Searching for Water on a cold dry Mars

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Water on Mars

Underlying the rationale for the search for extant water on modern Mars is the assumption that surface features record a history of flowing water. The strongest evidence for past water comes from the outburst flood channels which clearly document episodes of fluid escape and erosion, and long-distance sediment transport, largely in the Hesperian (pre 3.0 to 3.5 Ga according to revised Neukum and Hartmann dating). Additional evidence comes from sapped valley networks in the Noachian, individual sapped channels at other geological times, and from the geologically recent gullies of Malin and Edgett. The contacts originally identified by Parker are also often interpreted as evidence for a Boreal Ocean. In short, there is ample observational evidence for fluid-related features on Mars and conventionally Occam's razor has been wielded in favour of water-based models despite some embarrassing paradoxes such as the lack of surface carbonates. Yet it should never be forgotten that water on Mars is an assumption, and one that does not match well with present surface conditions.

Non-Aqueous Flows

In the last couple of years, new flow models have been developed for non-aqueous flows that enable us to make a far more parsimonious interpretation of Mars' history. One that is Uniformitarian, is simple, and is fully compatible with the modern condition of Mars and also with Earth and Venus. This "White Mars" model proposes that phase changes of Carbon Dioxide are responsible for the vast majority, if not all, of the fluid flows on Mars. It is important that mission planners are aware of the implications of the White Mars model and that project scientists include the predictions of this model in the list of those they need to examine before evidence of water can be declared conclusive. In particular, extensive accumulations of liquid CO_2 are predicted within the regolith of Mars and are likely to be the shallowest subsurface liquids. Remote sensing and geophysical techniques must be able to discriminate between the properties of liquid water and liquid CO_2, and to identify the occurrence and proportions of the three possible ices – pure water ice, pure dry ice, and CO_2 Clathrate. Some of these distinctions are easily made with the right instruments. Others are more subtle, and interpretation of the data resulting from remote measurements must carefully account for all possibilities.

