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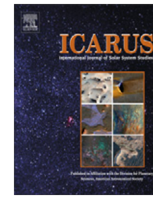

Lithospheric drift on early Mars: Evidence in the magnetic field

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ABSTRACT

The crustal magnetic anomalies on Mars may represent hot spot tracks resulting from lithospheric drift on ancient Mars. As evidence, an analysis of lineation patterns derived from the ΔBr magnetic map is presented. The ΔBr map, largely free of external magnetic field effects, allows excellent detail of the magnetic anomaly pattern, particularly in areas of Mars where the field is relatively weak. Using cluster analysis, we show that the elongated anomalies in the martian magnetic field form concentric small circles (parallels of latitude) about two distinct north pole locations. If these pole locations represent ancient spin axes, then tidal force on the early lithosphere by former satellites in retrograde orbits may have pulled the lithosphere in an east–west direction over hot mantle plumes. With an active martian core dynamo, this may have resulted in the observed magnetic anomaly pattern of concentric small circles. As further evidence, we observe that, of the 15 martian giant impact basins that were possibly formed while the core dynamo was active, seven lie along the equators of our two proposed paleopoles. We also find that four other re-magnetized giant impact basins lie along a great circle about the mean magnetic paleopole of Mars. These 11 impact basins, likely the result of fallen retrograde satellite fragments, indicate that Mars once had moons large enough to cause tidal drag on the early martian lithosphere. The results of this study suggest that the magnetic signatures of this tidal interaction have been preserved to the present day.

1. Introduction

Intense magnetic anomalies on Mars due to crustal sources were discovered in 1997 by the Mars Global Surveyor (MGS) orbiter (Acuña et al., 1998, 1999, 2001). Using MGS data, many models of the martian magnetic field have been produced (e.g. Connerney et al., 2001; Arkani-Hamed, 2002; Cain et al., 2003; Langlais et al., 2004; Hood et al., 2005; Lillis et al., 2008b). These models clearly showed strong east–west trending anomalies in the Terra Cimmeria/Sirenum regions and isolated anomalies elsewhere. However, the most revealing map of the global pattern of the martian crustal magnetic anomalies is the GSFC ΔBr map (Connerney et al., 2005). ΔBr represents the mean change of the radial component of the magnetic field with latitude and is an excellent proxy for the θ (southward) component of the field at MGS mapping altitude. The data for the ΔBr map was acquired in a manner that beneficially suppressed unwanted noise due to externally generated fields. This noise suppression resulted in a high dynamic range and excellent detail of low amplitude anomalies. ΔBr as measured by MGS on N–S tracks is ideally situated to detect line sources directed generally E–W, the overwhelmingly dominant orientation of most of the elongated anomalies on Mars. This map, unlike other depictions of the field, showed elongated magnetic anomalies in the northern hemisphere that differed from those observed in the southern hemisphere only by their much weaker amplitude.

Many possible interpretations of the global pattern of magnetic anomalies on Mars have been suggested including sea floor spreading (Connerney et al., 1999, 2001, 2005; Sprenke and Baker, 2000; Whaler and Purucker, 2005), accretion of terranes (Fairén et al., 2002), hydrothermal demagnetization of a magnetic shell (Sprenke and Baker, 2000), swarms of dike intrusions (Nimmo, 2000; Hood et al., 2007), and a single-hemisphere dynamo (Stanley et al., 2008). In this paper we propose, based on a geometric analysis of the ΔBr map, that the linear magnetic anomalies on Mars represent the tracks of ancient hot spots.

Hot spot tracks on Earth, such as the Hawaiian Island chain and Idaho's Snake River Plain, occur as a result of the lithosphere moving laterally over plumes of magma rising from the core–mantle boundary (Wilson, 1963; Pierce and Morgan, 1992). On Earth, hot spots, though more or less fixed in the mantle, generally appear to move eastward as the lithosphere moves westward over them. In plate tectonics theory, this phenomenon is referred to as westward drift (Le Pichon, 1968; Bostrom, 1971; Knopoff and Leeds, 1972; Ricard et al., 1991; Doglioni, 1993; Gripp and Gordon, 2002; Doglioni et al., 2003; Crespi et al., 2007; Husson et al., 2008). Additional geological evidence for westward drift comes

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from observations of asymmetry both in subduction zone angles (Doglioni, 1993; Doglioni et al., 2007) and in oceanic rift structures (Doglioni et al., 2003; Panza et al., 2010). Estimates of the average speed of westward drift range from 49 mm/year to 134 mm/year depending on the hot spot reference frame employed in the calculation (Gripp and Gordon, 2002; Scoppola et al., 2006; Crespi et al., 2007).

