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Spatial and alignment analyses for a field of small volcanic vents south of Pavonis Mons and implications for the Tharsis province, Mars

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ABSTRACT

A field of small volcanic vents south of Pavonis Mons was mapped with each vent assigned a two-dimensional data point. Nearest neighbor and two-point azimuth analyses were applied to the resulting location data. Nearest neighbor results show that vents within this field are spatially random in a Poisson sense, suggesting that the vents formed independently of each other without sharing a centralized magma source at shallow depth. Two-point azimuth results show that the vents display north-trending alignment relationships between one another. This trend corresponds to the trends of faults and fractures of the Noachian-aged Claritas Fossae, which might extend into our study area buried beneath more recently emplaced lava flows. However, individual elongate vent summit structures do not consistently display the same trend. The development of the volcanic field appears to display tectonic control from buried Noachian-aged structural patterns on small, ascending magma bodies while the surface orientations of the linear vents might reflect different, younger tectonic patterns. These results suggest a complex interaction between magma ascension through the crust, and multiple, older, buried Tharsis-related tectonic structures.

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1. Introduction

The Tharsis province of Mars displays a variety of small volcanic vent (<10 s km in diameter) morphologies that were identified using Mariner and Viking images (Carr et al., 1977; Greeley and Spudis, 1981; Plescia, 1981; Hodges and Moore, 1994). Post Viking-era Mars Orbiter Laser Altimeter (MOLA) data delineates more abundant small volcanic vent features (Sakimoto et al., 2002; Plescia, 2004). Specifically, recent studies have classified a variety of small volcanic vent (small vent) morphologies, including cones, domes, fissure vents, and low shields (Hauber, 2007, 2009-this issue; Bleacher et al., 2007a, 2008; Baptista et al., 2008; Plescia and Baloga, 2008; Sakimoto, 2008). These small volcanic vents frequently occur in groups, referred to here as small vent fields. In the Tharsis region, some of these fields are located in the plains, while other fields are located in close proximity to the larger shield volcanoes. The large shield volcanoes, the Tharsis Montes, experienced main edifice construction through eruptions from the summit, followed by eruptions along northeast-trending rift zones on the northeast and southwest flanks (Crumpler and Aubele, 1978; Scott and Zimbelman, 1995; Scott et al., 1998; Bleacher et al., 2007a). MOLA data (Fig. 1) show fields of small vents south of both Pavonis Mons and Ascraeus Mons (Plescia, 2004) that appear to have formed synchronously with rift zone activity, in some cases at distances >400 km away from the main volcanoes (Bleacher et al., 2007a). However, the genetic relationship between the small vent fields and the large volcanoes remains unclear.

Ongoing identification, characterization, and mapping of small vents across the Tharsis province utilizes MOLA, Thermal Emission Imaging System (THEMIS), and High Resolution Stereo Camera (HRSC) data (Bleacher et al., 2007b; Hauber, 2007; Plescia and Baloga, 2008; Sakimoto, 2008; Baptista et al., 2008; Hauber et al., 2009-in this issue). Although small vents are observed across the province and have been qualitatively grouped for discussion in publications, a quantitative study of their spatial distribution is yet to be completed. We hypothesize that fields of small vents in the Tharsis province are representative of significant magmatic events much as they are on the

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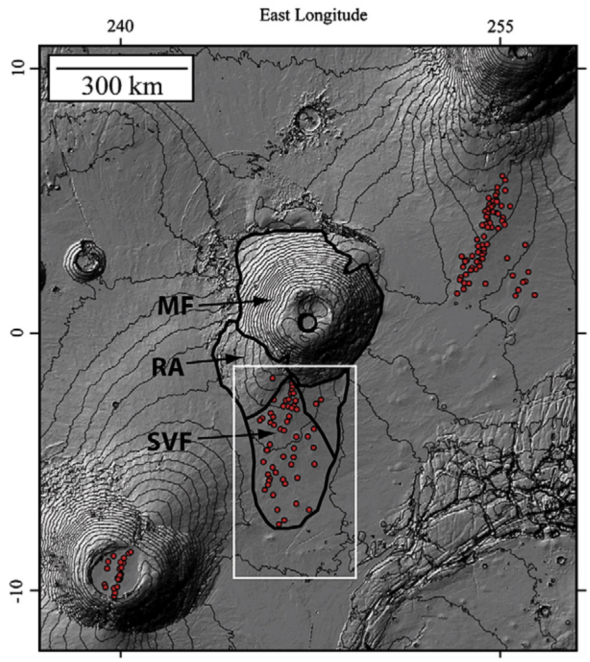

