

LARGE VOLCANOES ON VENUS: MORPHOMETRIC AND MORPHOLOGIC CHARACTERISTICS, AREAL AND TEMPORAL DISTRIBUTION, AND ROLE IN HEAT AND VOLATILE TRANSFER AND REGIONAL PLAINS RESURFACING. Mikhail A Ivanov¹ and James W. Head² ¹V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow, Russia, milhail_ivanov@brown.edu; ²Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 USA.

Introduction: Large volcanic edifices (LV) on planetary surfaces provide insight into the thermal structure of the planet, the mobility of the lithosphere, the locations of mantle thermal anomalies, mantle convection patterns, the nature of magma ascent and eruption processes, and the role of point-source volcanism in advective heat transfer and volatile transfer to the atmosphere. On Venus, large volcanoes have been catalogized [1] as significant areas (100s km diameter) of radial lava flows, presumably with a central construct. The spatial distribution of these volcanoes indicate that they are preferentially concentrated within the Beta-Atla-Themis (BAT) region [2]. Volcanoes outside BAT are associated with dome-shaped rises (e.g., Eistla, Bell Regiones [3]). When the catalogue [1] was completed, both topographic shape and stratigraphic position of LVs were poorly known; classification was mostly based on morphology seen in SAR images.

Goals of Our Study: We have revised the listed population of large volcanoes, assessing their (1) topographic configuration (using averaged topographic profiles) and (2) stratigraphic position (using the global geological map of Venus [4]). We have included in our list only those features characterized by a distinct central topographic feature (a volcanic edifice) and a topographic break in slope at the transition from the edifice to the surrounding lava flow apron. We have excluded from the list coronae, clusters of small shields, and complexes of lava flows without a central edifice (fluctuses): such features comprise a significant portion of the original catalogue [1] but display different types of volcanic activity.

Our final list includes 89 LVs, each characterized by a distinct central edifice of a generally conical shape: we characterized the morphometry, key associated features, and stratigraphic position of each, and their global distribution. We used these data to address the following questions: How are LVs distributed in time and how is this related to the history of Venus volcanism [5]? What is the global spatial distribution of LVs and their associated terrain types? What is the total volume of LVs and how does it compare with the inferred volume of major volcanic plains units? What quantity of volatiles could the volume of LV edifices potentially contribute to the atmosphere?

Analysis Results:

a) Stratigraphy and Relation to Dimensions: The surface of all LVs is comprised of regionally extensive units (Fig. 1): either the upper unit of regional plains (rp2, ~26% of LV) or lobate plains (pl, ~71% of LV). A few LV (3%) have both these units. The rp2-volcanoes are significantly smaller (~136±32 km diameter ($\pm = 1$ sigma)), whereas pl-LV (~340±175 km diameter) and rp2-pl-LVs

(~230±180 km diameter) are much larger in diameter. Despite their smaller sizes, the rp2-volcanoes are more commonly characterized by a topographic moat at the volcano base: ~65% of rp2-LV and only ~14% of pl-LV show the presence of a moat.

b) Morphometric Characteristics: As a population, LVs are characterized by a diameter range from ~75 to ~740 km: the vast majority (>95%) are larger than 100 km, and the mean diameter is ~285±175 km. The height range of LVs is ~0.1-6.1 km (mean height 1.2±0.9 km). Only one volcano, Maat Mons in Atla Regio, has an anomalous height (~6.1 km). The total volume of all LV (truncated cone approximation) is ~6.2 x 10⁶ km³. The apparent volume of the apron may be negligible compared to the central edifice volume: the apron displays little topographic difference from the background plains and generally follows background topography. The central edifice, however, could have additional extruded volume below the surface due to edifice loading, flexure and subsidence [6-7]. In addition, the intrusive component is not accounted for in our calculations: the extrusive/intrusive (E/I) ratio [8] is unknown. If we assume that E/I is 1/10, an approximate estimate of LV surface/subsurface volume is ~66 x 10⁶ km³.

