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The history of volcanism on Venus

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ABSTRACT

Completion of a global geological map of Venus has provided documentation of the relative age relationships, spatial distribution, and topographic configuration of the major geologic units and permitted us to address several important problems concerning the volcanic history of Venus. We use these data to: 1) assess the stratigraphic position of volcanic units and landforms, 2) determine their relationship with structure and tectonics, 3) identify changes in volcanic style, flux and activity with time, and 4) determine the topographic configuration and stratigraphic position of volcanism in relation to the evolution of long-wavelength topography.

Tectonic Associations: The scale and abundance of tectonic structures helps to divide the spectrum of volcanic units into two main groups: 1) volcanic units where tectonic structures played a subordinate role and 2) tectonized units/terrains, in which tectonic structures are the primary features relative to volcanism.

Sequence of Volcanism: Volcanic units embay the majority of the tectonized terrains and a sharp transition from heavily deformed units to mildly tectonized volcanic plains indicates that a tectonically driven regime dominated the earlier stages of the geologic history of Venus. This was followed by a regime of predominantly volcanic activity during the middle stages of observed geologic history. The latter stage is characterized by a volcano-tectonic resurfacing regime.

Volcanic Units: Regional plains are the most widespread volcanic unit and are likely to have an average thickness of the order of 400-500 m. Buried and partly buried 'ghost' craters, seen commonly on Mars and Mercury, are very rare, strongly suggesting that the previous cratering record was erased prior to formation of regional plains. The vast plains show a very small number of obviously flooded craters, which strongly suggests massive volcanic flooding over large provinces. In contrast to regional plains, the stratigraphically younger and much less widespread lobate plains embay ~50% of craters interacting with them. This suggests that emplacement of lobate plains was more in equilibrium with the growing population of impact craters.

Relations with topography: There are two major groups of topographic highs on Venus: 1) plateau-like, tessera-bearing regions, and 2) dome-shaped and rifted rises. Tessera is the oldest stratigraphic unit and its association with the plateau-like highlands suggests that they formed near the beginning of the observable history during the tectonically dominated regime. Regional plains preferentially occur within the lowland regions. The correlation of the older tectonized units and the vast volcanic plains with this regional topographic pattern suggests that the major features of the long-wavelength topography of Venus (the plateau-like highs and the lowlands) formed prior to emplacement of regional plains. Lobate plains and rift zones postdate formation of regional plains and are closely associated with the dome-shaped rises. The characteristic features of lobate plains and rift zones match the gravity and topography signatures of the rises and suggest that they were active during the latest episodes of the history of Venus. The alignment of wrinkle ridges and the topographic configuration of the upper sub-unit of regional plains and lobate plains suggest that the beginning of formation of the rises somewhat overlapped the late stages of formation of regional plains.

Volcanic Styles: The main volcanic plains have different morphologies that indicate different volcanic styles. Small and abundant volcanic constructs of the older shield plains imply that their sources were pervasive and nearly globally distributed, but that the supply of magma at individual sources was limited. The steep-sided domes are spatially and stratigraphically associated with the shield plains. The small size of the constructs of shield plains and their association with the steep-sided domes are most consistent with shallow crustal melting and differentiation of magma in reservoirs and/or partial melting of the

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crustal materials. Regional plains that postdate shield plains are very abundant (~1/3 of the surface of Venus) and ubiquitous but their sources are not visible at the available resolution. These features strongly suggest that regional plains formed by voluminous volcanic eruptions from near globally distributed sources. This style of volcanic activity resembles that of terrestrial flood volcanism, but its scale is more easily reconciled with the decompression melting of a fertile mantle layer that underplated the crust. The style of volcanism of the younger lobate plains was distinctly different from those of shield plains and regional plains. The numerous flows of lobate plains suggest multiple episodes of volcanic activity. The areal distribution of lobate plains implies that their sources were discrete, that they formed in different areas at different times, and that some of them may represent feeders of radiating dike swarms. Several lines of evidence suggest that lobate plains formed during a prolonged time span from just after the emplacement of regional plains until geologically recent times.

Volumes and Fluxes: Estimates of the volume of the main volcanic units on Venus show that both shield plains and regional plains are the major contributors to the volcanic resurfacing on Venus. The total volume of volcanic materials erupted during the volcanically dominant regime is estimated to be from about 140 to 200x106 km3. In sharp contrast to this, the total estimated volume of lobate plains is much smaller, ~20-30 x106 km3, corresponding to a volcanic flux that is about an order of magnitude smaller that the average intraplate volcanic flux on Earth.

