GLACIAL LOADING AND UNLOADING AT ARSIA MONS, MARS: POTENTIAL INFLUENCE ON INTRUSIONS, ERUPTIONS, LOCATIONS AND ORIENTATIONS.

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Introduction: With the availability of higher resolution image data, morphologic evidence emerged for the presence of mid-latitude cold-based glaciers on the flanks of the Tharsis Montes and Olympus Mons shield volcanoes [1,2,3]. The presence of these glaciers during the late Amazonian is attributed to ice mobilization in response to a period of higher obliquity in Mars' spin axis [3, 4]. The largest fan-shaped glacial deposit in the Tharsis Montes is located on the western flank of Arsia Mons, and covers ~166,000 km^2 [2]. Both the introduction of, and the removal of such a large glacial mass could have significant effects on magma storage and eruption in the active edifice. For example, recent studies of the Kverkfjöll volcanic system in Iceland [5] indicate that ice removal influences magma production and storage, and that the resulting change in regional stress state is a factor in the direction of dike intrusion. We examine the geometry of a reconstructed ice sheet on the northwest flanks of Arsia Mons volcano, and assess the location and orientation of candidate dikes in relation to the modeled growth and decline of the regional ice sheet [6].

Arsia Mons Glacial and Dike-Related Features: The extent of the fan-shaped glacial deposit on Arsia Mons [1, 2, 6] is shown in Figure 1a; it extends primarily to the northwest of the main volcanic edifice. *Fastook et. al.* [2008] modeled ice accumulation on the Tharsis Montes, and Figure 1b shows a map of ice thickness for the Arsia Mons glacial deposit [6].

Many dikes (manifested by graben, linear rows of cones, and various candidate subglacial eruption deposits [7-11]) are located in the region. Low ridges, steep-sided flows, tephra cones, moberg-like ridges, and linear troughs are all interpreted to be surface manifestations of synglacial dike intrusion [8-11]. The flanks of Arsia Mons also contain numerous concentric graben features related to the growth of the volcanic edifice [12]. We also, note the presence of significant dike swarms surrounding the Tharsis region [7].

Stress Field Effects on Magma Intrusion: Magma generation in the mantle is the result of decompression melting [13]; thus a removal of surface mass decreases pressure on the mantle and can lead to increased magma generation [5]. This relationship between mass unloading and increased melt production is likely to be analogous between Iceland and Arsia Mons, as both are located over zones of mantle upwelling—a spreading ridge beneath Iceland [5] and a plume beneath Tharsis [7]. The orientation of the stress field in the overlying crust is responsible for the subsequent magma intrusion processes. *Segall et. al.* [2001] [14] demonstrate that regionally compressive stress fields and isotropic stress fields favor eruptive scenarios; whereas intrusion is favored in systems where there exists a heterogeneous stress field [14]. Given a heterogeneous stress field, dike intrusion will preferentially take place in the direction of the least principle stress, perpendicular to σ_3 [5]. This principle of stress field guiding intrusion direction and orientation applies to dikes that propagate both from the mantle, and also from or near magma reservoirs beneath volcanoes [5].

Kverkfjöll Volcano: *Hooper et. al.* [2011] [5] utilize GPS data to track swarms of small earthquakes which are the result of dike intrusion at Kverkfjöll volcano in Iceland between February 2007 and April 2008. Models of dike intrusion into the postulated crustal stress state were then performed. Results indicate that dike orientation is primarily directed by the plate spreading direction [5]. There exists, however, a non-primary component in intrusion direction that is rotated clockwise from the direction of plate spreading [15] ; this deviation is interpreted to be the result of smaller regional stresses contributed by the removal of glacial mass [5].

Glacial Loading and Unloading at Arsia Mons: As Mars lacks plate tectonics, the stress state in the crustal region beneath Arsia Mons is governed solely by topographic stresses. The growth of the volcanic edifice is governed by the interplay between the lithospheric stresses as they are affected by the increasing edifice load [14]. The series of stress states produce concentric and radial graben on the upper and lower flanks of the volcano as a result of both normal and thrust faulting [12]. The location and stability of the magma reservoir changed with time [16], with maximum stable reservoir conditions being reached once the volcano summit was 13 to 18 km above the surrounding plain [16]. We also note that the decreased Martian gravity results in magma reservoirs that have a greater vertical extent than terrestrial magma reservoirs [16]. The process of glacial loading and unloading occurs after the period of edifice growth, and during the period of stable reservoir conditions.

The emplacement and removal of ice from the flanks of Arsia Mons could produce changes in the location and orientation of dike emplacement. Figure 2 represents schematically the postulated effects on dike orientation associated with each stage of glacial loading and unloading on Arsia Mons. The initial state of the volcano (Figure 2a) is characterized by a stable magma reservoir, and isotropic stress state. During the process of glacial loading (Figure 2b), additional mass on the northwestern flank of the volcano increases stress in this direction, and this becomes the principle stress direction. The perpendicular least principle stress direction is then the preferred direction for intrusion [5]; this corresponds to southeastern flank of Arsia Mons. The amount of intrusion in response to this magma reservoir compression is unclear; however, it will likely decrease once the glacier is emplaced, and the magma reservoir equilibrates to the stress state.

