# Modern geothermal gradients on Mars and implications for subsurface liquids.

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**Introduction:** Historically, Mars has been viewed as an Earth-like planet and the consensus for geothermal gradients has been close to that for Earth or no less than 50% of that value [1]. As a consequence, liquid water is envisaged as a likely occurrence in the relatively shallow subsurface (1-2km). Recent data from MGS, however, has added weight to the alternative view [2] that Mars is in fact much less thermally active than the Earth and has significantly lower heat flux and geothermal gradients (1/4 to 1/3 that for Earth). Consequently, liquid water requires exceptional local conditions before it will be found in the upper few km of the regolith and the most likely liquid in the subsurface may be liquid $CO_2$.

**Heat Flow on Mars:** There are two principal contributors to the modern heat flow on Mars: The amount of radiogenic heat and the efficiency over geologic time of heat loss processes. For modern heat flow, questions such as the effective temperature of accretion and the timing of core differentiation are essentially irrelevant. Their effect has decayed to negligible proportions at present day.

*Radiogenic Heat:* The standard approach assumes that Mars has an Earth-like distribution of elements, and therefore its radiogenic heat will scale with mass compared to the Earth. However we know that this cannot be true since Mars has a mean density of 3.9 compared to Earth's 5.5, therefore there is a significant light vs. heavy element fractionation between Earth and Mars (i.e. heavy elements on Mars are diluted by more light elements than on Earth).

This makes for a difficult analysis, since one of the long-lived radioisotopes – Potassium – is a light/volatile element and should be enriched on Mars compared to Earth, while two – Uranium and Thorium are heavy/refractory and should be diluted. In the space available here, let us simply acknowledge that radiogenic heat on Mars will be proportionally less than on Earth, say 75% per unit mass. As we will see later, this agrees with values of lithospheric thickness and surface age distributions.

*Heat Flux:* This will essentially scale as heat production (barring gross differences in the heat storage properties of Mars' internal convection compared to Earth), with a correction for the surface area to volume ratio of the smaller sphere of Mars. Again, the lower mean density of Mars requires that its radiogenic heat be spread further than on Earth. We find that heat flux per unit area would be 38% of Earth's without correcting for the dilution by light elements but is 28% once dilution is factored in. On Earth, the mean geothermal gradient is 61.5 $mW/m^2$ for both oceanic and continental crust. Therefore on Mars we expect 28% of this i.e. 17.5 $mW/m^2$. This is at the low end of the range of 17-24 $mW/m^2$ found by [2].

***Reality Check:*** We can confirm the accuracy of these figures for heat flow by comparing lithospheric thicknesses for Earth and Mars. On Earth, old continental lithosphere is around 100km in thickness. On Mars, we do not have direct seismic evidence for the lithospheric thickness but the elastic thickness of the outer shell can be determined from the ratio of gravity anomaly to topographic depression. MOLA data show that the lithosphere of Mars has grown with time [3]. The Tharsis rise, the largest gravity and topography feature on the planet dates back to Noachian times, but already had an effective elastic thickness of 150 km. Younger features have greater thickness. Olympus Mons, for example is around 1 Ga in age, and has an elastic thickness of 250 km. A reasonable estimate of the present-day elastic thickness is in excess of 300 km [4]. Therefore the ratio of gross crustal heat flux of Earth to Mars is about 3:1, which confirms the values calculated here from first principles.

*Geothermal Gradients:* For a given heat flux, geothermal gradients depend on thermal conductivity. On Earth, typical geotherms are around 30-35 K/km. Everything on Earth is water saturated, and water is actually a relatively poor conductor of heat (although in convecting systems it is an excellent advector). In the upper layers, at least, of Mars we expect water to be frozen. Ice is a much better conductor of heat, especially at lower temperatures, so for ice-filled porosity on Mars we expect conductivity ~ 25% better than on Earth. For dry but compacted regolith, we expect conductivities ~25% worse than on Earth. Consequently in dry regions of Mars we might find geothermal gradients of ~ 10.6 K/km, while in ice-saturated zones we would expect values of a mere 6.4 K/km.

**Depth to liquid water:** The melting temperature of brine is significantly lower than that of liquid water, while clathrate formation tends to increase the melting point, even for a brine. The combination of both leads to moderate freezing-point depression by say, 25 K. Therefore the vital isotherm on Mars is ~250K.

*Equator:* For equatorial mean surface temperatures of ~ 220K, only 30K of temperature increase is required to reach the first aqueous liquids – very strong brines. These will be found at depths of 30/6.4 km (4.7

km) for a uniformly ice-saturated regolith and 30/10.6 km (2.8 km) for a uniformly dry regolith.