1. Introduction

Major interior processes, such as magmatism, are directly related to the loss of internal heat of the planets, which determines their thermal evolution and governs their geological histories to a large extent (Solomon and Head, 1982). Thus, unraveling of the history of volcanic activity is one of the keys for understanding the evolution of planetary bodies. Several specific first-order features of Venus indicate that this planet has great importance in contribution to our understanding of planetary volcanism.

1) Venus is almost as large as Earth and has both gravitational and compositional potentials for a long-lasting volcanism, in contrast to the smaller terrestrial planets (e.g., Moon, and Mars), where conduction dominates, lithospheres thicken relatively quickly, and volcanic activity is sparse in the last third of solar system history (e.g., Tanaka, 1986; Wilhelms, 1987). Comparison of the spatial and temporal patterns of volcanism on Venus and Earth can put important constraints on the geological evolution of the larger terrestrial planets, particularly in relation to early history.
2) Extrusive volcanic materials make up about 80% of the surface of Venus. Thus, unraveling the history of volcanism is crucially important for the understanding of geological evolution of Venus. There is a rich variety of volcanic landforms on Venus ranging from small (several kilometers in diameter) volcanic constructs to morphologically homogenous volcanic plains units thousands of kilometers in extent (e.g., Head et al., 1992; Crumpler and Aubele, 2000). Establishing typical associations and the stratigraphic position of these landforms are necessary steps toward the solution of the problem of the geodynamic evolution of Venus.
3) Atmospheric conditions on Venus (Moroz, 1983; Self, 1983; Avduevsky et al., 1983) preclude the existence of liquid water near the surface and suppress wind activity. Both these factors strongly inhibit erosional/depositional processes (Arvidson et al., 1990, 1992). This feature of Venus is of an extreme importance because it narrows the spectrum of possible mechanisms that shape the morphology and topography of the surface and, in fact, it leaves room almost exclusively for the preservation and analysis of volcanic, tectonic, and impact processes.
4) The number of impact craters on the surface of Venus is small (Herrick et al., 1997; Schaber et al., 1998) and impact structures commonly do not obscure landforms of either volcanic or tectonic origin.
5) The very high atmospheric pressure on Venus inhibits gas exsolution, magma disruption, and pyroclastic volcanism (Head and Wilson, 1992), thus further preserving the record of extrusive volcanic activity.

Unraveling of the history of internal processes requires an understanding of the sequence of major events through the observable portion of the geological record. The small number of craters on Venus largely prevents the use of standard techniques for estimating unit absolute model ages and relative ages by crater counting (Neukum and Wise, 1976; Neukum et al., 2001). Thus, the assessment of relative ages of morphologically homogenous (at the scale of mapping) units based on stratigraphic embayment and crosscutting relationships plays a major role in the reconstruction of the sequence of events.

The stratigraphic approach was successfully applied for many individual areas of Venus (the USGS quadrangles of the program of the geological mapping of Venus) (e.g., Chapman, 1999; Bridges and McGill, 2002; Ivanov and Head, 2010). However, the isolated nature of the quadrangles and different mapping philosophies of the geologists who mapped specific regions resulted in a number of maps that often poorly match each other. Detailed analysis of the published geological maps (Ivanov and Head, 2011) shows two important features: (1) the majority of units mapped in different regions by different authors appear to be similar morphologically and hold the same stratigraphic position and (2) the general stratigraphic sequence documented in the published maps appears to be the same (Basilevsky and Head, 2000a). The sequence starts with tessera (Ivanov and Head, 1996; Guest and Stofan, 1999) and other tectonized units at the bottom of regional stratigraphic columns, followed by vast volcanic plains at the middle levels (Ivanov and Head, 2011), and more recently by a variety of volcanic flows at the top of the columns (e.g., McGill, 2000).

The recently compiled global geological map of Venus (Ivanov and Head, 2011) portrays the spatial distribution of specific volcanic and tectonic units. The global-scale correlation chart that summarizes the stratigraphic observations documented throughout entire surface of Venus accompanies this map (Fig. 1). This chart shows the same general stratigraphic relationships of units that have been established in many individual quadrangles (see the review and comparison in Ivanov and Head, 2011). In contrast to the mosaic of the quadrangles, however, the global map presents a coherent picture of units/structures and their stratigraphic relationships that characterize the entire planet. Thus, the