On Earth, plate rotations are induced by irregular plate shapes, differential basal drag, and lithospheric anisotropies along subduction zones resulting in Euler poles scattered near the Earth's spin axis (Doglioni, 1993). The lithospheric plates move along a mainstream that is not perfectly west but describes a sinusoidal line of flow oriented northwest in the Pacific Ocean, west in central Asia, southwest in the Middle East, and west in the Atlantic Ocean. The situation on early Mars would have been quite different. Beyond the magnetic stripe anomalies discovered by Connerney et al. (1999), there is little evidence for past plate tectonics on Mars (Nimmo, 2000; Hood et al., 2007). The prevailing view of martian evolution involves stagnant lid convection in which the planet cools slowly by conduction through a gradually thickening lithosphere which forms an elastic shell around the planet. Lithospheric drift, if it occurred on such a one-plate early Mars, would have involved the entire lithospheric shell rotating differentially with respect to the mantle. If this drift were related to the rotation of the planet, tracks of stable hot spots on Mars would have traced small circles (parallels of latitude) about the contemporary spin axis.

The cause of westward lithospheric drift on Earth is hotly debated. Most researchers ascribe it to chance, simply the result of randomly oriented convention cells in the mantle. On the other hand, some researchers have hypothesized that the westward drift is the result of rotational drag on the lithosphere due to the tidal effect of the Moon (Bostrom, 1971; Knopoff and Leeds, 1972; Moore, 1973; Scoppola et al., 2006). Rotational drag is energetically feasible; the dissipation of energy by tidal friction exceeds the energy released by tectonic action (Denis et al., 2002). The problem lies in the viscosity of the asthenosphere which would need to be orders of magnitude lower than present estimates from post-glacial rebound analysis to allow decoupling between lithosphere and the mantle (Jordan, 1974; Ranalli, 2000). However, others argue that a thin ultra-low viscosity partially melted layer within the asthenosphere could accommodate the relative motion (Scoppola et al., 2006). Such a thin shear zone would have little affect on post-glacial rebound, yet still allow horizontal sliding. Geochemical experiments have shown that both hydration and melt content can significantly lower asthenospheric viscosity (Hirth and Kohlstedt, 1995; Mei et al., 2002). Furthermore, low velocity shear zones in the upper mantle beneath the Sierra Nevada have been interpreted from seismic receiver functions (Zandt et al., 2004).

Mars has only two very small moons at present, certainly incapable of exerting any tidal drag on the planet. However, recent research suggests that Mars may have had much larger satellites in its early history when its core dynamo was active (Arkani-Hamed, 2005, 2009a). The core dynamo may have actually been powered by tidal forces created by a large captured satellite in a retrograde equatorial orbit which eventually fragmented and impacted Mars creating the giant basins of Argyre, Hellas, Isidis, and Utopia along the then equator of the planet (Arkani-Hamed, 2005, 2009a). Early Mars may have had many such captured moons during the late heavy bombardment of the inner Solar System. These ancient moons, if in long duration retrograde orbits, may have been capable of exerting a tidal drag on the early martian lithosphere. Furthermore, upon degradation of their orbits, these ancient satellites would have likely impacted Mars along the equators of the ancient spin axes.

2. Methods

Our investigation of the global pattern of the lineations in the martian magnetic field proceeded as follows. The martian magnetic data used in this study are from a global map of ΔBr (Connerney et al., 2005). These data (Fig. 1) represent the filtered radial magnetic field above a threshold intensity of 0.3 nT per degree of latitude, well above the noise level, so that the data include little noise. In this study, the pattern of the original global magnetic anomalies is the parameter of interest. Although the intensity of the field at any particular location is largely determined by subsequent demagnetization, the original polarity of the anomaly may persist. Accordingly, all clearly positive anomalies are weighted equivalently regardless of their intensity; similarly, all clearly negative anomalies are weighted equivalently regardless of their intensity. We ignore low amplitude signals below the threshold limit of the data.

