ABUNDANCE, GEOLOGICAL SETTINGS, AND AREAL DISTRIBUTION OF YOUNG SMALL SHIELD VOLCANOES ON VENUS.

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Introduction: Small (1-20 km) shield-like volcanoes are the most abundant volcanic constructs on Venus [1]. Typically, they occur in clusters known as shield fields (SF) which are tens to hundreds of kilometers across [2]. The recent studies of the stratigraphy of a large number of SFs have shown that these features appeared during a large portion of the observable geologic history of Venus [3,4] and thus they provide the means to analyze the character of changes in the same style of volcanism as a function of time. A detailed stratigraphic analysis of SFs [4] has revealed that ~80% of the population of these features either postdates emplacement of regional plains (plains with wrinkle ridges, pwr [5]) or appears to be synchronous with them; ~8% of the population postdates regional plains. The analyzed sample of SFs comprises ~22% of the total population [2] and the subpopulation of young fields (postdating regional plains) was small and specifics of their distribution and associations remained unclear to a large extent. In order to adequately describe the distribution, associations, and geological settings of the young SFs, we have analyzed the whole population of fields [2] and compiled the subpopulation of SFs postdating emplacement and deformation of regional plains.

Criteria for shield field selection: In [4] two sets of criteria to determine the relative age of SFs were established. The first set consists of features that collectively suggest an older age of a shield field: 1) Specific tectonic pattern is confined in the field; 2) Edges of the fields are outlined by a smooth and sharp boundary; 3) Individual shields off a shield field have a distinct break in slope and are outlined by a smooth, sharp, and circular boundary; 4) Radar albedo of both contiguous SFs and individual shields nearby differs from that of surrounding regional plains; 5) There is a systematic change in the number and density of shields away from SFs with abrupt drop of shield density within regional plains; 6) SFs are in close spatial association with older units (either in direct contact or in proximity); 7) SFs are local highs showing a kipuka-like relation in contrast to construction; 8) Wrinkle ridges deform SFs.

The second set includes four additional criteria, suggesting a younger age of a shield field: 1) Shields and associated flows are superposed on structural elements (fractures, wrinkle ridges) in regional plains; 2) Shields and associated flows either gradually merge with or are superposed on lava flows that post-date regional plains; 3) Shields are in close spatial association with distinct lava fields and/or volcanic constructs that appear to postdate regional plains; 4) Shields are at higher elevation than regional plains consistent with a construction relation in contrast to a kipuka-like relation.

We used these criteria to assess the age of SFs relative to regional plains and divided the whole population of SFs into three groups: a) SFs that either predate or are synchronous with regional plains (old fields), b) SFs that are superposed on both regional plains and wrinkle ridges (young fields), and c) SFs whose relationships with regional plains is either unclear or ambiguous. For a shield field to be classified as "young" it should display no features from the first set of criteria and have more than three criteria from the second set. We analyzed the stratigraphic position of each field, and classified them into the categories using the computer enhanced Magellan images of F-MAP (75 m/px) and C1-MIDR (225 m/px) resolutions. In order to characterize the regional-scale topographic and gravitational signatures of broad areas where SFs occur, we also used the digital representations of the topographic and gravity fields of Venus [6,7].

Results: *1) Abundance of the young SFs:* There are 554 (85%), 66 (10%), and 30 (5%) features of the "old", "young", and "unclear/ambiguous" categories, respectively. Thus, the young SFs make up a small portion of the total population of these features. These percentages of the SF categories almost exactly coincide with the relative abundances of the fields of different stratigraphic position established in [4].

2) Associations with larger volcanic features: The older SFs represent either outliers of a much broader unit of shield plains or concentrations of small volcanoes on the surface of this unit [4]. In contrast to this, the young fields represent distinct volcanic sources, and materials related to the fields cover areas around them. Three types of association with larger volcanic sources characterize the population of the young SFs.

In 9 cases (14% of the population of the young fields), SFs are associated with coronae and occur inside (6 fields) and outside (3 fields) of these features. SFs associated with coronae form equidimensional clusters and do not display evidence for the linear arrangements. Another important characteristic of the corona-related young SFs is that they occur almost exclusively at coronae associated with the rift zone of Parga Chasma. The majority of coronae elsewhere on Venus do not have young SFs associated with them.

In 10 cases (15%), SFs are associated with large volcanoes (> ~100 km, [2]) and occur either in the summit areas (5 fields) or on the flanks (5 fields) of these structures. As in the case of association with coronae, the fields at large volcanoes form equidimensional clusters and there is little (if any) evidence for the linear arrangement of the small volcanoes there.

Much more often, the young SFs do not display a clear association with other larger volcanic features and form individual volcanic centers within regional plains. There are 47 (71%) such fields. SFs of this type produce clusters of small constructs surrounded by an apron of lava flows that are superposed on both regional plains and wrinkle ridges.

