CONDITIONS AND PRINCIPAL TIME SCALES FOR BASAL MELTING OF MARTIAN POLAR CAPS.

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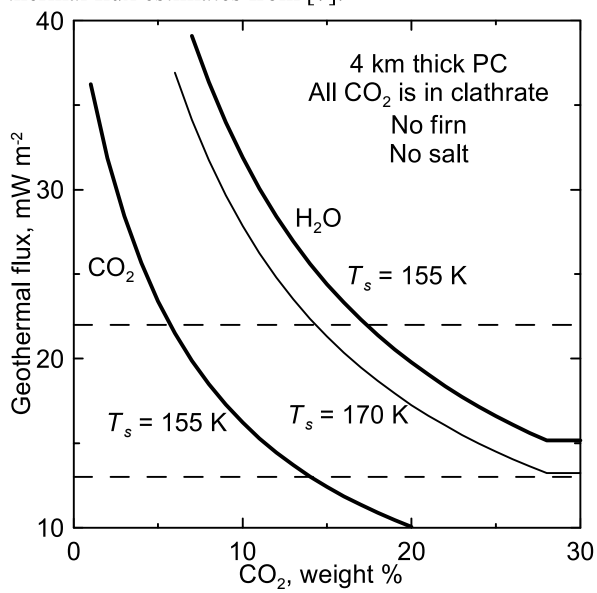
Introduction: Martian polar caps (PCs) consist of residual ice deposits and layered terrains distinctive from any other terrains on Mars. PCs are thought to be made of water ice, solid CO_2, CO_2 clathrate hydrates and dust in unknown proportions [e.g., 1]. Basal melting of these deposits could occur due to geothermal heating [e.g., 2]. It was suggested [2] that several features in the PCs, including Chasma Boreale and Chasma Australe, were formed by the catastrophic discharge of a large subglacial reservoir of basal meltwater. Recent studies [3-5] added new evidence for meltwater discharge from PCs. In this study we consider energy and timing constraints related to basal melting of the PCs.

Steady-state conditions for basal melting: Following [3] and [6] we consider a simple steady-state model of the geothermal gradient within a PC. In this model the depth of melting is $k_e (T_m - T_s) / Q$, where k_e is the effective thermal conductivity of the PC, T_m is the melting point, T_s is the long-term-average shallow subsurface temperature, and Q is the geothermal heat flux. An estimate $Q = 30$ mW·m^{-2} is frequently used [6]. Recent estimates from the elastic thickness of the lithosphere derived from Amazonian-age loading gave $Q = 13$ - 22 mW·m^{-2} [7]. The melting temperature is $T_m \approx 215$ K, 273 K, and 285 K for CO_2, H_2O, and clathrate, respectively [6]; the presence of salts decreases the latter two temperatures. The annual average surface temperature from the surface thermal model [8] $T_s \approx 155$ K for obliquity $\theta = 25°$, which is in agreement with the observations. The surface temperature increases with increase of obliquity, and $T_s \approx 170$ K for obliquity $\theta = 35°$ [8]. If there is a porous poorly conducting layer at the surface (firn), the T_s value would be higher than these estimates [6]. Following [6] we estimate the effective thermal conductivity k_e as that for a layered structure made of a high-conductivity material ($k_I = 2.8$ W m^{-1}K^{-1}) representing water ice, and low-conductivity material ($k_C = 0.5$ W m^{-1}K^{-1}) representing CO_2 ice and/or clathrate: $k_e^{-1} = f k_C^{-1} + (1-f) k_I^{-1}$, where f is the volume fraction of the low-conducting material. An addition of a modest amount of CO_2 in the form of clathrate reduces the effective conductivity significantly. The simplified model described neglects the dependence of the melting points on pressure and the thermal conductivity on temperature. However, the model is accurate enough to assess the conditions for basal melting of PCs of reasonable thickness (~3 km like the present northern PC [8] or 1-2 km thicker). The plot below shows an example of the model results. In this figure, the minimal geothermal flux necessary to produce basal melting of CO_2 and H_2O for a 4-km thick PC is plotted against CO_2 content under the supposition that all CO_2 is in clathrate and there is no firn and no salts. Dashed lines outline the range of geothermal flux estimates from [7].



Melting of CO_2 is possible for the whole range of geothermal flux values. For the lowest $Q = 13$ mW·m^{-2} a large proportion of clathrate is necessary for melting to occur. For high Q, melting of CO_2 would occur at rather shallow depth. If solid CO_2 is included into H_2O ice as relatively thin layers, the melting of CO_2 would lead to formation of clathrate rather then to segregation of the liquid CO_2. Outflow of liquid CO_2 is only possible, if there were thick layers of solid CO_2.