Fig. 1. A MOLA shaded relief image showing the Tharsis Montes and centered on Pavonis Mons. The Main Flank (MF), Rift Apron (RA), and Small Vent Field (SVF) mapped by Bleacher et al. (2007a) are outlined by the heavy black lines. The white box outlines the study area shown in Fig. 2. The dots indicate small volcanic vents identified by Bleacher et al. (2007b).

Earth, and that together with detailed mapping, statistical studies will provide insight into the role that small vent field formation played in the development of the province. Study results are reported here for the spatial and alignment relationships between small vents south of Pavonis Mons (Fig. 1), as determined by nearest neighbor and two-point azimuth analyses. This is the initial report related to a larger ongoing Mars Data Analysis Program project (Bleacher et al., 2008) focused on cataloging all small volcanic vents in the Tharsis province using post *Viking*-era data, as was motivated by Hodges and Moore (1994) in their *Atlas of Volcanic Landforms on Mars*.

2. Statistical analyses

Terrestrial monogenetic fields display analogous small vent morphologies to those identified on Mars. These fields are typically characterized by recurrence rate of eruptions, vent abundances, vent distributions, and tectonic relationships (Connor and Conway, 2000). On Earth, fieldwork and analysis of remotely sensed data are used to map the abundance and location of vents, and spatial statistical studies enable the spatial distribution and alignment relationships between vents to be quantified. A variety of statistical approaches are used to characterize geographic spatial patterns within volcanic fields using mapped vent locations. Supported by field studies, these techniques have revealed that shifts in the locus of activity are common and that vents often form clusters and define alignments at several scales (Connor and Conway, 2000). As stated by Bishop (2007a), volcanic vents represent the end point of a pathway of magma ascending from the melt zone though the crust to the surface, and thus, spatial studies of vent locations provide insight into the nature of the travel and eruption of magma. Therefore, the goal of spatial studies is to provide insight into the link between the distribution of vents and causal processes (Connor and Conway, 2000; Baloga et al., 2007). To this end, vent alignments can be statistically quantified to identify the possible interaction between ascending magma and crustal tectonics. Ideally the combination of spatial and alignment statistics, mapping, and age dating of vents within a volcanic field provides a thorough basis from which the development of the field is interpreted (Connor and Conway, 2000; Connor et al., 2008).

In a spatial study of the Mount Gambier volcanic sub-province, Australia, Bishop (2007a) reviews spatial statistical studies as applied to the location of volcanic vents within several other terrestrial monogenetic fields including the Bunyaruguru field in West Uganda (Tinkler, 1971), cinder and scoria cones on Mauna Kea, Hawaii (Porter, 1972), six globally distributed cinder cone fields (Settle, 1979), the Michoacan–Guanajuato field in Mexico (Wadge and Cross, 1988), the Springerville field, Arizona (Connor et al., 1992), the Pinacate field in Mexico (Lutz and Gutmann, 1995), and the Yucca Mountain region, Nevada (Connor and Hill, 1995). Recently Gudmundsson and Andrew (2007) also conducted a study of the central region of the active Icelandic rift zone.

The nearest neighbor technique (Clark and Evans, 1954) has been established for decades as the standard statistical tool for evaluating randomness in spatial distributions. Nearest neighbor techniques were demonstrated to be useful for several Mars geological applications. Bruno et al. (2004, 2006) used nearest neighbor statistics to show that a population of martian features matches the distribution of terrestrial ice mounds and rootless cones as opposed to the distribution of secondary impact craters. Nearest neighbor techniques were further refined and applied to the study of Hawaiian tumuli, rootless cones, and possible martian analogs providing insight into the development of these features (Glaze et al., 2005; Baloga et al., 2007). Nearest neighbor analysis was also applied to a north polar dune field on Mars by Bishop (2007b) who concluded that fields of compound crescentic dunes display a higher level of organization than mixed fields of simple dunes. Bishop (2008) also applied nearest neighbor analyses to cone groups in the Tartarus Colles region of the Elysium rise further demonstrating that spatial and alignment statistical studies can be used to provide insight into planetary surface development.

