A perchlorate brine lubricated deformable bed facilitating flow of the north polar cap of Mars: Possible mechanism for water table recharging

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[1] The Phoenix Wet Chemistry Lab (WCL) discovered substantial amounts of magnesium, calcium, and sodium perchlorate in the soil of polar Mars. Magnesium perchlorate is likely the dominant salt in the polar region's soils. But it could be that the cations are contributed by a mixture of Mg, Ca, and Na. Mg, Ca, and Na perchlorate brines can stay liquid as low as ∼−69, −74, −32°C, respectively. WCL reports 0.7 % (wt) of the soil is pure perchlorate, and if 5% of the northern permanent ice cap is soil, then the perchlorate could make about 1/2800 of the ice cap. This suggests there could be enough perchlorate in the ice cap to generate about 1−3 m of brine at the bed. Large areas under the north polar cap have basal temperatures above −69°C so the Mg and Ca perchlorate brines would be liquid. Because of its high density, the perchlorate brine would pool over impervious layers and make the bed into a perchlorate sludge, which could be mobilized and deformed by the weight of the overburden of ice and soil. The sludge would be deformed and moved outward and stop where the basal temperature dropped below −69°C. During the warmest climates, any frozen cold dam at the edge could be breached and the brine reintroduced to the polar surface. Some of the brine could have penetrated downward under the ice cap. This mobile sludge-bed ice cap has been modeled with a 2-D time-varying model. Results of such model runs have similarities to measured layers found by shallow subsurface radar.

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1. Introduction

[2] The discovery of significant amounts of the soluble anion perchlorate $(ClO_4)_2^=$ [*Hecht et al.*, 2009] paired with Mg^{+2}, Ca^{+2}, and Na^{+1} in the soils of polar Mars by the Phoenix mission [*Smith et al.*, 2009] could change a basic assumption about the possibilities of flow of the northern ice cap. Presently, the basal temperature of the ice cap is about 205 K, and the ice would be frozen to its bed. At such low temperatures there can be very little ice deformation and a stationary ablating scarp/trough would penetrate eventually to the bed [*Fisher*, 2000]. Because there is some evidence for flow [*Winebrenner et al.*, 2008; *Herkenhoff et al.*, 2007], there is a need for a mechanism that allows it at very low basal temperatures. Magnesium and calcium perchlorate salts have a strong exothermic affinity for water and make brines that have eutectic freezing points around −69 and −75°C, respectively, and sodium perchlorate's eutectic is −32°C [*Hecht et al.*, 2009; *Besley and Bottomley*, 1969; *Pestova et al.*, 2005]. *Hecht et al.* [2009] estimate that 0.7% by mass of the polar soils are perchlorate salt. If it is assumed that 5% (mass) of the ice cap [*Langevin et al.*, 2005] is made of such soil/dust, then a 1 km thickness of ice cap would contain 0.4 m of pure perchlorate which could form about 1 m of a brines with eutectic temperatures of −69, −75, and −32°C [*Pestova et al.*, 2005]. Making reasonable assumptions about the temperature cycles in Mars polar climate shows that the basal temperatures under the ice cap get above some of these eutectic temperatures. This would cause the salts to "melt" ice and form brines, which could mix with the basal soils and form a perchlorate brine sludge that could then act like the deformable beds under some terrestrial ice sheets [*Paterson*, 1994]. Flow by this mechanism implies some ice ablation at the base.

[3] This paper explores the possibilities of assuming a 10 m thick brine basal layer that "freezes" below 203 K even though it is understood that the perchlorate salt mixture components have a range of eutectic temperatures on either side of 203 K. In addition to producing flow and stable scarps at very low basal temperatures, the process could also move

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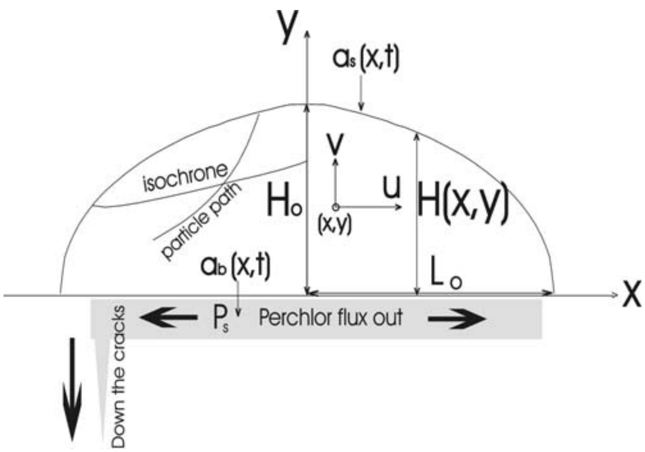

Figure 1. Coordinate system and variables. See Appendix A for definitions.

the brine sludge outward and concentrate the brine toward the edges of the ice cap (and possibly in the ablation scarp/troughs), where it might penetrate downward through existing cracks. The high density of the perchlorate hydrate (e.g., 1980 kg m^{-3} for magnesium perchlorate octahydrate) could aid in expanding existing cracks in the ice and possibly allow penetration of the brine down through the cryoshell, thus, aiding recharge of the ground water system for the planet.

2. Ice Sheet Model

[4] The model is an extension of the simple two dimensional time-varying model presented by *Fisher* [2000] (see Appendix A). Model variables and coordinates are summarized in Figure 1. The coordinates x,y are centered on the bed surface and in the middle of a flat-bedded symmetric ice cap. The velocity vector at some time t at any given point (x,y) is (u(x,y,t),v(x,y,t)), and the thickness at x at time t is H(x,t). The central thickness and half width at time t = 0 are denoted H_o and L_o, respectively. Calculated particle paths originate on an accumulation surface and exit on some ablation surface on the surface or at the bed.

[5] The surface net balance at a given surface position x at time t is $a_s(x,t)$. The concept of net balance is tied to some averaging interval. On Earth it is usually 1 year and includes a period of accumulation and an ablation period. At a given point x, the difference between the two is the net balance for the year and the overall net balance for the whole ice cap determines whether the ice cap grows (positive balance) or shrinks (negative). In the model extension, there is a basal loss rate $a_b(x,t)$ which is set at 1/2860 the surface accumulation rate. The runs are constrained arbitrarily to zero net mass balance averaged over the length of the ice cap. The ablation zones are relatively narrow (20 km) bands, and there is always an ablation zone at the margin and the ablation rate decreases toward the central region. Some inner part of the ice cap is held always as accumulating. The accublation pattern is allowed to move up-ice at a fixed velocity u_b (scarp "burn-in" velocity).

[6] A "standard" third power flow law is used for the internal deformation of ice [*Winebrenner et al.*, 2008]. The present model starts with the *Fisher* [2000] model and adds deformable beds and ablation at the ice-bed interface (see Appendix A).

