

### 3D NUMERICAL MODEL FOR THE FORMATION OF THE MARTIAN DICHOTOMY AND THE THARSIS AND ELYSIUM RISES. G. Leone<sup>1</sup>, P. J. Tackley<sup>1</sup>, T. Gerya<sup>1</sup>, D. A. May<sup>1</sup>, and G. Zhu<sup>1</sup>

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**Introduction:** Past works have suggested that the Martian dichotomy may have been generated either by a giant impact occurring on the northern hemisphere of the planet forming the lowlands through the so-called Borealis basin [1][2][3], or by endogenic processes like degree-1 mantle convection [4] forming the southern highlands. However, these models suffer from several problems: (i) the multi-ring feature indicated by [1] in Arabia Terra as sign of the impact is fretted terrain visible at different extent in other regions of Mars, (ii) impacts so large create magma oceans and/or crustal flows that are inconsistent with both topography and the evident lack of volcanism in the northern lowlands [5]; (iii) [2] provide a set of results for several combinations of impact energies and angles at least, but the same objections are applicable to their model; (iv) [3] propose a vertical impact in 2D through the same  $10^{29}$  J energy requirements of [2] (taken from [6]), and place the Martian dichotomy at the same age of the Moon forming event around 100 Ma after CAI. (v) Degree-1 mantle convection may indeed produce crustal thickening consistent with the Martian dichotomy but the required timescale is too long; the dichotomy formed early in Martian history as evidenced by studies on  $^{182}\text{Hf}$  and  $^{182}\text{W}$  isotopic anomalies in the inner Solar System [7][8][9][10][11][12]. The quasi-circular depressions (QCD's) present in the lowlands [13] hint at a similar crustal age for both hemispheres, which are estimated to start formation during or immediately after the planet's accretion so the crustal dichotomy is thought to be the most ancient feature on the planet [11][14].

A model combining both endogenic and exogenic processes provides a better solution to the various problems of the single approach models. A giant impact in the southern polar region would melt the proto-crust and the mantle into a roughly hemispherical magma ocean which, after cooling, would produce a thick crust forming the southern highlands and a residual asymmetrical thermal anomaly inside Mars [15][16][17]. Such an hypothesis is also supported by the combined analysis of MOLA topography and MGS gravity data [18], from which a crust thickness of 58 km below the highlands and 32 km below the northern lowlands has been estimated.

Following the 2D study of this scenario by [17] and the suggestion that a giant impact by a (non-compositionally specified) body between 0.1 – 1 lunar

masses ( $\approx 800 - 1700$  km radius) may have formed and shaped the Martian dichotomy [15][16], we extend the study in 3D using suitable versions of the I3ELVIS and StagYY thermo-mechanical codes [19][4] to simulate both short-term and long-term evolution following a giant impact in the southern polar region that created the Australis Magma Ocean (AMO) as large as the Martian highlands. We tested impact times from 0 to 5 Ma after CAI, when impactors up to Moon-size were already available [20][15][16], then settled on a starting time of 4 Ma, when radiogenic heating was weaker than early accretion time [22] due to the end of the short-lived radionuclides ( $^{26}\text{Al}$  and  $^{60}\text{Fe}$ ) and the Martian core was not yet completely formed. A value above the earliest time of 3 Ma indicated by the geochemistry [10] but still within upper bounds which place the core formation around 12 Ma and 15 Ma, respectively [8][9]. In our simulations the core is formed around 5-6 Ma after CAI. If a Moon-sized iron core impactor hypothesis is viable, we shall show shortly that the contribution to the whole iron/nickel of the Martian core would be approximately a sphere of 1120 km of radius thus raising evident implications on the evolution timescale and formation of the core, estimated at between 1600-1800 km in radius by several studies of the Martian moment of inertia [23][24].

**Discussion:** We have performed our 3D runs for different combinations of impactor sizes and compositions, testing from mesosiderite-type composition (50% radius iron but nickel content neglected at the moment) to sideritic (up to 80% radius iron). The main reason for including siderites in our runs is the presence of M-type asteroids like 16 Psyche as well as several others in the asteroid belt [25], the likely remnants of larger parent bodies in the 1-2 AU range which then migrated in the current position after giant impacts with protoplanets [26]. Although the 2D study of [17] obtained a crustal dichotomy with a mesosideritic impactor of 500 km radius, our 3D results show that the impact of a 500 km radius mesosideritic body is insufficient to form a hemispherical magma ocean because its heating effect is smaller than the radiogenic internal heating. A larger impactor of around 1600 km of radius and 70% of iron at an impact speed of  $5 \text{ km s}^{-1}$  is needed to achieve a hemispherical magma ocean comparable to the extent of the Martian dichotomy. A nearly Moon-sized impactor colliding to Mars with enough energy to produce a comparable thermal effect of a

rocky body providing 30-65% planet surface melting in case of an impactor/target mass ratio of 0.14 and impact speed of  $15 \text{ km s}^{-1}$  or total melting if the ratio is  $> 0.4$  at the same speed [27]. N-body simulations have also provided the interesting statistical result that the impactors' speed is more frequent around the escape velocity of the target body [20]. The speed of  $5 \text{ km s}^{-1}$  in the case of Mars is also suitable to avoid bouncing or disruption processes during the giant impact [21].

The magnetic anomalies of Mars have been emplaced on both highlands and lowlands by a transient magnetic field [28] perhaps triggered by the giant impact itself. The transient nature of this magnetic field is demonstrated by the lack of anomalies from subsequent impacts that generated Argyre and Hellas and other basins in the north [29].

The time of the giant impact and the geologic age of the main volcanic centres on Mars are of fundamental importance to a) establish landmarks in the reconstruction of the sequence of events between the formation of the dichotomy and the first volcanic eruptions on the surface, and b) follow the evolution and eventual migration of the mantle plumes that have fed the first volcanic centres and the later eruptions that built both the Tharsis and Elysium Rises. Now, simply analysing the position of these volcanic provinces on the Martian surface, it appears that two mantle plumes followed two main paths from the south polar region: 1) a main one to northwest through the Dorsa Argentea formation to the Tharsis Rise and 2) a secondary one to northeast until the Elysium Rise through Tyrrhena Patera, from which a small branch heads northwest towards Syrtis Major, forming a large open V on the planisphere of Mars. Worth noticing are the dominant NE and NW trends of the volcanic alignments that can be easily observed on the surface of the planet.

**Conclusions:** Our simulations indicate that a giant impact in the southern hemisphere is capable of producing the crustal dichotomy within the timing required by the geochemistry. A sideritic (around 70% radius iron) impactor of 1600 km radius is our best result. Such an impact did not happen before 4 Ma after CAI despite the availability of impactors, because the strong heating effect of short-lived radionuclides would have erased the effect of the giant impact.

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