3. Methods

The study area discussed here is ~480 by 270 km in size and extends from 244°–249° E longitude to 1°–9° S latitude (Fig. 2). This area is largely comparable to the areal extent of member 6 of the Tharsis Montes Formation as mapped by Scott and Tanaka (1986) including the small vent field (SVF) south of Pavonis Mons as mapped by Bleacher et al. (2007a), a distal portion of the Arsia Mons NE rift apron, and a portion of the Tharsis plains east of Arsia Mons (Fig. 3). In this report, we refer to the study area as the Pavonis Mons South Volcanic Field. The 100 m/pixel THEMIS Infrared mosaic (Christensen et al., 2004) was spatially co-registered to the MOLA 128 pixel/degree gridded data product (Smith et al., 2003). A THEMIS Visible (VIS) mosaic composed of 18 and 36 m/pixel images and HRSC images H0891 and H0902 with projected resolutions of 12.5 m/pixel (Neukum et al., 2004a) were also co-registered to the base map. Our mapping was conducted using ArcGIS 9.2 software and our near equatorial data were in a simple cylindrical projection.

The Pavonis Mons South Volcanic Field was initially assigned a crater retention age of Late Amazonian based on geological investigations of *Viking* data (Plescia and Saunders, 1979; Neukum and Hiller, 1981; Scott and Tanaka, 1986). More recently a global assessment of the crater retention ages of volcanic materials was conducted using HRSC and THEMIS data (Werner, 2009). Due to the ongoing debate over the use of impact craters with diameters of <300 m in crater counts (Hartmann, 2005; McEwen et al., 2005), Werner (2009) presented crater retention ages at a reference diameter of ≥1 km. Our study area displays a cumulative number of craters ≥1 km ranging from 4.99^{-5} to 1.03^{-4}, corresponding to estimated absolute dates ranging from 232 to <100 Ma (Hartmann and Neukum, 2001). Within a factor of two these values suggest that the Pavonis Mons South Volcanic Field formed subsequent to the Late/Middle Amazonian boundary.