It is generally accepted that the upper few hundred metres of the equatorial regolith is dry [5], but the regolith should begin to have appreciable ice content below 500m so an average of these two values ( 3.7 km) is probably a slightly optimistic estimate of the depth to the first eutectic brines on Mars.

Fresher waters require a further 25 K of warming and would not be expected for a further 4 km – i.e. a total depth of ~8 km

*Temperate Mars:* A typical mean annual temperature of 200-210 K requires 40-50 K of warming to the first melt depth. Small quantities of aqueous liquids will first occur at depths of ( 3.8 or 6.3) to (4.7 or 7.8) km – say 5-6 km.

*Polar regions:* below the permanent polecaps, year-round temperatures are buffered to ~150 K by subliming $CO_2$ ice. 100 K of warming is required for even the most potent eutectics. The ground is saturated by ice from the surface and high conductivities prevail. Melting will not, therefore, occur until depths of 100/6.4 = 15.7 km. This is below the base of any expected porosity in the regolith and essentially means that the polar cryosphere cannot melt at any depth.

*Cryosphere*: In summary, a cryosphere of permanently frozen water ice (or clathrate) is anticipated to extend from the base of the desiccated zone to depths of 4 km in equatorial regions, deepening to 5-6 km in temperate zones before plunging to over 15 km in polar regions. The fraction of ice in this zone will depend on the available $H_2O$ inventory of Mars and the actual porosity of the regolith, but is capable of accounting for over 1km global equivalent layer of $H_2O$.

**Depth to liquid $CO_2$:** Liquid $CO_2$ forms above 216 K, at pressures of at least 5.1 bars. Providing that a barrier of water ice or clathrate exists at some point in the cryosphere, the pressure can be contained by lithostatic load. Below about 45 degrees latitude, the surface temperature exceeds the melting point of liquid $CO_2$, so pockets, veins and layers of liquid $CO_2$ – “liquifers” are possible within a few tens of metres of the base of the desiccated zone – assuming that a pore-occluding water-ice or clathrate region exists. The liquid $CO_2$ will occupy voids, fissures, and pores in the regolith that are not filled by cements and water ice.

Poleward of 45 degrees, the subsurface temperature is initially too cold for liquid $CO_2$ and a dry ice permafrost layer becomes likely. Again, this will still require a pressure barrier since above ~145 K, the vapour pressure of dry ice exceeds the atmospheric pressure of Mars. Both dry ice and clathrate will coexist (water ice cannot co-exist as well over geologic time since the phase equilibrium permits only one end-member of the $H_2O$-$CO_2$ system, and the ratio of $CO_2$ to $H_2O$ on modern Mars is expected to grossly exceed the stochiometry of clathrate). The depth to the base of the dry ice will deepen poleward, reaching perhaps as deep as 10 km at the poles due to the thick and $H_2O$-rich ice present in the polecap and underlying regolith.

**Implications for Mars:** The recognition of multiple lines of evidence for low geothermal gradients on Mars leads us inexorably to a planet where exceptional conditions are required to bring liquid water to reasonable drilling depths (e.g. 2 km for a light portable and automated drilling rig). Evidence of very recent volcanic activity should be sought to find intrusive centres less than $10^6$ years old whole thermal halo has not decayed away.

At the same time, liquid $CO_2$ is thermodynamically stable in the regolith at much shallower depths and models of Mars regolith must recognise the physical and chemical effects of this. Even if only small quantities are present at any one time, over geological time much of the regolith will have been flushed by liquifers of $CO_2$ with its unusual solvent properties.

The existence of liquid $CO_2$ in the regolith represents an important energetic source of vapour for generating cryovolcanic features [6] and major density flows [7]. It also represents a significant drilling hazard in an environment when conventional drilling mud may be precluded due to cryogenic temperatures and to the expectation of severe losses into porous and brecciated regolith.

**References:** [1] Schubert S.C. et al. (1992) Chapter 5 in Kieffer et al *Mars*. [2] Solomon S.C. and Head J.W. (1990) *JGR* **95**, 11073-11083. [3] Zuber, M.T. et al. (2000) *Science*, **287**, 1788-1793. [4] Hoffman N. (2001) *LPS XXXII* Abstract 1494. [5] Carr M.H. (1996) *Water on Mars*. [6] Hoffman, N. (2001) *LPS XXXII* Abstract 1493. [7] Hoffman N. (2000) *Icarus* **146**, 326-342.