RESPONSE OF NEAR-SURFACE ICE TO MILANKOVITSCH CYCLES: THREE HISTORIES OF ICE AGES ON MARS.

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Introduction: Near-surface ice stretches from the mid-latitudes to the polar caps [1–3] and is thought to respond to Milankovitch cycles [4]. The ice may consist of pore ice, which forms inside soil pores from atmospheric water vapor [5,6], or of almost pure ice, now buried [7,8], or a combination of the two. A numerical model [9] is used to follow the growth and retreat of near-surface ice as a result of regolith-atmosphere exchange [5] for three initial conditions: 1) No ice sheet, so that only pore ice forms, 2) an ice sheet emplaced “a long time” ago, so it has reached equilibrium with the atmosphere, and 3) a recent ice sheet that has not yet reached equilibrium at all latitudes. We explore the consequences of these assumptions for the present-day subsurface ice distribution and for the stratigraphy of the North Polar Layered Deposits (NPLD) and compare the results with observational constraints.

All model calculations use GCM-based atmospheric humidities [8,10], which vary slowly with obliquity. The subsurface model [9] incorporates zonally-averaged topography, thermal inertia, and albedo, and it consists of a temperature model and an ice evolution model. The ice evolution model simulates the exchange of water vapor with the atmosphere, which can lead to retreat of the ice sheet, growth of pore ice, or retreat of pore ice. Limitations to the growth of ice by the geothermal temperature gradient are also incorporated.

Climate Scenario 1: No ice sheet, pore ice only. Model calculations are carried out over 20 Ma of orbital history [11], beginning with an initially dry regolith. Figure 1 shows the result for the northern hemisphere.

Figure 2a shows the subsurface ice volume as a function of time. If all of the ice lost from the northern sub-surface ice reservoir ends up on the north polar cap, and if all subsurface ice gained during growth periods is lost from the north polar cap, the layering of the NPLD will mirror the subsurface ice volume. Figure 2b shows the predicted layering of the NPLD, assuming a polar cap of present-day size. In this scenario, the exchanged volume is very small compared to the actual NPLD, which is several km thick.

Figure 3a further illustrates the near-surface ice distribution.

Climate Scenario 2: In this scenario an ice sheet with 3% dust is emplaced 4.45 Ma years ago and initially stretches from 30°N to the polar cap. As the ice sheet retreats, it leaves behind a sublimation lag. This sublimation lag is allowed to refill with pore ice anywhere that conditions allow. At present-day the ice sheet is very close to equilibrium with the atmosphere (Fig. 3b)

An important feature of this model result is that the pore ice layer is very thin (neutrons can penetrate it), and thus the ice sheet gives rise to high neutron-derived ice concentrations.

A detailed study of the dynamics of the ice table variations at and near the Phoenix Landing Site (PLS), at 68°N, reveals three insights: a) There is a partial cancellation of humidity and temperature changes with obliquity variations, which lead to exceptionally small variability of the equilibrium ice table depth (and thus to a very thin pore ice layer) [12,13]. b) The growth and depletion of the pore ice layer is controlled by the precession cycle, not the obliquity cycle [12,13]. c) The pore ice grows by vertical upward movement of the ice table with complete pore filling and never partial pore filling, and thus leads immediatly to ice-cemented soil without intermediate stages of pore filling [13].

Climate Scenario 3: Recent massive ice sheet; not yet in equilibrium. This third scenario also begins with an ice sheet, but far more recently, 0.86 Ma ago (Fig. 3c). Over this shorter time period, the ice still had time to equilibrate at higher latitudes, but has not yet

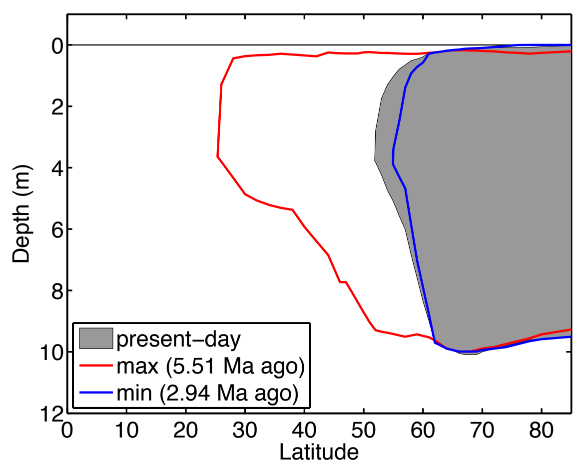
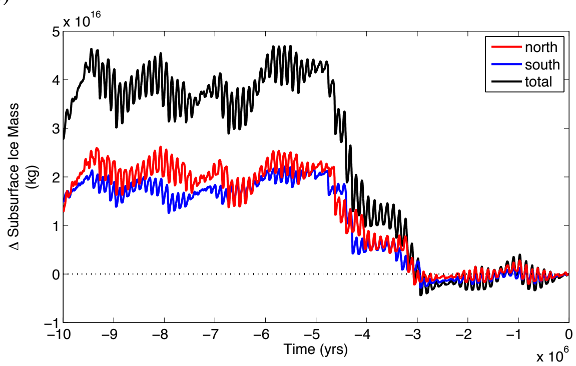


Figure 1: Subsurface ice distribution according to climate scenario 1. The figure shows maxium and minimum extent over the past 10 Ma as well as the present-day extent. The thickness of the ice layer is limited by geothermal heat and is about 10 m.

a)



b)