Almost all the magnetic anomalies on Mars appear to be elongated in generally unambiguous directions. The strike directions of the anomalies are represented as the lineations we have drawn in Fig. 1. We drew these, working from the underlying map data array (MGS/MAGER file: pnas_102_42_connerney_data.html), using a computer algorithm to correlate the minima and maxima of

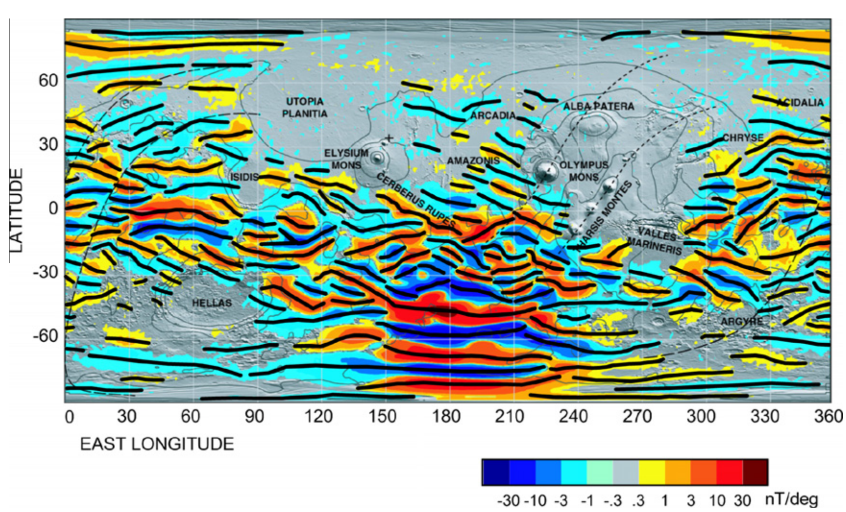

Fig. 1. The ΔBr map (Connerney et al., 2005) shows the crustal magnetic anomalies on Mars with higher detail than other models, particularly in the northern hemisphere. The lineations shown follow the strike of each elongated magnetic anomaly.

the anomalies between adjacent lines of longitude along linear trajectories. Inspection of Fig. 1 shows that the lineations clearly follow the crests and troughs of the elongated anomalies.

The lineations drawn along the magnetic anomalies are not meant to represent continuous crustal sources. The magnetic data were collected at an altitude of about 400 km. At this height, the anomalies due to individual sources are merged together. Thus, a long lineation in the magnetic data does not require a continuous source in the crust. Indeed, Hood et al. (2007) point out that the sparse data collected at lower altitudes during the MGS experiment suggest that the sources of the strong east–west magnetic anomalies in the southern hemisphere of Mars are in fact due to discrete sources.

Furthermore, the maxima and minima of magnetic anomalies may not be coincident with the location of the crustal sources. For data collected at 400 km altitude, the sources may be offset some hundreds of kilometers depending on the direction of crustal magnetization. However, in our study, we are interested in the global pattern of the magnetic anomalies. The nature of the crustal sources is not directly relevant to our analysis. Whether they be volcanic centers, or underplated crust, or dike swarms, or irregular intrusions, or hydrothermal vent systems, is not knowable from magnetic data at this altitude, but a global pattern in the magnetization is certainly apparent.

In this study, the elongated magnetic anomalies, represented by our drawn lineations, are analyzed mathematically to see if the lineations follow small circles about some pole. Initially, we looked for a set of concentric small circles about a single pole to fit the lineation pattern, but we could not find a satisfactory fit. We then proceeded to search for two overlapping sets of small circles about two distinct poles to fit the lineation pattern. This was accomplished by dividing the lineations into two sets and then proceeding to move lineations from one set to the other in search of the two sets of concentric small circles that best fit the lineations. The method is essentially a form of cluster analysis, a commonly used technique in pattern recognition (e.g. Duda et al., 2000; Theodoridis and Koutroumbas, 2008).