3. Perchlorate and Deformable Bed Assumptions

[7] The ice cap is presently thought to ablate from the dark spiral plan trough/scarps and accumulate on the whiter flatter areas at a rate $a_s = 10^{-4}$ m(ice) a^{-1} or 0.092 kg m^{-2} a^{-1} [see, e.g., *Fisher*, 2000]. During other phases of obliquity and precessional climate cycles the ablation and accumulation rates are certainly different than present and the accumulation and loss rates probably vary across the ice cap. The Titania Lobe (Gemina Lingula), in particular, "looks" more active and has a surface profile close to what would be expected of an active flowing ice sheet on Earth [*Winebrenner et al.*, 2008]. Using the 0.7% (by mass) of the perchlorate concentrations in polar soils found by Phoenix [*Hecht et al.*, 2009] and an approximate impurity content of the ice cap of 5% of the ice cap (by mass) [*Langevin et al.*, 2005], the pure perchlorate accumulation rate in the whiter areas is about 0.32×10^{-4} kg m^{-2} a^{-1}. Assuming the bed temperatures are $-69°C$ or higher this perchorate can take up water up to an eight times hydration and form a brine with a free water fraction of ~1/2 [*Pestova et al.*, 2005]. Given the free water and eight waters associated with each perchlorate molecule, 1 kg of pure (Mg) perchlorate can "melt" and keep liquid about 1.5 kg or water (such a brine is very dense 1890 kg m^{-3}). Thus, the above assumed surface accumulation rate of water implies a bed brine formation rate of $2.5 \times 0.32 \times 10^{-4} = 0.8 \times 10^{-4}$ kg m^{-2} a^{-1} and a bed melt rate in water equivalent of 0.5×10^{-4} kg m^{-2} a^{-1} equivalent to a basal ice loss rate of 0.53×10^{-7} m (ice) a^{-1}.

[8] There is still uncertainty and debate about whether the ice cap flows. For example, *Winbrenner et al.* [2008] conclude from the surface profiles of the Titania Lobe that it flows episodically. But *Phillips et al.* [2008], using shallow subsurface radar (SHARAD) internal layers, conclude that there is no flow. If the ice cap does flow then the dust and perchlorate can reach the bed by flow and form brine. If it does not flow, then it must periodically largely ablate and leave its dust and perchlorate load as part of the bed for subsequent re-formed ice caps. Either way perchorate accumulates in the bed material, and 1 km of ice cap thickness contains enough to form about 0.7 m of brine at the bed. For the sake of argument and in the absence of any data, assume the brine mixes with 10 m of loose bed material to form a sludge or mud that is mobile for temperatures above 203 K, with velocities given by equation (A4) in Appendix A. What then are the bed temperature ranges?

4. Ranges of Ice Cap Surface and Basal Temperatures

[9] Presently, the obliquity and precessional variations of Mars climate cycle are at their midpoints so one can take the present temperatures as long-term (50 Ma) means. The yearly mean temperatures for latitude 70°N and the ice cap are shown in Figure 2. The 70°N temperature is from an energy balance model, and the ice cap surface values come from applying a vertical lapse rate of 2.5 ± .9 K km^{-1}, which is an average of measured values for many seasons and latitudes from *Kahn* [1990] and *Kondratyev and Hunt*

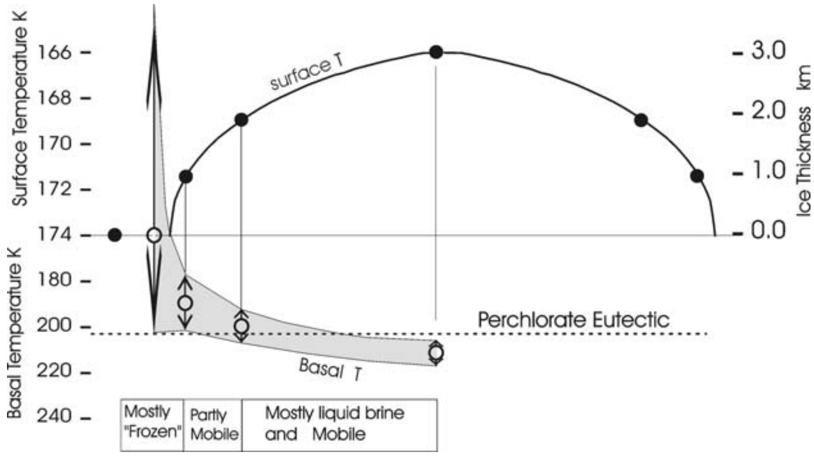

Figure 2. Surface and basal temperature ranges versus thickness for a 27 K amplitude and period of 120,000 years. Dotted line shows the magnesium perchlorate eutectic temperature for octahydrate. The shading shows what is left of a 27°C surface temperature amplitude with a period of 1.2 ka. The average temperature at 70°N is presently ~174 K.

[1982]. Representative ice cap elevations are also shown in Figure 2. In that ice is a good insulator, the average bed temperatures are higher depending on the thickness H and the areothermal heat flux G. The difference between the mean surface temperature T_{surf} and the bed temperature T_{basal} is [*Paterson*, 1994]

$$T_{basal} - T_{surf} = \frac{GH}{K} \tag{1}$$

where K, the thermal conductivity, is taken as typical of ice or icy soils 2W $(m\ C)^{-1}$ [*Clifford*, 1993]. Values of K range from 1 to 2W $(m\ C)^{-1}$ [*Larsen and Dahl-Jensen*, 2000]. The value of G, the heat flux from Mars, is not well known. Earth's average G = 50×10^{-3} W m^{-2} [*Paterson*, 1994] is undoubtedly too large and *Clifford*'s [1987] G = 30×10^{-3} W m^{-2} is what is used here. However, a recent G estimate is considerably lower [*Phillips et al.*, 2008], and if this is correct, then our using the high value for K would tend to offset what might be a too large G. Superimposed on the average surface temperatures are variations caused by climate changes driven by obliquity, precessional, and chaotic changes [*Toon et al.*, 1980]. If the amplitude of a given surface temperature cycle of period p (in years) is A_{surf}, then by the time this wave penetrates though a thickness H to the bed the amplitude has been attenuated to A_{basal} [*Paterson*, 1994; *Larsen and Dahl-Jensen*, 2000]:

$$A_{basal} = A_{surf} \mathrm{Exp}\left(-H\left[\frac{\omega}{2k}\right]^{1/2}\right) \tag{2}$$

where $\omega = 2\pi/p$ and k = 62 $m^2\ a^{-1}$ is the thermal diffusivity for cold ice (T~200 K) [*Fisher et al.*, 2002]. There is a time lag between the surface temperature T_{surf} and the basal temperature T_{basal}:

$$timelag = H\frac{p}{2\pi}\left[\frac{\omega}{2k}\right]^{1/2} \tag{3}$$

Very long secular shifts in average surface temperature that had, for example, a period like 4 Ma would transfer over 70% of its amplitude through 3 km of ice cap.

[10] Figure 2 shows that under ice 2 km or thicker the bed perchlorate sludge would be above the eutectic temperature most of the time. This assumes the surface T had a 1.2×10^5 year period and an amplitude of 27 K around the present mean (Table 1). It should be noted that there is a time lag between the surface temperature wave and the basal wave. For example, under 3 km thick ice, the bed experiences the maximum temperature about 40 ka after the surface [*Larsen and Dahl-Jensen*, 2000]. By varying key input parameters, the "mobility zones" in Figure 2 can be shifted around somewhat, but the general picture remains of a mostly mobile bed if the thickness is >2 km, "mostly frozen" bed if the thickness is 1 km or less and varying status if the thickness is between 1 and 2 km. A frozen ring surrounding the thicker part of an ice sheet with a "wet base" is typical of large terrestrial ice sheets like the East Antarctic ice sheet. To lever the hypothesis further down this analogue path suggests the possibilities of brine pools under the thicker ice.

