# POLAR WANDER OF MARS DRIVEN BY DEGREE-1 MANTLE CONVECTION AND ITS IMPLICATIONS FOR THE FORMATION OF THE CRUSTAL DICHOTOMY AND THE THARSIS RISE.

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## Introduction

The topography on Mars is dominated by the crustal dichotomy between the northern and southern hemispheres and the Tharsis rise on the equator[1]. No explanation has been offered so far as to why the dichotomy should be in its current orientation rather than another. The geoid is currently dominated by Tharsis [2] and rotational stability suggests that a Tharsis-sized load would induce polar wander to place itself on the equator if it did not originate there [3]. However, little tectonic evidence for this excursion exists [4]. Furthermore, it is possible to place Tharsis on the equator and allow the dichotomy to have an arbitrary orientation.

Here, we examine mechanisms that may be responsible for the formation of the crustal dichotomy and its current orientation. It has been shown that degree-1 mantle convection can arise in early Mars-like conditions on a timescale (within the first couple hundred Ma) appropriate to the formation of the dichotomy [5]. Geoid anomalies arising from mass heterogeneities due to convection and from the resulting dynamic topography may induce polar wander and reorient the planet.

## The Geoid, The Inertial Tensor, and The Pole Position

Degree-1 convection can lead to the formation of the dichotomy, either by melt from the plume leading to volcanism and increased crustal production in the southern hemisphere, or by the plume eroding the base of the crust in the northern hemisphere [6]. We took the temperature and topography profiles from several 3D spherical convection models that produced degree-1 pattern [5]. An example plume is shown in Fig. 1. Although such a plume is predominantly $\ell = 1$, it has a strong $\ell = 2$ component as well. We calculated the geoid based on the thermal anomalies and topography at the surface and CMB [7]. We determined the inertial tensor from the $\ell = 2$ geoid according to MacCullagh's formula [8]. Diagonalization of this tensor reveals the principal axes. The axis with the largest principal moment of inertia should be the new rotation axis. We assume that the rotational bulge will adjust to the new pole position on a timescale short compared to the convective motions [9].

Figure 1: Degree-1 upwelling plume from a 3D convection model

The surface topography and geoid for the example plume are shown in Fig. 2. A region of high topography develops above the plume (Fig. 2a). This results in a positive geoid anomaly coincident with the topography and antipodal to it. Our calculation of the inertial tensor indicates that the plume and the associated geoid anomalies should lie near the equator, roughly equidistant from the new pole positions (shown as white circles). The other degree-1 convection models exhibit similar behavior. The pole position is always roughly 90° away from the upwelling. If the plume is responsible for formation of the dichotomy [6], then these results suggest that the dichotomy originally was oriented east-west. Another phase of TPW is required to bring the dichotomy into its current position.

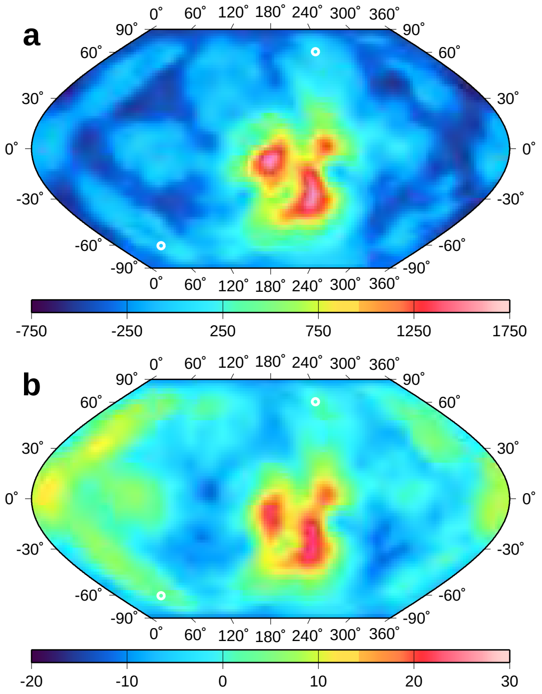

Figure 2: Topography (a) and Geoid (b) in meters for the plume shown in Fig. 1. The calculated pole positions are shown as white circles superimposed on the plots.

## Effect of the Lithosphere

The crustal dichotomy is a very old feature, at least 4.1 Ga [10]. At the time of the formation of the dichotomy, the thickness of the elastic lithosphere ($T_e$) is essentially zero. However, as the planet cools, this elastic layer will thicken and act as a filter, reducing the dynamic topography.

