) (D = 900 km) is apparently the youngest large impact basin recognized on Mars, but it is still an ancient and heavily eroded structure that has itself been struck by large projectiles since it formed (e.g., the large crater cutting the basin rim at top). This orbital panorama shows the smooth floor deposits within the basin and the mountainous nature of the enclosing rim. Because of the high degree of erosion, the actual diameter of Argyre is uncertain; a minimum diameter of about 900 km is indicated by the rugged rim shown in this picture, but the existence of additional rings (with diameters of 540, 1140, and 1852 km) has been suggested. The white streaks above the horizon (upper right) are hazes in the thin martian atmosphere. (Viking Orbiter image JPL P-17022.)

higher. Then volcanism would add additional heat to the atmosphere, particularly around the Poles, preventing them from reforming quickly.

Summary

The advantages of this terraforming theory are then as follows:

1. **Melting of ice.** After the Argyre impact there is good evidence the Polar icecap melted and the floodwater poured down the future Valles Marineris into Margaritier Sinus [11], Xanthe Terra, and Chryse Planitia. This area has abundant evidence large amounts of water flowed there, probably from the Pole melting after the Argyre impact[12]. So we might expect the ice from the current North Pole[13] would do the same, melting and pouring into the Northern Lowlands around Arcadia and Acidalia Planitia. This would create an ocean[14] of ice and water[15]. The melting of much of the

---

[11] http://www.nasm.si.edu/ceps/research/grant/grant_marg2.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]." J. A. Grant "Valley Evolution in Margaritifer Sinus, Mars" Available online at

[12] http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1799.pdf
"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

[13] http://astrobiology.arc.nasa.gov/news/expandnews.cfm?id=9623

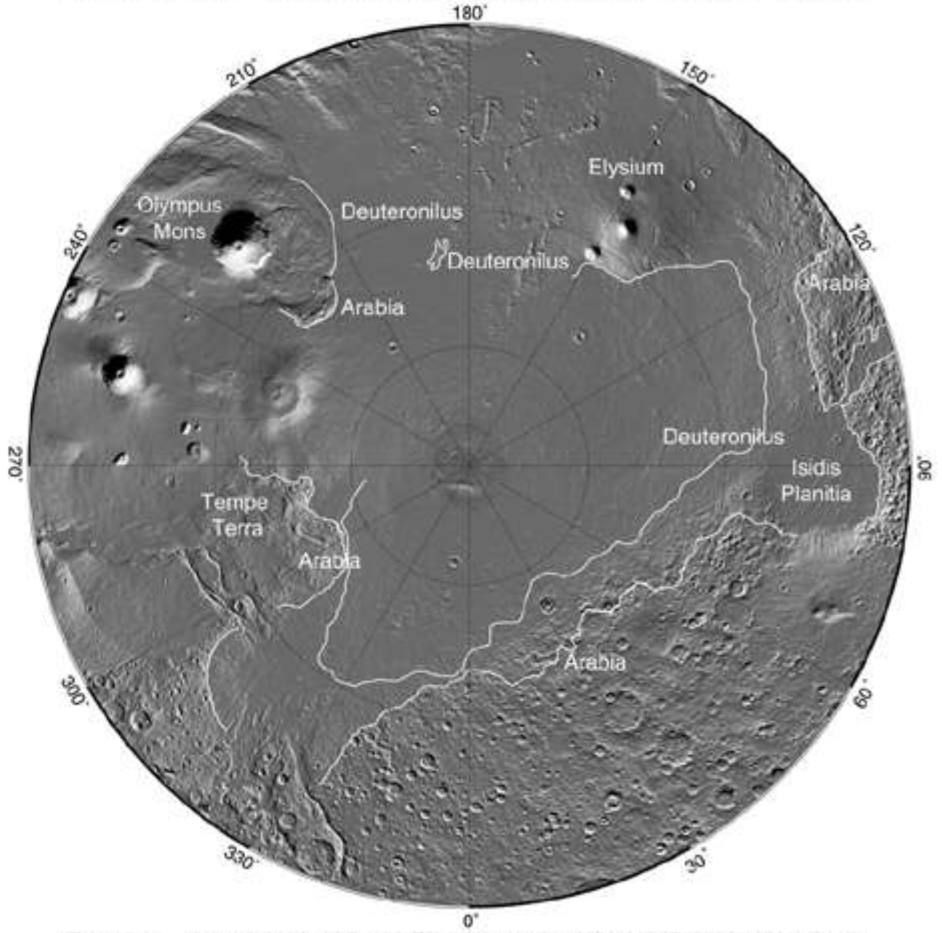
2003-07-03 | SCIENCE
Mars North Pole Water Stokes Life Hunt

A team of U.S. and Russian scientists may have discovered more ice on Mars' north end than was previously identified at the planet's south pole. The researchers detected large amounts of hydrogen, which combines with oxygen to form water. They believe that there is too much hydrogen for it to be present in any other form than water ice. The discovery means that Mars' north pole may be a good place to look for signs of past life.

Life as we know it cannot exist without water, and the search for water on Mars is a vital part of determining whether or not the planet could have supported ancient life.

[14] http://www.psrd.hawaii.edu/July03/MartianSea.html

Proposed Shorelines Arabia and Deuteronilus



(From Carr and Head, 2003, *JGR*, 108(E5),5042, doi:10.1029/2002JE001963,2003; Fig. 3.)

The two most continuous contacts, called the Arabia and Deuteronilus shorelines, generally parallel the southern boundary of the northern plains. The Arabia shoreline can be traced all around the planet except through the Tharsis region. The elevation of the Arabia contact varies by several kilometers, in some places by 11 kilometers. This large range in elevations does not support a shoreline interpretation. Features of the proposed shoreline that have been interpreted as formed by wave actions or other marine processes can be equally argued as being formed by mass wasting and volcanic processes.