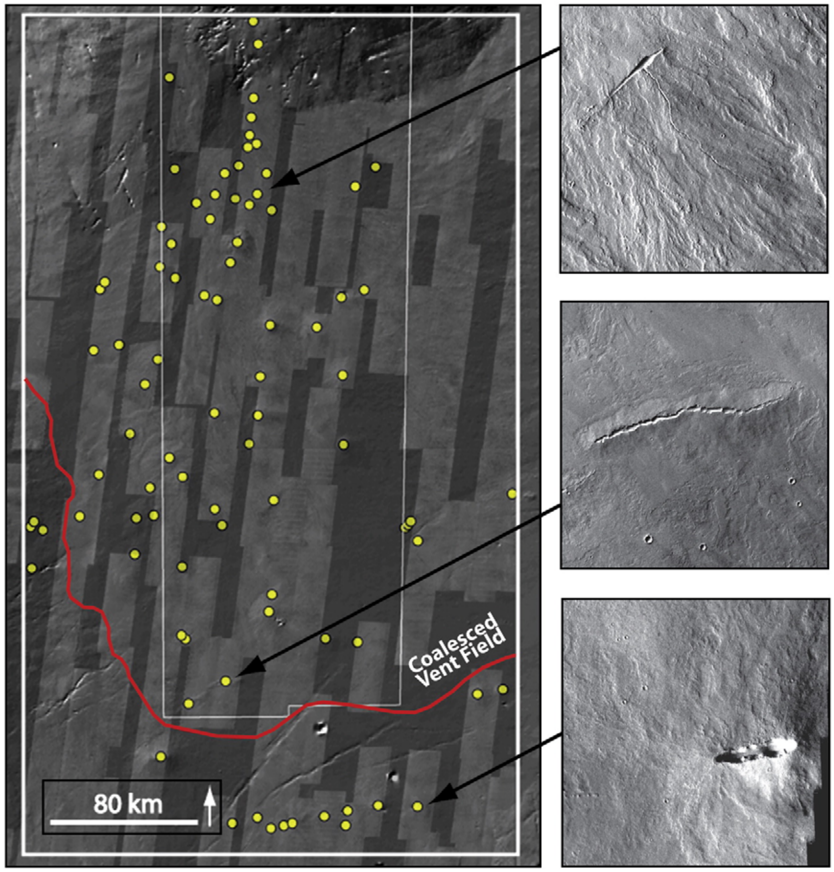

Fig. 2. The image to the left is the THEMIS VIS mosaic draped over the MOLA shaded relief image. The heavy white line delineates the study area and the thin white line marks the extent of HRSC image coverage. The extent of the 71 coalesced vents to the north of the Pavonis Mons South Volcanic Field is marked. Vents south and west of this line are considered part of the Pavonis Mons South Volcanic Field but do not form a continuous embayment relationship with the northern 71 vents in the field. Circles mark the location of the 88 small vents identified in this study. The images on the right side show the change in small vent summit feature orientation with increased distance from Pavonis Mons.

The locations of all identifiable vents within the study area were mapped. Vents are identified as positive topographic features that display radiating flows, and in some cases summit collapses (for a more detailed description of vent morphologies see Hauber et al. (2009-this issue) and Wilson et al. (2009-this issue)). These vents were broadly divided into point (low shields) or linear (fissure vents) sources regardless of the shape and dimensions of the related flow field. The location assigned to linear vents was selected as the geometric center of the vent structure. The smallest features identified in this study, based on the mapped boundary of each vent's flow fields, are three ~900 m diameter point sources with distal margins embayed by younger lavas, thereby masking their true dimensions. All other vents identified in this study area are larger than 1 km in diameter, or semi-major axis if the flow field is asymmetrical in plan form.

We do not rule out the possible existence of <1 km diameter vents, or nearly completely buried vents, which might not be detectable at THEMIS VIS and HRSC scales. If this volcanic field is analogous to terrestrial volcanic fields, then it is likely composed of additional older, buried vents. Statistical analysis by definition is the analysis of incomplete data sets. As such, we do not rule out the existence of vents and volcanic fields that are currently unrecognized, but we do present a robust assessment of the spacing and alignments between features within a statistically significant population of vents within the Pavonis Mons South Volcanic Field.

As described by Bishop (2007a), the act of mapping each vent's location for spatial analysis essentially reduces each vent's four-dimensional position in space and time to a two-dimensional point, despite the likelihood that these vents formed over the span of 100 s of millions of years (if directly analogous to terrestrial monogenetic fields (Connor and Conway, 2000)). A nearest neighbor analysis was applied to these location data to determine the degree of spatial randomness. Lutz (1986) and Lutz and Gutmann (1995) show that once a group of randomly spaced vents are identified and reasonably assumed to represent one statistical population (e.g., not two temporally distinct but spatially overlapping populations, which should produce a non-random statistical distribution), the alignments between vents can be quantified. To quantify the alignment relationships between vents in the Pavonis Mons South Volcanic Field a 2-point azimuth analysis was used here.

The classic nearest neighbor approach described by Clark and Evans (1954) is based on the work of Hertz (1909), and it is an established method for evaluating the degree of randomness in a spatial distribution. The basic approach is to measure the distance from every point to its nearest neighbor. Typical applications of the nearest neighbor approach compare a single statistic (the so-called *c* statistic) describing an observed distribution of nearest neighbor distances to that expected for a nearest neighbor distribution resulting from a spatially Poisson process (Clark and Evans, 1954). However, other “random” probability distributions are equally plausible. For example, Baloga et al. (2007) have proposed three alternate nearest neighbor distributions that have useful applications to geologic features. One accounts for a minimum threshold on the size of features, while the other two distributions, a ‘scavenged nearest neighbor’ and the classical logistic, describe the influence one feature has on the formation of neighboring features (e.g., small shields fed by a shared magma chamber). Both of these distributions reflect a depletion of resources, but one evokes an underlying Poisson process and the other does not. Baloga et al. (2007) also suggested using the skewness (a quantitative measure of asymmetry)