Melting of water ice is not possible for the lowest values of Q. However, already for $Q \sim 20$ mW·m^{-2} basal melting of water ice is possible for a wide range of other conditions.

Time scale of meltwater accumulation: The geometry of Chasma Boreale and related deposits [5] is interpreted to mean that the total fluid discharge is on order of 10^4 - 10^5 km^3. Before such a catastrophic outflow this amount of fluid would have to accumulate beneath the thickest part of the PC. If we suppose that the conditions for basal melting hold in an area of several degrees latitude around the pole, the discharge volume estimate leads to the requirement of melting of hundred(s) of meters of ice before the catastrophic discharge. The geothermal heat flux provides a melting rate of water ice on the order of 1 mm per year. This gives a time scale of the fluid accumulation on the order of a few 10^5 years.

As noted in [2], conditions for basal melting are simultaneously conditions for enhanced ice creep. Ice creep inevitably releases some heat, mostly close to the PC base. The power of this heat input can be comparable with the geothermal heat flux [2]. Total heat released due to ice creep, however, is limited by the available gravitational energy of the PC. For example, if spreading of a dome-shaped PC decreases its height from 4 to 2 km, the released amount of heat is equivalent to the latent heat of melting of ~1% of the PC mass (if the ice to be melted had been at the melting temperature already). This estimate shows that the thermal contribution from creep can be responsible for tens but not hundreds of meters of melting.

Time scale of establishing geothermal gradient: Our estimation of the melting conditions assume a steady-state geothermal gradient. If the conditions change, establishing the steady-state geothermal gradient would take some time, which is scaled simply as H^2/χ, where H is the PC thickness and χ is the thermal diffusivity of the PC material. For a 3 km thick PC made of water ice, the time scale is 2×10^5 yr. This time scale is a few times longer, if the PC contains significant amount of CO_2 or clathrate, and/or is thicker.

Comparison with astronomical time scales: Variations of the eccentricity of Mars' orbit and especially variations of obliquity of its spin axis [e.g., 10] influence the thermal regime of the PCs both directly through changes of the incident solar energy flux and indirectly through climate-driven changes in the sublimation / deposition balance. During the last 3.5 Myr the obliquity oscillated quasi-periodically about the mean value of ~25° with the amplitude up to ±10° and the period of 0.12 Myr. This means that periods of warmer (high obliquity) and colder (low obliquity) surface temperature lasted ~0.04 Myr, that is, much shorter than the thermal time scale of the PCs and the time scale of meltwater accumulation. If the main part of the PC material does not recycle during the obliquity cycle (which is probably the case [11]), the variations of the surface temperature do not lead to significant change of the thermal regime at the PC's base, and the obliquity-cycle average temperature should be taken as T_s in the estimates. If the PCs noticeably wax and wane along the obliquity cycle, the PC's interior would have no time to be heated with the geothermal flux, and no basal melting would occur.

At time scales of ~5 Myr and longer Mars' obliquity experiences chaotic variations [12,13]. In addition, the unknown response of the PC masses to obliquity changes strongly influence the long-term obliquity evolution [13-15]. This means that for periods sufficiently longer than ~5 Myr the obliquity cannot be inferred from celestial mechanics calculations.

Two different calculations of the past obliquity ([13] and [10] based on [16]) led to the same systematic change of obliquity about 4 Myr ago, while beyond 5.5 Myr the results of these calculations strongly diverge. Estimates [13] showed that the prediction for 4 Myr is reliable. Thus it is very probable that there was an at least 2-Myr-long period when the obliquity oscillated about ~35°, which ended ~4 Myr ago. For this period, the obliquity-cycle-average surface temperature at the poles could be ~15 K higher than at the present epoch. This lasted long enough to control the thermal regime at the PC base and to accumulate much meltwater, if the conditions allow melting. The ~15K difference in T_s is equivalent to hundreds of meters shift of the melting level.

Discussion: We believe that this period ~4 Myr ago is a probable time for formation of Chasma Boreale. Ice creep, basal melting, catastrophic outflow events, enhanced ice deposition due to release of water to the atmosphere erased pre-existing features and formed the modern northern PC from the material of older cap 4-6 Myr ago. Probably, few changes have occurred in the polar deposits on both PCs since that time. Possible changes could include gradual sublimation of ice outliers [17], modest sublimation and deposition [11], as well as trough migration [e.g., 1]. See [18] for further discussion of time scales and ages.

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