ON THE EFFECT OF THE Mg/Si RATIO ON THE MANTLE DYNAMICS OF THE MASSIVE ROCKY PLANETS. IMPLICATIONS FOR THE HABITABILITY AND SUPERHABITABILITY OF HZ-SUPER-EARTHS. P. Futó[1] [1]University of Debrecen, Cosmochemical Research Group, Department of Mineralogy and Geology, Debrecen, Egyetem tér 1. H-4032, Hungary (dvision@citromail.hu)

Introduction: Rocky planets, thus habitable-zone (HZ) super-Earths may have highly favorable conditions for a complex biosphere making the planet more hospitable for life than Earth. These are the so-called superhabitable worlds [1]. The one of the plausible conditions for superhabitability (SH) is likely to be the relatively long-time plate tectonics, which depends on the physical criteria of mantle convection. The possibly strong effect of adiabatic compression on the mantle convection due to the high viscosity contrast may result in stagnant or sluggish lid regime in super-Earths [2].The low efficiency of convective mantle heat transport can hinder the cooling of the core and thus the maintenance of the magnetic field. At the same time, it is known that the planetary composition may significantly affect the mantle dynamics, lithospheric properties and plate movements. Stellar abundances of the key rock-forming elements impacts on the planetary mineralogy and tectonics. The observed low C/O (<0.8) and the Mg/Si ratios (mainly 1<Mg/Si<2) in photospheres of planet host stars indicates that the Earth-like magnesium silicate composition may be relatively common for terrestrial planets in the Milky Way Galaxy [3, 4].

Surface conditions, thermal evolution and planetary habitability of rocky planets are strongly depend on their tectonic regime [5]. Accordingly, long-time active tectonics has been assumed to be crucial to SH. Therefore, this study is being based on the importance of the active-lid tectonic regime for maintaining a relatively long-term SH on super-Earths. Among the possible conditions, I focus on that silicate mineralogy and a determined range of Mg/Si ratio, which may permit an assumed optimal mantle composition for Earth-like habitability and for SH. I made an attempt to determine approximately the mass range for rocky super-Earths, in which tectonic processes could work on them assuming an Earth-like structure and mantle composition.

Modeling the effect of Mg/Si ratio on the mantle convection in rocky planet interiors: I investigated the conditions of mantle convection by making simple magnesium silicate mantle models for rocky super-Earths (SEs). Scaling laws of $R_p=M^{267}$, $d=M^{0.29}$ have been applied for total radius and mantle thickness.

The adiabatic compression, which becomes stronger with increasing planetary mass, and the effect of higher Mg/Si ratio have also been considered in modeling the mantle dynamics of SEs with masses ranging from 1-5 $M_{\oplus}$. The Rayleigh number Ra is defined by $\rho_0 g\ \alpha\ \Delta T\ D^3/\ \eta_0\ \kappa$. Rayleigh number parameters for the mantle are ρ_0 = 3416 kg m^{-3}, g = 9.81-20.8 ms^{-2}, the coefficient of thermal expansion $\alpha = 4 \times 10^{-5}$ K^{-1}, the temperature contrast is being calculated in all model $\Delta T = (T_b\text{-}T_s)$, mantle thickness D = 2900 - ~ 4600 km, η_0 = is the viscosity on the bottom boundary of the model layer ($T=T_b$) and the average thermal diffusivity $\kappa = 10^{-7}$ m^2 /s. Pressure-dependence of α has been taken into accounted based on the study of Tachinami et al. 2014 [6] while as opposed to it κ is constant for simplicity. The viscosity predictions for the mantle-models can be expressed in terms of the Arrhenius law and the viscosity contrast (r) across the mantle has been pescribed by $r= \eta\ (T_s)/\ \eta\ (T_b)$.The activation energy E_a=30 kJ/mol^{-1} and the activation volume V=10^{-6}. Effects of the adiabatic compression have been computed by utilizing model parameters of this study and considering the methods and results of previous studies.

Two main minerals constitute the lower mantle: (Mg, Fe)SiO_3 bridgmanite and ferro-periclase (Fp) [(Mg, Fe) O]. Throughout the modeled lower mantles, Fp is in rock-salt (B1) phase (Fp is in B2 phase only at core mantle boundary (CMB) pressure of ~ 5$M_{\oplus}$) and its molar ratio increases with increasing Mg/Si ratio related to the perovskite (pv) and post-perovskite phase (ppv) bridgmanite, respectively. The mantle volume fraction (MVF) of $MgSiO_3$ pv and ppv + B1 (+B2) Fp layer increases with increasing planet mass.

The increased amount of Fp, which is the one of the most abundant minerals in terrestrial planets, may have a considerable impact on mantle dynamics thereby that a large amount of it could decrease the lower mantle viscosity [7, 8]. The pressure-induced high-to-low-spin transition of iron may have a large effect on the viscosity of Fp [8]. Computing the varying molar Mg and Si ratios during the examination of the effect of increasing Mg/Si ratio, Fp has been characterized by a composition of $Mg_{(1-x)}Fe_xO$ with iron concentrations (x) of 0.2.