The Deuteronilus contact is more subtle than the Arabia contact but has a smaller range in elevations. For nearly half its length the Deuteronilus marks the southern extent of the geologic unit called the Vastitas Borealis Formation. For the rest of its length it is seen only intermittently around clusters of hills or across lava flows. There is sparse direct evidence that the Deuteronilus contact is a shoreline, such as inward-facing cliffs or channels that end abruptly at the contact.

According to the report by Carr and Head clear evidence of post-Noachian shorelines around the northern plains is ambiguous. They argue that some of the previously mapped contacts are clearly of volcanic origin, that all have significant variations in elevation, and that there is no strong support at this time for most of the proposed shorelines. But his does not mean shorelines never existed. Shorelines or other marine depositional or erosional features could have been obscured or destroyed by later geologic processes such as cratering impacts, erosion, volcanism, and tectonism. The difficulties in proving the existence of shorelines would appear to weaken the oceans hypothesis, but Carr and Head show that it gains support from other geologic evidence.

[15] Ibid..

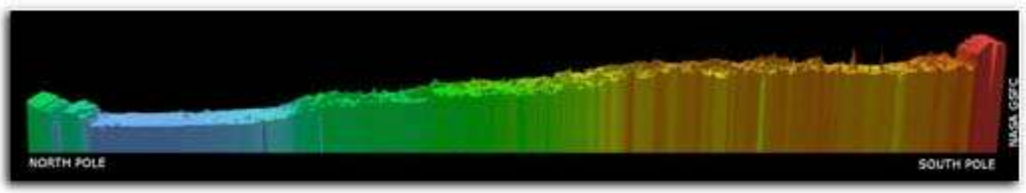
To cover all the area now mapped as the Upper Hesperian VBF would take about $2.3x10^7$ km^3 of water according to Carr and Head's assessment. Spread over the surface of Mars, this volume is equal to a global layer of water (Global Equivalent Layer or GEL) about 156 meters deep.

water ice on the Poles would tend to refill low areas on Mars near them. So the Northern Lowlands[16], comprising much of the Northern Hemisphere might be partially filled with water, some of which might reform as ice, and other areas nearer the impact site remaining liquid if Mars is warm enough. So the areas near the hot crater impact would vaporize water forming clouds, rain, etc which would likely condense in colder areas of Mars as rain or snow. Near the impact crater should be found liquid water and further away depending on the overall amount of heat release. Salts [17] would dissolve in the water and keep some of it liquid at lower

[16] http://www.astro.virginia.edu/class/oconnell/astr121/test/mars-status-aaas-200.html

Analysis of MOLA data has shown conclusively that Mars' northern hemisphere is extremely smooth, one of the smoothest regions seen on any planet. The southern hemisphere, on the other hand, is very rough- indeed; Mars is shaped with a gentle slope such that north is "downhill" from south on Mars. The north pole of Mars is 6 km lower than the south pole. This is of extreme importance when consideration is give to the behavior of liquid water on the surface of Mars.

The global maps made of Martian topography show what would seem to be a large ocean basin in Mars northern hemisphere compete with drainage system running from South to North which could have fed it with water. The images his team generated have different colors assigned to different elevations. Blue is lowest (5 km below the average planetary mean) white is highest (23 km above). While Smith was leery of suggesting that there was indeed an ocean, he did point out that it would have had to have existed long ago. Some channels which seem to have been caused by flowing water lead from the highlands all the way up to the present ice cap and have left channels in the flat northern plains. This could only have happened after the area was free of water.



Just as Martian oceans were described as being quite ancient, the age of the current polar caps was described as being quite the opposite. While the southern ice cap is at a higher elevation than the northern cap, they both show a similar profile and are thought to be composed of water ice covered and/or mixed wit with carbon dioxide ice. When one looks at the way in which Mars poles wander over time and the effect this has on lighting conditions at the poles, it becomes clear that there were periods where the poles would receive sufficient sunlight so as to cause the caps to melt and not reform.

[17] http://www.spacedaily.com/news/mars-water-science-00a.html

The substantial enrichment of the Martian soil with chlorine and sulfur discovered at the Viking 1 and 2 and Mars Pathfinder landing sites [1, 3] makes it more probable that the water-soluble salts (as chlorides and sulfates) may exist on Mars surface [6].

Such salts as NaCl, MgCl2, and CaCl2 are considered as the most probable candidates for salts contained in the Martian regolith [2, 6].

The solutions of the salts have eutectic points (or temperature of total solution freezing) at 252, 238, and 218 K respectively [7, 8].

If the Martian regolith contain multi-component salt solutions, their eutectic point is lower and will attain 210 K [7].

The zone of the temporal existence of the solutions in the surface regolith may be associated directly with the layer of seasonal temperature variation within the ice-containing regolith.

When the temperatures in the layer are higher (seasonally) than the freezing point of the eutectic mixtures (ice + salt), an appearance of the liquid phase in the soil is becoming possible.

The ultimate amount of the liquid phase will depend on the amount of ice and salts in the regolith.

The quasi-periodic axial-obliquity changes (from minimal to maximal over a period of 125 kyr [9, 10]) are one of the chief factors responsible for time-dependent changes of the ground ice stability on the Martian surface as the function of the latitude.

temperatures, in other areas ice sheets might form. Since much of Mars is already warm enough to melt ice, these ice sheets might be confined to higher latitudes. This large amount of water and ice should form oceans, rivers[18 19], aquifers[20], and lakes[21],

---

[18] http://www.pnas.org/cgi/reprint/99/4/1780.pdf

Valley networks and channels on Mars were discovered during the Mariner 9 mission (1, 2). Alternatives for their origin have been suggested, but the most widely accepted formation hypothesis is by erosion, and the most likely erosive agent is water (3, 4). The interpretation of ubiquitous erosion by surface runoff has often been taken to imply a warmer, wetter
climate on early Mars than the present cold and tenuous atmosphere can support (e.g., refs. 5, and 6). Recent precise observations of Martian topography (7) afford, for the first time, the opportunity to carry out the type of watershed analysis that has been traditionally restricted to Earth, developing quantitative measures relevant to erosion style and intensity.

