

THE CASE FOR A MARTIAN INERTIAL INTERCHANGE TRUE POLAR WANDER EVENT. M. A. Wieczorek¹, M. Greff-Lefftz¹, S. Labrosse¹, P. van Thienen¹, H. Rouby¹, J. Besse¹, and W. C. Feldman², ¹Institut de Physique du Globe de Paris, ²Los Alamos National Laboratory, (email: wieczor@ipgp.jussieu.fr).

Introduction

Although planetary bodies are relatively immobile on human timescales, large redistributions of mass can occur over geologic time as a result of mantle convection, magmatic processes, and large impact events. These processes can alter the moments of inertia of the planet and by consequence modify its rotational configuration. (The differences of a planet's three principle moments of inertia, $A < B < C$, are determined by its degree-2 gravity field.) In particular, if angular momentum is conserved, and if there is some mechanism for dissipating internal energy, then the planet will reorient over geologic time such that its maximum principle moment will coincide with its spin axis [1]. This is referred to as true polar wander and is well documented to have occurred on Earth [2].

A particular type of true polar wander occurs when the maximum principle moment C (which should be aligned with the planet's spin axis) becomes smaller than the intermediate moment B (which should lie in the equatorial plane). This case is referred to as *inertial interchange true polar wander*, and can give rise to a rapid 90° reorientation of the planet. Several such events may have occurred on the Earth [3-5], and here we suggest that a single inertial interchange true polar wander event may also have occurred early in Martian history.

In support for this hypothesis, we argue that two antipodal equatorial deposits possessing high abundances of hydrogen are the relicts of ancient polar caps. In addition, magnetic paleopole locations based upon orbital magnetic data appear to be consistent with the dipole axis once having passed through the Tharsis province. We will show that the formation of the "Tharsis plume" could have altered the moments of inertia of Mars such that the plume axis would have initially aligned with the rotational axis. Following this, the construction of a large volcanic edifice above this plume would have altered the moments of inertia in the opposite sense, causing Tharsis to end up at its current equatorial position.

Equatorial Hydrogen Deposits

Data from the Mars Odyssey gamma-ray spectrometer have been able to constrain the abundance of hydrogen in the upper meter of the Martian regolith [6]. In addition to measuring high hydrogen abundances in the polar regions, relatively high concentrations (up to 10 wt.% water equivalent hydrogen) have been found in the equatorial regions as well (see Figure 1). In particular, there appear to be two relatively isolated anomalies that are nearly

antipodal to each other, with one being centered exactly on the equator in Arabia terra, and the other just to the west of the Tharsis province. While the two deposits are not exactly antipodal to each other, it is reasonable to hypothesize that they were when they formed, and that the planform of the deposit close to the Tharsis rise was subsequently modified by being overlain by young volcanic flows and sediments to the north and east.

As liquid water and ice are not currently stable at equatorial latitudes [7], these deposits are most likely composed of hydrated minerals. The confines of these deposits do not strictly coincide with the current stability fields of hydratable minerals [8], and this implies that they were not formed exclusively by atmosphere-rock interactions under current climatic conditions. Instead, some localized process involving ground water is most likely required for creating the hydratable minerals at these locals, and that current atmospheric conditions are capable of sustaining them in a hydrated form [e.g., 9]. Based on the nearly antipodal locations of these two deposits, we hypothesize that they were formed beneath ancient polar caps, and that basal melting beneath these [10] was capable of aqueously altering the underlying bedrock.

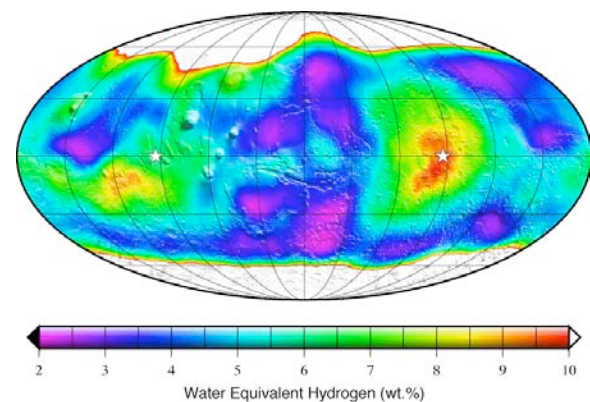


Figure 1. Minimum abundance of water equivalent hydrogen in the upper meter of the Martian regolith. The white stars signify the central location of the Arabia terra deposits and its corresponding antipode.

Magnetic Paleopole Locations

When silicate magmas are cooled in the presence of a magnetic field, the alignment of magnetic minerals causes the rock to retain a natural remnant magnetization. If oriented samples are available, and if it is assumed that the magnetizing field was an internal dipole, then the direction of the rock's

remnant magnetization can be used to determine the location of the magnetic poles when it cooled through its Curie point. It is then commonly assumed that this dipole axis was at that time coincident with the planet's rotation axis.

