Are the northern plains of Mars a frozen ocean?

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[1] In this brief report we consider the possibility that the northern plains of Mars would today be a frozen ocean, covered by a rather thin (at most of the order of a few hundred meters) layer of volcanic and impact debris and dust that prevents the ice beneath from being directly observed and thermally protects it from summertime sublimation (according to current models, subsurface ice in the high latitudes is stable under current climatic conditions). The frozen ocean hypothesis would naturally explain the striking topographic flatness of the northern plains. We show that the frozen ocean is plausible in terms of current models of paleoclimatic development. We also discuss the possibility that a remnant salty brine ocean could still exist under the ice and that electric currents flowing in it would be responsible for the recently observed ~40 nT Northern Hemisphere magnetic anomalies. The latter hypothesis could be tested by suitably placed surface magnetometers. *INDEX TERMS:* 5416 Planetology: Solid Surface Planets: Glaciation; 5418 Planetology: Solid Surface Planets: Heat flow; 5430 Planetology: Solid Surface Planets: Interiors (8147); 5462 Planetology: Solid Surface Planets: Polar regions; *KEYWORDS:* Mars, frozen ocean, northern plains, magnetic anomalies, brine ocean

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1. Introduction

[2] We consider the possibility that the northern plains of Mars would today be a frozen ocean, covered by a rather thin (at most of the order of a few hundred meters) layer of volcanic and impact debris and dust that prevent the ice beneath from being directly observable. The structure of the paper is such that we first point out that such a model would naturally explain the striking topographic flatness of the northern plains. We then show that such a frozen ocean would remain stable under current climatic conditions and discuss the plausibility of the hypothesis in terms of current models of paleoclimatic development. Finally we discuss the possibility that part of the ocean might still exist in liquid form under a thick ice cover and that electric currents flowing in its conducting salty brine might be responsible for the ~40 nT magnetic anomalies observed recently by Mars Global Surveyor (MGS) spacecraft over the northern plains.

2. Frozen Ocean Under Northern Plains

2.1. Topographic Hints

[3] Recent measurement of the Mars Orbiter Laser Altimeter (MOLA) instrument have shown that the northern plains are very flat and mostly at a common elevation [*Head et al.*, 1999]. Specifically, ~20% of the Northern Hemisphere surface area lies within ±200 m of the −4.0 km altitude level (Figure 1). This anomalously peaked elevation histogram calls for a physical explanation. The most straightforward explanation is that a liquid surface has covered the northern lowlands and thereafter solidified or frozen. As possible liquids, lava and water are the most likely alternatives. While lava remains a possibility, in this Brief Report we will concentrate on water because it would more easily form a planetwide single elevation and smooth surface due to its much greater fluency.

2.2. Stability in Current Climate

[4] Permanent subsurface ice at high latitudes is likely to be quite stable under current climatic conditions [*Squyres et al.*, 1992]. Generally, atmospheric water vapor tends to accumulate as ice on the coldest spots on a planet. When estimating coldness for this purpose, more important than the annual mean temperature is the annual maximum temperature, because sublimation of ice during summertime is a relatively rapid process compared with accumulation during other seasons. The polar deposits are naturally sinks (cold traps) for ice, but also the surrounding high latitude area has very low annual maximum temperature if we exclude the uppermost few meters that are vulnerable to higher summertime temperature. The large unglaciated permafrost regions in the Siberian tundra, for example, are in this sense analogous to the northern Martian lowlands: the mean annual temperature is well below freezing so a layer of permafrost exists, but higher summertime surface temperatures prevent glaciation. The stability of subsurface ice at high latitudes also comes out of existing quantitative models [e.g., *McKay and Stoker*, 1989, Figure 9]. Thus, subsurface ice sheets under the northern plains are very likely to be stable, provided that they are covered by at least a few meters of rock material that protects the ice from

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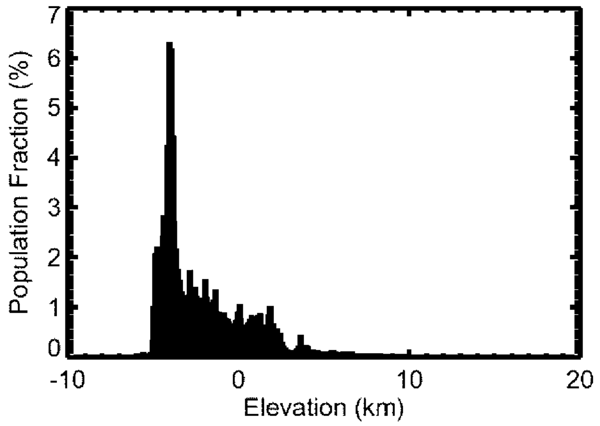

Figure 1. Histogram of Martian Northern Hemisphere elevation distribution. Notice that a substantial fraction of the surface is close to -4.0 km altitude level. Reprinted from *Zuber et al.* [1998].

summertime sublimation. Such a cover, which is rather thin in the planetary scale, could have formed easily from volcanic debris, impact debris, and dust accumulation during the Martian history.

