MARS THERMAL EVOLUTION REVISITED. G. Choblet[1], O.Grasset[1], E.M. Parmentier[2], C. Sotin[1]. [1]Université de Nantes, 2 rue de la Houssinière, Nantes, France, [2]Department of Geological Science, Brown University, Providence, R.I., U.S.A.

Introduction: Models describing the thermal evolution of Mars are revisited on the basis of recent 3D numerical experiments on thermal convection in a fluid with strongly temperature dependent viscosity. The present study describes the conditions for which the cooling of a fluid can be described by scaling laws of a volumetrically heated fluid. Applied to Mars, these models show that a chondritic abundance of radiogenic elements within the martian mantle are not consistent with the present knowledge of this planet. An alternative model assumes that the radiogenic elements were concentrated within the martian crust during the early history of the planet. The following cooling of Mars is described and the evolution of the lithospheric thickness is discussed.

Models describing the thermal evolution of Mars have been proposed in the last 20 years assuming that isoviscous scaling laws for heat transfer can be used below a lithosphere defined by a constant temperature below which viscosity can be considered infinite on geological time scales[5,6]. More recently, models were proposed that used a scaling law determined for a fluid with complex viscosity[3,4]. These studies have shown that the martian characteristics fall into the stagnant lid regime, leading to very high temperatures which are much larger than the melting temperature of peridotites. Compared to these previous studies, the present work deals with 3D numerical experiments of transient cooling for describing more accurately the heat transfer through strongly temperature dependent convecting fluids. Implications to the cooling of Mars will be discussed.

Three dimensional numerical experiments have been carried out in order to study the cooling of a fluid with strongly temperature dependent viscosity[1]. Using both these numerical experiments and laboratory transient cooling studies[2], it has been shown that the cooling of a liquid shell can be well predicted by using a scaling law which describes the stationnary state of strongly convecting fluid with large viscosity contrast. The scaling law links the mean temperature of the convecting fluid to the Rayleigh number and the viscous law. Rayleigh number is computed by assuming that the cooling rate is similar to an uniform volumetric heating rate. Parameters describing the scaling law and derived from our 3D numerical experiments[1] are very close to the parameters obtained by *Grasset and Parmentier* (1998) for a 2D geometry. An example of the comparison between a cooling experiment and the prediction by the scaling law is showed in Figure 1. Up to a non-dimensional time equal to 0.031, the agreement is not good. That period corresponds to first the time required for the onset of convection and then the time required for getting continuity between the vigour of convection below the stagnant lid and the surface heat-flux. After this period, the evolution is very well described by the 3D scaling law.

Application of these numerical studies to the thermal evolution of Mars has been conducted. Assuming that the initial period of transient cooling is short, the cooling of the planet can be described using the scaling law which describes the thermal equilibrium of the volumetrically heated mantle**.** The important point is that the cooling rate is added to the radiogenic heating rate to provide an uniform volumetric heating rate which is incorporated in the scaling law. The model starts with an initial temperature at the base of the thermal boundary layer. The amount of energy transfered by convection is then computed using the scaling law. By taking away the radiogenic heating rate, the instantaneous cooling rate of the mantle is known. A fourth-order Runge-Kutta scheme is then used to determine the evolution of the temperature. In Figure 2a, the thermal evolution of Mars has been plotted assuming a viscosity equal to 10^{21} Pa.s at T=1350°C, an activation energy equal to 430 kJ/mole, and a chondritic abundance of radiogenic elements. The main result is that the temperature at the base of the thermal boundary layer is always much larger than the liquidus temperature. Several parameters may have important effects like the initial temperature at the base of the thermal boundary layer, the viscous law, and the amount of radiogenic elements. Different values of the initial temperature have been investigated, all providing the same thermal evolution after a period lower than 1 Ga. We have investigated models with a viscosity at T=1350°C ranging from 10^{19} Pa.s to 10^{21} Pa.s and activation energy in the range 300 to 500 kJ/mole. In all these models the temperature at the base of the termal boundary layer is always larger than the liquidus temperature. Such models are not consistent with what we know about the martian internal structure (non-hydrostatic shape of the planet).