5. Results From the Model

[11] Previous efforts to model the north polar ice cap invoked basal temperatures high enough to produce flow but which also necessarily filled in the surficial scarp/troughs [*Fisher*, 2000; *Hvidberg*, 2003]. *Winebrenner et al.* [2008] showed that except for the scarp/troughs, the surface profiles along flow lines of the Titania Lobe are very close to the Vialov profile [*Paterson*, 1994], which strongly indicates active ice flow. Winebrenner et al. felt that the scarp/troughs were incised into the Vialov profile during periods of lower basal temperature and that the Vialov profile was set during warmer periods, when flow was possible. This is an elegant and tempting explanation, but given the discussion surrounding Figure 2, it seems unlikely that the basal temperatures under the Titanian Lobe never get near the 225 K that allow rapid enough ice flow to reestablish the Vialov profile in times less than 2 Ma. Also, studies of the geometry of the iscochrone layers within the north cap have shown

Table 1. Basal Temperature Amplitude and Surface Temperature Amplitude and the Time It Takes a T_{surf} to Reach the Bed for Various Periods and Thicknesses

Period, P (Years)	Thickness of Ice, H (km)	Basal Amplitude/ Surface Amplitude, A_{basa}/A_{surf}	What Is Left of a 27 Degree Surface Amplitude at the Bed	Time Lag (ka)
120000	3	0.14	3.8	37
120000	2	0.27	7.3	25
120000	1	0.5	13.5	12
50000	3	0.05	1.4	24
50000	2	0.13	3.5	16
50000	1	0.36	9.7	8

[*Fishbaugh and Hvidberg*, 2006; *Phillips et al.*, 2008] continuous layering over large areas but not the upward trending (under stationary scarps) originally suggested by *Fisher* [1993; 2000].

[12] Introducing a hypothetical deforming bed material kept fluid by the perchlorate (Mg, Ca, and or Na) brine allows motion of the ice cap at more plausible bed temperatures (Figure 2). It also, however, introduces new unknowns like the thickness P_s of the deformable bed, the amount of perchlorate in the bed layer P_{chlor}, its state of hydration, and the ice cap's soil load D_{dust} (see Appendix A). The hypothesis results in a number of predictions relating to the geometry of the internal layers (isochrones) and to the concentration of the perchlorate under and near the edge of the ice cap.

[13] These model results should be viewed as sensitivity tests rather than simulations. There are large uncertainties in the model parameters especially pertaining to the deformable bed. For example very different results can be obtained by changing P_s, B, and f in equation (A4) (all taken here as 10 m, 85 kPa, and 100%, respectively). Also, the model just prescribes accumulation/ablation fields, and it is an isothermal model that cannot generate the time offsets between surface and bed temperatures (see Table 1). Nevertheless, it can assess the effects of changing key variables and indicates what could come out of full simulation model supported eventually by known parameters.

[14] The run shown in Figure 3 starts with a surface (black solid line) that is incised deeply with static scarp/troughs and evolves with a mobile bed right to the cap

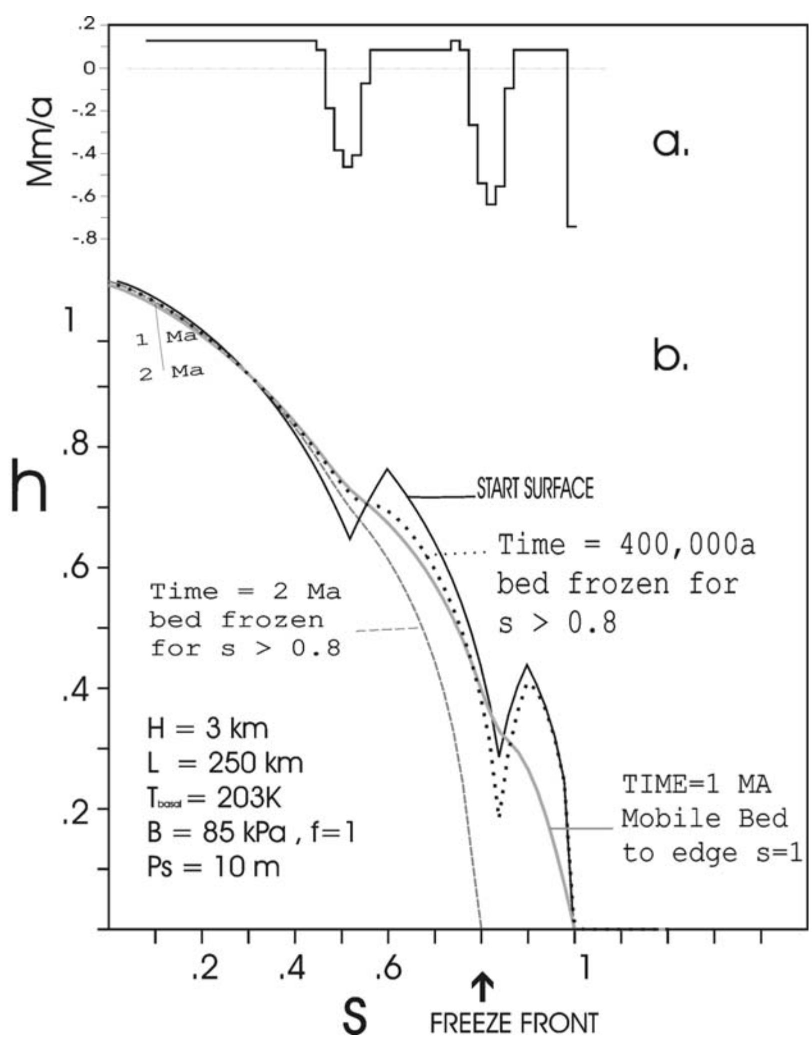

Figure 3. Making and smoothing scarp/troughs. (a) The input net mass balance field. (b) The surface after specified times and using various mobile bed conditions.

margin. It evolves to the (solid grey) surface in 1 Ma and with start scarps almost completely smoothed out. If, however, the basal temperature near the edge (for $s \geq 0.8$) is set below the perchlorate eutectic, then the bed material is "frozen" for $s \geq 0.8$ and the start scarp/trough near the edge remains even though that higher up has been largely smoothed away by 400 ka (dotted line) after time zero. By 2 Ma, this example has retreated the edge of the ice cap back to the dashed line. The start profile (solid black line) is produced by applying the static accumulation/ablation field shown in Figure 3a to a Vialov profile, for 2 Ma, while having $T_{basal} < 203$ so that the bed is "frozen." The switching on and off of the mobile bed by invoking plausible shifts in T_{basal} above and below the eutectic temperature of 203 K generates the sort of scenerio envisaged by *Winebrenner et al.* [2008].

