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Eruption history of the Elysium Volcanic Province, Mars

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ABSTRACT

Volcanism has played a significant role in shaping the surface of Mars. Volatiles released during eruptions profoundly altered the composition and density of the Martian atmosphere in the past. Quantifying the amounts of volcanic outgassing has been attempted regionally and globally, however, volume estimates of erupted volcanic material in time are still poorly constrained. Here we show the first eruption frequency record of a volcanic region, the Elysium Volcanic Province, which is the second largest volcanic province on Mars. Studied lava flows show model ages ranging from 3.4 Ga to 60 Ma. Together with observed resurfacing ages, the 'visible' record of volcanic activity extends back to 3.9 Ga. Based on our 190 model ages, continuous volcanic activity is apparent with a major peak at 2.2 Ga. In the last 1 Gyr, the activity rapidly waned. Although the majority of volcanic material (including volatiles released to the atmosphere) erupted within a short time span of less than 200 Ma, activity continued until the very recent past. Extrapolating the eruption record, it appears likely that this region of Mars is still volcanically active today. Our derivation of the eruption record has profound implications for global thermal and atmospheric modeling, indicating sustained heat production, melt generation, and magma ascent at a single location over most of the planet's geological history.
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1. Introduction

Mars has been volcanically active over most of its geological history. The majority of volcanic material was erupted in the Noachian and Early Hesperian (>3.6 Ga) with infrequent eruptions scattered throughout the Late Hesperian and Amazonian according to the general conception (Greeley and Schneid, 1991; Neukum and Hiller, 1981; Neukum et al., 2004, 2010; Werner, 2009). More recently, lava flows as young as 2 Ma were discovered which mostly relate to shield volcanoes (Hauber et al., 2011; Neukum et al., 2004; Vaucher et al., 2009). In the past, ages of large shield volcanoes were derived by counting craters on volcano flanks (Hauber et al., 2011; Vaucher et al., 2009; Werner, 2009). This way, however, a mixed population is obtained since flanks are built up during individual eruptive episodes and therefore consist of multiple geological units. The age derived is younger than the oldest unit on the flank and does not reveal anything about possible younger events. In addition, flank slopes are often >10° and are therefore not suitable for crater counting.

In the past, inferences were also made about the total quantity of released volatiles into the Martian atmosphere during volcanic eruptions by estimating the total volume of volcanic material on the surface (Craddock and Greeley, 2009; Greeley and Schneid, 1991; Phillips et al., 2001). However, no detailed age estimates have been performed to understand the release of volatiles (and the periods of volcanic activity) in relation to time. Therefore, to understand the eruptive history of Mars, the spatial and temporal distributions of the individual eruptive events in the major volcanic provinces or at individual volcanoes should be carefully analyzed.

In this study we focus on lava flows formed at the Elysium Volcanic Centre which is dominated by the volcanic edifices of Elysium Mons and Albor and Hecates Tholi. The individual calderas of each volcano were included in this study since caldera formation is often accompanied by volcanic activity. We also consider Elysium Planitia volcanism as well as that along fracture systems radial to the Elysium rise (e.g., the Cerberus fossae system) as part of the broader Elysium Volcanic region. Hence, we define this region as the Elysium Volcanic Province.

We also introduce a new method for aggregating age measurements based on crater populations which properly accounts for the uncertainty in each measurement, and avoids the need to divide the timeline into discrete bins.

2. Elysium Volcanic Province

The Elysium Volcanic Centre is dominated by the volcanoes Elysium Mons and Hecates and Albor Tholi. All three edifices are located on or at the flanks of the broad, >1200 km wide Elysium rise (Fig. 1). The Elysium rise itself is located on the southeastern rim of the large >3300-km-sized impact basin Utopia. The inferred formation time of the Utopia impact basin is 4.1 Ga (Frey, 2008; Frey et al., 2004). Based on the geological map of Tanaka et al. (2005), the Elysium volcaniclastic deposits (unit AHEe) extend over an area of c.3.4 × 10^6 km^2. A minimum