A similar procedure can sometimes be carried out using orbital magnetic field data. In particular, if one assumes that an isolated magnetic anomaly was formed when a region of the crust cooled in the presence of a steady internal dipole field, then the magnetization direction of the crust can be used to infer the location of the magnetic pole at the time this anomaly formed. While the validity of the assumptions used in this procedure are difficult to quantify, several studies employing this technique have found magnetic poles that differ substantially from the current rotation axis [e.g., 11, 12] (though see [13] for a contrary example).

We plot the locations of the north and south magnetic paleopoles of Arkani-Hamed and Boutin [11] in Figure 2, and it is immediately evident that these seem to cluster at equatorial latitudes. Assuming that the magnetic anomalies employed in that study all formed when an internal dipole field was oriented along the same axis, we plot the average angular distance between each point on the surface and those paleopoles that are within 90° of this point. It is seen that the best fit paleopole location lies within the Tharsis plateau, suggesting that this volcanic province was once located at either the planet's north or south pole and that $\sim 75^\circ$ of true polar wander has since occurred. We remark that this best fit paleopole (which is based solely on 9 data points) is only $\sim 30^\circ$ away from the center of the Arabia terra hydrogen enhancement.

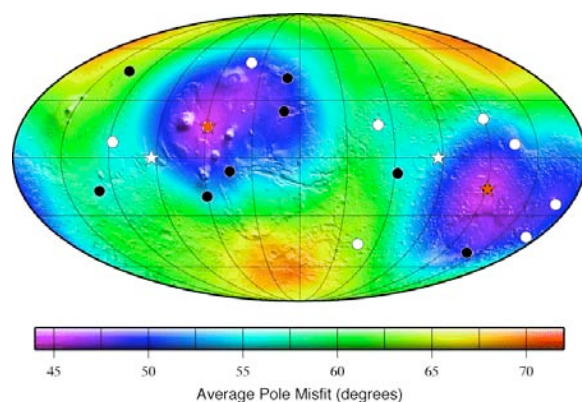


Figure 2. North (white) and South (black) magnetic paleopoles of [11]. Color scale indicates the average angular distance between each point of the surface and those paleopoles that lie within 90° of this point. Red stars correspond to the best-fit paleopoles, and the white stars correspond to the location of the Arabia terra hydrogen deposit and its antipode.

Inertial Interchange True Polar Wander

The equatorial hydrogen abundances and magnetic paleopole data can be easily accounted for if Mars underwent large amounts of true polar wander early in its geologic evolution. In particular, our hypothesis requires that Tharsis was once located close to either the north or south pole of the planet, and that after the crustal magnetic anomalies and hydrated minerals beneath the polar caps formed, that it was subsequently rotated to its current equatorial location. We suggest that such a polar wander history is a natural consequence of forming the "Tharsis plume" early in Martian history and the subsequent construction of the Tharsis plateau above this plume.

The Tharsis plume could have initially been located along the planet's spin axis for one of two reasons. Firstly, because of the rotational flattening associated with the core-mantle boundary, we have found that convective upwellings would preferentially occur along the planet's spin axis. Secondly, because of the mass anomalies associated with low-degree mantle convection and the corresponding lithospheric deflection, the degree-2 gravity field and moments of inertia of a planet can be significantly modified. In particular, preliminary calculations show that the symmetry axis associated with a degree-1 or 2 convective pattern should eventually align with the planet's spin axis. After this occurs, volcanic construction above this plume would alter the planet's moments of inertia in the opposite sense, causing the Tharsis province to eventually end up near the equator. This phase of inertial interchange true polar wander should occur over a very brief interval of time, lasting only a few millions years [14].

In order to further quantify and test the above hypothesis, we are in the process of modeling the expected polar wander paths associated with an axisymmetric convecting mantle. In particular, the density anomalies obtained from realistic mantle convection simulations are being used as input to a visco-elastic true polar wander code [15]. The polar wander behavior and associated timescales will be presented as a function of several parameters, of which the lithospheric thickness and convective planform are expected to have the largest influence.

References [1] Goldreich and Toomre, *JGR*, 74, 2555, 1969; [2] Besse and Courtillot, *JGR*, 107, 2300, 2002; [3] Kirschvink et al., *Science*, 277, 541, 1997; [4] Evans, *Tectonophysics*, 362, 303, 2003; [5] Evans, *EPSL*, 157, 1, 1998; [6] Feldman et al., *JGR*, 109, E09006, 2004; [7] Mellon et al., *Icarus*, 169, 324, 2004; [8] Feldman et al., *GRL*, 31, L16702, 2004; [9] Bish et al., *Icarus*, 164, 96, 2003; [10] Clifford and Parker, *Icarus*, 154, 40, 2001; [11] Arkani-Hamed and Boutin, *JGR*, 109, E03001, 2004; [12] Hood and Zakharian, *JGR*, 106, 14, 2001; [13] Frawley and Taylor, *Icarus*, 172, 316, 2004; [14] Spada et al., *JGR*, 101, 2253, 1996; [15] Greff-Lefftz, *GJI*, 159, 1125, 2004.