[15] Figure 4 shows what happens when the bed material is frozen beyond s = 0.8 and when the scarp/trough ablation features shown in Figure 4a move upward on the ice cap with a constant velocity, $u_{burnin} = -0.025$ m a^{-1}. It is assumed that T_{basal} and T throughout the ice cap is 203 K. The run uses $L_o = 250$ km and $H_o = 3$ km and runs for about 100 Ma. The initial (Vialov) profile is the thick gray dashed line and the final surface is the thick black line. The model cap always has a zero net mass balance and is forced to maintain its width. There is always an ablation field right at the edge and the inward migrating ablation fields stop 100 km from the center and get less ablative inward. The resulting particle paths are the solid "wavy" lines in Figure 4d and reflect the inward moving ablation fields. The dashed lines are the mean position of the isochrones. The isochrones would also have a wavy character but only the mean position is shown. The waviness is exaggerated in this run because there is only one scarp/trough on the cap at one time. The waviness decreases with depth and with the number of scarps. Also, in reality, throughout an obliquity or precessional climate cycle the accumulation and ablation rates would vary at least 2 orders of magnitude, with the small values in the cold phases. Also, the bed temperatures and flow velocities would be much out of phase with the climate cycle accumulations and ablations. For all these reasons, the waviness is partly an artifact of model simplicity.

[16] One point immediately noticed, when comparing Figures 3 and 4, is that when the ablation zones are mobile as in Figure 4 the resulting surface is smooth even in the frozen bed zone. This is unlike in Figure 3, where the static ablation zones produce scarp/troughs relatively quickly in the frozen zone. This substantiates *Winebrenner et al.*'s [2008] contention that the Titania Lobe scarp/troughs are probably formed during some episodes and filled in during others to reform a smooth surface profile. The driver is the basal temperature being above or below the eutectic. The isochrones in Figure 4d tend upward under the region that are swept by inward migrating scarps but bend downward toward the edge of the cap, so there is "bump" in the layering and there is also a bump under the central region. Since the model has bottom ablation of ice to produce the brine, the oldest isochrones (>100 Ma) disappear into the surface of the bed. The nature of the surface and the internal layers depends on the size of the cap modeled and how close to the center the scarps are allowed to penetrate. For larger caps with scarps getting closer to the center, the model typically produces results like Figure 5.

[17] When the model ice itself is extremely cold but basal deformation is possible and the surface accumulation/ablation (accublation) features move inward, the older isochrones are bowed upward under the "scarped" region but then bend downward where the surface slopes increase. In the example shown in Figure 5, most of the ice older than 10 Ma originates in the innermost part of the ice cap (s < 0.2). The ice within the surface undulations is all relatively young and originates locally (Figure 5d). So, to some extent, this long flow line run disconnects the surface layers from the much older deeper ones. The highest point reached by a given isochrone in Figure 5c moves progressively toward the edge. The Z-Z line demonstrates this.

[18] The upward bowing of isochrones in Figure 5 is also present in Figure 4 for the smaller ice cap but it is further out along the flow lines and less pronounced. It is largely due to the accublation regime and to the stability of the scarp/troughs. For the larger ice caps it was found that the scarp/troughs were more stable, i.e., there are none left in the small cap of Figure 4 but are in the larger of Figure 5. One can regain them relatively quickly in the smaller caps by making the accublation pattern stationary and freezing the bed (Figure 3).

[19] Numerical runs with accumulation rates 5 times those shown in Figure 5 reduce the ages by about 1/5 and increasing the sludge thickness Ps from 10 m to 100 m also reduces the model ages by about an order of magnitude. However, the geometrical pattern made by the isochrones does not change much.

6. How Much Perchlorate Accumulates and Where Does It Go?

[20] Using the equation (A9) in Appendix A and the accublation field shown in Figure 5a, the horizontal perchlorate brine flux can be estimated at the end of a long (500 km) flow line to be about 20 kg $(m\ a)^{-1}$ at the margin. However, this assumes that the bed material is deformable right to the edge and that all the down flux gets to the edge. A more reasonable estimate would probably be that the down flux in the "whiter areas" exits through all the ablation scarps, not just the margin scarps. Since the model suggests that the nonmarginal scarps have relatively younger ice exiting through them, which has not be in touch with the basal regions, the concentration (mass perchlorate/mass of dust) coming out of these scarps would not be much different than in the surrounding polar environment that was the original source of the salt-rich dust. Possibly right at the edge of the marginal scarp the perchlorate concentration would be higher because the ice exiting there is much older and would have been mixed with and/or in close proximity to the bed's perchlorate sludge layer.

[21] Figure 2, however, suggests that for an ice thickness less than 1 km, the basal temperature is usually below the brine's eutectic and that, therefore, there is usually a frozen basal ring at the edge of the ice cap. Such a ring would confine or dam the brine and force it to accumulate under the ice cap. Under the interior deep parts of the East Antarctic ice cap [*Oswald and de Robin*, 1973], nearly pure water ice melts and gets trapped in lakes at the bed. Figure 2 leaves open the possibility of occasional dam melting episodes that could "drain" any such hypothetical subglacial brine pools.