The more vigorous convection of Mg-rich planets may result in a more effective mixing between in the interior and surface. This process may lead to a less oxidized surface with a more intensive carbon outgassing and a CH_4 - enhancement as opposed to CO_2 [7].

Previous studies shows that Mg/Si ratio may vary throughout the mantle [9, 10]. Present model does not consider the effects of variable Mg/Si on the P-T-dependent viscosity, effect of the elevated Mg/Si ratio on the lithospheric properties and other factors that affect thermal convection. It has been interpreted as an idealized homogeneous mantle-material system in respect of the Mg/Si ratio due to the efficient mixing.

A favorable mantle compositional range for H- and SH-super-Earths: In the range of Mg/Si ratio >1.25, a decrease may occur in r compared to that of an Earth-analog mantle composition by up to a factor of ~1-3 due to the reduced viscosity of ppv with an enhanced Fp ratio. Note that ~10^2 viscosity reduction occurs by the B1-B2 phase transition in MgO (at 0.5 Tpa) [11]. It can enhance the maximum mass limit of mantle convection having a major impact on the dynamics and evolution of rocky planets above ~ 4 $M_{\oplus}$.

I find that planets with higher Mg/Si ratios relative to Earth, may have a limited growth in mass, within which the mantle convection may be more efficient compared to planets with lower bulk Mg/Si ratios. It can have a small favorable effect on H and SH of SEs, moreover, as planet mass increases in this range MVF of lower mantle viscosity region also grow. Hence, r can remains under a critical value up to determined mass limits depending to the elevation of Mg/Si ratio, the iron concentration of Fp, the pressure and the thermal state of the planet.

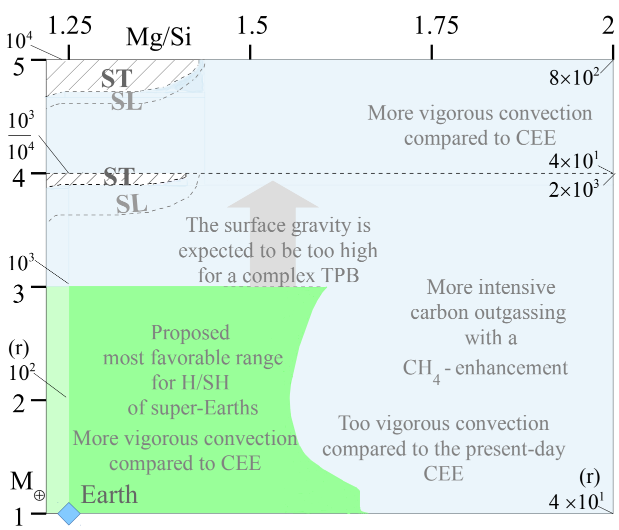

Figure 1. …

ST-L and SL-L denote the stagnant- and sluggish lid modes of convection. TPB: terrestrial-type photosynthetic biosphere. CEE: The level of present-day convection efficiency in Earth's mantle, which is based on the calculated Ra and convective velocities.

Conclusion: The adiabatic compression of convective fluids may have a strong impact on the efficiency of thermal convection and thus, on the thickness and mechanical properties of the lithosphere. The activity of hot ascending mantle plumes decreases with increasing r. At the same time, the higher Mg/Si ratio may reduce further the viscosity of the lower mantle and hence r across the entire mantle, thereby improving the efficiency of convective heat transport. In terms of this model, the effect of higher Mg/Si is slight for the efficiency of mantle convection in super-Earths and it may still be negligibly small for the case of larger planetary masses. Conversely, it has been suggested that it may have a favorable impact on surface conditions for a complex terrestrial-type photosynthetic biosphere on super-Earths through, for example, the alteration of planet's habitable lifetime in a small degree, mostly for the case of a possibly superhabitable state.

In terms of the conclusions of this model approach, it is likely that, those rocky planets can provide more favorable conditions for H and SH, which have a mineral compositions in the range of 1.25-2 Mg/Si ratios and total masses between 1 and ~3 $M_{\oplus}$. Owing to a moderately elevated level of r and containing an adequate amount of radioactive elements for radiogenic heating, an optimal range of CMF can also be very important for efficient mantle convection, having been proposed to be ~ 0.25-0.4. Note that a not too slow planet cooling and an adequate outer core convection, this CMF range is thought to likely be optimally suitable to maintain magnetic field for complex life.

Thermal history, interior and surficial dynamics of terrestrial exoplanets may show a greatly picture due to the mineral diversity. Therefore, life-harboring planets with relatively long-term habitability may only be a small fraction of the HZ- rocky planets in the Galaxy.

Summary: According to the prediction of this model approach, a determined range of elevated Mg/Si ratio can helps to form the neccessary conditions for being a super-Earth is habitable or „superhabitable”.

References:

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