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Alignments of volcanic features in the southern hemisphere of Mars produced by migrating mantle plumes

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ABSTRACT

Mars shows alignments of volcanic landforms in its southern hemisphere, starting from the equatorial regions and converging towards the South Pole, and visible at global scale. These composite alignments of volcanoes, calderas, shields, vents, heads of valley networks and massifs between the equatorial regions and the southern polar region define twelve different lines, fitted by rhumb lines (loxodromes), that I propose to be the traces of mantle plumes. The morphology of the volcanic centres changes along some of the alignments suggesting different processes of magma emplacement and eruptive style. The diameters of the volcanic centres and of the volcanic provinces are largest at Tharsis and Elysium, directly proportional to the number of alignments starting from them. A minor presence of unaligned volcanic features is observed on the northern lowlands and on the highlands outside the 12 major alignments. The heads of channels commonly interpreted as fluvial valleys are aligned with the other volcanic centres; unaltered olivine is present along their bed-floors, raising severe doubts as to their aqueous origin. Several hypotheses have tried to explain the formation of Tharsis with the migration of a single mantle plume under the Martian lithosphere, but the discovery of twelve alignments, six starting from Tharsis, favours the hypothesis of several mantle plumes as predicted by the model of the Southern Polar Giant Impact (SPGI) and provides a new view on the formation of the volcanic provinces of Mars.

1. Introduction

Leone et al. (2014) found that the Southern Polar Giant Impact (SPGI) model for the early history of Mars specifically predicts, as a consequence of the impact, the formation of mantle plumes originating at four points located near the equator and 90° of longitude apart and migrating from the equator towards the South Pole. Since mantle plumes are commonly the sources of volcanism, I examined all of the existing volcanic features on Mars documented in the literature and recorded their locations. I also examined large numbers of CTX and HiRISE images in order to: (a) identify lava fields that might have radiated from central volcanic sources which have been masked by later impact craters or other modification processes and (b) identify other features that might be related to plumes. These other features specifically include the sources of what are generally assumed to be fluvial features formed by crustal deformation due to the presence of a mantle plume that caused fracturing that released water from deep aquifers (Bargery and Wilson, 2011); here I argue that these features are channels largely formed by erupted lava from deep or shallow magma reservoirs (Leone, 2014), but the correctness or otherwise of this interpretation does not detract from using these features as indicators of crustal stresses induced by mantle plumes, and so I included these locations. Given that I identified four volcanic provinces near the equator (Tharsis, Elysium, Syrtis Major and Western Arabia Terra) located 90° apart as the expected four plume track starting points in the SPGI model, I have then assigned by eye the documented volcanic and related centres to plume tracks radiating from these locations towards the South Pole and checked using a Matlab programme if they formed alignments. Although this method of selecting candidates for each plume track can be criticised as not proving statistically that it is the only way of assigning track members with minimal outliers, it is justified by the underlying physical requirement of the SPGI model that plumes do not meander at random in the mantle.

Three large volcanoes of Tharsis (Arsia, Pavonis and Ascraeus Montes) are aligned so perfectly that it would be amazing if this alignment formed just accidentally. Another group of massifs, the Sisyphi Montes, was studied by Ghatan and Head (2002) who concluded (without any statistical analysis) that these edifices were aligned, were not the remnants of impact crater rims or the result of tectonism, but instead were produced by sub-glacial volcanic eruptions. Aligned volcanic plains along the Dorsa Argentea formation were interpreted by Zhong (2009) and Hynek et al. (2011) as formed by a single mantle plume migration to Tharsis due to one-plate lithosphere rotation. These authors concluded that a similar trend does not exist elsewhere on Mars. However, the several alignments of volcanic features along different directions converging to the South Pole of Mars described in this paper neither supports this hypothesis (Leone et al., 2013) nor that of

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hypothetical superplumes below Tharsis and Elysium as suggested by Baker et al. (2007).

The SPGI model explains the formation of the Martian dichotomy as an alternative to other hypotheses, such as degree-1 mantle convection (Zhong and Zuber, 2001), multiple impacts (Frey and Schultz, 1988) and a single giant impact in the northern hemisphere (Andrews-Hanna et al., 2008; Marinova et al., 2008; Nimmo et al., 2008). The SPGI model suggests instead a vigorous phase of volcanism in the first 500 Ma after the giant impact, characterized by the migration of mantle plumes, and a phase of decreasing volcanism in the subsequent 500 Ma until the heat flux of the planet reached the current values when no active volcanism is observed. This sequence of events is in agreement with other petrological (Baratoux et al., 2013) and thermal evolution (Baratoux et al., 2011; Morschhauser et al., 2011) studies but there is disagreement on the age when the volcanism ceased. Although there is again a general agreement on the fact that the crust formed early in Martian history and it might have reached thicknesses of ~100–150 km upon mantle cooling and a heat flow decrease from 38 to 26 mW m^{-2}, the age ranges from Amazonian (Baratoux et al., 2011) to Noachian–Hesperian (Hauck and Phillips, 2002; Grott et al., 2005; Leone et al., 2014). In any case, a thick crust would make the rise of magma to the surface difficult, so that active volcanism would not happen even if the planet were still internally hot today (Baratoux et al., 2011).

The specific goals of this paper are: 1) the development of a global inventory of all the volcanic eruptive centres, including their diagnostic characteristics; 2) the assessment of potential alignments; 3) the comparison between crater counts and SPGI plume model ages to deduce plume migration rates; and 4) the first verification on the surface of Mars of the SPGI model for the formation of the Martian dichotomy and the onset of the volcanism.