3) Areal distribution: 57 (~88%) of young SFs occur in the hemisphere of Venus centered at 270^{o}E where they form a mega-cluster within the Beta-Atla-Themis (BAT) region. In the opposite hemisphere, there are only eight (~12%) of the young SFs. The older fields, although also tending to occur preferentially in the BAT region [4], are distributed more evenly over the surface: ~64% of the old fields are in the hemisphere dominated by BAT and ~36% of these features occur in the opposite hemisphere.

Being strongly concentrated in the BAT region, the distribution of the young SFs is also correlated with the distribution of the large chasmata and positive anomalies of the geoid. About half of the young fields occur in close spatial association with the chasmata and ~80% of all young SFs are above the geoid zero contour and the remaining 20% are near this contour line. In contrast to this, the distribution of older fields does not correlate with the distribution of chasmata and weakly correlates with the geoid anomalies.

Discussion: The style of volcanism that produced small volcanic constructs (SFs) occurred during a larger portion of the observable history of Venus [3,4]. Thus, the analysis of abundance, areal distribution, and type of associations of SFs are the key points in understanding possible changes of this style of volcanism through time.

The small volcanoes are low structures, a few hundred meters high [8,9]. To be currently exposed, they should be formed toward the latest stages of volcanic activity in areas where they occur or, alternatively, represent earlier constructs that were not covered by several hundred meters of lava subsequently. The rarity of SFs at coronae and large volcanoes, however, suggests that a small shield stage is not the typical situation in the evolution of these large volcanic sources. There is little evidence for linear arrangements of small shields either within (summit areas) or on the flanks of both large volcanoes and coronae. This suggests that the sources of the shields within the larger features were likely related to multiple intrusions of dikes rather than being fed through a single dike.

The majority of the young SFs occur within regional plains without a clear association with the larger sources. Such fields may be related to the final episodes of formation of the plains. Alternatively, they may manifest independent phases of volcanic activity that were far less powerful compared with the volcanism of regional plains and not as persistent as in the case of large volcanoes. If the young SFs represent the final stages of regional plains volcanism, the fields probably would be more widespread and evenly distributed over the surface. The young SFs, however, are strongly concentrated within the BAT region and there is a distinct paucity of these features within regional plains elsewhere on Venus. Such a character of areal distribution of the young fields favors the second alternative and suggests large-scale changes in the pattern of small shield volcanism as a function of time. The small shield volcanic activity, which was globally distributed in the period just before emplacement of regional plains, later waned and began to be concentrated in the BAT area together with the majority of other types of younger volcanism [10].

The other important result of our study of the young SFs is that their number decreased significantly after emplacement of regional plains: only ~10% of the catalogued population of fields postdate regional plains. This change in the abundance of the fields likely reflects major changes in the rate of formation of small volcanoes. Most impact craters on Venus are superposed on regional plains and the most reliable estimates of the absolute age of the surface of Venus [e.g. 11] are applicable to this unit. The crater density on the stratigraphically oldest unit, tessera, which is consistently embayed by regional plains in all cases where these units are in contact [12], is estimated to be ~40% higher than on the surface of regional plains [13]. Due to uncertainties in the age of tessera age estimates, however, duration of the time span between tessera and regional plains may vary from 0.93 to 0.01 T, where T is the mean age of regional plains [13].

The older SFs (~90% of the total population) were formed after tessera and before emplacement of regional plains within the time interval that was either as long as time since formation of regional plains or much shorter. This implies that the rate of the small shield volcanism was much higher before formation of regional plains and largely diminished since that. For the one end-member model (the tessera age is 1.93T) the rate of the small shields production was ~10 times higher before emplacement of regional plains and for another end-member (the tessera age is 0.01T) this rate is ~1000 times higher. The much higher rate of the small shield volcanism close to the beginning of the observable geologic record of Venus is consistent with the predictions of the directional model of the geologic history of Venus [e.g. 14] and contradicts to the nondirectional model [15].

Conclusions: The results of out study of the young shields on Venus can be summarized as follow. 1) SFs postdating both emplacement and deformation of regional plains comprise ~10% of the total population of SFs. 2) Majority of the young SFs (57 fields or ~71%) form individual small volcanic centers without clear association with larger volcanic features. Only 19 fields (~29%) associate either with coronae (9 fields) or with large volcanoes (10 fields). 3) Young SFs are clustered within the BAT region and largely absent in other areas on Venus. The concentration of the young fields in the region characterizing by the geoid highs and young volcanic and tectonic activity is consistent with the stratigraphy of the fields and suggests that the fields do not represent final stages of formation of regional plains but rather manifest independent volcanic activity. 4) The rate of formation of small shield volcanoes had largely diminished (by factor of 10 up to 1000) after emplacement of regional plains, which strongly contradicts the predictions and consequences of the nondirectional [15] model of the history of Venus.

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