SCENARIOS FOR THE FORMATION OF CHASMA BOREALIS, MARS

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Introduction. An intriguing feature of the Martian polar caps is the presence of large chasms and smaller scarps/troughs which have no counterpart in terrestrial ice sheets. In this study, the focus is on Chasma Borealis, which cuts about 500 km into the western part of the north-polar cap (NPC). A possible explanation for its origin is a temporary heat source under the ice due to a tectono-thermal event or a volcanic eruption (see the discussions by Refs. [1] and [2]). This possibility will be explored by assuming a locally increased geothermal heat flux in the region of Chasma Borealis for a limited period of time in the past, and simulating the dynamic/thermodynamic response of the ice cap with the model SICOPOLIS (SImulation COde for POLythermal Ice Sheets). The questions to be investigated are (i) how much geothermal heat over which amount of time is required to form the chasm, (ii) how much water is discharged by a process of that kind (catastrophic flooding?), (iii) what are the local ice-flow velocities at the slopes of the chasm, and (iv) which processes can keep the chasm open after the end of the heating event.

Modelling approach. The ice-sheet model SICOPOLIS describes the material ice as a density-preserving, heat-conducting power-law fluid with thermo-mechanical coupling due to the strong temperature dependence of the ice viscosity, and computes three-dimensionally the temporal evolution of ice extent, thickness, temperature, water content and age as a response to external forcing. The latter is specified by (i) the mean annual air temperature above the ice (surface temperature), (ii) the surface mass balance (ice accumulation minus melting and evaporation), and (iii) the geothermal heat flux from below into the ice body.

Items (i) and (ii) constitute the climatic forcing and are provided by the Mars Atmosphere-Ice Coupler MAIC. The current version MAIC-1.5 [3] is driven directly by the orbital parameters obliquity, eccentricity and anomaly of vernal equinox [4]. Surface temperature is parameterized by the Local Insolation Temperature (LIT) scheme [5], which uses a daily and latitude dependent radiation balance and includes a treatment of the seasonal CO_2 cap. Surface mass balance is parameterized by an equilibrium-line approach in analogy to terrestrial glaciology [2,6], with the present-day accumulation rate (of the order of 0.1 mm/a) as the main free parameter. As for item (iii), the geothermal heat flux, a standard value of 35 mW/m^2 is chosen. The assumed thermal anomaly under Chasma Borealis is described by an increased heat flux, q_{CB}, between 100 mW/m^2 and 10 W/m^2 for the entire chasm area. The basal heat flux is imposed 5 km below the ice base, and any basal meltwater is assumed to be drained instanteneously.

Further settings include an elastic-lithosphere-relaxing-asthenosphere (ELRA) isostasy model with a lithospheric flexural rigidity of 10^{25} Nm and an asthenospheric time lag of 3 ka [7,8], Glen's flow law with stress exponent $n = 3$ and activation energy $Q =$ 60 kJ/mol [9], a spatially and temporally constant dust content of 20%, a grid spacing of 20 km and a time-step of 1 ka. Other physical parameters are the same as in Ref. [6].

Reference simulation of the NPC. This simulation is driven by the orbital parameters provided by Ref. [4]. Owing to the high obliquities prior to 5 Ma BP and correspondingly high summer evaporation rates, an ice-free initial state at $t = 5$ Ma BP is assumed, the simulation is run until the present ($t = 0$), and the accumulation rate is chosen such that the simulated present-day maximum surface elevation matches the observed value of –1.95 km w.r.t. the reference geoid [10,11]. This tuning procedure yields a present-day accumulation rate of 0.2674 mm/a. A thermal anomaly under Chasma Borealis is not considered, so that the geothermal heat flux is equal to 35 mW/m^2 everywhere.

The result of the reference simulation is an almost axi-symmetric ice cap centered at the north pole with an area of 0.998 x 10^6 km^2 and a volume of 1.6647 x 10^6 km^3. Thus, the overall shape of the ice cap is modelled well, whereas medium- and small-scale structures like Chasma Borealis and the spiralling pattern of surface troughs are not reproduced. The maximum basal temperature (relative to the pressure melting point) is $T_{\mathrm{b,max}} = -69.30$°C, and the maximum surface velocity is $v_{\mathrm{s,max}} = 0.66$ mm/a (very slow glacial flow, four to five orders of magnitude slower than typical values for terrestrial ice sheets).

Simulations with thermal anomaly. In addition to the set-up of the reference simulation, a thermal anomaly (increased heat flux, q_{CB}) is now considered under the entire area of Chasma Borealis.

