

THARSIS MONTES AS COMPOSITE VOLCANOES?: 2. LINES OF EVIDENCE FOR EXPLOSIVE VOLCANISM IN FAR-FIELD DEPOSITS.

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Introduction and background: On the basis of theory [1, 2], hawaiian and basaltic plinian eruptions should be common under martian conditions, and should be favored as a function of the increasing altitude typical of growing edifices on Mars. One might therefore expect that these types of eruptions and their deposits might be common during the construction of edifices such as the Tharsis Montes. Here we examine evidence for the presence of far-field pyroclastic deposits (more distal than the topographic base of the volcano) emplaced during the construction of the Tharsis Montes. Elsewhere we describe lines of evidence that suggest that these types of eruptions may have occurred in the construction of the edifices and that the Tharsis Montes might plausibly be reinterpreted as composite volcanoes [3].

Potential lines of evidence for distal pyroclastic deposits at the Tharsis Montes:

1) Regional deposits as pyroclastics: Dune fields: Edgett [4] recently documented the presence of two eolian transverse dune fields in southwestern Tharsis interpreted to be due to emplacement of fragmental volcanic deposits by explosive volcanic eruptions in the Late Amazonian, and their eolian reworking. One is located about 70 km northwest of Biblis Patera and the other (the largest dune field known in equatorial Mars) is about 500 km northwest of Arsia Mons. These deposits have low thermal inertias, high albedos, superposed features, appear inactive, and are mantled by fine-grained material. The Arsia deposit is estimated to have a volume of about 4 km³. On the basis of the analysis by Wilson and Head [1], this volume could easily be emplaced at this distance in a single plinian eruption event with a volume eruption rate of 10⁴ m³ s⁻¹ (plume height ~70 km) lasting for about 4 days. Thus, it is very plausible that these types of deposits, as previously documented in the Hecates Tholus region [5], could be derived from pyroclastic eruptions associated with the construction of the major shield volcanoes on Mars. If the interpretation of a Late Amazonian age [4] is correct, then pyroclastic volcanism has continued well into the period during which effusive flank eruptions appear to dominate on the Tharsis Montes.

2) Regional deposits as pyroclastics: The 'Stealth' area: Muhleman et al. and Butler [6] discovered and defined an area of highly anomalous radar characteristics in the equatorial region of southwestern Tharsis extending for about 2000 km west of Pavonis and Arsia Montes. Called 'Stealth' because it has no distinguishable radar return (it also shows high microwave emissivity [7]) it was interpreted to be a deposit of fine-grained (<<1 cm), unconsolidated surface material with a minimum thickness of several meters (5-10 m minimum); 8) containing few radar scatterers, and thought to be of pyroclastic origin [6]. In a more detailed photogeologic analysis, Edgett et al. [9] have underlined that pyroclastic volcanism may be an important source for the 'Stealth' de-

posit, and that, because of the relative youth of the deposit, such volcanism may have occurred here relatively geologically recently. In the 2000 km area west of Arsia and Pavonis Montes the 'Stealth' deposit overlies lava flows, the lobate slide deposit on the west flank of Arsia Mons, and the Medusae Fossae Formation, indicating that the age of the deposit is Upper Amazonian. In addition, through careful photogeological analysis of Viking images, Edgett et al. [9] show that pre-'Stealth' mantle deposits many meters thick are interlayered with lava flows; this association, and the absence of evidence for other processes to produce the fine grained material, led Edgett et al. [9] to conclude that the fine-grained material was of pyroclastic origin. These observations and interpretations of the intimate intermixing of flows and pyroclastic deposits strengthens our hypothesis that the Tharsis Montes may be composite volcanoes [2, 3].

Pyroclastic deposits of this scale can have several origins: 1) pyroclastic airfall deposits from plinian eruption plumes, transported by prevailing winds; 2) pyroclastic flow deposits (ignimbrites) produced by runout from a "collapse" column forming a fountain over the vent; and 3) co-ignimbrite deposits produced by ingestion of atmospheric gases into an ignimbrite and the convective sorting and redeposition of its finer grained portion. The physical properties of the 'Stealth' deposit (fine-grained and unwelded [6]) favor the airfall and co-ignimbrite options, and its dispersal distance requires that small pyroclasts be lofted to at least ~100 km [1, Fig. 20], implying an eruption rate of at least ~10⁸ kg s⁻¹. To maintain a convectively stable plinian plume to this height requires a very gas-rich (several wt %: [1, Fig. 19]) magma, whereas there is no such volatile-content limitation on a co-ignimbrite plume. On the basis of our analysis of Mars eruption conditions [1], therefore, we favor the co-ignimbrite scenario for the formation of the 'Stealth' deposit.

3) Regional deposits as pyroclastics: The 'Greater Stealth' area: Butler [6] documented the presence of a region of relatively low radar reflectivity that extends from the west flank of Pavonis Mons for more than 5000 km along the equator to the area south of Elysium, and which includes the 'Stealth' area. This larger area, named 'Greater Stealth' by Edgett et al. [9], was suggested by Butler to be a much larger deposit of tephra, of which the 'Stealth' region was simply the thickest accumulation. If the 'Greater Stealth' deposits are pyroclastic and indeed related to the Tharsis Montes, then the implications are that they consist mainly of co-ignimbrite airfall deposits from ignimbrite eruptions with high (10⁸ to >10⁹ kg s⁻¹) eruption rates. On Earth, about half of the mass of an ignimbrite is elutriated to form the associated co-ignimbrite airfall; on Mars, more efficient magma fragmentation, leading to up to a 100-fold decrease in mean grain-size[1], may ensure that an even larger magma fraction eventually resides in the co-ignimbrite deposit.