The glacial unloading process exists as a two phase process, depicted in Figure 2c. As addressed previously, the removal of mass from the volcano will induce additional mantle melting, leading to an increased rate of volcanic activity during the process of glacial unloading, and lasting for a period of a few thousand years after the entire removal of the glacier [5, 17]. This increased magma flux will be manifested as dikes which propagate in the least principle stress direction. This direction is parallel to the retreating glacial edge [5]; Figure 2c depicts the orientation of dikes in response to multiple phases of ice retreat. Changes to the intrusion orientation can be accomplished by significant ice loss at different parts of the glacial edge. Thus by noting changes in the orientations of dikes, one can potentially trace the edge retreat of the glacier.

The period of residual volcanic activity following complete glacial removal is likely to be dominated by volcanic eruptions as opposed to the dike intrusions that characterized the prior stages (Figure 2d); this in response to the volcano now being in a compressive, isotropic stress state, which favor eruption over intrusion [5, 18].

Discussion and Summary: The regional stress state of a volcanic edifice influences the eruption style, and can affect the location of faults and intrusions around the edifice [12, 16]. Recent studies of Kverkfjöll volcano in Iceland [5] suggest that changes in the regional stress state produced by the removal of glacial ice, can affect the location and orientation of dike intrusions. We propose the process of glacial loading and unloading at Arsia Mons, Mars [1-3] could also have affected the locations and orientations of dike intrusions at the volcano. Morphologic features such as low ridges, steep-sided flows, tephra cones, moberg-like ridges, and linear troughs are interpreted to be the synglacial expressions of dike intrusion [7-11]. The proposed relationship between evolving regional stress state and dike orientation (Figure 2) can be used to analyze the orientation of dikes on Arsia Mons, and assess their relationship to the process of glacial loading and unloading.

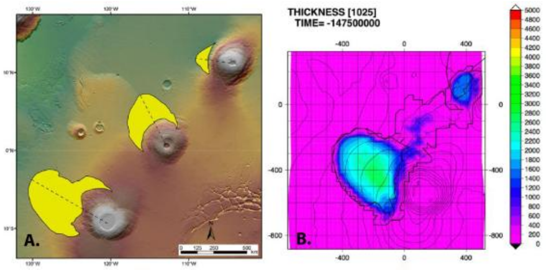

Figure 1: a) Areal extent of the fan-shaped glacial deposits on the Tharsis Montes; Arsia Mons is located in the lower left corner. b) Results of an ice accumulation model for Arsia Mons during a period of high spin-axis obliquity. Thickness of ice deposited is given in meters. [6].

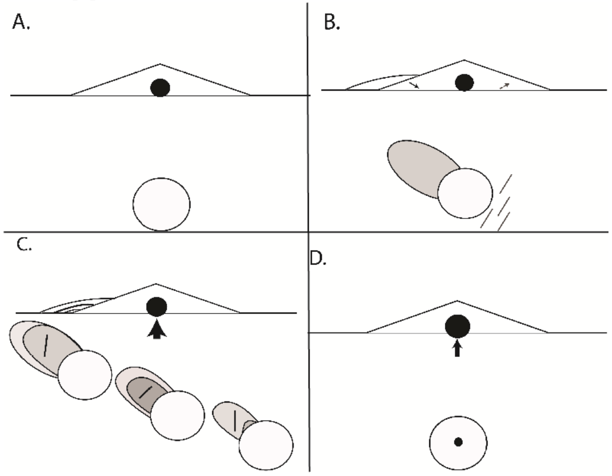

Figure 2: Schematic showing the general trends of how changes in the regional stress field associated with glacier emplacement and removal affects the orientation of dikes. Upper figure: cross-section of the volcano with the magma reservoir shown in black; lower figure: aerial view of the volcano depicting the orientation of dikes relative to the glacier. A.Volcanic edifice prior to glacial emplacement, isotropic stress state. B. Glacial emplacement increases stress beneath the glacier, the corresponding least principle stress direction is opposite this force [5], and would result in dike emplacement to the SE of the volcanic edifice. C. Glacial retreat results in an increase of magma production in the mantle [5] (denoted by an arrow below the magma reservoir), and a progressively changing stress state. Dikes would be emplaced parallel to the retreating ice edge [5]. A hypothetical progression of this process is shown in the aerial view. D. Increased magma flux caused by the removal of the glacier lags the removal time, and results in continued eruptions following glacial removal (summit eruptions denoted by the black dot in the center of the aerial volcano view) [5, 17].

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