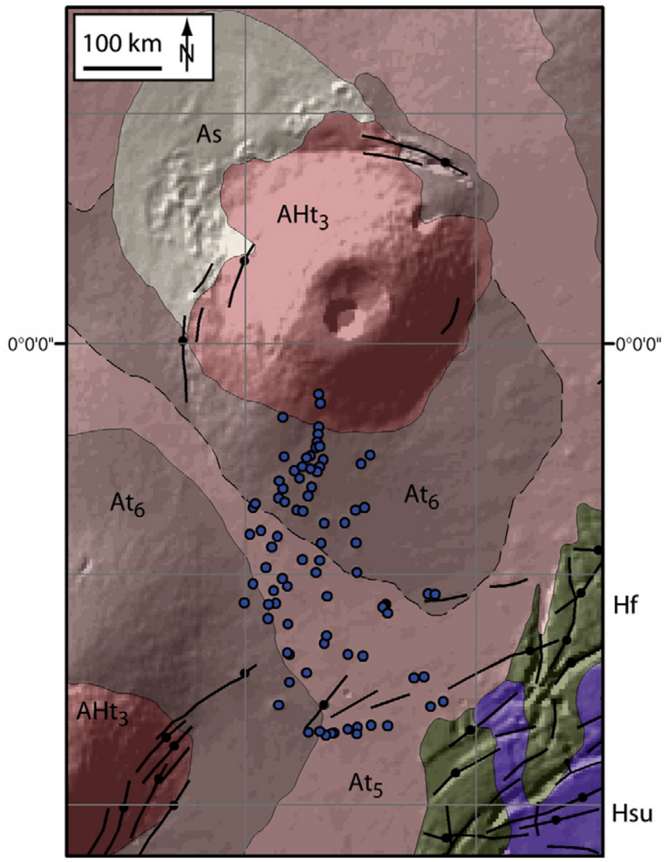

Fig. 3. Scott and Tanaka (1986) geologic map draped over the MOLA shaded relief image and centered on Pavonis Mons. Circles indicate vents that were mapped as part of this study. Geologic unit names shown in the figure are: As) Surface deposits, At6) Tharsis member 6, At5) Tharsis member 5, AHt3) Tharsis member 3, Hf) High deformed terrain materials, Hsu) Syria Planum formation.

and kurtosis (a quantitative measure of "peakedness") to evaluate and characterize an observed nearest neighbor distribution. Based on simulations of spatial distributions, Baloga et al. (2007) identified the range of nearest neighbor skewness and kurtosis pairs, as a function of sample size, which are consistent with a Poisson process.

The 2-point azimuth technique (Lutz, 1986; Wadge and Cross, 1988, 1989; Connor, 1990; Lutz and Gutmann, 1995) was applied as a fundamental statistical measure of the significance of alignments between vents in the study area. The basic intent of the 2-point azimuth analysis is to quantitatively identify structurally controlled trends within a field of vents that are spatially distributed in a Poisson sense. Using ArcGIS, the azimuth of line segments connecting each vent to all other vents east of its location was measured so as not to duplicate any measurements. Histograms of azimuth values (0° = north, 90° = east, 180° = south) were produced with 10° bins. Peaks in the frequency distribution of the azimuths are suggested to result from preferred formation of vents in response to structural controls within a region (Lutz, 1986). Alignments quantified in this study were compared with published tectonic trends identified by previous mapping (Plescia and Saunders, 1982; Megé and Masson, 1996; Anderson et al., 2001, 2004; Wilson and Head, 2002) to identify any possible relationships.

4. Results

The Pavonis Mons South Volcanic Field contains 88 identifiable vents satisfying the criteria described above. It is possible that some small vents remain unidentified as only 45% of the study area is covered by HRSC, and ~65% of the remaining area is covered by the

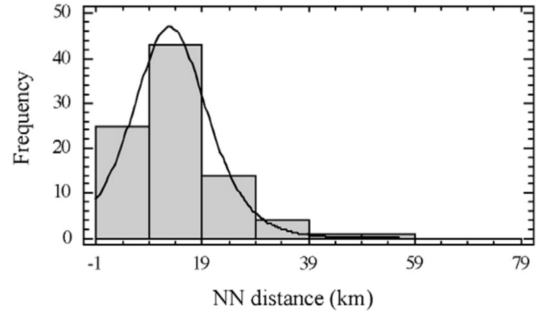

Fig. 4. Histogram of measured nearest neighbor distances for the 88 small vents within the Pavonis Mons South Volcanic Field. The Poisson nearest neighbor probability distribution is also shown (solid line) for comparison. The small vents in this region are consistent with a random Poisson spatial process.