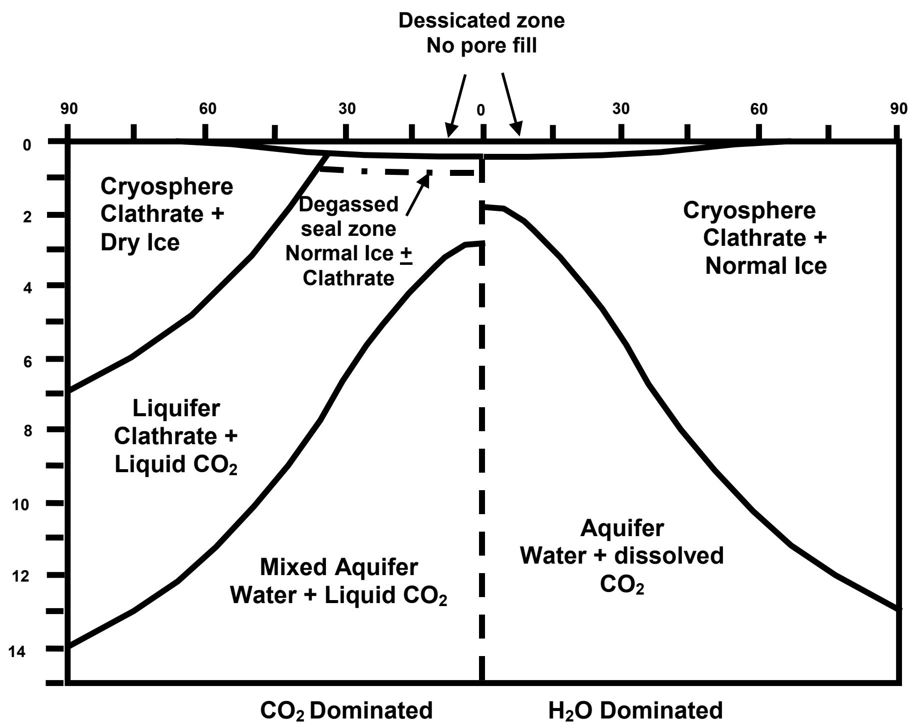
Carbon Dioxide on Mars

It is well known that the atmosphere of Mars consists largely of CO_2, and that seasonal polecaps of CO_2 frost & snow are deposited annually, accounting for over 25% of the atmospheric mass. This seasonal deposition is markedly asymmetric between the poles, with the south pole deposits being more extensive and thicker in the colder aphelion winter. A semi-permanent residual cap of CO_2 ice persists at the south pole through most winters. At the north pole, temperatures regularly exceed the frost point of CO_2 and the polecap there clearly contains large amounts of H_2O. It is not yet clear, however, whether the polecap consists of normal water ice or the preferred equilibrium phase – CO_2 clathrate (or a mixture of both).

The total CO_2 inventory of Mars is not known, but since atmospheric C and O isotopes are buffered strongly compared to H, it is reasonable to assume that permafrost deposits of CO_2 in the near-polar region account for a significant inventory (at least several hundred millibars and possibly as much as a few bars). The unfortunate loss of the Mars Polar Lander mission has left a number of gaps in our understanding of the polar ice and permafrost composition and extent.

What is less well understood is that the third phase of CO_2 – liquid CO_2 – is required to be present on Mars to at least some extent. Within the thick regolith of Mars, if pressure seals exist, as they commonly do on Earth, then pore pressures can rise towards the lithostatic pressure gradient (a condition that on Earth we would call "overpressured" and one that is integral to many water recycling scenarios in a wet Mars model). Mars also has low mean surface temperatures (~213 K) and low geothermal gradients (MOLA lithosphere thicknesses are at least twice those of Earth, and possibly 3 or 4 times at present day, implying ½ to ¼ the heat flux of Earth – i.e. 16 to 32 mW/m^2 and gradients of 7 to 15 K/km). This means that subsurface conditions are cryogenic (frozen) and overpressured – a perfect environment for liquid CO_2.

At the base of the CO_2 permafrost of Mars, and at the base of any polecap that contains inclusions or layers of pure CO_2 ice, basal melting will occur at depths of 2-4 km under pressure to yield liquid CO_2 at around –56 ^{o}C. This basal melt phase will permeate the near-polar regions as a deep fluid system – a "liquifer". Liquid water, even for strong brines, will not be encountered until temperatures have risen significantly. Given the low geotherms, this will be several km deeper and in polar regions is likely to be below the effective porosity floor of the regolith at ~10 km. In passing, we note that the best and most easily achieved pressure seal for a CO_2 liquifer is a pore-occluding deposit of water ice or clathrate.



Alternative views of the Martian Cryosphere - Present day surface temperatures, 10 K/km

Figure 1

A number of consequences arise from this crustal reservoir of CO_2. If the regolith is relatively permeable, then the CO_2 will escape readily and small CO_2 geysers and fumaroles will surround the permafrost regions. Escape of CO_2 from the liquid phase can be energetic and may be responsible, in part, for the erosion of pit chains along fissures and for the construction of cryptovolcanoes in “thumbprint” terrains of the northern lowlands.

If the regolith is not permeable, then larger deposits of liquid CO_2 will accumulate over geologic time and may be available for energetic breakout events following fracture of the seals by tectonic, volcanic or impact events. It is notable in this context that “splosh” craters attest to the existence of buried fluid reservoirs in the regolith, but are not uniquely evidence for water. In the hot and energetic aftermath of an impact, both water and CO_2 will be vaporised and will fluidise non-liquid flow of the splosh crater aprons.