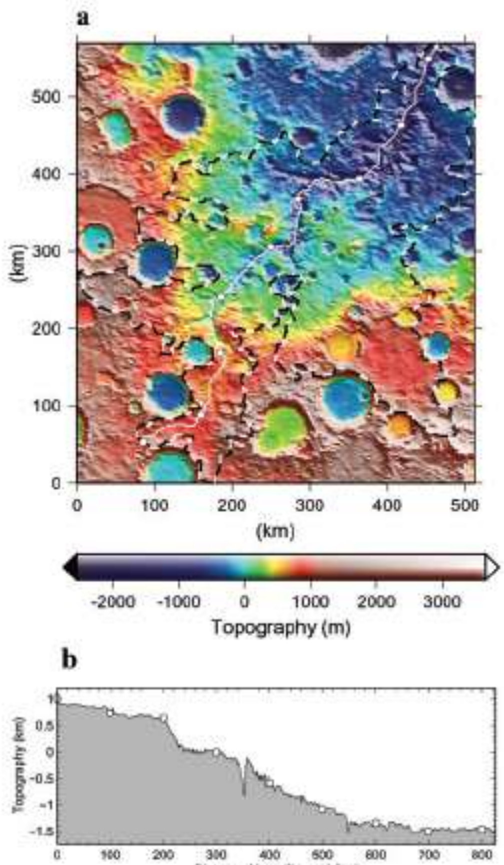


Fig. 3. Topography of Al-Qahira Vallis, Mars. (a) Map view and (b) longitudinal profile. The basin boundary, main stream, and 100-km intervals are as in Fig. 1.

[19] http://geology.geoscienceworld.org/cgi/content/abstract/31/9/757

Earlier analyses of valley networks on Mars often concluded that they were poorly integrated, immature drainage systems. Consequently, surface runoff from precipitation was generally thought to be an unimportant geomorphic process. Combination of Mars Global Surveyor (MGS) imaging and altimetry data sets, however, provides a vast improvement in image clarity and resolution. Although we have used the same defining characteristics for valley networks as used in previous work, our mapping in the Martian highlands reveals up to an order of magnitude higher values for the number of valleys, total valley length, and drainage density. Segments can now be mapped a greater distance with the result that the heads of numerous systems reach right up to the drainage divides. Moreover, MGS data show that many previously mapped, unconnected, low-stream-order segments are part of larger, integrated, mature drainage networks. In light of these new data, it is likely that surface runoff (and, by inference, precipitation) played an important role in the sculpting of large regions of the Martian landscape early in the planet's history.

probably in the existing low areas and ancient river systems[22]. This should create weather on Mars and rainfall in land areas, such as on most of higher ground in the

[20] http://www.spaceref.com/news/viewpr.html?pid=6237

An enormous ancient drainage basin and aquifer system lies hidden and deformed in one of the most geologically dynamic landscapes on Mars, scientists conclude from a comprehensive, more than 10-year study.

They estimate that a basin almost the size of the United States or Europe for billions of years covered part of Tharsis, a magmatically active bulge in the western hemisphere. Tharsis landforms are a complex of towering volcanoes, lava flow fields, igneous plateaus, fault and rift systems, flood channels, vast canyon systems, and tectonic features. Most scientists believe that periodic release of internal planetary heat at Tharsis has for more than three billion years had a major impact on Mars' geology, hydrology and climate.

Parts of the aquifer may harbor near-surface water and possibly life, they add.

[21] http://www.centrofermi.it/download.php?doc=upload/doc/doc43d75bcfc73f5.pdf

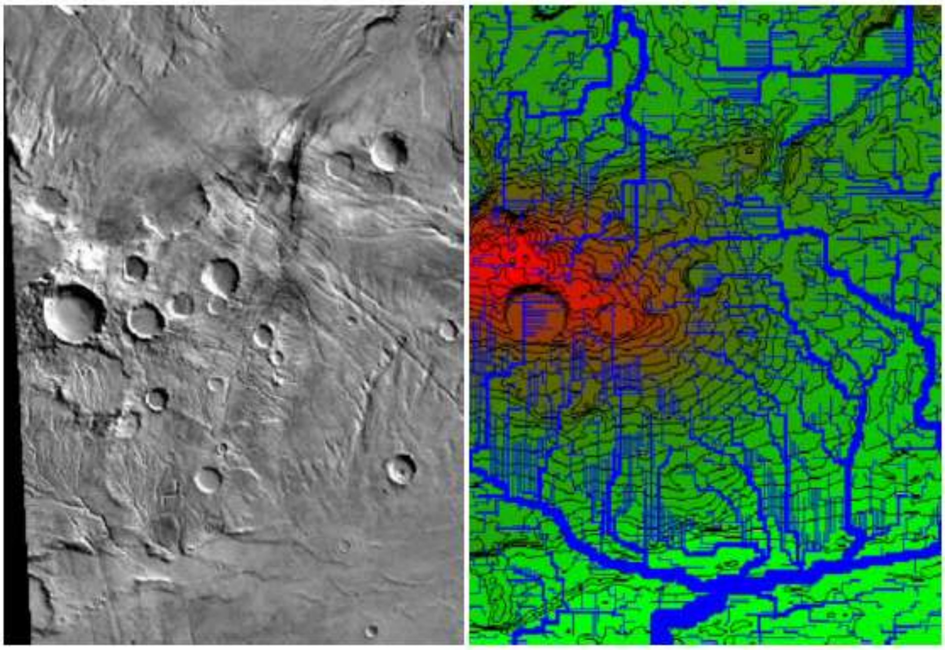
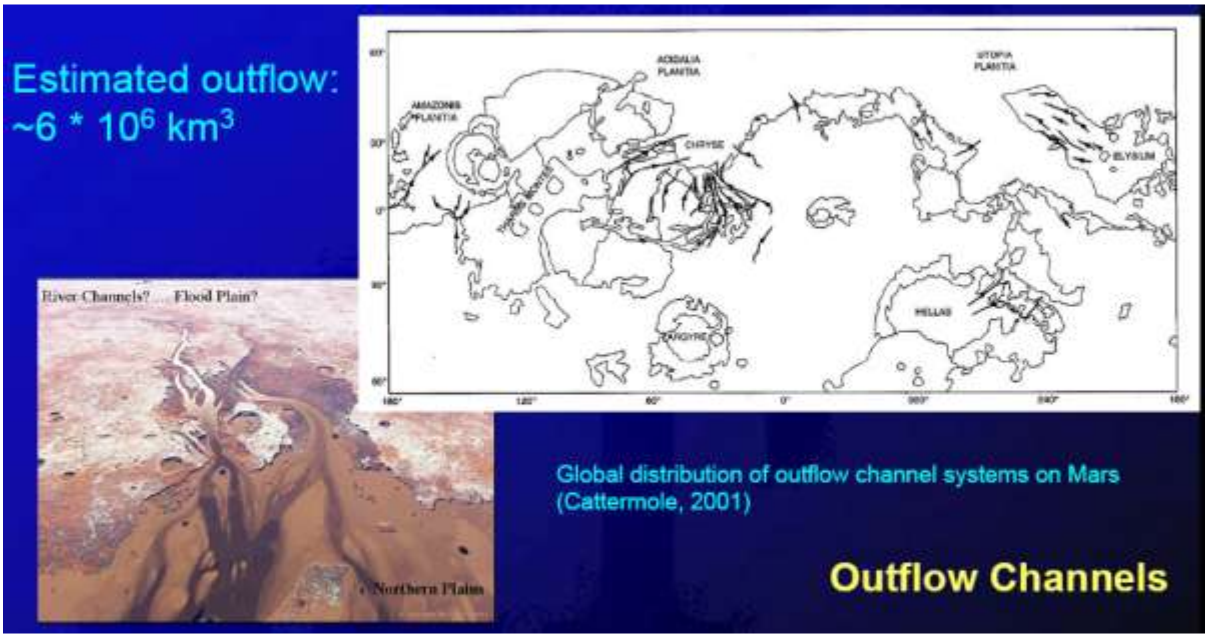