The steps in the process, especially those particular to fitting the geometry of small circles, are as follows. The geographic coordinates of the points are converted to Cartesian coordinates. The points along each lineation are then normalized such that their centroid is located at the center of a reference sphere. The best-fit plane and its pole location are calculated for each set as follows. A plane through the origin in the Cartesian coordinate system is defined as: $z = ax + by$. Then, we find a and b in a least squares sense. The lineations consist of equally-spaced points, so the least-squares procedure gives more weight to the longer lineations. The solutions are used to calculate the coordinates of the pole in the spherical coordinate system. The direction from the origin to the northern pole is the vector $(-a, -b, 1)$. The RMS (root-mean-square residual) is used to determine how much each lineation deviates from the best-fit plane. Next, the results are sorted. Lineations with low RMS residual (more consistent with the best-fit plane), are retained. Those with high RMS residual are moved to the other set, which is further analyzed for another possible pole with the operation described above. The calculated best-fit planes are then refined by moving lineations from one set to the other repeatedly until the best-fit planes through the maximum number of the lineations are obtained. Then, the final resulting poles are calculated.

3. Results

The linear magnetic anomalies on Mars can be divided into two groups, each of which forms separate sets of concentric small circles centered on poles offset from the present-day spin axis (Fig. 2). One pole is at (79.5 ± 0.5°N, 272 ± 2.5°E), the other at (67 ± 0.8°N, 111 ± 3.5°E).

The fact that the magnetic anomalies follow concentric small circles strongly suggests that the pattern of the anomalies is associated with the rotation of the planet about these poles at some time in the past. If the lithosphere on early Mars was decoupled from the asthenosphere, fixed hot spots in the deep mantle of the planet would have traced out hot spot tracks oriented along concentric small circles. If the dynamo were active as the magma in the hot spots tracks cooled, magnetic anomalies along or parallel to the tracks would have resulted. To create correlated magnetic anomalies at mapping altitude on Mars, immense volumes of magma would be involved. On Earth, huge flood basalt eruptions are indeed thought to result from deep mantle plumes (Richards et al., 1989). Continental flood and oceanic plateau basalt eruptions have resulted in sudden and massive accumulations of basaltic lavas in excess of any other volcanic processes.

That two poles are necessary to describe the pattern suggests that the spin axis of the planet reoriented between the emplacements of the two sets of magnetic lineations. Such polar wander is a definite possibility on early Mars (Ward, 1979; Melosh, 1989; Schultz and Lutz, 1988; Sprenke and Baker, 2000; Sprenke et al., 2005; Perron et al., 2007). Recently, on the basis of the locations of the 20 largest impact basins on Mars, Arkani-Hamed (2009a) has proposed three different positions for the rotation pole of ancient Mars (3.9–4.2 Gyr), besides the present one.

Could satellites, probably much smaller than Earth's Moon, have provided sufficient tidal force to exert a drag on the early martian lithosphere? The Utopia impactor, the largest at Mars and only a fragment of a larger satellite, had a mass about 2.6% of Earth's Moon (Arkani-Hamed, 2009a). However, if the Utopia satellite orbited Mars at less than 116,000 km (30% of the Earth–Moon distance), it would have exerted more tidal effect on ancient Mars than the Moon currently exerts on Earth because tidal effect increases with planetary radius and with the inverse cube of satellite distance. A retrograde Utopia satellite has an orbital lifetime of over 450,000 years at this distance (Arkani-Hamed, 2009a). Similarly, the Hellas impactor, the sixth or seventh largest at Mars, had a mass only about 0.4% of Earth's Moon (Arkani-Hamed, 2009a). However, if the Hellas satellite orbited Mars at less than 62,000 km (16% of the Earth–Moon distance), it would have exerted more tidal effect on ancient Mars than the Moon currently exerts on Earth. A retrograde satellite the size of the Hellas impactor would last about 30 myr before impact (Arkani-Hamed, 2009a). Thus it appears that even the fragments of the purported ancient satellites would cause sufficiently large tidal force over long enough periods to exert a lithospheric drag on Mars comparable to that of the Earth–Moon system.