THEMIS VIS mosaic. Based on visual inspection, we identified no additional vents south of the volcanic field or west of the study area on the Arsia Mons main flank. Additional vents are identified east of the study area in the Tharsis plains (Plescia and Baloga, 2008). Any additional vents located within the NE Arsia Mons rift apron are not yet identified.

The distribution of nearest neighbor distances within the Pavonis Mons South Volcanic Field is very well fit by the classic Poisson nearest neighbor distribution (Fig. 4), with a mean value of 14.1 km ± 2 km. Thus the spatial distribution of these small vents is consistent with a Poisson process. This result suggests that small vents were equally likely to occur at any location within the study area, and that the existence of any one vent did not influence the location of any other vent. Analyses of skewness and kurtosis of the nearest neighbor distribution also fall within the acceptable ranges for a Poisson spatial process (Fig. 5). 17 vents within the Pavonis Mons South Volcanic Field are not embayed by the flow fields of the other 71 coalesced vents. Four of these 17 vents are in the distal portion of the Arsia Mons rift apron, and 13 vents are located east of Arsia Mons. Removal of these vents from the analysis has negligible impact on the nearest neighbor analysis.

Vent alignments for the full population of 88 vents in the Pavonis Mons South Volcanic Field show concentrations at 0°–10° and 170°–180° (Fig. 6), which is comparable with the previously measured trend of the SVF's axis (Plescia, 2004; Bleacher et al., 2007a). Analysis of the 71 coalesced vents produces a slightly stronger N/NE-trending result. Both the 71 coalesced vents and the full data set within the Pavonis Mons South Volcanic Field display weak east-trending relationships. Because there are only 17 vents beyond the extent of the coalesced portion of the field, any statistical analyses on this small sample have

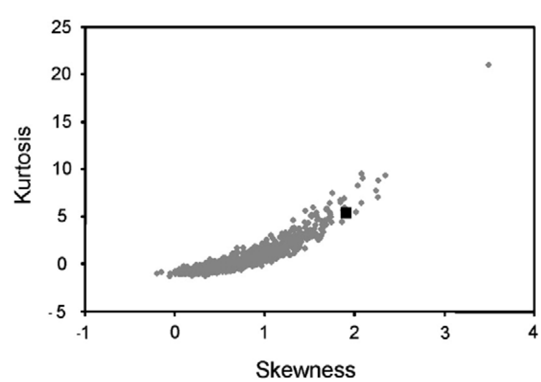

Fig. 5. The skewness (degree of asymmetry) and kurtosis (degree of "peakedness") for the nearest neighbor distribution shown in Fig. 4 are 1.9 and 5.4 respectively. These values plotted against each other are indicated by the black square in this figure. The cloud of gray diamonds represents skewness and kurtosis combinations for 1000 simulated Poisson spatial distributions of 88 points (see Baloga et al. (2007) for more discussion of the simulation method). The distribution of small vents south of Pavonis clearly lies within the range of values representing 95% of the simulated pairs.

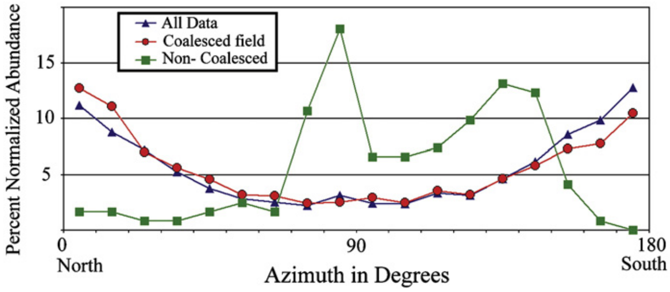

Fig. 6. Distribution of azimuth measurements between the small vents in the Pavonis Mons South Volcanic Field. All 88 vents are shown as triangles and the 71 coalesced vents (71 vents) are shown in circles. Both sets of vents display a strong north-trending relationship. Vents outside the coalesced majority (17 vents) are shown with squares and display relationships significantly different than the trend shown for the entire study area.