An alternative model (end-member model) is performed assuming that all the radiogenic elements are concentrated within a crust, leaving the mantle free of internal source. This case corresponds well to the cooling of an initially hot fluid. Figure 2-b presents a model similar to the one reported in figure 2-a with no internal heating of the mantle. This model in spite of an initially hot temperature field, allows an efficient cooling so that late evolution (after 2.5 Ga) of the martian mantle occurs below the solidus temperature. While our model for a solid convecting mantle does not take into account the cooling rate associated to the presence of a magma ocean, it indicates that the end-member case of all radiogenic heat sources concentrated in the crust is more consistent with our present knowledge of Mars.

In addition, stagnant lid thickness as defined by a viscous temperature scale^2 is different from the elastic lithosphere thickness. Figure 3, obtained for the same case than presented in figure 2-b (no internal heating of the mantle), shows a lid thickness larger than the depth of isotherm 700°C, representing the bottom of elastic lithosphere. The bottom of the stagnant lid undergoes a temperature of 1300°C during the cooling, confirming the idea that the depth below which isoviscous scaling laws may be applied to the convecting mantle does not fit with the lithosphere thickness as commonly assumed in scaling models of thermal evolution.

Conclusions : Models derived from our 3D numerical experiments indicate that cooling of the martian mantle heated from within at a chondritic rate is not consistent with our knowledge of Mars. This suggests that models proposing concentration of radiogenic elements in the crust are more adequate. In addition, the stagnant lid of the asymptotic regime for variable viscosity convection is different from elastic lithosphere.

References : [1] Choblet G. (1999) *thèse Rennes I* ; [2] Davaille A. and Jaupart C. (1993) *J. Fluid Mech.*, **253**; [3] Grasset O. and Parmentier E.M. (1998) *J. Geophys. Res*; [4] Reese C.C et al. (1998) *J. Geophys. Res.*, **103**; [5] Schubert G. et al. (1979) *Icarus*, **38**; [6] Shubert G. and Spohn T. (1990) *J. Geophys. Res.*, **95**.

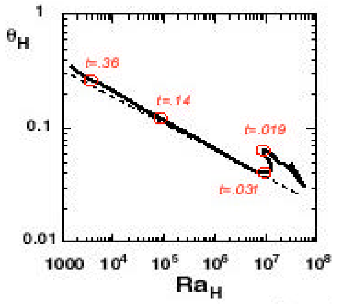

figure 1

Figure 1 : Transient cooling in the stagnant lid regime. Mean cooling in the convective sublayer (bold line) compared to the quasi-static prediction (dashed line) obtained for an isoviscous layer. Initial surface Rayleigh number : 370 ; initial viscosity contrast : 54 000.

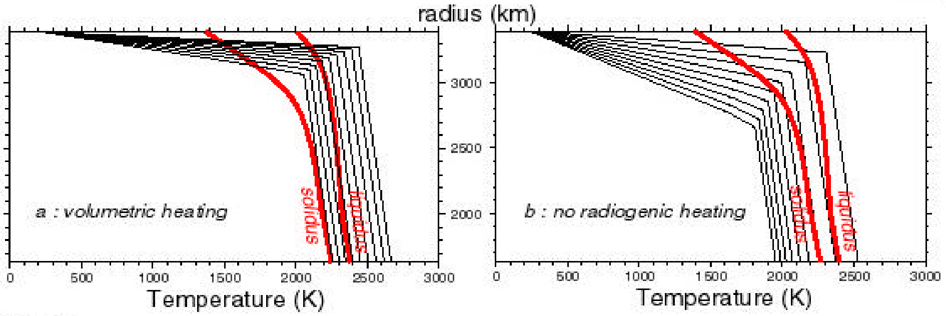

figure 2

Figure 2-a,b : Thermal evolution of the martian mantle. Temperature profiles are computed with the stationnary law scaling heat transfer in the stagnant lid regime. Each profile is a snapshot ranging from 0.5 Ga (right) to 4.5 Ga (left). Time between two consecutive profiles is 0.5 Ga.

Figure 3 : Time evolution of the lid thickness and heat fluxes. The lid thickness (bold line) can be compared to the depth of several isotherms in the model (700°C, 900°C, 1100°C, 1300°C, dashed lines). Both mantle heat flux and surface heat flux are plotted assuming that all radiogenic elements are emplaced in the martian crust.

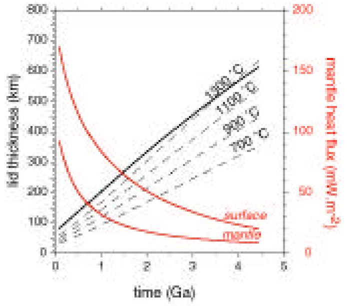

figure 3