Thermal anomaly always active. Runs #1–5 have been carried out with $q_{\mathrm{CB}} = 100$, 150, 200, 500 mW/m^2 and 1 W/m^2, respectively, active throughout the simulation time of 5 Ma. For run #1, the basal temperature does not reach the melting point ($T_{\mathrm{b,max}} = -33.56$°C), and the surface velocity in the chasm region increases only slightly ($v_{s,max}$ = 1.91 mm/a). For runs #2–5, the basal temperature in the chasm region is at the melting point, and $v_{s,max}$ reaches values of the order of 10 mm/a. Runs #2 and 3 only produce a small topographic depression, whereas runs #4 and 5 produce a depression similar to the real chasm. For the result of run #5 see Fig. 1.

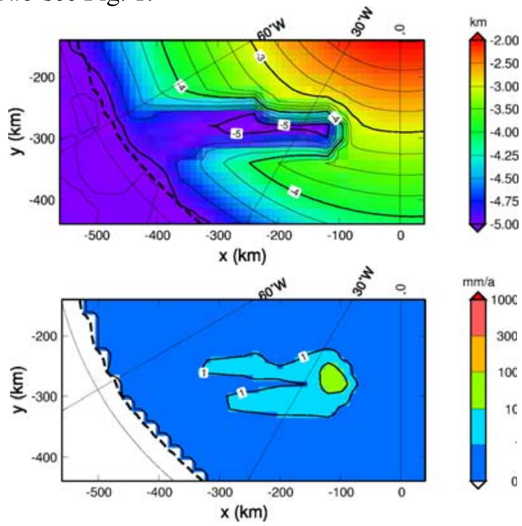

Fig. 1: Surface topography (top) and velocity (bottom) for run #5 (q_{CB} = 1 W/m^2) and t = 0 (present).

Thermal anomaly temporarily active. It is now assumed that the thermal anomaly was only active during a limited period in the past. For run #6, q_{CB} = 1 W/m^2, active during the last 500 ka, and for run #7, q_{CB} = 10 W/m^2, active during the last 100 ka. For the present, both runs produce a fully developed chasm similar to the one shown in Fig. 1 and a maximum surface velocity $v_{s,max}$ of approximately 30 mm/a. Figure 2 shows the maximum basal temperature and water discharge rate for run #7. The by ≈ 30 ka delayed reaction of the basal temperature is due to imposing the heat flux 5 km below the ice base (which is debatable). The melting point is reached at t = –54 ka, and from then on the chasm forms. The basal melting rate (meltwater drainage) peaks at t = –27 ka at a value of 0.635 km^3/a, which is a considerable amount, but still far away from constituting a catastrophic outflow event.

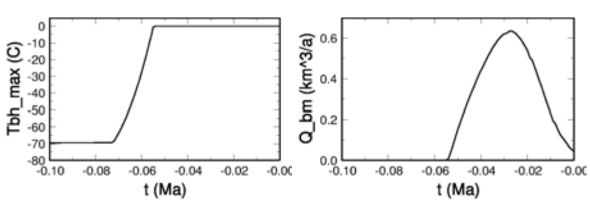

Fig. 2: Maximum basal temperature (left) and water discharge rate (right) for run #7 between t = –100 ka and t = 0.

Further, the maximum surface velocity reaches its largest value of 529 mm/a at t = –53 ka, shortly after the first occurrence of basal-melting conditions.

Chasm closure. Run #8 focuses on the closure of the chasm after the shutdown of the thermal anomaly. Like for run #7, q_{CB} = 10 W/m^2, but the active period is now between t = –1 Ma and –0.9 Ma. Figure 3 shows the maximum basal temperature and surface velocity. Evidently, the basal temperature drops to very low values within some 100 ka after the shutdown of the anomaly (the oscillations are due to the 125-ka obliquity cycle), and the accelerated ice flow stops almost immediately. Therefore, until t = 0 no significant closure of the chasm takes place.

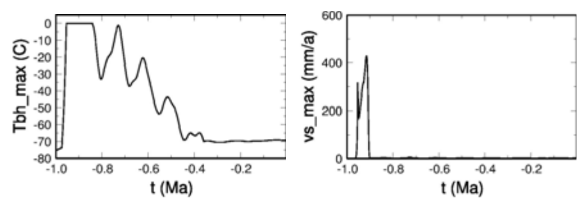

Fig. 3: Maximum basal temperature (left) and maximum surface velocity (right) for run #8 between t = –1 Ma and 0.

Conclusions. (i) A thermal anomaly with a heat flux of ≥ 500 mW/m^2 leads to the formation of a topographic depression similar to Chasma Borealis.

(ii) Simulated discharge rates are of the order of 1 km^3/a. Catastrophic outflow would require either more extreme events or subglacial storage of water (jökulhlaup).

(iii) If the thermal anomaly is switched off, the chasm closes at an extremely slow rate.

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