large associated uncertainties. Although no definitive inferences can be drawn, alignments for these 17 small vents are suggestive of a bimodal distribution with weak north-trending relationships. A peak centered at 85° represents the alignments within the 13 small vents located in the Tharsis plains east of Arsia Mons. The smaller peak centered at 135° represents the alignments between the 4 vents located at the distal extent of the Arsia Mons rift apron and the 13 vents east of Arsia Mons.

5. Discussion

Nearest neighbor analyses of vents in the Pavonis Mons South Volcanic Field indicate that the spatial distribution of these features is consistent with a random Poisson process. The inference that the formation of one vent did not influence the subsequent formation of younger vents is consistent with the hypothesis that the development of each vent was related to the ascension of independent shallow magma chambers, as opposed to a single, centralized plumbing system throughout the full time period during which the small vent field developed (Hughes et al., 2005; Bleacher et al., 2007a).

This study quantitatively supports a north trend in small vent alignments within the Pavonis Mons South Volcanic Field, consistent with the overall orientation of the field (Plescia, 2004; Bleacher et al., 2007a). This trend is offset by several 10 s of degrees from the trend of the Tharsis Montes chain of 35° to 40°, suggesting a different structural influence. Tectonic mapping (Anderson et al., 2001) suggests that tectonism during the Noachian likely produced north-trending crustal fractures that might extend into this area related to the formation of Claritas Fossae, and that later Noachian and Hesperian tectonic activity likely produced east-trending crustal fractures in this area parallel to Valles Marineris. The small vents inside the Pavonis Mons South Volcanic Field display alignment relationships that are parallel to, and in line with, an extension of the older, north-trending tectonic pattern. The formation of some small vents south of the coalesced majority of the field to the north appear to display east-trending alignments that might have also been influenced by an extension of the Noachian–Hesperian structural fabric, though this is a small population with high statistical uncertainty. Whereas vents in the Pavonis Mons South Volcanic Field display a north-trending structural influence, individual vent summit structural orientations do not consistently parallel this trend (Fig. 2). This difference in trend might support the interpretation of more than one structural control on vent spacing and alignment, and/or an influence from regional slope, to which most elongated vent structures are generally perpendicular. A more detailed study of vent structure orientations within this field is currently underway.

The vent alignments and elongated summit structure orientations suggest that a complex mixture of buried tectonic patterns, extending back to the Noachian, influenced the final morphology of the individual small vents and the field as a whole. While the oldest, north-trending Claritas pattern (Anderson et al., 2001) appears to have had the dominant influence over the formation of the field, the northeast-trending Tharsis Montes pattern and the east-trending Valles Marineris pattern might have influenced the surface orientation of the linear summit structures near their respective margins of the study area. As a point of clarification, this study does not suggest that the Late Amazonian vents developed synchronously with, or as a result of, the older tectonic events. It appears that the pre-existing tectonic patterns in the buried Noachian-aged Tharsis crust structurally controlled the ascension of magma through the crust in the Amazonian related to a magma generation event in that time period.

6. Implications

The formation of the Tharsis Montes includes main flank formation followed by rift zone activity (Crumpler and Aubele, 1978) but the relationship between the two is not entirely clear. The surfaces of the Tharsis Montes are associated with an age of Middle to Late Amazonian on the basis of crater size-frequency distributions (Plescia and Saunders, 1979; Neukum and Hiller, 1981; Neukum et al., 2004b; Werner, 2009). However, it is suggested that the Tharsis Montes might have begun to form earlier than a billion years ago (Hodges and Moore, 1994; Wilson et al., 2001; Werner, 2009). If Tharsis Montes development includes a continuous pulse of magma from the proposed onset of eruptions through the emplacement of Late Amazonian rift apron and small vent flows then the life cycle of the Tharsis Montes magma production event is at least an order of magnitude longer than for shield volcanoes on the Earth (Neukum et al., 2004b; Plescia, 2004). It is proposed that slow and/or episodic magma production, storage in magma chambers, and episodic eruptions could explain this inferred longevity (Wilson et al., 2001) or that main flank and rift apron development are representative of spatially overlapping but unique magma production events both of which are reflected by unique regional structural patterns and are separated by a significant eruptive hiatus (Bleacher et al., 2007a). Determining the developmental history of these volcanoes holds important implications for inferring magma generation rates in the Tharsis province and as such identifying if rift zone and/or small vent field eruptions are related to Tharsis Montes main flank development is a critical piece of the puzzle.