Gas-Supported flows

A wide range of flows on Earth are classified as density flows. They involve the flow of a mass of debris supported by a fluid, within an ambient fluid. Familiar examples include submarine turbidites, where clay, sand, and rocks are supported by turbulent water and flow at the base of the ocean. Volcanic pyroclastic flows and surges are supported by hot air (volcanic gas and entrained atmosphere) and flow at the base of the atmosphere. Many meteorological phenomena such as dust storms and downdraughts are also density flows.

All that is required for a flow to occur is an initial mixing event where debris becomes airborne, and the persistence of a density contrast between the flow and the surrounding medium. Density flows can travel at near-supersonic speeds, extend for thousands of km, and transport metre-scale boulders for considerable distances. Larger flows travel further and carry larger loads. Density flows tend to erode channels in the proximal and medial reaches where erosion and transport predominate, and in distal regions they spread out into wide fans or sheet deposits. An extensive literature exists on these flows.

On Mars, new concepts have recently been proposed by this author that the association of chaos zones and outburst “flood” channels represent an explosive outburst of liquid CO_2 from subsurface storage. Extremely large density flows are sourced from these regions and over a matter of hours the flows make their way across thousands of km of Mars' surface to lowland depocentres where they spread out as airfall deposits.

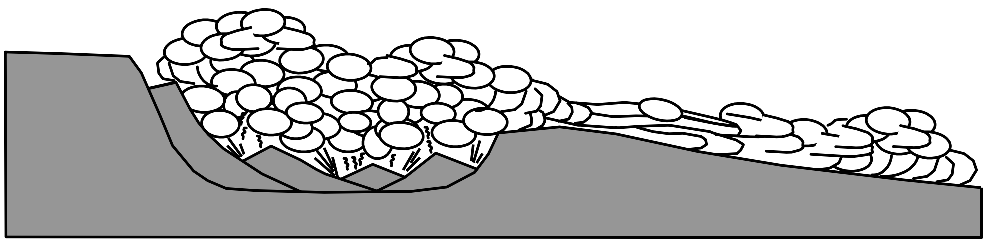


Figure 2 – Generation of a cryogenic vapour-supported density flow from a collapsing chaos zone saturated with liquid CO_2

Each individual chaos zone may be active over a period of hours to days (the same timescale as paroxysmal volcanic eruptions associated with caldera subsidence). Each chaos zone “erupts” once only and does not require the repeated episodes of aquifer recharge that a water model does. (Due to the expansion of CO_2 from liquid to vapour state, abundant gas is generated to carry the solid debris. A water flow, on the other hand, simply cannot supply enough liquid for the relatively dilute flows attested by the channel geometries and hence the aquifer must recharge multiple times to produce the final result).

White Mars

If we accept the basic tenet that liquid CO_2 outbursts can generate gas-supported flows that carved the outburst “flood” channels, then Mars’ entire history becomes clearer and simpler. We call this new model “White Mars” in emphasis of the role played by ices and cryogenic materials. White Mars attempts to explain the surface features and chemistry of Mars using CO_2 in the first instance, since this appears to be the dominant volatile on Mars with its own cycle between liquid, vapour and solid just like the hydrological cycle on Earth. Only when CO_2 fails to explain an aspect of Mars do we need to invoke liquid water.

Standard solar evolution models predict that the early Sun was cooler than at present (only 75% of present output at its formation). Mars already receives only 43% the solar energy of Earth, and 4 billion years ago this would have been reduced a further 20% to ~34%. If we apply a modern-day climate model to this reduced solar input, the polar equilibrium with dry ice drives the atmosphere down to less than 1 millibar and the mean surface temperature to ~196 K (c.f. present-day ~10 mbar and 213 K).

Large tracts of Mars surface become CO_2 permafrost zones at this level of insolation, and under pressure in the regolith solid and liquid CO_2 persist to low latitude. It is these deposits of CO_2 that are available in the Hesperian to explosively disrupt chaos zones and generate giant density flows that carved the outburst flood channels.