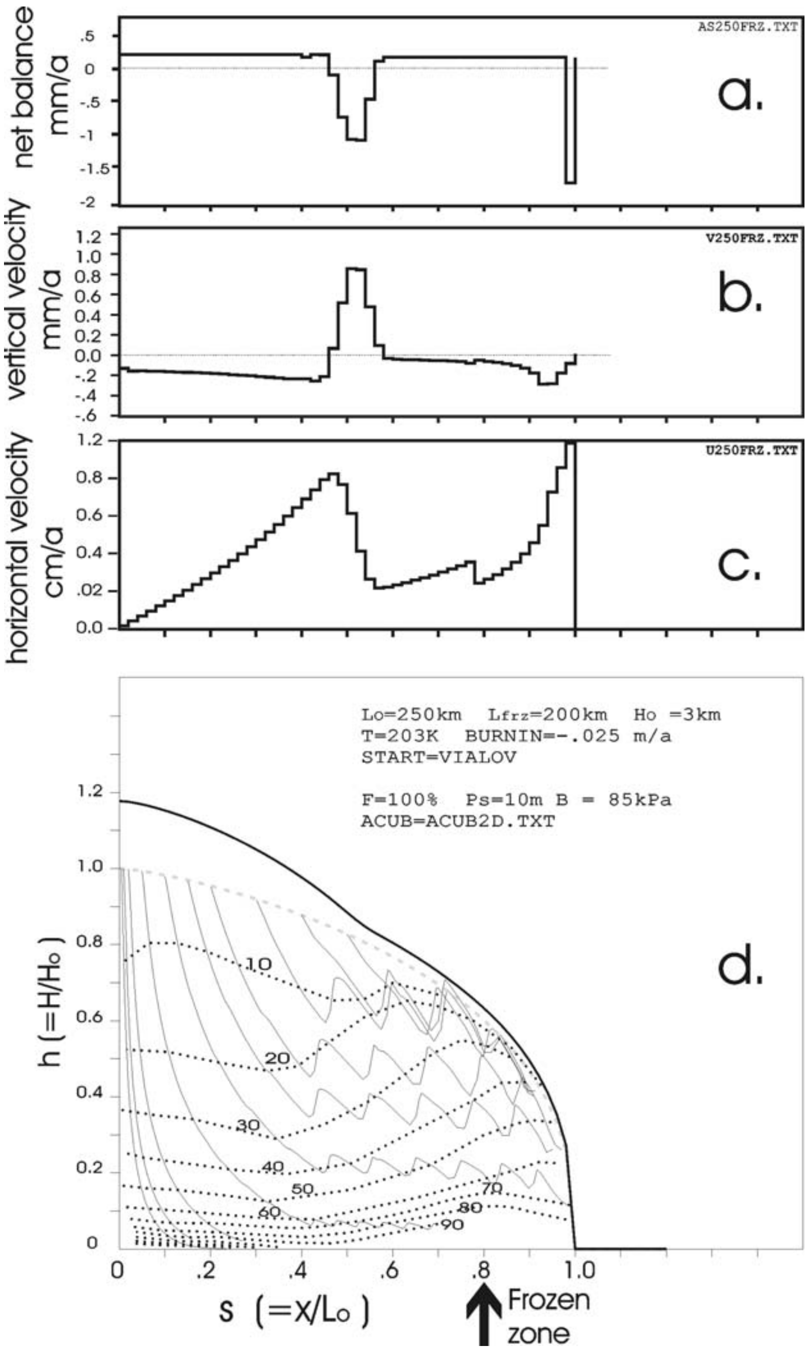

Figure 4. Example of particle paths and isochrones for a brine lubricated ice cap 3 km thick in the middle and 250 km from top to edge assuming the bed temperature is above the eutectic for $0 < s < 0.8$ beyond which the bed is "frozen." (a) The assumed mass balance function that is forced to move inward at 0.025 m a^{-1}, but with the edge zone always negative and the innermost zone ($s < 0.4$) always positive. (b) Vertical surface velocity. (c) Horizontal surface velocity, assuming the deformable bed is "frozen" for $s > 0.8$. (d) smoothed isochrones within the ice in Ma units. The start profile is Vialov (dashed grey line) and after 100 Ma the surface is the solid line. The mass balance is forced to be zero and the width is forced to be constant.

The section 1 estimates of about 1 m of brine contained in each vertical 1000 m of ice cap suggests that there is about 2 m of brine contained in an ice cap 2000 m thick. If the ice cap came and went with a cycle time of 10 Ma and left its impurities behind each time it left, there could be an equivalent of ~140 m of brine concentrated in the bed in 10^9 years. A similar order estimate comes from assuming the ice cap has always been at its present position accumulating ice at 10^{-4} m a^{-1} for 10^9 years. Given that the inputs to these estimates are speculative, so too are the brine thickness, but a flowing or a static ice cap seem to "collect" brines under their footprints at about the same rate. What the

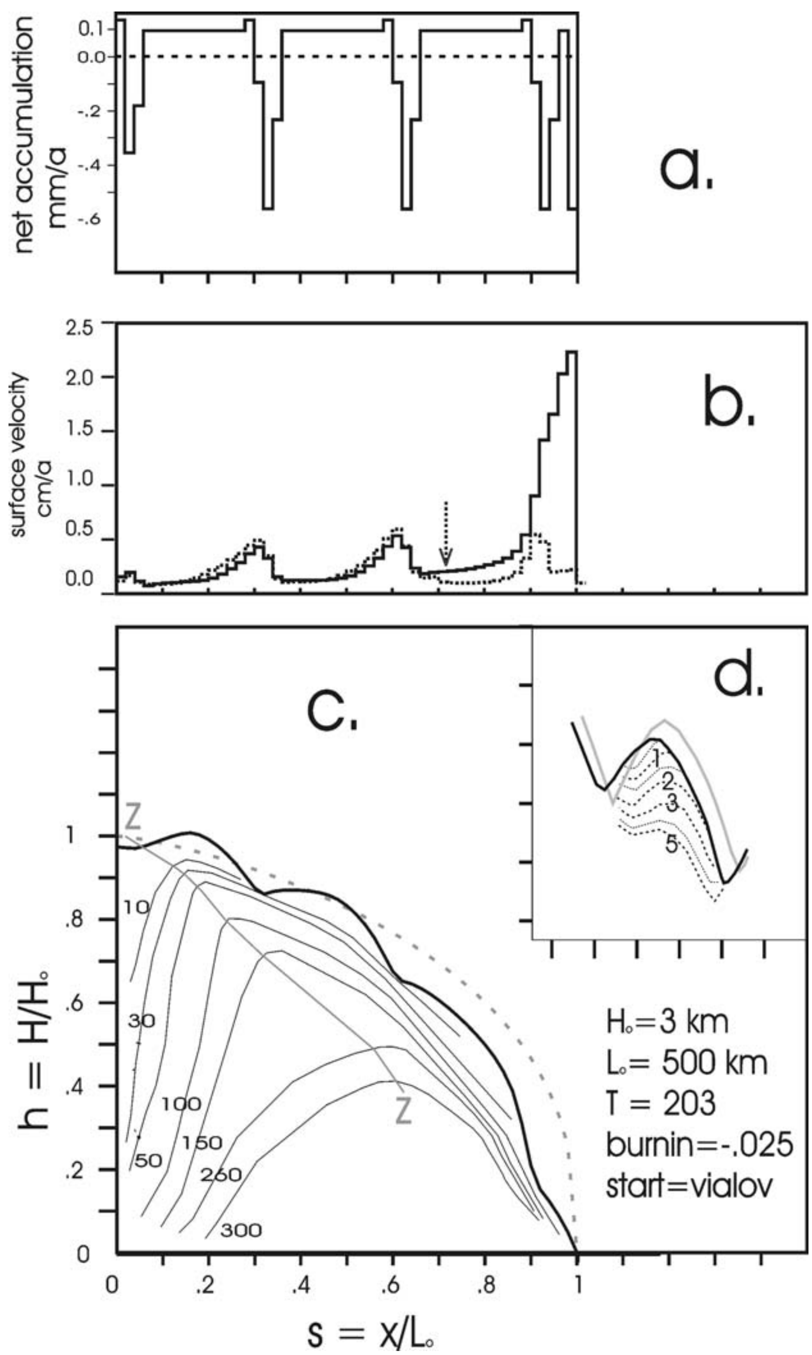

Figure 5. A model run for a large ice cap L_o = 500 km with T = 203 K and with a deformable bed. (a) The surface mass balance that is forced to move inward at a constant velocity 0.025 m a^{-1} except at the edge which is always negative. (b) The horizontal surface velocity that results after 100 Ma, when there is a deformable bed (Ps = 10 m; B = 85; f = 100%) right to the edge (solid line) and when there is a ''frozen'' bed for $s \geq 0.72$ (360 km) (dashed line and arrow). (c) The smoothed position of the isochrones in Ma. The start profile shown in dashed grey is Vialov, and the surface profile at 100 Ma is the solid line. (d) An expanded example of the isochrone structure within a surface undulation when the scarps move inward at 0.005 m a^{-1}.

flowing cap seems to add is the concentration of the brines toward the periphery of the ice cap.