If the Pavonis Mons South Volcanic Field is the result of Late Amazonian magma ascension through the crust and not magma emplaced through a rift zone from a Pavonis Mons magma chamber, a logical question to ask is how this field might be related to the adjacent Pavonis Mons volcano, which is located >400 km away from some of the small vents? Magma production events, possibly on the order of 1000 km in diameter (Megé and Masson, 1996), are suggested to be responsible for the formation of radiating fractures extending over 1000 km away from the Tharsis province, including the Claritas Fossae fault system (Anderson et al., 2001). Amazonian-aged fractures are suggested to converge on a position somewhere near the Tharsis Montes chain (Carr, 1974; Plescia and Saunders, 1982; Megé and Masson, 1996; Anderson et al., 2001; Wilson and Head, 2002). Kiefer (2003) suggests that the Tharsis province experienced a combination of broad mantle upwellings, responsible in part for the larger scale topographic rise, and more focused upwellings, responsible for large shield development. The identification of at least five major tectonic centers in the Tharsis province some of which do not correlate with major shield volcanoes (Anderson et al., 2001), supports the idea that major magma production events occurred throughout the history of the Tharsis province, some of which were unique from large shield-forming magma production events. The spatial relationship between this field of small vents and Pavonis Mons suggests that the small vents could represent late stage eruptions related to the larger volcano's magma production event (Hughes et al., 2005). However, control over the formation of these Amazonian-aged small vents by deep-seated, Noachian-aged crustal structures leads us to suggest that these vents formed from magma that ascended through the crust independently of processes related to the construction of the Pavonis Mons main flank, likely being related to a unique and younger magma production event. This inference is consistent with the suggestion of regional magmatic-driven activity that would have produced the igneous plateaus of Tharsis, Tempe Terra, and Thaumasia (Dohm et al., 2009-this issue), or uplifted regions such as hypothesized for the central parts of Valles Marineris, Melas (Dohm et al., 2009-this issue).

If this small vent field (or any small vent fields across the province) is not related to a large shield volcano, then its formation represents a significant magma production event in the development of the Tharsis province. Such events might also have contributed to the demagnetization of the province (Johnson and Phillips, 2005). If the early Tharsis crust was originally magnetized, the magma conduits associated with the development of large volcanoes would have near-completely demagnetized the crust in the immediate vicinities of those volcanoes (Johnson and Phillips, 2005) but alone would not have demagnetized the entire province. If any small vent fields in the Tharsis province represent mantle upwellings and magma rise through the crust, these events would likely have contributed to the demagnetization of the crust between the larger shield volcanoes. The crust beneath the Pavonis Mons South Volcanic Field is demagnetized and the boundary between magnetized and demagnetized Tharsis crust is located south of this field. Lillis et al. (2009-this issue) show that if this volcanic field is responsible for demagnetizing the crust in the area between Arsia Mons, Pavonis Mons, and Valles Marineris, a minimum volume of ~10 to 35 km, or 0.6 to 1.8 million km^3 is required to have ascended through the crust (including intruded and extruded materials), which suggests that a significant amount of magma ascended through the crust in this area between major volcanoes for which the only surface manifestation was small volcanic vents.

Whether or not the small vent field south of Pavonis Mons is related to a major shield-forming magma production event or a unique event, this field of small vents does display a complex interaction between magma ascension and multiple, older crustal basement structures. Other vent fields, such as the volcanic field south of Ascraeus Mons also display alignments that qualitatively suggest similar structural controls. Continued mapping of other small vent fields in the Tharsis province and comparisons of spatial and alignment analyses between the various small vent fields and regional tectonic trends will provide insight into the developmental history of the Tharsis province.

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