At other times, continued supply of liquid CO_2 into specific areas such as the flanks of volcanic edifices can lead to sapping-style erosion as the surface channel backtracks the feeder vein of liquid CO_2.

Since water is never required to carve the channels of Mars, surface conditions can remain cryogenic throughout geologic time and Mars need never have been warm and wet, nor had an ocean, lakes, or rivers of liquid water. The lack of surface carbonates is a direct consequence of the lack of liquid water. Mars in the past, therefore, appears to have been very much like modern-day Mars, but colder and drier. Mars’ warm and wet episode is now!

An interesting aspect of the White Mars model is that it provides a mechanism for the rapid emplacement of thick sediment deposits in the northern lowlands and elsewhere, as discussed by Tanaka’s “Mud Ocean” papers.

Recent Gullies on Mars

The excitement of the recent gullies rests on their interpretation as groundwater escape features. Unfortunately, recent presentations by Pascal Lee and by Francois

Costard at the 32nd Lunar and Planetary Science Conference have shown that groundwater is not involved in equivalent features in Earth's polar regions. Instead, springtime thaw of snowpack in the gully heads produces brief flows down the channels, while permafrost persists below 1 metre or so. The location of the gullies in cold poleward-facing regions suggests that a similar snow accumulation and thaw mechanism operates on Mars.

However, at the colder ambient temperatures, it is difficult to melt water ice/snow in this manner. The difficulty is resolved by reference to near-polar gullies on Mars. Here, we see deposits of CO_2 snow and ice in the gullies which defrost in the springtime and generate brief avalanches of CO_2-lubricated debris as the snowpack sublimes and collapses down-channel. All of this occurs at <150 K, the equilibrium temperature of dry ice and far below the limit of any water-based eutectic. Therefore it is likely that no liquids are involved at all in the flows and that the fluidising agent is, again, CO_2.

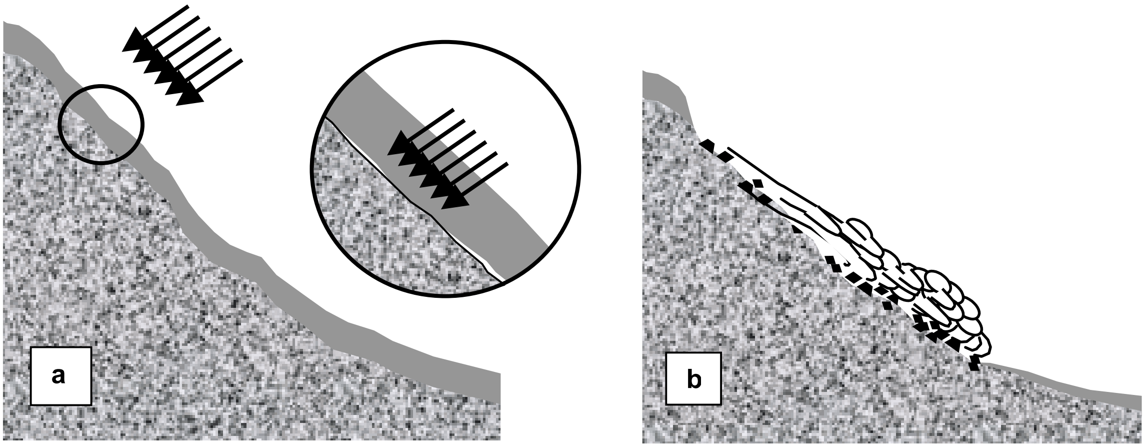


Figure 3: Sunlight warms CO_2 snowpack in a gully on Mars. As on earth, the energy largely penetrates the snow and warms the underlying substrate, which then thaws the ice from beneath. Subliming CO_2 builds gas pressure which triggers an avalanche of warm debris and cold ice – an ideal recipe for further outgassing and generating a gas-lubricated flow.