Fig. 1. (left):Viking Image for the Warrego Vallis (around 41°S, 91°W); some "river-like" structures are present on the center-left (courtesy from NASA, PDS Planetary Image Atlas). (right): Computer reconstruction of the landscape in the area of Warrego Vallis, after pit removal. The reconstructed river structure is similar to the visible one on the photograph.

[22] http://www.museum.hu-berlin.de/min/lehre/vorlesung/GeoDynMars/Mars7Fluviatile.pdf

Southern Hemisphere. For example in the Northern Summer there would be more water vaporized on the North Pole and more ice forming on the South Pole. In the Southern Summer the extra heat and air pressure should cause ice on the South Pole to partially melt rather than convert directly to vapor and so create a sea around the Pole such as in the Prometheus Basin[23].

2. **Thickening the atmosphere.** The fracturing of the ground should cause gases to be expelled from volcanoes, and thicken the atmosphere. Also the impact heat on the Pole should stop CO2 from freezing there. The air pressure on Mars from melting the poles might be increased to 10% or more of Earth pressure, even higher in lower areas[24]. This is based on studies of increased axial tilt sublimating all the CO2 at the poles on Mars[25]. In addition volcanoes formed by this terraforming meteor impact



[23] http://en.wikipedia.org/wiki/Promethei_Terra

Promethei Terra is a large Martian region, centered at 57.7S, 100E and covering 3300 km at its broadest extent. It lies to the east of the massive Hellas basin. Like much of the southern part of the planet it is a heavily cratered, highland region planet. Promethei Terra was named for a classic albedo feature of Mars, with the original name derived from that of the Greek god Prometheus.

[24] http://en.wikipedia.org/wiki/Colonization_of_Mars

Valles Marineris, the "Grand Canyon" of Mars, is over 3,000 km long and averages 8 km deep. Atmospheric pressure at the bottom would be some 25% higher than the surface average, 0.9 kPa vs 0.7 kPa. The canyon runs roughly east-west, so shadows from its walls should not interfere too badly with solar power collection. River channels lead from the canyon, indicating it was once flooded.

[25] http://www.spacedaily.com/news/lunarplanet-2001-01a6.html

Another possibility has to do with the fact -- pretty universally accepted -- that Mars, without a large moon to stabilize it, has its "obliquity" (the tilt of its spin axis) slowly rock back and forth between 0 and 45 degrees over a cycle of about a hundred thousand years -- with less frequent periods during which it may tile all the way over to 60 degrees, leaving the planet "lying on its side" the way Uranus and Pluto do.

could increase the air pressure even more[26] [27] [28]. Initially this air pressure would be mostly CO2 but terraforming would include the use of plants to convert much of this to Oxygen. If this could be done then the atmosphere of Mars could not refreeze at the Poles because oxygen has a much lower freezing temperature than CO2. So the window of opportunity would be to convert this CO2 into Oxygen with various plants, lichen, algae[29], etc. Once most of the CO2 was converted to Oxygen then the atmosphere of Mars might be 20% of our own air pressure but with a higher concentration of oxygen. So since most of our atmosphere is Nitrogen the higher

---

Very strange things happen to the weather of such a planet; because one pole or the other is continually exposed to sunlight for months at a time while equatorial regions still go through a day-night cycle, both poles actually get warmer year-round than the equator.

Such a climate cycle could cause water ice near the poles to thaw out and vaporize in Mars' thin air, migrate to somewhat lower latitudes and then refreeze -- after which, as Mars' tilt reduced again and its lower-latitude regions warmed up, the water ice stored there would again thaw out, erupt from the gully sites as liquid and then evaporate into the thin air, and then migrate back to the poles and refreeze.

John F. Mustard pointed out at the Conference that MGS has shown that this same 30 to 60-degree latitude zone on Mars is widely covered by "stippled" terrain covered by pits just a few meters across.