2. Criteria for the identification and mapping of the volcanic features

A rich literature served as a basis for the identification of the volcanic features indicated in Table 1 and the collection of their crater counts ages listed in Table 2 (Neukum and Hiller, 1981; Hodges and Moore, 1994; Plescia, 1994; Maxwell and Craddock, 1995; Dohm and Tanaka, 1999; Dohm et al., 2001a; Stewart and Head, 2001; Tanaka and Kolb, 2001; Ghatan and Head, 2002; Anguita et al., 2006; Head et al., 2006; Fassett and Head, 2008; Tanaka et al., 2008; Hoke and Hynek, 2009; Werner, 2009; Williams et al., 2009; Fenton and Hayward, 2010; Murray et al., 2010; Robbins et al., 2011; Xiao et al., 2012; de Pablo et al., 2013; Isherwood et al., 2013; Michalski and Bleacher, 2013; Platz et al., 2013; Richardson et al., 2013; Tanaka et al., 2014). Some other papers described the morphometric properties of the volcanic features (Plescia, 2004; Acocella, 2007; Grosse et al., 2012), and others showed the morphology of the typical lava flows on Mars (Keszthelyi et al., 2000, 2008; Jaeger et al., 2007, 2010). The recognized volcanic landforms were thus considered geographic data points, that is, source (or eruptive) data points for the assessment of the alignments. Although very many volcanic features were already available from the literature and thus incorporated in this paper, many other new volcanic features were discovered and only some of which have been officially named (e.g. Aonia Mons, Aonia Tholus, Eridania Mons, Sirenum Mons, Sirenum Tholus). Some volcanic features were partially or totally destroyed by impact craters and only the presence of surrounding lava flows has made it possible to infer the presence of the original structure (Xiao et al., 2012). The geomorphic criteria for the identification of the geographic data points are those indicated for the morphometric properties of the volcanic features of high relief (Plescia, 2004; Grosse et al., 2012) and low relief (Acocella, 2007; Bleacher et al., 2009; Richardson et al., 2013). The typical features are shown in Fig. 1. The identification of the largest volcanic features (i.e. Alba and Olympus Mons) was already possible at global scale 1:25 M on the Topographic Map of Mars (USGS, 2003) where the main directions of some alignments were already indicated by the largest volcanoes. However, after this first observation, the refinement of the mapping was performed at regional scale looking for every occurrence all over the surface of the planet, on maps of 1:5,000,000, of smaller shields, calderas and massifs between 200 and 50 km in diameter. The final refinement was done at local scale using CTX and HiRISE imagery again on the whole surface of Mars looking for massifs, low shields and every volcanic feature that might appear as a source point for lava flows or heads of valleys between 50 and 1 km diameter that are not immediately evident in THEMIS imagery. All the surface of Mars covered by any available imagery was observed, and all the volcanic features outside any alignment were listed in the unaligned section. The lowest limit of 1 km was determined from the diameter of the heads of small valleys and of the vents on top of the smallest low-relief volcanic landforms encountered on the surface of Mars but even vents of hundreds of meters were also observed in the CTX images of Tharsis. All the diameters of the volcanic landforms in the alignments were then listed in Table 1. In the case of clusters of volcanic features, the along-path and cross-path distances are given. The diameters of the named features were taken from the Gazetteer of the Planetary Nomenclature, and the diameters of the unnamed features were geodetically measured through ArcGIS. The observations were supported by the Mars Orbiter Laser Altimeter (MOLA) dataset for the volumetric calculations and the analysis of the altimetry mentioned in the next sections. These datasets are already easily accessible on the web so it was not necessary to show them all due to the limited space in figures. Priority was given to visible images, and THEMIS mosaics were used where gaps in CTX data coverage was found.

The best way to unambiguously discern uncertain features with weakly supportive characteristics and alternative interpretations like craters and heads of valley networks (Fig. 1a, b, and f) was to identify lava flows in the inter-crater plains and to track them back to their sources. Some valley networks probably were initially incised directly from the flows according to a plausible mechanism of the preferential pathways explained by Bleacher et al. (2015) and then subsequent channelization of lava deepened them further, so that the valley networks appeared draped with lava. The heads of the valleys formed directly from lava flows were excluded from the alignments because they were formed away from the eruptive points. Other features like fields of vents (Fig. 1c), calderas (Fig. 1d), minor shields (Fig. 1e), Noctis Labyrinthus (Fig. 1g), major shields (Fig. 1h) and massifs (Fig. 1i) with either flat-tops and/or dissected flanks were considered unambiguous. The figures shown in the Appendix of this paper are meant to illustrate all the new features identified that are not already mentioned in the literature and to show how lava flows can be helpful in the identification of volcanic features that have ambiguous, partial, or no interpretation yet. Where possible, features commonly considered of tectonic origin like fossae and labyrinthi (Fig. 1g) were analysed with MOLA data to assess a possible volcanic origin in addition to the methodology used by Hodges and Moore (1994) and by Leone (2014). Particular care has been placed on distinguishing calderas from melt generating impact craters, the latter being excluded for their different significance, although both might be surrounded by lava flows. Generally calderas have a low and smooth rim due to periodic lava overflows, concentric inner and outer depressions, and an irregular sub-circular shape (Fig. 1d). An impact crater has higher rims and a more circular shape, sometimes characterized by a central peak, with distinguishable ejecta (Xiao et al., 2012). Other key observations were the MOLA profiles showing flat floors in putative impact craters, compared to the profiles published in a work specifically dedicated to the characterization of the topography of the impact craters (Mahanti et al., 2014). The MOLA profiles are not shown for reasons of limited space in the figures but they are all available on the MOLA website and they can all easily be checked for every mentioned feature. Many craters with tributaries and distributaries located near large volcanic centres and showing infill of lava flows were not considered as geographic data points, although they might also have an underground feeder, because the origin of the