Water on White Mars

The implications and predictions of a White Mars model to the search for water are, primarily, that any liquid water will be deeply buried on cold modern Mars. Specifically, in polar regions liquid water will be highly unlikely in the upper 10 km of regolith and most geophysical techniques will be unable to sense deeply enough to detect this water. In equatorial regions where mean annual surface temperatures are around 220 K, modest brines are possible at temperatures down to 250 K. Given the low heat flow of Mars, however, this still equates to depths of 2-4 km. These depths should be reachable by a variety of electromagnetic geophysical techniques, but poor resolution would be expected of the detailed distribution. Pure water ice or clathrate would not melt until about twice this depth – again approaching the limits of sounding techniques, especially from orbit.

Clearly, the locations where liquid water will be easiest to detect will be those where the water comes closest to the surface. White Mars offers no special recipe for finding those locations. Conventional insights such as the search for geothermal or volcanic areas with signs of recent activity are clearly sound, although any such feature needs to have been active in the last 1 million years, otherwise its thermal effect will have decayed away completely down to ~ 5km depth.

Geophysical techniques will need to distinguish between solid and liquid phases of both H_2O and CO_2. Depending on temperature and pressure a range of possibilities exist. Different geophysical techniques are sensitive to different physical properties of the materials. For subsurface materials, only electromagnetic techniques have any real value from orbit and these are effectively limited to low frequency radar methods with short integration times due to the high ground speed, even with a steerable system that actively scans a fixed spot as the satellite passes overhead. From the surface, a wider range of electromagnetic techniques is possible, with longer integration time. This includes magnetotelluric methods, direct resistivity measurement, GPR, and magnetic surveys. In addition seismic methods become possible as do micro-gravity surveys and gravity gradiometry to analyse density distributions.

The exact electrical and other physical properties of these materials are not well characterised at Mars ambient temperatures, however the following generalisations are of value: In dielectric and resistivity terms, liquid and solid CO_2 are similar to each other and to normal rock-forming minerals. Therefore CO_2 will be effectively invisible to electromagnetic methods such as Ground-Penetrating Radar or magnetotellurics. H_2O-bearing phases have a clear dielectric signature, and should stand out from minerals and CO_2, however it is not always possible to distinguish water from ice (with some methods, ice at high concentrations can look like water at low concentrations). It is not clear whether clathrate can be distinguished from normal water ice except by physical sampling.

Seismic methods offer perhaps the best method for detecting subsurface liquid CO_2. Liquid pore fill leads to distinctive changes in elastic properties (particularly to reduced Shear wave velocity). AVO (amplitude-vs-offset) methods are routinely used in the oil industry to characterise fluid fill. It will be relatively simple to detect subsurface fluids, given a multi-km seismic array and suitable energy sources. Distinguishing liquid CO_2 fill from liquid water fill will be very difficult seismically (akin to distinguishing water from oil on Earth, which is at the limit of reliable AVO technology). However, the detection of subsurface liquids in regions that lack the strong dielectric signature of liquid water would be very strong evidence for liquid CO_2.

An interesting implication of liquid CO_2 having permeated the regolith is that a CO_2-based solvent and evaporite system will exist. CO_2 is a non-polar solvent and preferentially dissolves light organic molecules such as PAH's and non-polar species such as CCl_4, SF_6 and other halogen compounds. Possibly, deposits of these materials may exist in the subsurface of Mars and may be responsible for some of the duricrusts at the surface of Mars. The non-polar nature of these materials means, fortunately, that they should not present false targets to electromagnetic sensors but the possibility of chemical modification of these deposits to alternative mineralogies that do present conductive or dielectric anomalies should be recognised.

At some future time, when a surface mission to Mars plans to drill a deep borehole, either for stratigraphic purposes or to tap a water aquifer, the existence of liquifers of CO_2 may present a major operational risk. Liquid CO_2 is indistinguishable from regolith minerals by many geophysical techniques and therefore may not be detected. Drilling into an overpressured liquifer will lead to a potential blowout of gaseous CO_2, which may cause severe damage to the drilling equipment and endanger any nearby facilities and personnel.