He proposes that the 100,000-year climate cycle alternately causes Mars' windblown dust in such regions to be fused together into a smooth permafrost surface when it lands, and then causes the surface to become rough again during the next stage of the cycle when the ice in the upper 1 to 10 meters of soil warms up and sublimates back into the atmosphere to migrate back to the polar regions -- which, despite their periodic warming, never get warm enough below the soil surface for their ground ice to sublimate, so that they remain smoother-surfaced.

In some areas, the buildup of a thick surface layer of "duracrust" -- soil fused together into a hardpan when water sublimates out of it and leaves behind crusted sulfate salts, which is definitely known to cover a great deal of Mars' surface -- could seal away melting subsurface ground ice from sublimating back into the air, so that a near-surface layer of liquid water would build up and could occasionally break through and gush out onto slopes to form the isolated gully sites.

[26] http://www.lpi.usra.edu/meetings/LPSC98/pdf/1125.pdf

6) Plinian eruptions, gas input into the atmosphere, and climate change: Gulick et al. [16] have hypothesized an episodic ocean-induced CO2 greenhouse on Mars. Pulses of CO2 (one to two bars) injected into the Mars atmosphere could place the atmosphere into a stable, higher pressure, warmer greenhouse state for tens to hundreds of millions of years. Our calculations indicate that a significant phase of plinian eruptions of magma containing 0.5 wt % CO2 could provide of the order of 1/10 bar of CO2 to the atmosphere. Thus, because of the significant gas release, phases of plinian eruptions may be an important contributor to the atmosphere and have significant global effects.

[27] http://www.astro.virginia.edu/class/oconnell/astr121/test/mars-status-aaas-200.html

The large quantities of carbon dioxide and water vapor that could have been outgassed by Tharsis magma may have also played a significant role in Mars' wet period; Roger J. Phillips calculated in 2001 that it could have formed a 1.5-bar carbon dioxide atmosphere and a global layer of water that averaged 120 meters thick.

[28] http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3021.pdf

Episodic volcanism is another possible mechanism for perturbing the climate, as recognized for Earth [30].
The construction of Tharsis can deliver substantial quantities of water and CO2 to the atmosphere. A global equivalent layer of 120 m of water and a 1.5 bar CO2 atmosphere have been estimated [1], and preliminary modeling has explored the climatic implications of Tharsis outgassing [31]. We have little information on the level of episodicity of Tharsis construction. The rate at which volatiles were supplied to the atmosphere versus the rate at which they were removed [e.g., by carbonate deposition (little observed), solar wind stripping, thermal escape, and impact erosion] would dictate the role of Tharsis in perturbing the climate sufficiently to carve valley networks and foster widespread erosion events.

[29] http://www.physorg.com/pdf4156.pdf

The algae also managed to survive when it was shielded from the direct onslaught of UV rays by a millimeter-thick layer of sand or rock.

percentage of Oxygen in the Martian atmosphere might make it easier to thicken later, perhaps one day to breathe it unaided or only wearing a respirator and no space suit. If one was breathing in mainly Oxygen Martian atmosphere and the air pressure 10% of our own, then each breath might contain similar amounts of Oxygen as on Earth. One analogy might be like a plane pilot flying at reduced air pressure with a respirator, walking on Mars might one day be similar to this experience.

3. **Antipodal effects[30] [31].** Opposite the Argyre impact crater there is Elysium Mons. It is likely this formed from a shock wave going through the Martian core and fracturing the ground opposite, which created the volcano. If the same thing happened in the terraforming process a volcano, or at least a hot spot[32] might form near the South Pole which would melt ice[33] and create a smaller sea[34] around the Pole.

---

[30] http://www.newgeology.us/presentation35.html

How much disruption would be caused has been argued among researchers. Some hold that many volcanic "hotspots" and even flood basalts were triggered by antipodal effects,[3] while others find the energy reaching the antipode to be insufficient to cause volcanism.[4] Disrupted terrain, and possibly volcanism, are thought to have been found antipodal to large impact craters on the Moon, Mars, and Mercury.[12,14]

[31] http://adsabs.harvard.edu/abs/1994Icar..110..196W

The regions anitpodal to Mars' three largest impact basins, Hellas, Isidis, and Argyre, were assessed for evidence of impact-induced disrupted terrains. Photogeology and computer modeling using the Simplified Arbitrary Lagrangian Eulerian (SALE) finite element code suggest that such terrains could have been found by the Hellas impact. Maximum antipodal pressures are 1100 MPa for Hellas, 520 MPa for Isidis, and 150 MPa for Argyre. The results suggest that if antipodal fracturing were associated with later volcanism, then Alba Patera may be related to the Hellas event, as proposed by Peterson (1978). Alba Patera is a unique volcano in the solar system, being a shield volcano which emitted large volume lava flows. This volcanism could be the result of the focusing of seismic energy which created a fractured region that served as a volcanic conduit for the future release of large volumes of magma. No disrupted terrain features are observed antipodal to the Isidis or Argyre basins, although some of the old fractures in Noctis Labyrinthus could have originated in response to the Isidis impact, and later have been reactivated by the Tharsis tectonics assumed to have produced Noctis. If the lower calculated antipodal pressures for Argyre were capable of producing disrupted terrains, then the terrains have been covered subsequently by volcanic or aeolian material, or modified beyond recognition.

[32] http://www.mantleplumes.org/WebDocuments/Antip_hot.pdf

5. Conclusions

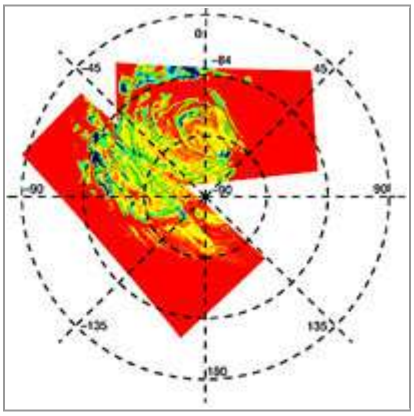
Models of hotspot (and LIP) origins are apparently in need of modification to explain the antipodal character of their distribution (Table 1). Herein, an inherently antipodal mechanism of hotspot formation is proposed in which one hotspot forms at an oceanic large-body impact site and a second hotspot and possible LIP are formed from seismic energy focused in the lithosphere and upper asthenosphere at the impact's antipode. Continental impact structures lack associated hotspot volcanism and are generally without antipodal volcanism, except for the largest ones that initially appear to have had small antipodal hotspots. Continents, due to their lower expected seismic efficiencies, therefore, are suggested to have mostly shielded the formation of antipodal hotspot pairs.