2.3. Formation and Early History

[5] There is widespread evidence for liquid surface water during and possibly shortly after the heavy bombardment. If accepting this, the existence of a primordial ocean on the northern lowlands (the lowest regions on the planet, excluding the Hellas and Argyre impact craters) is hard to escape [*Clifford*, 1993; *Clifford and Parker*, 1999]. Most paleoclimatic models predict that the mean planetary surface temperature dropped below freezing towards the end of heavy bombardment (3.8 Gyr ago) [*Carr*, 1999]. Thus the high latitude primordial ocean must have developed a permanent ice cover rather early on. After receiving a regolith cover from impacts and volcanic eruptions, the ice at these high latitudes is safe from summertime sublimation regardless of atmospheric pressure, which was in any case still of the order of 0.5 bar at that time [*Carr*, 1999]. Under cooling climate after heavy bombardment, the ice cover thickened until the ocean was almost or completely frozen. The ice may have lost its upper few hundred meters due to sublimation or other slow processes along the way, which would be compatible with the observed existence of an ancient shoreline slightly above the northern plains [*Parker et al.*, 1993].

2.4. Possibility of Brine Ocean

[6] The thermal conductivity of ice is $\sim$2.5 W m^{-1} K^{-1} at 250 K and about twice as much at 150 K and the probable geothermal heat flux q is 30 mW m^{-2} [*Clifford and Parker*, 2001]. Since oceans on Earth are salty it is not unreasonable to expect the same to be true on Mars as well. When water freezes the salt remains in the water. Thus the salinity should increase when the ocean freezes up, possibly finally producing an eutectic brine with melting point $\sim$252 K (assuming NaCl). Since the mean annual surface temperature on the northern plains is $\sim$154 K, the ice cover above an eutectic brine ocean should be $\sim$11 km thick which would probably mean that the ocean if frozen to its bottom everywhere. However, many factors could change this estimate. For example, only 200 m of dry soil with a low thermal conductivity of $\sim$0.1 W m^{-1} K^{-1} on top of the ice would make the ice cover only 4.5 km thick. Also there is the possibility of locally enhanced geothermal heat flux in the northern plains where the crust is thinner than elsewhere. Thus the possibility of an ocean still remaining somewhere deep under the northern plains cannot be totally excluded.

[7] The Mars Global Observer (MGS) has recently observed $\sim\pm 40$ nT magnetic anomalies [*Acuna et al.*, 1999, Figure 1]. While permanent magnetism can be invoked to explain the anomalies [*Acuna et al.*, 1999], let us consider the possibility that they could be due to electric currents flowing in an eutectic NaCl brine ocean. A similar idea has been previously considered, for example, for the Jovian satellites [*Kargel and Consolmagno*, 1996]. We estimate the brine conductivity σ to be 20 S m^{-1} and the temperature $\sim$252 K. For getting rough estimates we take the horizontal dimension L of the ocean to be 1000 km and the depth h to be 2 km.

[8] Because salty water expands when heated and the ocean is heated from below, it is most probably freely convecting. The estimation of the typical convection speed v is not easy, but let us assume that because the Coriolis force breaks up the convection cells, the state is fully turbulent and that the convection develops to the point where the turbulent heating becomes comparable to the geothermal heat flux q. The turbulent heating power density $u_{\rm turb}$ is $\rho\nu_{\rm turb}\,(v/h)^2$ where $\nu_{\rm turb}$ is the turbulent viscosity of smaller eddies, $\nu_{\rm turb} \sim (1/4)vh$. Thus $u_{\rm turb} \sim (1/4)\,\rho v^3/h$ which gives the turbulent power per unit area $q_{\rm turb} = u_{\rm turb}h \sim (1/4)\rho v^3$. Equating $q_{\rm turb}$ with q = 30 mW m^{-2} and solving for v yields $v \sim 5$ cm s^{-1}. In this state the temperature difference between the ocean floor and top is minimal, i.e., the turbulent convection keeps the brine essentially isothermal. Incidentally, using these parameters the vertical eddy turnover time is about the same as the planet's rotation period.

[9] The large-scale horizontal flow in the ocean is two dimensional, with the effective viscosity given by the turbulent eddy viscosity ν^* of vertical convection eddies, $\nu^* = vh = 100$ m^2 s^{-1}. The magnetic diffusivity η is given by $\eta = 1/(\mu_0\sigma) = 4 \cdot 10^4$ m^2 s^{-1} and the magnetic Reynolds number Rm is LV/η, where V is a typical horizontal large-scale flow velocity. Taking V be of the same order as v (5 cm s^{-1}) we obtain $Rm = 1.3$. The magnetic Prandtl number Pm^* of the large-scale flow is rather small, $Pm^* = \nu^*/\eta = 0.003$. A classical dynamo action where the Coriolis force and the Lorentz force are about equal does not seem possible, nor is it wanted since it would produce magnetic fields far stronger than the 40 nT observed anomalies. However, we can conclude that the ocean behaves magnetohydrodynamically in the sense that an introduced magnetic field is convected by the flow to some extent before dissipating.