7. Evidence That Mobile Beds Exist

[22] There are two types of prediction that the mobile bed model makes: (1) about perchlorate concentration around the cap and (2) about the geometry of the internal isochrones or layers. The model suggests there should be a build-up of perchorate concentration toward the edge of the ice cap and possibly in the outer ablation scarps. Investigations are underway presently to see if remote (CRISM) spectral data can find a ''hydrated perchlorate band'' and, thus, map surface concentrations and test this prediction. In principle,

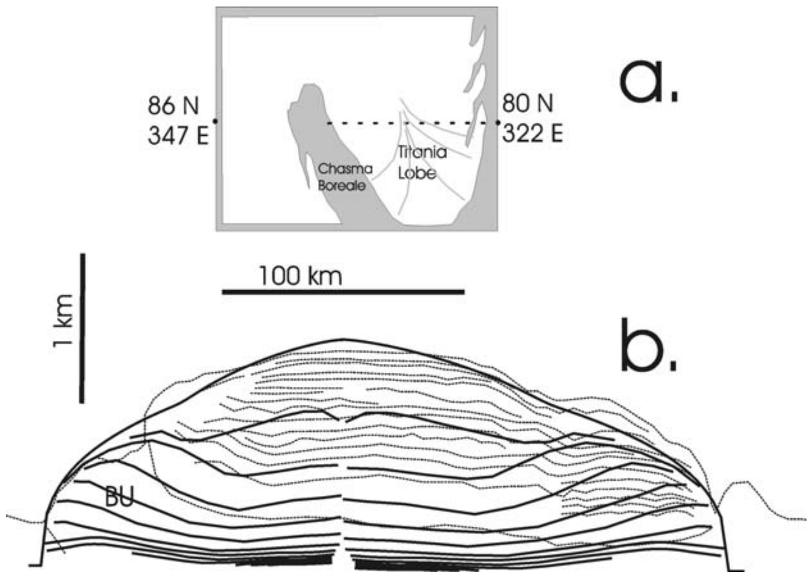

Figure 6. Comparison of Figure 4 layering with that of SHARAD over the Titania Lobe (Gemina Lingula). (a) Gives the position of the SHARAD transect. (b) The solid lines are isochrones from Figure 4. The dotted lines are the author's freehand traces of layers found by SHARAD [*Phillips et al.*, 2008]. The grey lines in Figure 6a approximate the hypothetical flow lines [*Fisher et al.*, 2002].

MRO/CRISM could see hydrated perchlorate in surface deposits at the 5% (wt) level. So far there are tantalizing prospects only, and the potential salt signatures are very difficult to see above the noise (S. Cull, personal communication, 2009).

[23] In previous models that relied only on internal ice deformation to produce flow, the isochrones always terminated at ablation surfaces with an upward angle. Inferred exit angles did not agree with this and *Fishbaugh and Hvidberg* [2006] concluded that this fact mitigated against flow. The recent SHARAD results [*Phillips et al.*, 2008] show internal layering that is continuous over most of the PLD and is assumed to be the isochrone geometry. The SHARAD transects do not follow flow lines, and the model isochrones along flow lines presuppose many assumptions. So, at best, the comparison can only be qualitative.

[24] Figure 6 shows layers revealed by SHARAD (dashed) along a profile across the Titania Lobe [*Phillips et al.*, 2008] and the "small cap" profiles from Figure 4 superimposed on it in solid black. There is qualitative agreement with down trending isochrones in places and upward in others. The Basal unit (BU) in Figure 6b uses *Phillips et al.* [2008] nomenclature.

[25] Figure 7 shows another SHARAD trace of internal layers compared with some short (Figure 4) flow line profiles and a long (Figure 5) model profile. The isochrones in Figure 5 bend upward under the scarped terrain and there is a tendency for turning point of the isochrones to be offset from the surface topography, see the "z-z" grey line in Figure 5c. The grey "z-z" line in Figure 7a shows a similar tendency, but it should be noted the SHARAD traverse "x-x" is not along any of the flow lines and that it crosses most of them at a large angle (Figure 7b). Additionally, the midpart of the SHARAD traverse in Figure 7 samples a complicated converging ice complex, which this simple model cannot begin to simulate.

[26] In future, the model could be inverted using the measured geometry of the surface and internal layers to calculate or limit the input variables B, f, a_s (x), P_s (x), T_{basal}(t),T_{surf}(t), n, Ao, Q. For example, the latter three rheological constants have been estimated by such an approach by *Winebrenner et al.* [2008] for the Titania Lobe, but without including the effects of perchlorate sludge.

8. Discussion

[27] Earlier views of the north polar ice cap suggested it flowed by ice deformation alone [e.g., *Fisher*, 2000]. This, however, required basal ice that was probably too warm and produced internal layer patterns that subsequently were not found [*Fishbaugh and Hvidberg*, 2006; *Phillips et al.*, 2008]. With the addition of a brine sludge at the bed that is mobile down to −69°C the view now can shift to a very cold stiff ice and soil sitting on top of a deforming bed. There is still movement outward and subsidence in the ice cap but now most of the action is done by the deformable bed. The model internal layer patterns, now show many similarities to those discovered by SHARAD, with a tendency for near surface layers in the undulating scarp/trough terrains to be much younger than the deeper layering, and for the older layers to bow upward under scrap/trough terrain.

[28] It is possible that basal sliding could also be invoked using perchlorate brine as the fluid. Sliding would likely be the mechanism, if the basal material was rock. Given the surrounding polar terrain, however, it seems better to assume the basal material is a mixture of "fines" similar to those observed by Phoenix. In any case the resulting isochrones within the model ice cap would not differ much from those presented, because the situation would still be one of very stiff ice moving on a thin basal layer activated at the eutectic temperature of some perchlorate.