On Mars, 20 giant impact basins have been identified (Frey, 2008). The equators of the two poles found in this study include eight of these basins (Fig. 3). The equator of Set 1 passes within several degrees of the centers of Hematite (He), Scopolus (Sc), Isidis (Is), SE-Elysium (SE), and very close to Ares (Ar); the equator of Set 2 passes within several degrees of the centers of Chryse (Ch), Zephria (Ze), N-Tharsis (NT) and very close to Hematite (He). The chance that our equators, derived from lineation patterns in the magnetic field, might include so many giant impacts seems very improbable. Arkani-Hamed (2009a), for example, has calculated the probability of any 3 of 20 random impacts tracing a great circle to within 3° at 0.065. Yet both of our equators include at least three impact basins, a combined probability, if the impacts are random, of 0.0042. Could these basins represent fallen satellite fragments? Arkani-Hamed (2005) has pointed out that large fragments of a parent satellite tend to separate and create a ringlet orbiting Mars on an almost Keplerian orbit. Although it may take years before all the large fragments impact on Mars, the resulting impacts occur at the pre-

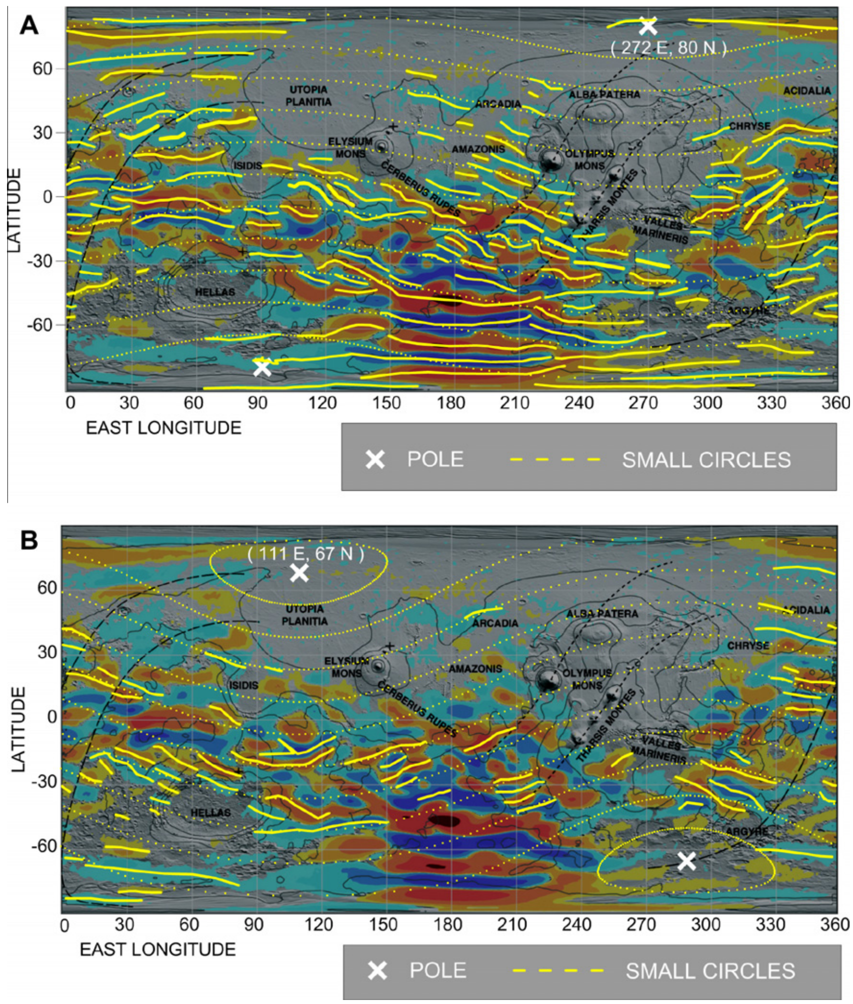

Fig. 2. (a) The lineations of Set 1 follow concentric small circles about a pole at 80°N, 272°E on the northern hemisphere. (b) The lineations of Set 2 follow concentric small circles about a pole at 67°N, 111°E on the northern hemisphere.