c) Associated Features and Structures: All LVs are characterized by numerous lava flows that tend to decrease in length toward the volcano summit as they become stratigraphically younger [e.g., 9-10]. The most common non-flow secondary features that occur on LV are small shields that form a specific unit of shield clusters (sc) [4] and morphologically resemble constructs of older shield plains [11-13]. About ~44% of LV are characterized by these shield clusters. About 30% of the edifices are characterized by radial graben systems, hinting at the important role of radial dike propagation and unbuffered magma supply [14-15]. About 20% of the LV population have steep-sided domes and/or viscous flows on the central edifice, usually near the summit, potential evidence of magmatic differentiation in the edifice summit magma reservoir [16]. Only 16% of the LV have nova/nova-like feature near the summit, suggesting that the formation of radial dike swarms in the final stages of LV evolution is not common.

d) Areal Distribution: LV are not evenly/randomly distributed across the planet (Fig. 2); they tend to be concentrated around BAT [2] and in association with dome-shaped rises (Eistla, Ulfrun, Bell Regiones and around Metis Mons and in Thetus Regio westward and eastward Ishtar Terra, respectively). Tesserae lack LVs. Extensive lowlands that are covered by shield and regional plains

lack large volcanoes and show no evidence for the presence of embayed/buried large volcanic edifices. The large volcanoes are not aligned along linear trends, nor do they occur in chains. Rather, they form diffuse, more or less equidimensional clusters (Fig. 2).

Discussion/conclusions: All LV edifices stratigraphically post-date shield plains (psh) and the lower unit of regional plains (rp1) (Fig. 1) that constitute the absolute majority of units emplaced during the global volcanic regime of resurfacing [17]. Only about 1/4 of LV formed contemporaneously with the upper unit of regional plains (rp2) and the majority of the volcanoes (~75%) have contributed significantly to the formation of lobate plains (pl) (Fig. 1). The stratigraphic position of LVs suggests that they represent the later phases of volcanic activity on Venus (Fig. 1). Earlier volcanism in the recorded history of Venus was characterized predominantly by either numerous small edifices of psh or by apparently sourceless flows of rp1. Both units have no associated contemporaneous LV. Thus, the formation of the LV edifices documents a significant change in the Venus volcanic style [5] from numerous and broadly distributed small sources (psh) toward much more concentrated, isolated, and centralized sources that were able to maintain volcanic activity long enough to build volcanic constructs (LV) hundreds of kilometers across.

The spatial distribution of LV (Fig. 2) is significantly different from that of terrestrial volcanoes: 1) Absence of linear LV trends is inconsistent with mobile lithospheric blocks/plates causing alignment of volcanoes along convergent boundaries, or hot-spot tracks from lithosphere moving relative to fixed hot spots. The character of the spatial distribution of Venus LV suggests that they are related to mantle plumes/upwellings acting at three different scales: 1) relatively small plumes (a few 100s km across) that caused formation of isolated large volcanoes; 2) larger plumes (many 100s km across) that are responsible for the formation of the dome-shaped rises populated by LV; 3) regional upwelling (superplume?) 1000s km across, and associated with rifting and concentration of volcanic features in the BAT region.

The total volume of LV (assuming a 1/10 E/I ratio) is estimated to be $\sim 66 \times 10^6 \text{ km}^3$, which is about equal to the total volume of volcanic plains formed during the volcanic regime of resurfacing (Fig 1) (psh and the rp1) [4] if their average thickness is $\sim 0.1 \text{ km}$. This volume of volcanic materials could supply $\sim 0.005\%$ of the volume of CO_2 in the current atmosphere if all LVs were active simultaneously and the CO_2 content in their parent magma was $\sim 20 \text{ wt}\%$. Numerous lava flows, common shield clusters, and the presence of steep-sided domes on some LVs suggest that their formation was multi-staged (likely active at different times). The unrealistically high 20 wt% CO_2 concentration would also cause explosive eruptions to be common, but we have found little evidence of these deposits in association with the LVs. Thus, the late phases

of LV volcanism made little contribution to the current Venus atmosphere [Head et al., 2022].