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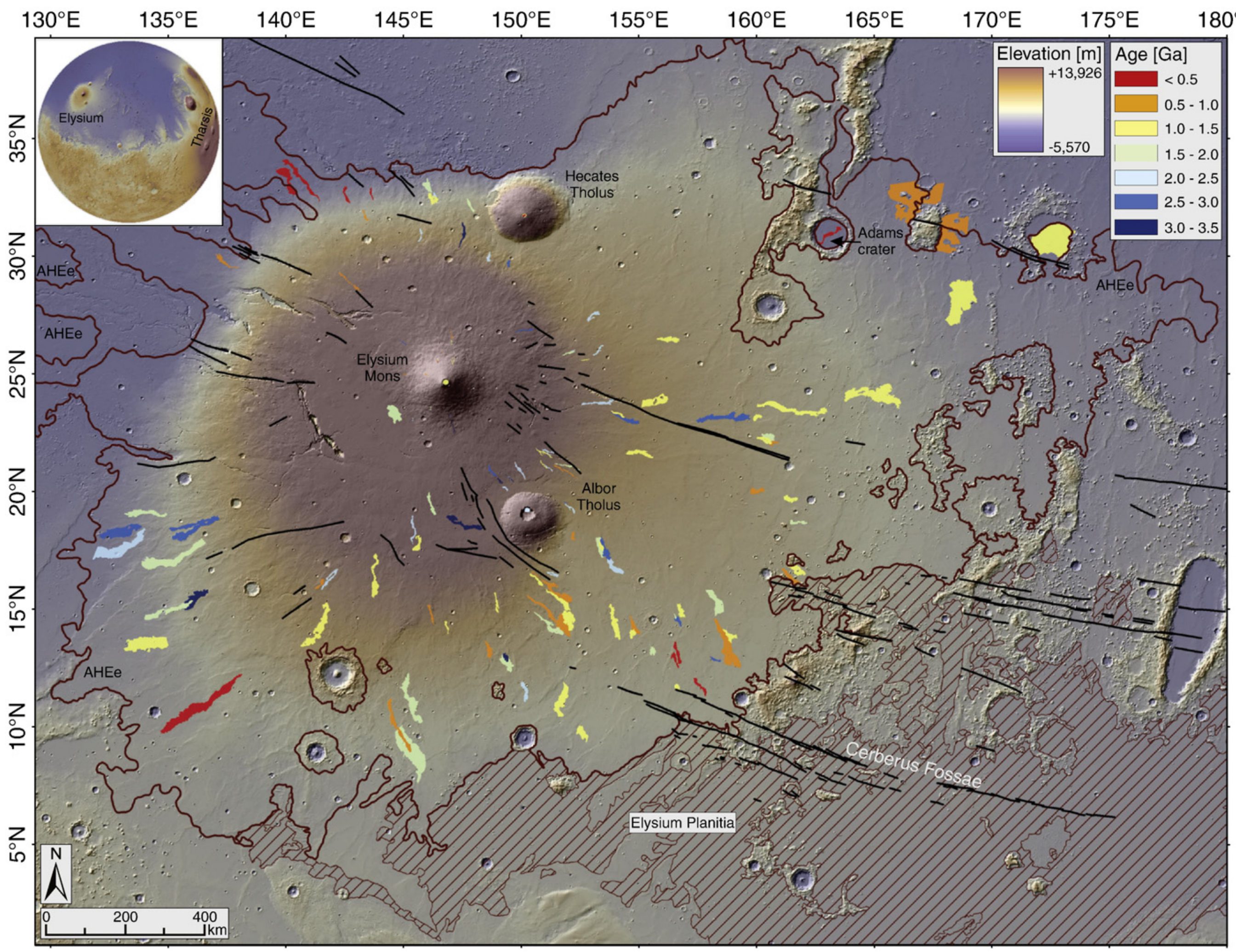

Fig. 1. Distribution of 146 mapped and dated volcanic units in the Elysium Volcanic Centre. Surface modeling ages of lava flows and calderas are shown in an age color-coded scheme at 500 Ma intervals. Note that many small lava flows on the upper flanks of Elysium Mons are not resolvable in this figure. For details of see also Fig. 4. Tectonic features in Elysium Planitia and radial fractures of the Elysium Volcanic Province were redrawn and complemented from Tanaka et al. (2005). The dashed S-SE area of the Elysium Volcanic Province represents the Cerberus Fossae units 1–3 (AEc1–3; Tanaka et al., 2005). Inset shows the Elysium Volcanic Province on Mars (orthographic projection at 0°/180°). Background data are MOLA-DTM superimposed on MOLA hillshade in equidistant projection.

estimate for the volcanic material erupted from the Elysium Volcanic Centre is 3.5×10^6 km^3 (Platz et al., 2010a).

To the south of the Elysium Volcanic Centre is another volcanic region known as Elysium Planitia or the Cerberus volcanic plains (Fig. 1). It contains some of the youngest known volcanic products on Mars (Plescia, 2003; Vaucher et al., 2009; Werner et al., 2003) and is often regarded as an isolated volcanic region. However, we argue that both the Elysium Volcanic Centre and the Cerberus volcanic plains share the same magma source at depth. It has been shown that several lava flows in Elysium Planitia originated at Cerberus Fossae forming, for example, the well-known Athabasca Valles deposits (Vaucher et al., 2009). The formation and distribution of multiple low shield volcanoes in this region (Baratoux et al., 2009; Vaucher et al., 2009) is often directly associated with Cerberus Fossae implying repeated supply of magma along the fractures.

The Cerberus fracture system also extends into the Elysium Volcanic Centre and is spatially related to the Elysium rise (Fig. 1). Fractures are arranged radially from the rise but are mainly covered by volcanic deposits. The radial fracture pattern suggests initiation and propagation due to dyke intrusions, which are typical volcano–tectonic features on both Earth and Mars (Kattenhorn and Meyer, 2010; Plescia, 2003).

3. Previous studies

There have been a number of studies where crater model ages of lava flows and calderas of the Elysium Volcanic Province were determined (e.g., Hauber et al., 2005; Neukum et al., 2004; Paskert et al., 2010; Robbins et al., 2011; Werner, 2009; Werner et al., 2011). If a direct comparison of the same unit(s) is made, significant discrepancies in crater model ages are found. There are a number of reasons for this variation: 1) usage of datasets with different spatial resolutions, 2) differing methods of data fitting and chronology functions, 3) poor choice of the counting area (a homogeneous surface area should be selected), 4) secondary craters were misidentified as primaries, 5) volcanic or endogenic pits misidentified as impact craters, and 6) neglect of the local to regional geology that could have affected the counted surface.

We use the caldera of Elysium Mons to demonstrate why previous studies failed to correctly determine its model age. The model age of the caldera of Elysium Mons has been variously determined by Werner (2009), Paskert et al. (2010), and Robbins et al. (2011) at about 3.49 Ga, 1.48 Ga, and 2.77 Ga, respectively. In all three studies impact craters on the floor of the entire caldera were counted and

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