[33] http://www.esa.int/SPECIALS/Mars_Express/SEMYKEX5WRD_0.html

Recent space missions then suggested that the southern ice cap, existing all year round, could be a mixture of water and carbon dioxide. But only with Mars Express have scientists been able to confirm directly for the first time that water ice is present at the south pole too.

4. **Shock wave rock heating.** Because the shock wave would extend along the surface then rock in its path would be heated. This heat would persist for a long time and

---



OMEGA view of Martian south pole, showing water ice areas (blue)

Mars Express made observations with its OMEGA instrument to measure the amounts of sunlight and heat reflected from the Martian polar region. When planetary scientists analysed the data, it clearly showed that, as well as carbon dioxide ice, water ice was present too.

The results showed that hundreds of square kilometres of 'permafrost' surround the south pole. Permafrost is water ice, mixed into the soil of Mars, and frozen to the hardness of solid rock by the low Martian temperatures. This is the reason why water ice has been hidden from detection until now - because the soil with which it is mixed cannot reflect light easily and so it appears dark.

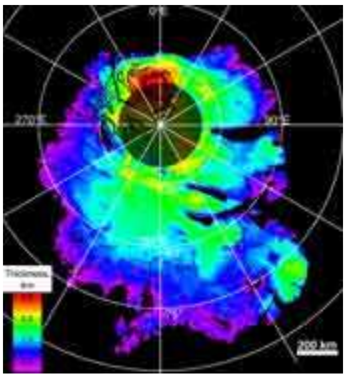
[34] http://news.nationalgeographic.com/news/2007/03/070315-mars-water.html

Mars Pole Holds Enough Ice to Flood Planet, Radar Study Shows

Richard A. Lovett
for National Geographic News
March 15, 2007

Mars's southern polar ice cap contains enough water to cover the entire planet approximately 36 feet (11 meters) deep if melted, according to a new radar study.

It's the most precise calculation yet for the thickness of the red planet's ice, according to the international team of researchers responsible for the discovery (see a map of Mars).


Enlarge Photo

Using an ice-penetrating radar to map the south pole's underlying terrain, the scientists calculated that the ice is up to 2.2 miles (3,500 meters) thick in places, said the study's leader, Jeffrey Plaut of NASA's Jet Propulsion Laboratory in Pasadena, California.

The radar, from the Mars Express orbiter, also revealed the surprising purity of the ice, Plaut added.

also lead to many smaller volcanoes in its path from fractures in the ground. These are similar to those seen in Solis Planum as well as the larger volcanoes of Tharsis and Olympus Mons. So CO2 and ice reforming on the poles should be heated and vaporized, creating a kind of weather pattern.

5. **Weather patterns.** The poles would become much hotter, so any ice depositing on the poles would be revaporized for a long time. This might create weather patterns, Hadley Cells, etc on Mars since some parts would be much hotter than others and limited oceans should form. With a hotter landmass and colder ocean, this on Earth forms clouds and rain. The Poles then might be surrounded by storms, rain, snow, etc and this constant injection of water into the atmosphere should create weather all over Mars.

6. **Moving ice and debris.** It is likely that ice, CO2 and rock from the impact would be sent up into the atmosphere, even into orbit and land in other areas. So this ice and CO2 would melt and sublimate if it lands at lower latitudes on Mars.

7. **Rifts.** Fractures caused by the shockwave should cause rifts in the Pole area, into which melted water would fall and be heated by rock in them creating steam. So these rifts might continue for a long time to add humidity to the atmosphere and thus rain.

8. **Buried ice.** Ice buried in other areas such as ancient poles might also melt creating and replenishing the water table, lakes, etc. Examples include around Solis Planum[35], Meridiani Planum, Gusev, etc.

9. **Polar wander.** The redistribution of water and CO2 would affect the weight distribution of Mars and likely lead to renewed Polar Wander[36]. So if this was

---

[35] http://epswww.unm.edu/iom/pubs/Elphic2011.pdf

Discussion: Both geologic evidence and GCM calculations point to past epochs of increased water ice deposition on the western flanks of the Tharsis Montes, and Olympus Mons. GCM simulations also suggest these same areas preferentially retain ice longer than other nearby locales. Taken together, these results suggest that enhanced surface and regolith ice accumulations on the windward slopes of the volcanoes during earlier periods of high obliquity led to either remnant ice deposits or stable hydrated minerals in the soils whose hydrogen can still be sensed today.

[36] http://www.lpi.usra.edu/meetings/lpsc2000/pdf/1930.pdf

A proposed wandering path [12] for the south pole of Mars is shown on Fig. 1. The solid triangles represent pole positions based largely on geomorphic evidence; the open triangles represent possible pole positions based on grazing impacts. The better fitting paleomagnetic pole positions (gray areas) in the equatorial regions near the prime meridian agree remarkably well with the Schultz and Lutz model for polar wandering. The best-fit paleomagnetic south pole position along the polar wandering path is near 45oE, 15o S, southeast of C'. This ancient pole corresponds to the chaotic terrains of eastern Valles Marineris, and at the antipode, to the southeast slope of Elysium Mons, not far from the very old and heavily eroded deposits south of Elysium Planitia.

relatively rapid then the old Poles would be moved closer to the Equator and thus fully melt, releasing all their ice as water. Since the Poles may have been near the current Equator before the terraforming may cause them to move back in that direction.

10. **Brine.** It is likely the Martian soil would contain large amounts of salts[37] [38]which would dissolve into this relatively pure water from the Poles. This would lower its freezing temperature and result in water staying liquid at lower temperatures[39].