We devised an elastic filter to determine the dynamic topography produced by the plume buoyancy on a planet with an elastic lithosphere [11]. We calculated the geoid due to this filtered topography and the plume buoyancy for several values of $T_e$. When $T_e$ becomes about 25 to 30 km thick, the $\ell = 2$ geoid vanishes and the pole position becomes unstable. When $T_e$ exceeds 30 km, the geoid is negative over the plume. The new pole position coincides with the negative geoid, bringing the dichotomy to a north-south orientation similar to today. Fig. 3 shows the geoid and pole position for a series of gradually increasing values of $T_e$.

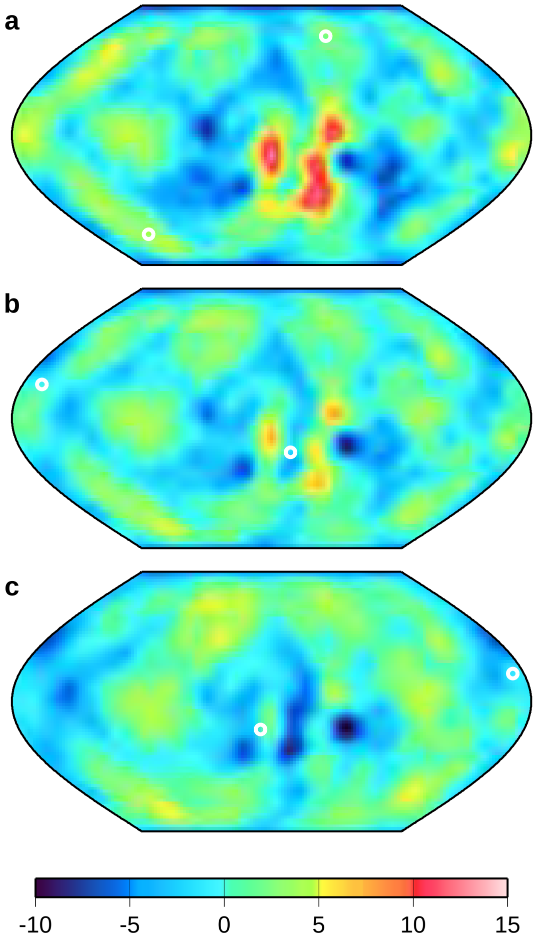

Figure 3: Geoid and pole positions in the presence of a lithosphere with $T_e$ = 20 km (a), 30 km (b), and 40 km (c).

## Discussion and Conclusions

We propose the following scenario for the formation of the crustal dichotomy and its evolution to the present state. Degree-1 mantle convection develops within the first few hundred Ma [5]. The one-plume structure (Fig. 1) drives a TPW event that places the plume near the equator (Fig. 2). Melt associated with the plume is erupted onto the surface above it, thickening the crust in that hemisphere. This melt cools in the ancient global magnetic field and produces remanent magnetism, consistent with suggested paleopole positions near the present-day equator [12]. As the planet cools the lithosphere thickens, reducing the dynamic topography. When $T_e$ exceeds about 30 km, the geoid above the plume becomes negative and the plume rotates the planet such that it is near the south pole (Fig. 3).

Some time after this reorientation, as the lithosphere continued to thicken, the Heavy Bombardment occurred, obliterating any surface expression of a fractured fossil bulge. Following the bombardment phase and possibly continuing until the end of the Noachian, Tharsis developed upon the dichotomy boundary. Why Tharsis lies on the dichotomy boundary remains an open question. Because this location was already near or on the equator, Tharsis induced little to no polar wander before reaching in its present position. The small amount of TPW due to Tharsis did not apply enough stress to fracture the lithosphere, and hence these tectonic features are not seen [4]. With Tharsis dominating the geoid of Mars and an ever-increasing $T_e$ inhibiting further TPW events, Mars remained essentially in this rotational state until the present.

We note that as the lithosphere thickens, there may be a fossil rotational bulge upon a TPW event. With a nonzero $T_e$, the bulge may not relax entirely in response to a new rotation axis. The geoid from even a small fossil bulge may dominate over the convective geoid signal and maintain the planet it the same orientation unless a sufficiently large load (e.g. Tharsis) develops [13]. In this scenario, our second phase of TPW becomes difficult. However, this scenario assumes that the planet's spin state was established at a time when $T_e \approx 0$, and that little to no TPW occurred as the planet cooled, which may not have been the case. The values of $T_e$ considered here are also very low, on the order of 30 km. A lithosphere this thin may easily have fractured, allowing the bulge to relax to a new orientation.

## References

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