4) Regional deposits as pyroclastics: The Medusae Fossae Formation: The Medusae Fossae Formation [10] is distributed in the equatorial region west of the southern Tharsis Montes, extending in irregular outcrops to the vicinity of about 160°W. It predates the 'Stealth' deposit and predates or interfingers with numerous lava flow units of the Tharsis Montes and Olympus Mons. The Medusae Fossae Formation is characterized by smooth and undulating surfaces with very low impact crater densities, as well as surfaces with parallel grooves interpreted to be yardangs [11]. The material appears to be soft to indurated and the total thickness may exceed 3 km [10]. The nature of the deposits, as well as the presence of both eroded and buried surfaces, led several investigators [11, 12] to propose that the Medusae Fossae Formation is composed of thick deposits of pyroclastic material that may have been erupted from local partly-buried depressions in the region, and is now undergoing eolian redistribution. The development of yardangs has led to the suggestion that at least some of the deposits in the Medusae Fossae Formation may be indurated by primary welding (e.g., ignimbrites) or later cementation. The lower member of the Medusae Fossae Formation contains interbedded lava flows. On the basis of these characteristics, and the range of modes of emplacement of pyroclastic material plausible for the 'Stealth' and 'Greater Stealth' deposits (see above), we consider that the Medusae Fossae Formation is an excellent candidate for accumulations of pyroclastic deposits from the Tharsis Montes and other nearby volcanoes over the course of their construction. On the basis of the age of these deposits and the interfingering of lava flows, we believe that their presence strengthens the hypothesis that the Tharsis Montes are composite volcanoes, the products of both explosive and effusive eruptions. On the basis of the distribution and characteristics of the Medusae Fossae Formation, the most plausible styles of emplacement [1 and above arguments] involve a mixture of pyroclastic flows and flow-derived co-ignimbrite airfall deposits in roughly equal volumes.

5) Global deposits as pyroclastics: Global dispersal and the record at the Viking and Pathfinder sites: Plinian plumes from primary vents and co-ignimbrite plumes from dispersed pyroclastic flow sources both have the potential to loft fine-grained (<100 microns) pyroclasts (and aerosols in the plinian case [13]) to great heights for widespread dispersal. Observations of convecting eruption clouds on Earth confirm theoretical model predictions that the height of a convecting eruption cloud formed in a high-speed pyroclastic eruption is proportional to the fourth root of the heat release rate from the vent [13, 14], which is in turn proportional to the mass eruption rate. Differences in the atmospheric pressure and temperature structure cause martian eruption clouds to rise about five times higher, for the same eruption rate, than terrestrial clouds [1; Fig. 19]. The terminal fall velocities of the sub-100 micron pyroclasts (which are much commoner in martian than terrestrial eruptions [1]) released from the highest parts of 200 km high martian eruption plumes are much smaller than the mean horizontal atmospheric wind speeds, which means that such particles are effectively en-

trained by the winds, a significant fraction of the total mass thus being transported for much greater distances than the ~1000 km predicted by assuming that they fall in a laminar fashion. These analyses of explosive volcanic eruptions occurring under martian environmental conditions, together with the evidence for widespread pyroclastic deposits outlined above, thus strongly suggest that these eruptions are capable of the global dispersal of material and its delivery to the Viking and Pathfinder landing sites [13, 15].

6) Plinian eruptions, gas input into the atmosphere, and climate change: Gulick et al. [16] have hypothesized an episodic ocean-induced CO₂ greenhouse on Mars. Pulses of CO₂ (one to two bars) injected into the Mars atmosphere could place the atmosphere into a stable, higher pressure, warmer greenhouse state for tens to hundreds of millions of years. Our calculations indicate that a significant phase of plinian eruptions of magma containing 0.5 wt % CO₂ could provide of the order of 1/10 bar of CO₂ to the atmosphere. Thus, because of the significant gas release, phases of plinian eruptions may be an important contributor to the atmosphere and have significant global effects.

Conclusions: On the basis of the nature of far-field deposits around the Tharsis Montes, we find evidence for a major contribution from pyroclastic eruptions that can be plausibly traced back to sources in the Tharsis Montes region and which appear to be interspersed throughout the period of time of their formation. A critical consequence of martian conditions is that basaltic plinian and ignimbrite-forming eruptions, rare on Earth, should be relatively common on Mars [1, 17]. The combination of the lower atmospheric pressure causing systematically finer-grained pyroclasts and the rapid acceleration of the spray of pyroclasts and released gas above the fragmentation level (essentially independent of the viscosity of the magmatic liquid), would encourage many basaltic eruptions that would be hawaiian on Earth to be plinian on Mars [1]. Thus mafic (and even ultramafic) lavas could easily produce plinian eruptions and products, and lead to the wide dispersal of ejecta and the construction of composite volcanoes. On the basis of theory and the above observations and interpretations, we believe that a case can be made that the Tharsis Montes are composite volcanoes.

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