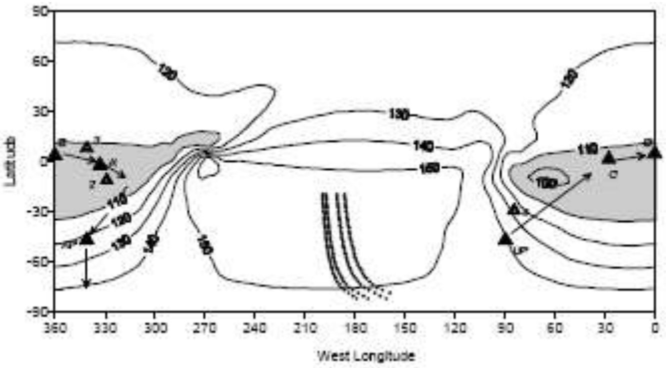


Fig 1.

[37] http://www.physorg.com/pdf7981.pdf

Chittenden and Sears used a planetary environmental chamber in the W.M. Keck Laboratory for Space Simulation to simulate the conditions found on Mars - an atmosphere of carbon dioxide, 7 millibars of pressure and temperatures from zero degrees Celsius to 25 degrees below - and examined the evaporation rates of brine solutions expected to be found on Mars. Most water on Earth contains salts that leech into the water when it comes in contact with soil, and similar processes might be expected to occur in any surface water found on the Red Planet. Salts in the water lower the freezing point of the solution. The University of Arkansas team placed the salt solutions in the planetary environmental chamber simulating Mars-like conditions, and then measured the evaporation rates at varying temperatures. "There's a huge decrease in the evaporation rate the colder it gets, more than anyone realized," Chittenden said. With the dissolved sodium and calcium in the water, the freezing point for the brine mixtures drops to 21 degrees below zero Celsius for salt water and 50 degrees below zero for water containing calcium chloride. Temperatures on Mars vary between 125 degrees below zero Celsius and 28 degrees above at different latitudes and different times of the day. Thus, there is a possibility that liquid water could exist on the planet's surface at different locations and times of day. "Brine formation could considerably increase the stability of water on Mars by both extending the temperature range over which liquid water is stable to negative-40 degrees Celsius and by decreasing the evaporation rates by two orders of magnitude," the researchers wrote.

[38] http://ndeaa.jpl.nasa.gov/nasa-nde/usdc/papers/Polar-Conf-Gopher-03-8019.pdf

Introduction: Evidence for the presence of ice and fluids near the surface of Mars in both the distant and recent past is growing with each new mission to the Planet. One explanation for fluids forming springlike features on Mars is the discharge of subsurface brines. Brines offer potential refugia for extant Martian life, and near surface ice could preserve a record of past life on the planet.

[39] http://www.lpi.usra.edu/meetings/lpsc2001/pdf/1689.pdf

Phase Equilibria:
H2O-salt. Addition of salt to water causes the triple point to migrate to lower temperatures and lower pressures.
While many workers have studied the depression of the freezing temperature when salt is added to water, there are relatively few studies of the vapor pressures over water-salt solutions at low temperatures, and these are summarized on Figure 2. To a first approximation, the vapor pressure at the triple point is controlled by the vapor pressure of water ice at that temperature. At the H2O-CaCl2 eutectic temperature (□ 223K) the vapor pressure is about 40 mbar. Stated differently, a calcium chloride-rich brine is stable at any temperature and pressure above 223K and 40 mbar, and much of the range martian surface P-T conditions
falls within the liquid stability field for a calcium chloride brine (Fig. 2).

11. **Triple Point.** Potentially Mars might be covered perhaps 40% or more with water and ice if the Northern Lowlands is filled, and the higher air pressure should maintain this liquid phase of water for a time. Currently on Mars the low air pressure causes the triple point of water to only be reached rarely so water ice usually goes directly to water vapor without forming water. However it is believed that even now brines can survive for long periods on Mars without evaporating, so with higher air pressure open water might be permanent[40].

Habitation

The North Pole impact might create a sea in the Northern Lowlands area, particularly near the impact crater. If the crater is near enough to the Pole then in winter CO2 and water ice would be vaporized creating more weather patterns.

The most stable area for weather would depend on the disturbances caused. If necessary people could settle on the opposite hemisphere to the crater could be used to be shielded from the weather, for example there may be caves[41] and lava tubes around Elysium Mons.

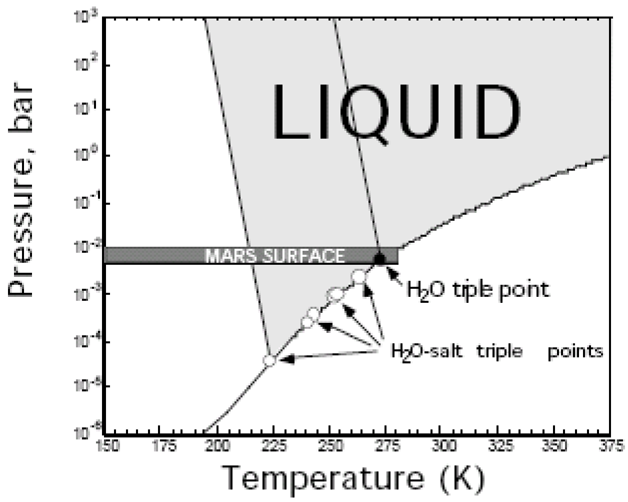


Fig. 2. P-T diagram showing the stability field for liquid brines, compared to the estimated temperature-pressure conditions on the martian surface (shaded horizontal box). Note that much of the range of surface P-T conditions falls within the liquid field.