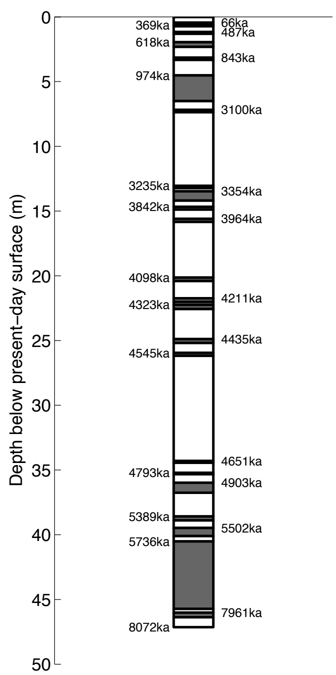


Figure 2: a) Total subsurface ice volume according to climate scenario 1 as a function of time and relative to present-day subsurface ice volume. b) NPLD stratigraphy arises from changes in subsurface ice volume. The white segments are ice layers that correspond to differences in ice volume between a local maximum and the previous local maximum that exceeded this volume. The gray segments represent dust layers; their thickness is proportional to the amount of ice lost from the cap.

reached equilibrium at all latitudes.

In this scenario, the mid-latitude subsurface ice has not yet reached equilibrium with the atmosphere; it still retreats and acts as active source of water vapor. As a result, there is net output of vapor and deposition on the polar cap due to the retreating subsurface ice.

Discussion: Figure 3 provides a comparison of the three scenarios. In all three climate scenarios, there is a transition in latitude between completely ice filled pores and partially ice-filled pores, indicated in the figure with C′/I or C/I [13].

Table 1 compares the model predictions for each scenario with major observational constraints. None of the scenarios is consistent with all known constraints, but scenarios with an ice sheet and an overlying layer of pore ice are consistent with most of the constraints.

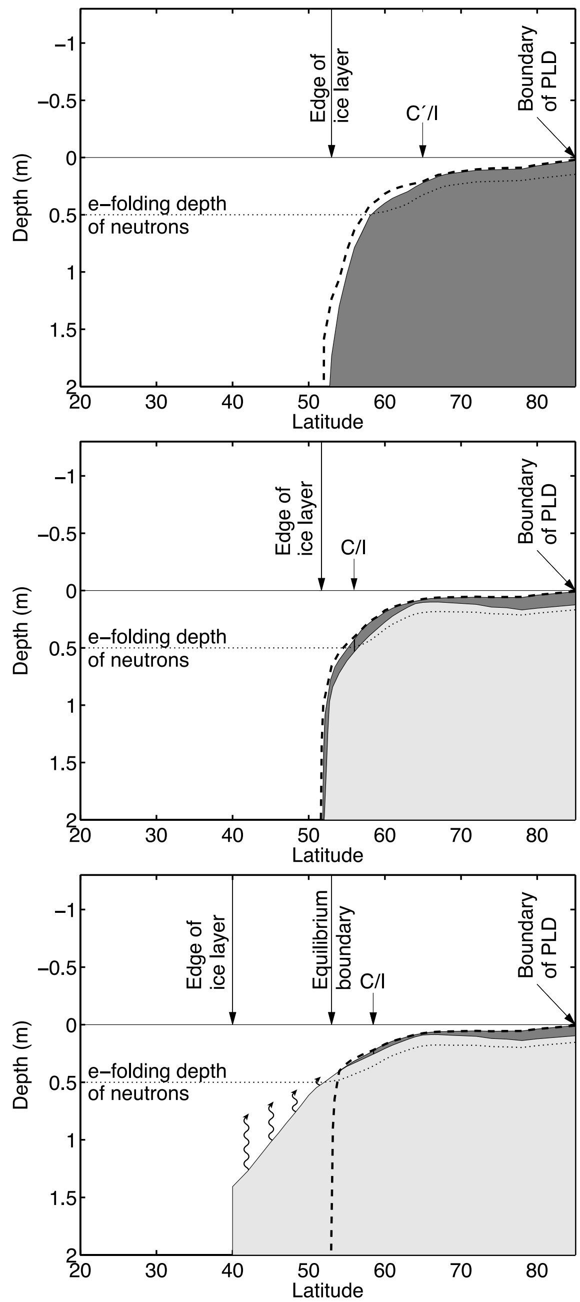


Figure 3: Present-day near-surface ice distribution based on three scenarios for ice ages on Mars. Pore ice is indi- cated with dark gray and the massive ice sheet with light gray. (Adapted from Ref. [13].)

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	Scenario 1 Pore ice only [4,5]	Ice sheet only [7,8]	Scenario 2 [14]	Scenario 3 [13]
MONS extentof ice [15–17]	yes	-	yes	yes
MONS burial depth of ice[1] [15–17]	yes	-	yes	yes
MONS ice concentrations[2] [1,18]	no[3]	yes	yes	yes
Pore ice nearest surface at PLS [19]	yes	no	yes	yes
Fresh icy midlatitude impacts [20]	no	yes	no	yes[4]
Boulders at PLS	yes	no[5]	no[5]	no[5]
Radarthicknessof ice layer [21, 22]	no	yes	yes	yes

Table 1: Matrix that compares climate scenarios with observational constraints. MONS = Mars Odyssey Neutron Spectrometer, PLS = Phoenix Landing Site, [1]includes hemispheric asymmetry of burial depths [3,16], [2]ice concentration far exceeds porosity, [3]Formation of excess ice has been proposed to reconcile with observations, [4]Several other explanations have also been proposed, [5]Lifting of boulders by slowly-growing ice sheet has been proposed to reconcile with observations.