[10] To compare the viscous and Joule heating power consumptions, we note that the observed anomalies correspond to $I \sim 40$ kA total current and $j \sim 20$ μA m^{-2} current density, giving hL^2j^2/σ = 40 kW Joule heating. With V = 5 cm s^{-1} a lower limit for viscous heating in the large-scale

horizontal flow is $hL^2\rho\nu^*(V/L)^2 = 500$ kW (this is a lower limit because we used ν^*, i.e., effectively assumed that the large-scale flow is laminar, only the vertical convection is turbulent). Thus, producing the observed magnetic anomalies is energetically cheap for the horizontal large-scale flow.

[11] We do not attempt to discuss in detail the mechanisms that could primarily generate the 40 kA current in the ocean. Such mechanisms could include, for example, thermoelectric effects or slightly different mobilities of positive and negative ions in the vicinity of rough surfaces or floating ice particles. Induction effects due to ionospheric currents also play a role, but are unlikely to be the primary mechanism. However, it is interesting to note that no matter what the actual source mechanism is, if the anomalies are due to currents flowing in moving water, small secular changes should occur as the pattern of the ocean currents slightly evolves. The timescale for such changes should be of the order of months or years and the amplitude perhaps $\sim$1 nT. To detect these changes reliably might require two surface-based magnetometers, one of them placed at one of the anomalies and the other one somewhere else.

3. Discussion and Conclusions

[12] We have shown that a frozen ocean under the northern plains could have formed naturally during the prehistory and it could have remained stable up to the present day. The hypothesis would explain the peculiar flatness of the northern plains in a very natural way. There are some details that need further consideration, like the existence of some regions in the northern lowlands that are $\sim$500 m lower than the presumed frozen surface. Such formations could be, for example, due to later crustal depressions or caused by early impacts in the ice sheet that have later smoothened because of erosion. One should also explain why no part of the ice sheet is presently visible, and estimate the thickness of the covering rocky material. Since the variations in elevation of the planetary surface are not more than $\sim$200 m, the thickness of the cover is also likely not to much exceed this value.

[13] The forthcoming Mars Express mission contains instrumentation (the subsurface radar MARSIS) that has the potential of confirming or refuting the frozen ocean hypothesis. Going a step further, the idea of ocean electric currents producing the observed magnetic anomalies could be tested by 1–2 suitably placed surface magnetometers. A detection of small variations in the anomalies at month or year timescale by such magnetometers would support the brine ocean hypothesis.

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References

Acuna, M. H., et al., Global distribution of crustal magnetization discovered by the Mars Global Surveyor MAG/ER experiment, *Science*, *284*, 790–793, 1999.

Carr, M. H., Retention of an atmosphere on early Mars, *J. Geophys. Res.*, *104*, 21,897–21,909, 1999.

Clifford, S. M., A model for the hydrologic and climatic behavior of water on Mars, *J. Geophys. Res.*, *98*, 10,973–11,016, 1993.

Clifford, S. M., and T. J. Parker, The evolution of the Martian hydrosphere and its implications for the fate of a primordial ocean, paper presented at 5th International Conference on Mars, Calif. Inst. of Technol., Pasadena, Calif., 1999.

Clifford, S. M., and T. J. Parker, The evolution of the Martian hydrosphere: Implications for the fate of a primordial ocean and the current state of the northern plains, *Icarus*, *154*, 40–79, 2001.

Head, J. W., H. Heisinger, M. A. Ivanov, M. A. Kreslavsky, S. Pratt, and B. J. Thomson, Possible ancient oceans on Mars: Evidence from Mars Orbiter Laser Altimeter data, *Science*, *286*, 2134–2137, 1999.

Kargel, J. S., and G. J. Consolmagno, Magnetic fields and the detectability of brine oceans in Jupiter's icy satellites, *Lunar Plan. Sci.*, *27*, 643–644, 1996.

McKay, C. P., and C. R. Stoker, The early environment and its evolution on Mars: Implications for life, *Rev. Geophys.*, *27*, 189–214, 1989.

Parker, T. J., D. S. Gorsline, R. S. Saunders, D. C. Pieri, and D. M. Schneeberger, Coastal geomorphology of the Martian northern plains, *J. Geophys. Res.*, *98*, 11,061–11,078, 1993.

Squyres, S. W., S. M. Clifford, R. O. Kuzmin, J. R. Zimbelman, and F. M. Costard, Ice in the Martian regolith, in *Mars*, edited by H. H. Kieffer et al., pp. 523–554, Univ. of Arizona Press, Tuscon, 1992.

Zuber, M. T., D. E. Smith, R. J. Phillips, S. C. Solomon, W. B. Banerdt, G. A. Neumann, and O. Aharonson, Shape of the Northern Hemisphere of Mars from the Mars Orbiter Laser Altimeter (MOLA), *Geophys. Res. Lett.*, *25*, 4393–4396, 1998.

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