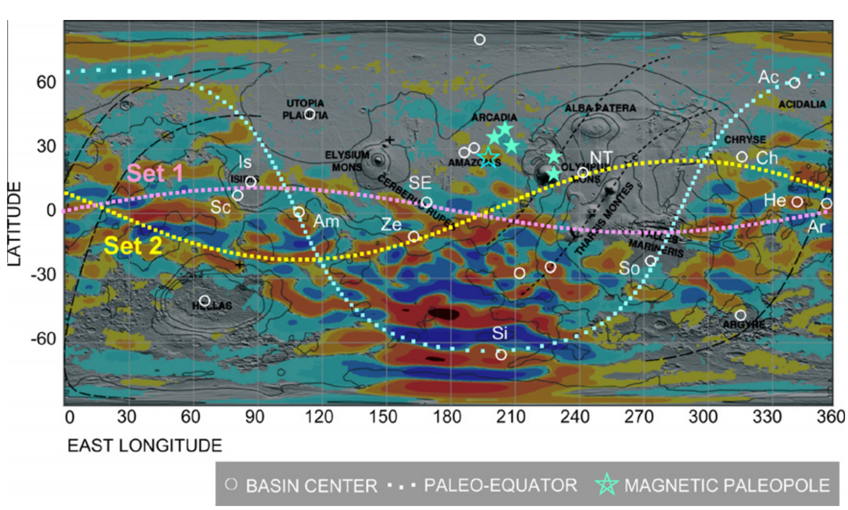

Fig. 3. The equator of the Set 1 lineations passes close to 5 of the 20 giant impact basins on Mars including Isidis (Is), Scopolus (Sc), SE-Elysium (SE), Hematite (He), and Ares (Ar). The equator of the Set 2 lineations includes three giant impact basins: Zephyria (Ze), North Tharsis (NT) and Chryse (Ch). Also shown, centered at the location indicated by the large star, is a great circle through Acidalia (Ac), Amenthes (Am), Solis (So), and Sirenum (Si). This was possibly the equator when martian crust acquired magnetization. The small stars indicate mean north paleopole positions reported by previous researchers.

vailing equator: the basins trace a great circle. If several craters trace a great circle, the chance that the circle was the prevailing equator at the time of impact is quite high (Arkani-Hamed, 2005, 2009b).

Due to the dynamic constraints imposed by a three-body system, satellite capture without collision or viscous effects is dynamically impossible. Thus, the concept that ancient Mars had large satellites captured in retrograde orbit may seem questionable. However, in a four-body system, some dynamic constraints can be lifted (Tsui, 2002). Indeed, Arkani-Hamed (2009a) has solved a restricted four-rigid body problem involving the Sun, Mars, Jupiter, and a heliocentric asteroid to show that an asteroid that is captured by Mars at a distance of some 100,000 km can remain in a Keplerian orbit around Mars. The IAU currently lists 984 Amor II asteroids with semimajor axes between that of Mars and the main asteroid belt; and there were many more such asteroids in the early Solar System. These cross the orbit of Mars and have generally moderate eccentricities. Phobos and Deimos may well have been Amor II asteroids before being captured by Mars.

The population of quasi-circular depressions and circular thin-crust areas on Mars provide retention ages for large martian impact basins (Frey, 2008). Despite significant uncertainties in the crater retention ages, there is a consistent separation in age between the mostly magnetized and mostly demagnetized giant basins (Lillis et al., 2008a). Except for the five youngest basins (Isidis, Argyre, Utopia, Hellas, North Polar), the other 15 possibly formed while the core dynamo was active. If we exclude Isidis from our Set 1, then, according to the giant basin magnetic timeline provided by Lillis et al. (2008a), there are no inconsistencies in age of the basins along each of our paleo-equators. Their 1σ error bars in crater retention ages overlap.

Furthermore, a recent observation was made by Arkani-Hamed (2009a) that Acidalia, Chryse, and Sirenum fall on another great circle that corresponds reasonably well to the equators about the mean magnetic paleopole positions suggested by previous investigators. We note that a better great circle fit can be found that includes four basins: Acidalia (Ac), Amenthes (Am), Solis (So), and Sirenum (Si). The pole of this great circle is at (24.3°N, 199°E) in excellent agreement with mean paleopole positions (34°N, 202°E), (30°N, 210°E), (17°N, 230°E), (38°N, 207°E), and (25°N, 230°E) as previously reported by Hood et al. (2005, 2007), Sprenke et al. (2005), Sprenke (2005), and Arkani-Hamed (2009a), respectively.