Further Reading

Documents concentrating on conventional wet Mars models are not specifically noted here. This reading list concentrates on the specialised literature pertaining to cryogenic and CO_2-rich Mars models.

Peer-reviewed Papers and journal contributions

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A Huge, CO_2-charged debris-flow deposit and tectonic sagging in the northern plains of Mars. Tanaka et al. *Geology* **29,** 427-430 (2001)

Active Polar Gullies on Mars and the role of CO_2., N.Hoffman *Submitted* to *Science*, April 2001

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White Mars: A global evolution model for Mars' surface based on CO_2. N. Hoffman Abstract 6001

Volatiles and Ices on Mars. . N. Hoffman Abstract 6001

Pressure and Temperature evolution of Mars' surface. N. Hoffman Abstract 6002

Ice and Layering on early and modern Mars. N. Hoffman Abstract 6003

The collapse origin of density flows on Mars. N. Hoffman Abstract 6004

Fluid-supported density flows on Mars 1: Turbidite analogs. N. Hoffman Abstract 6005

Fluid-supported density flows on Mars 1: Pyroclastic analogs. N. Hoffman Abstract 6006

31st Lunar and Planetary Science Conference, Houston Tx. (2000): Abstracts available online at http://www.lpi.usra.edu/meetings/lpsc2001/pdf/

The interior lowland plains unit of Mars: Evidence for a possible Mud Ocean and induced tectonic deformation. K.L. Tanaka & W.B. Banerdt. Abstract 2041.

Mars' Oceanus Borealis, Ancient glaciers, and the MEGAOUTFLO hypothesis. V.R. Baker et al. Abstract 1863.

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Fossil mud sheet flows on Mars: H_2O or CO_2? H.-P. Jöns & H. Kochan. Abstract 1764.

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Low temperature phase relations in the CO_2-H_2) system with application to Mars. J. Longhi. Abstract 1518.

32nd Lunar and Planetary Science Conference, Houston Tx. (2001): Abstracts available online at http://www.lpi.usra.edu/meetings/lpsc2001/pdf/

Fresh polar channels on Mars as evidence of continuing CO_2 vapour-supported density flows. N. Hoffman. Abstract 1271

Explosive CO_2-driven source mechanisms for an energetic outflow "jet" at Aromatum chaos, Mars. . N. Hoffman. Abstract 1257

CO2 phase changes and flow mechanisms for non-aqueous "floods" on Mars. N. Hoffman. Abstract 1288

Emplacement of a debris ocean on Mars by regional-scale collapse and flow at the crustal dichotomy N. Hoffman et al. Abstract 1584

Habitable zones for Terrestrial planets in a CO_2 polar condensation scenario. N. Hoffman. Abstract 1286
Isidis basin – a potential focus of cryovolcanic activity on Mars. N. Hoffman. Abstract 1493
The origin of pervasive layering on early Mars through impact/atmosphere feedback mechanisms. N. Hoffman Abstract 1582
Structural state of Mars from MOLA implies a cooling planet. N. Hoffman and A. Lark. Abstract 1494
Evidence for magmatically driven catastrophic erosion on Mars. K.L. Tanaka et al. Abstract 1898
Subsurface models for the formation of mound-like morphologies on Mars G.G. Ori et al. Abstract 1539
Debris Flows on Mars: Analogy with Terrestrial Periglacial environment and Climatic implications. F. Costard et al. Abstract 1534
Snow and Ice melt flow features on Devon Island, Nunavat, Arctic Canada as possible analogs for recent slope flow features on Mars. P. Lee et el. Abstract 1809
Wet evidence for a dry Mars. J.D. Parsons Abstract 1256
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Clathrate and ice stability in a porous Martian regolith. J. Longhi. Abstract 1955.
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