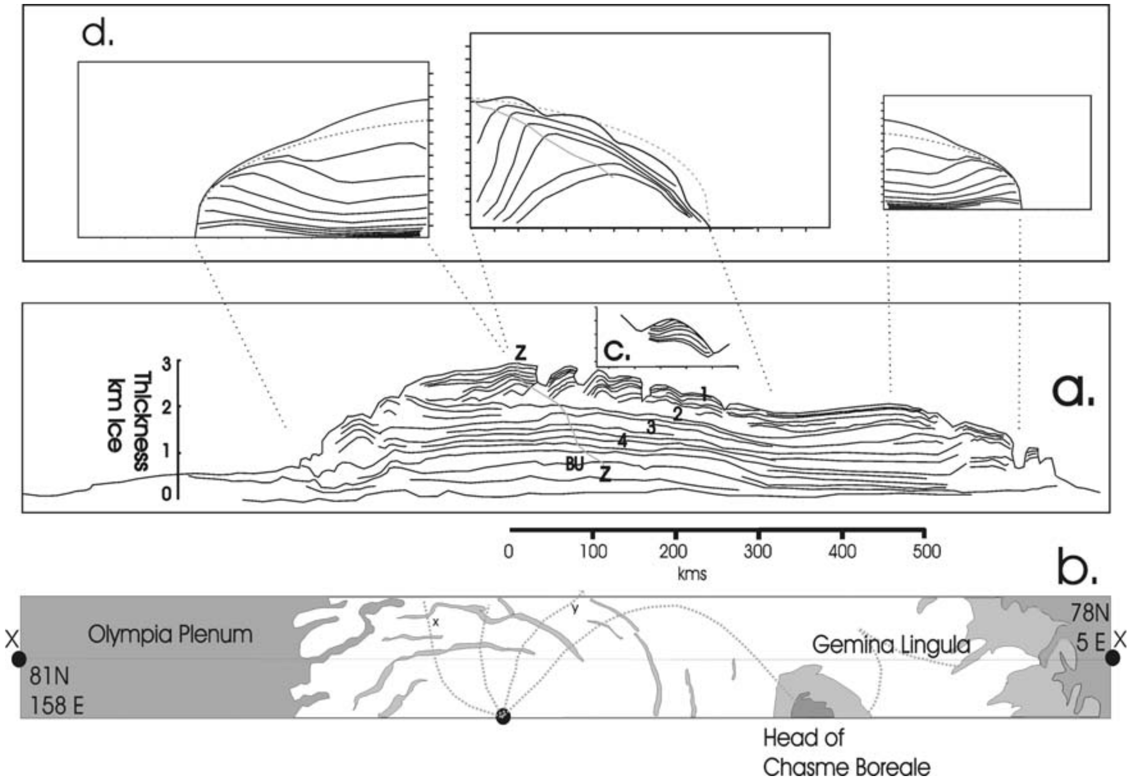

Figure 7. (a) A trace made from SHARAD [*Phillips et al.*, 2008] of internal layers along the dashed black line, "x-x" in Figure 7b. (b) Map of transect line for Figure 7a. (c) The inset shows the model isochrone structure in one of the scarp/troughs from Figure 5. (d) The end profiles are from Figure 4 and the central profile is from the model results shown in Figure 5. Assuming the flow lines would be down the maximum surface gradient they would look about like the grey dashed lines in Figure 7b [*Fisher et al.*, 2002]. The SHARAD profiles are not along flow lines, so comparisons have to keep this in mind.

[29] There remains the possibility that the ice cap is completely and always stagnant and the layers shown by SHARAD [*Phillips et al.*, 2008] are a sequence of "dead" layers draped over the underlying landscape. The up-bowing extent of the layering has been cited as evidence of no-flow, but as the model results here show (e.g., Figure 7) this need not be the only inference. The smooth nearly perfect Vialov profiles interspersed with scarp/troughs found on Gemina Lingula [*Winebrenner et al.*, 2008] strongly suggest there is episodic flow.

[30] The model also supposes that perchlorate accumulates at a depth where the eutectic temperature is reached and forms the enabling mobile sludge. There is ablation at the bed of the model ice cap because the salt converts ice to brine. There is an outward flux of sludge that gets stopped where the ice cap depth is insufficient to make the bed warmer than $-69°$C. This "frozen ring" could possibly be melted during warm climate excursions and release the accumulated brine/sludge behind it. Presently, in the summer, the outermost part of the basal sludge layer could "melt" and/or diffuse through the soil load that it bore to the edge. Once the frozen brine had "melted" and been removed, the soil would presumably slump and flow down the surface slope, much as noted by *Herkenhoff et al.* [2007] using MRO/HiRISE images. The soils thus released could be rich in desiccated perchlorate. Since the calcium perchlorate hydrate has a lower eutectic ($-74°$C) it might get further out along the flow lines before freezing out.

[31] It is conceivable that because of its high density (1980 kg m^{-3}) the perchlorate might collect and pool at the bed. Higher-resolution radar sounding could possibly find such features. Even on Earth, however, high-resolution radargrams of the Greenland sheet have missed predicting wet based conditions, which were subsequently found by drilling [*Buchardt and Dahl-Jensen*, 2007]. If such brine soaked deformable beds and maybe even small brine pools exist under the ice cap, one is forced to at least speculate about what sort of environment they would provide for some robust life form.

[32] The issue of the age of the ice cap is still open. Using present estimates for accumulation rates, the model predicts a very old ice cap ~100 to 300 Ma. Martian climate changes no doubt alter the accumulation rate though several orders of magnitude, whereas the ablation rate changes are probably moderated by the negative feedback caused by the formation of surficial sublimation lags during warm episodes. For example the 3 to 10 cm of soil is enough to protect the ice table at the Phoenix site. Thus, the representative accumulation rate that actually puts most of the thickness down could be much higher than present and make the isochrone ages younger. The flow model work though does suggest ages in the 100 Ma range that would span many warm episodes

caused by orbital variations. The ice cap could probably survive even the warmest excursions with a surface sublimation lag of order 1 m. Since the present model does not envisage or require nearly pure ice from surface to sludge bed, the ancient lag layers would just move along with the rest of the ice cap. Frustratingly, one of the only missed goals of Phoenix, the measurement of the D/H ratio of the air during the mission and of the ground ice, could have shed light on the age and stability of the ground ice/ice cap couple [*Fisher et al.*, 2008]. The presence of the perchlorate and ice in the icy soils would not allow passage of icy samples past the protective inlet mesh into the TEGA [*Smith et al.*, 2009] until the offending but targeted ice had so sublimated that there not enough to measure for D/H!

Appendix A: The Model: Ice Flow on a Deformable Bed

[33] The mass conservation condition over a whole thickness H(x,t) is

$$\frac{\partial H}{\partial t} + \frac{\partial (u_{av} H)}{\partial x} = a_s + a_b \qquad \text{(A1)}$$

where u_{av} is the vertically averaged horizontal velocity, a_s is the surface mass balance, and a_b is the loss rate at the bed due to "melt" of ice into brine and flow down into the bed. If the ice deformation is simplified to shear only and the strain rates are given by [*Paterson*, 1994; *Budd et al.*, 1986]:

$$\frac{d\varepsilon_{xy}}{dt} = 1/2 \frac{\partial u}{\partial y} = A {\tau_{xy}}^n$$

where, with n = 3,

$$A = E A_o \exp\left(\frac{-Q}{RT}\right)$$

where A is a constant dependent on temperature, impurity content, and crystal orientation [*Paterson*, 1994]. Where R (8.3143 J mole^{-1} K^{-1}) is the gas constant, and Q (60 kJ mole^{-1}) is the activation energy, A_o is a constant (for T < 263 1.35 10^{-5} Pa^{-3} a^{-1}), and E is an enhancement factor connected to impurity content. For this simple modelling exercise, E is just taken as 1 and T is a constant, (205 K). Using n = 3 seems to best match the surface profiles from Titania Lobe of the northern cap [*Winebrenner et al.*, 2008].