Thus, remarkably, 11 of the 15 giant impact basins on Mars that may have formed while the core dynamo was active appear to fall on great circles associated with the geometry of the martian magnetic field, either with respect to the global magnetic lineation pattern or with respect to inferred magnetization directions (Fig. 3).

4. Discussion

The lithosphere at the time of emplacement of the apparent hot spot tracks on Mars must have been very weak, with an elastic thickness of less than 5 km, if polar wander was so prevalent at the same time on early Mars (Arkani-Hamed, 2009b). These conditions would also seem ideal for lithospheric drift in that the normal force on the presumed shear zone at the base of the lithosphere would have been minimal, resulting in less friction at the base of the lithosphere for the tidal drag to overcome.

One prediction of the hypothesis of this study might be that the paleomagnetic poles at the time of magnetization should agree with the purported rotational poles at the time of magma emplacement. They do not. As mentioned above, the mean location of the north paleomagnetic pole on ancient Mars is well south of the poles of this study. However, the magnetized crustal sources on Mars are different from those on Earth. Although the relatively small intrusive igneous bodies on Earth cool and acquire magnetization over tens of millions of years, the likely much larger magnetized sources on Mars would take about 100 myr to cool (Arkani-Hamed, 2009a). Thus, the intrusions along the hot spot tracks proposed in this study may not have cooled and acquired magnetization until as long as 100 myr later when the spin axis had perhaps wandered to the paleomagnetic pole.

Of course, the magnetic lineations on Mars could be the result, not of magnetization directly, but of demagnetization of a previously magnetized shell by the heat of a rising plumes. In this scenario, there is no reason that the paleomagnetic poles should reflect the spin axes at the time of lithospheric drift. Such an interpretation would place the timing of the magnetic lineations after the cessation of the core dynamo at a critical time when the crust was still thin enough to be heated above the Curie Point by underplating. The demagnetization would have ceased when the crust became thicker and the under-plating no longer affected the magnetized layer or when lithospheric drift stopped, stabilizing the hot spots to form the great volcanic edifices apparent today on Mars.

Hot spot tracks on Earth are coincident with topographic features. There is no correlation of topography with the crustal magnetic anomalies of Mars. However, the apparent hot spot tracks revealed by the magnetic field patterns on Mars may represent only a snapshot of the total lithospheric drift activity on the planet. If the magnetic lineations were formed by thermoremanence, only the magma that cooled while the dynamo was active would have been magnetized. Additional magma that cooled before and after the active core dynamo may have obscured any correlation of the magnetic lineations and topography. If the magnetic lineations were formed by demagnetization, the perhaps subtle surface expression along the hot spot tracks may have been removed by subsequent erosion.

It is difficult to propose explanations of the pervasive trends in the elongated anomalies of Mars other than lithospheric drift. Unless the globally pervasive east–west magnetic trends on the planet are there by mere chance, any explanation must somehow involve symmetry about the poles in order to create magnetic anomalies along lines of latitude. For example, when SL-9 impacted Jupiter in 1994, the large fragments followed a small circle of high latitude on Jupiter. Repeated impacts like this on Mars could have presumably demagnetized the crust along east–west lines. However, there is no crater pattern on Mars parallel to the magnetic trends to support such an explanation. Or perhaps, mega-impacts at the proposed paleopoles might have created global patterns of circular symmetry in the magnetization. However, there is nothing in the martian impact record to support this idea either.

5. Conclusions

The results of this study are consistent with our hypothesis that the lineations in the magnetic anomalies on Mars are hot spot tracks representing an east–west drift of the lithosphere over fixed mantle plumes on ancient Mars. The lineations in the magnetic anomalies on Mars have been separated into two groups, each of which forms a set of small circles about two distinct pole locations, offset some tens of degrees from the present-day spin axis. If these poles represent ancient spin axes, then the magnetic anomalies were oriented in an east–west direction at the time of their source emplacement. Furthermore, 11 of the 15 giant impact basins on Mars that probably were formed while the dynamo was active lie along three paleo-equators that we have delineated, suggestive that these impact basins were formed by fragments from former satellites of Mars. These ancient martian moons could have provided the tidal force to create a rotational drag on the ancient martian lithosphere, resulting in the east–west hot spot tracks. The results of this study indicate that the magnetic signatures of this tidal interaction have been preserved to the present day.

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