References: [1] Crumpler & Aubele, 2000. Encyclopedia of Volcanoes, Houghton et al. eds., Acad. Press, 727; [2] Head et al., 1992, JGR, 97, 13153; [3] Smrekar et al., 1997, Venus II, Bougher, et al. eds., U of A Press, 845; [4] Ivanov & Head, 2011, PSS 59, 1559; [5] Ivanov & Head, 2013, PSS, 84, 66; [6] McGovern & Solomon, 1997, JGR 102, 16303; [7] McGovern et al., 2013, JGR 118, 2423; [8] White et al., 2006, G3 7, Q03010; [9] Ivanov et al., 2019, LPSC 50, #1272; [10] Braga et al., 2021, Moscow Solar Sys. Symp. 12, #12MS3-VN-03; [11] Addington, 2001, Icarus, 149, 16; [12] Ivanov & Head, 2001, JGR, 106, 17515; [13] Ivanov & Head, 2004, JGR 109, NE10001; [14] Ernst et al., 2001, AREPS, 29, 489; [15] Parfitt & Head, 1993, EMP, 61, 249; [16] Pavri et al., 1992, JGR, 97, 13445; [17] Ivanov & Head, 2015, PSS 113-114, 10. [18] Wilson & Head, 1994, Rev. Geophys. 32, 221. [19] Head et al., 2021, LPSC 53.

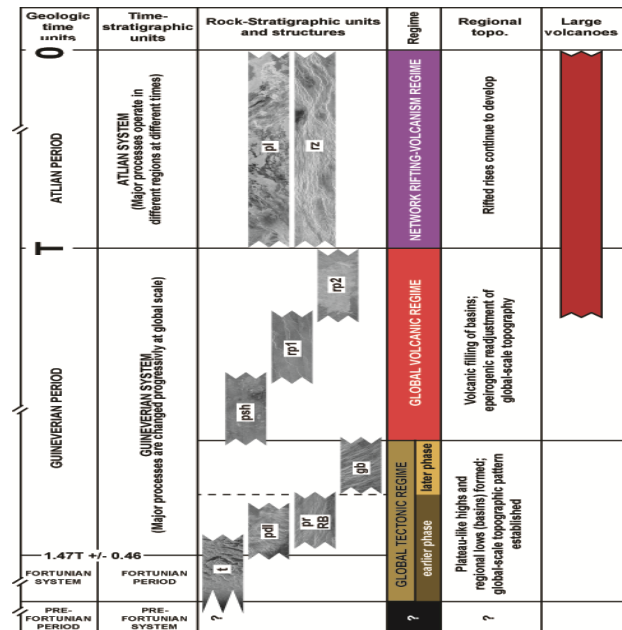


Fig. 1. Global stratigraphic column [4] showing temporal position of large volcanoes (LV).

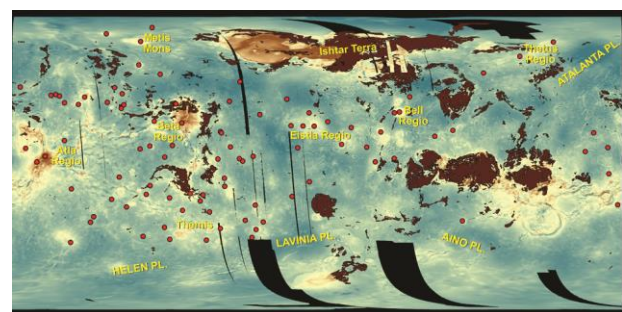


Fig. 2. Global topographic map showing the distribution of large volcanoes (LV) mapped in the study.