[34] Assuming laminar flow the horizontal velocity can be written [*Fisher*, 2000]:

$$u = u_{basal} + A {\tau_b}^n H \left(1 - \left(1 - \frac{y}{H}\right)^{n+1}\right) \qquad \text{(A2)}$$

where τ_b is the basal shear stress and u_{basal} is the basal velocity. The basal velocity can be a combination of sliding velocity and velocity of the basal soil itself. Deformable beds are not uncommon in terrestrial settings, when the bed material is weak and the bed temperatures are above the melting point. The shear strain rate across a deformable till bed has been found empirically to be [*Fowler and Walder*, 1993]

$$\frac{d\varepsilon_{xybasal}}{dt} = B {\tau_b}^a (N + N_o)^{-b} \qquad \text{(A3)}$$

with a = 1.47, b = 2.34, B = 172 (kPa)$^{0.87}$, and N_o = 4.5kPa. Here N is the effective pressure, which is the hydrostatic or overburden pressure minus the pore pressure within the deforming bed material. Since there is no measure of the latter, N +N_o is replaced with some fraction f of the overburden pressure, fρgH, with a check that f cannot be zero. Also, for simplicity, it is assumed that a = 1, b = 2, and the constant B = 85 (kPa). These simplifications are close to those introduced by *Alley* [1989]. If the deformable bed has some thickness Ps and if the flow within this thickness is laminar, zero at its base and u_{basal} at the top of it then using equation (A3) with a = 1, b = 2 and N+No = fρgH gives

$$u_{basal} = P_s B \frac{\tau_b}{(f \rho g H)^2} \qquad \text{(A4)}$$

where g is the acceleration due to gravity on Mars (3.73 m s^{-2}) and ρ is the ice cap's density ($\sim$920 kg m^{-3}).

[35] *Boulton and Hindmarsh* [1987] formulated an empirically based till deformation law (very like equation (A3)) from observations of Icelandic glacier beds. They observed till deformation over a range of effective pressures and shear stress indicating a wide range of water saturation conditions. The ice streams of West Antarctica are thought to have deformable beds of order 10 m thick that are inflated with water so that the effective pressure is a fraction of the overburden [*Paterson*, 1994, chap. 8]. The southern margins of the Laurentide ice sheet that covered North America had very low surface slopes and probably moved on deforming beds [*Mathews*, 1974; *Fisher et al.*, 1985]. The constants and even the powers for deformation equations like (A4) are not well constrained yet and assessing the effective pressure (f in this formulation) for terrestrial cases has proven difficult. It seems that f may be very horizontally and temporally variable [*Paterson*, 1994, chap. 8]. Terrestrial cases of deforming beds are invoked, because often the bed till is saturated with water and the effective pressure so low that most of the ice motion is in fact due to the deforming bed. In such cases there needs to be an abundant water source either from basal melting or vertical penetration of surface melt. There also has to be a less permeable layer under the deforming till in order to confine the water. The "function" of deforming beds on Mars would be somewhat different. Since the ice temperatures are so low, any deformation of the bed material is going to be a significant or dominant form of motion. There are no ice stream like features on the Martian ice cap and given the slow rates of brine production this seems reasonable. For the runs presented here f = 1 and P_s is taken as 10 m. With the brine estimate of $\sim$2 m, within these 10 m and a porosity of 50%, this means the pores are not saturated making the f = 1 assumption seem necessary (i.e., the effective basal pressure equals the overburden pressure).

If P_s was reduced from 10 to 4 m then the pores would be saturated with brine and an $f < 1$ might be possible. Even with f = 1 however the deformation generated within the beds using equation (A4) dominates because the ice is so cold and stiff. The basal shear stress can be written [*Paterson*, 1994]

$$\tau_b = -\rho g H \frac{\partial H}{\partial x} \tag{A5}$$

The horizontal ice velocity component u(x,y) comes from combining equations (A2), (A4), and (A5). The vertically averaged u component u_{av}, that goes into equation (A1), is then

$$u_{av} = -\frac{P_s B}{\rho g f^2}\frac{\partial H}{H \partial x} - A_r{}^*\left(\frac{\partial H}{\partial x}\right)^3 H^4 \tag{A6}$$

where $A_r^* = 2A(\rho\ g)^3/5$. Equation (A6) into equation (1) produces

$$\frac{\partial H}{\partial t} - A^*\left[5H^4\left(\frac{\partial H}{\partial x}\right)^4 + 3H^5\left(\frac{\partial H}{\partial x}\right)^2\frac{\partial^2 H}{\partial x^2}\right] - P^*\frac{\partial^2 H}{\partial x^2} = a_s + a_b \tag{A7}$$

where $P^* = P_s B/(\rho g f^2)$ which is made dimensionless with the transformations $s = x/L_o$ (length), $h = H(x,t)/H_o$ (thickness), $\Gamma = t\ (H_o^7\ A^*/L_o^4)$ (time), $r = y/H(x,t)$ (distance over bed), $\lambda_s = L_o^4/(H_o^8\ A^*)(a_s)$ (net surface mass balance), and $\lambda_b = L_o^4/(H_o^8\ A^*)(a_b)$ (net basal mass balance). The dimensionless form of equation (A7) is

$$\frac{\partial h}{\partial \Gamma} - \left[5h^4\left(\frac{\partial h}{\partial s}\right)^4 + 3h^5\left(\frac{\partial h}{\partial s}\right)^2\frac{\partial^2 h}{\partial s^2}\right] - S^*\frac{\partial^2 h}{\partial s^2} = \lambda_s + \lambda_b \tag{A8}$$

where $S^* = (P^*/A^*)\ (L_o^2/H_o^7)$.

[36] Equation (A8) is solved numerically for h (s,Γ), using finite difference procedures. The solutions for the surface shape either start with the smooth steady state Vialov approximation [*Paterson*, 1994]: $h^{(2+2/n)} + s^{(1+1/n)} = 1$, or from some prescribed start surface that has scarp/troughs. There is usually zero overall mass balance, i.e., $\int_0^1 (\lambda_s + \lambda_b)ds = 0$.

[37] For the particle paths, the horizontal and vertical velocity components are needed. Once H(x,t) is known, the horizontal component u comes from equations (A2), (A4), and (A5) and the vertical v comes from the point-wise mass conservation equation for an incompressible medium:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0.$$

[38] Assuming a model ice cap is moving on a deforming bed of perchlorate sludge, it is easy to estimate the outward horizontal flux of perchlorate F_{Pclor} in an equilibrium situation

$$F_{Pclor} = \int^L a_s \rho_{icecap} D_{dust} P_{chlor} dx \tag{A9}$$

where a_s is the surface accumulation rate in m(ice) a^{-1}, ρ_{icecap} is the ice cap average density, close to pure ice ~ 920 kg m^{-3}, D_{dust} is the mass ratio of impurity (soil) to ice cap (~0.05), and P_{chlor} is the mass ratio of pure magnesium perchlorate measured in the polar soils [*Hecht et al.*, 2009] by the PHOENIX lander. As described in section 3, the pure perchorate can hydrate itself up to octahydrate and associate itself with free water, so the maximum possible brine flux is about $2.5F_{pclor}$. In the integration of (A9), a_s is assumed always to be positive or accumulating value, because dust and perchlorate exhumed on an ablating scarp is assumed to be reintrained in the ice cap. The PHOENIX observed that, while the dug up soils were still hydrated or icy, they were "sticky" and thus probably resistant to wind erosion [*Smith et al.*, 2009].

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