[40] http://www.uark.edu/depts/cosmo/publications/pub%20by%20year/2004%20papers/sears%20et%20al%202004d.pdf

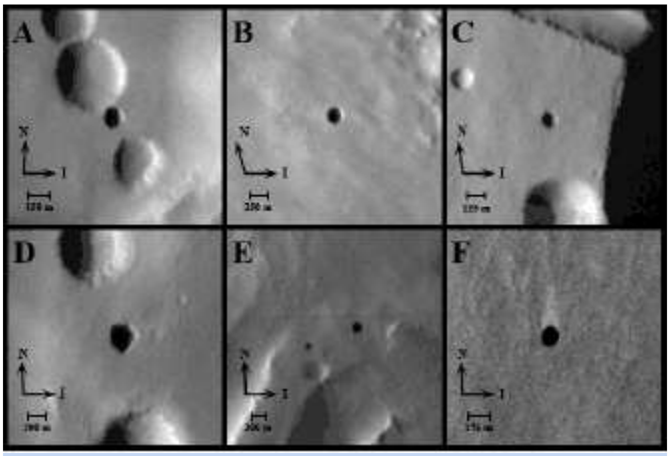
Implications for Mars: The existence of solute ions in the water does not decrease evaporation rates so this is not a mechanism for increasing the stability of water on Mars. However, the suppression of the freezing point caused by the presence of solute in the water does enlarge the stability field of water. Haberle et al. showed
that, if sufficiently concentrated, brine could exist over most of Mars depending on the availability of ice and a
heat source, and the evaporation rate [5].

[41] http://www.astrobio.net/news/modules.php?op=modload&name=News&file=article&sid=2290

Also higher ground would be needed if widespread flooding occurs so the Southern hemisphere may be best. Hellas Crater might partially fill with water from the melting South Pole and the air pressure would be higher in it for settlements.

The water might be seeded with algae and there would be less radiation owing to the depth of water and thickened atmosphere. Snow[42] has been shown to reduce radiation enough for life to survive even without a thicker atmosphere. Some areas[43] may already have moisture in the soil, so the thickening of the atmosphere could only increase this.

Also there are places on the Martian surface[44] which are more shielded from the solar wind by remnants of the magnetic field. These would have reduced radiation for human habitation.



Researchers propose these images of seven black spots near a massive Martian volcano may actually be caves rather than impact craters. The images were taken from the Thermal Emission Imaging System aboard NASA's Mars Odyssey orbiter.

Applying techniques used to scope out caves on Earth to probe the possibility of caves on Mars is paying off.
NAU researchers Glen Cushing and J. Judson Wynne, working at the U.S. Geological Survey, propose that photos from the Mars Odyssey mission reveal football-field size holes that could be entrances to caves.

[42] http://www.astrobio.net/cgi-bin/h2p.cgi?sid=380&ext=.pdf

On steep slopes in martian craters, recently melting snow may have created a system of gullies, says Philip Christensen, the principal investigator for the Mars Odyssey THEMIS camera system and a professor from Arizona State University. He says that the melted water collecting underneath these snow packs also could have created an ideal abode for life. "I think we have discovered remnants of snow packs on Mars that in the recent past have melted," says Christensen. "I think if you were to land on one of those and stick a shovel in the ground, you´d be shoveling snow. And if life ever existed on Mars, I can´t think of a more exciting place to possibly go and look."
Christensen examined martian images of gullies and what he termed "pasted–on materials." In his paper,
published in the electronic February 13 issue of Nature, Christensen argues that that the pasted–on materials are remnants of a once very extensive layer of snow that covered the mid–latitudes of Mars.
"This snow draped the landscape, and as the climate warmed, the snows melted," says Christensen. The snow sheltered the water, which otherwise would have rapidly evaporated in the planet´s thin atmosphere. "That melt water trickled through the snow and eroded the gullies underneath this overlying pack of snow."

[43] http://mars.spherix.com/5555-14.PDF

The evidence presented strongly indicates the presence of liquid water or moisture at the Mars Exploration Rover sites. Recent or current mini-erosion features have been seen. Images taken through filters indicate the presence of moisture or liquid water. Evidence that could be interpreted as standing liquid water has been presented. Soil surface temperatures at both the Opportunity and Spirit Rover sites, as at the Viking Lander sites and the Pathfinder site, rise above freezing at some portion of the day, perhaps seasonally. It would thus seem that all factors necessary to constitute a habitat for life as we know it exist on current-day Mars.
[44] http://www.berkeley.edu/news/media/releases/2000/12/15_mars.html

Conclusions

This theory attempts to recreate a known event in the Martian past to terraform Mars. So, if correct, we can determine much of what is likely to happen from observing the geology of the Valles Marineris and Solis Planum areas. Such an impact would cause large amounts of heat to melt CO_2 and ice, but after a few decades this is likely to reach equilibrium. So people might be able to inhabit Mars, particularly in caves and lava tubes[45] and areas with high levels of magnetism in the rocks soon after the impact.

If the events depicted of the Argyre impact are accurate then such an impact would be a cost effective way to heat Mars, melt its Polar ice caps and thicken its atmosphere.

Mars' patchwork magnetic field acts as array of umbrellas to protect planet's atmosphere, according to new mapping study by Mars Global Surveyor

15 Dec 2000

By Robert Sanders, Media Relations

Color maps of the ionosphere and the surface magnetic fields are available for download

Berkeley - Though Mars lacks a global protective magnetic shield like that of the Earth, strong localized magnetic fields embedded in the crust appear to be a significant barrier to erosion of the atmosphere by the solar wind.

This conclusion by a researcher at the University of California, Berkeley, emerges from a new map of the limits of the planet's ionosphere obtained by the Mars Global Surveyor spacecraft, which was launched in 1996 and reached the planet 10 months later. The new data show that where localized surface magnetic fields are strong, the ionosphere reaches to a higher altitude, indicating that the solar wind is being kept at bay.

[45] http://www.norwebster.com/mars/lavatube.html

The idea of making use of lava tubes has been explored by many others. The largest body of research I have encountered, comes from the Moonbase group of the **Oregon L5 Society**. This Portland-based space advocacy group is the Oregon chapter of the National Space Society, has been actively involved in this concept for over a decade, only focusing on lunar lava tubes rather than Martian ones. Between 1987 and 1988, a series of experimental bases were constructed by the group in Central Oregon[2].