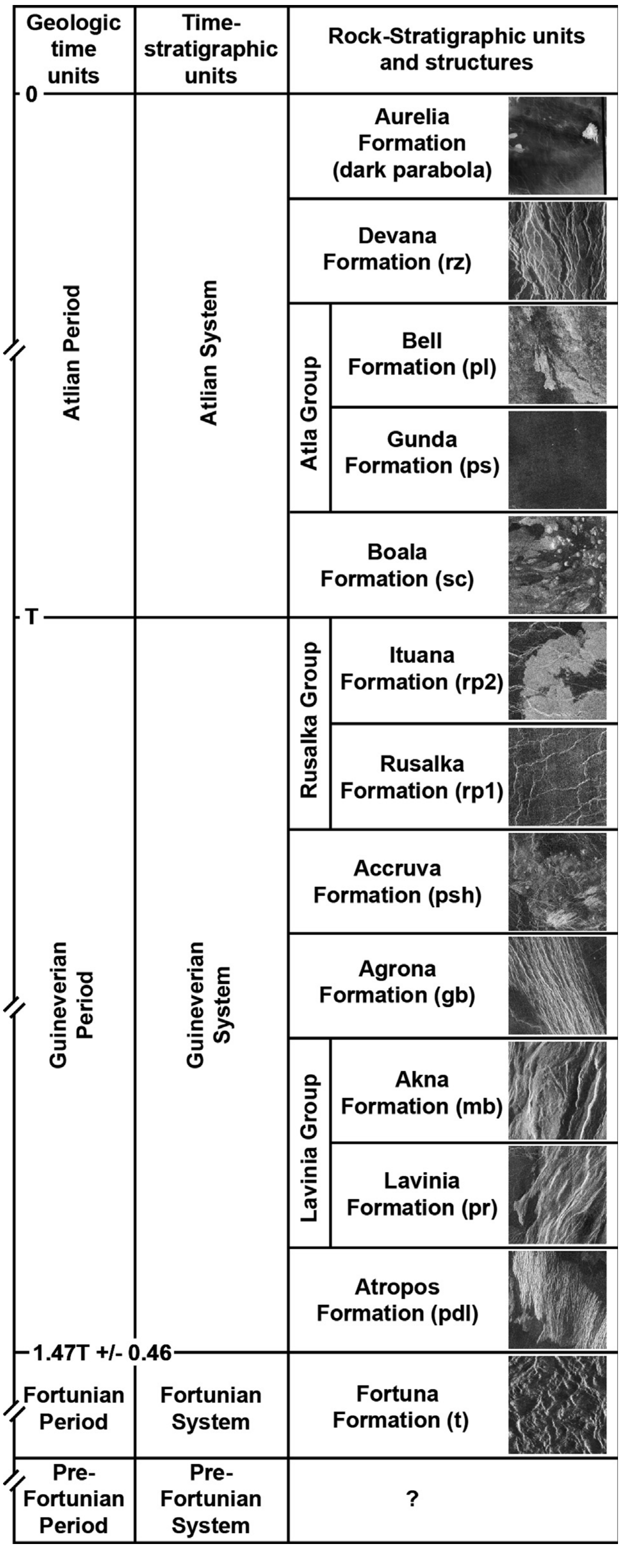

Fig. 1. The global stratigraphy of Venus based on the analysis of the relative age relationships among the units shown on the global geological map of Venus (reproduced from Ivanov and Head (2011)).

map provides a firm geological basis that allows assessment of the spatial and temporal distributions of landforms of different origin.

Among related problems (for example, the role of mantle plumes, factors that control access of magma (Phillips and Hansen, 1994), the composition of volcanic units, etc.), the understanding of the history of volcanism on Venus includes several important questions that are closely related to morphology, associations, and stratigraphy of volcanic features:

1) What is the variety of volcanic landforms on Venus, what is their petrogenetic significance, how do they contrast to the tectonized units/terrains, and what is their stratigraphic position?
2) What constraints do the relationships between the volcanic and tectonic units/terrains put on the nature of the observable part of the geologic history of Venus?
3) What style of volcanic activity do the volcanic landforms suggest and/or indicate? What does the stratigraphic position of volcanic landforms and their styles tell us about the evolutionary changes in volcanic styles and their relationship to the geodynamic evolution of the planet?
4) What constraints do the topographic configuration and stratigraphic position of the volcanic landforms introduce into the history of the long-wavelength topography?

The keys to these issues are the temporal, spatial, and topographic distribution of volcanic landforms that are summarized in the global geological map and correlation chart. In this paper we thus use the map as the basis to address the above problems and reconstruct the observable portion of the volcanologic history of Venus. We first describe the sequence of volcanic units, assess the nature of specific landforms that make them up, examine the age relationships, document the link to tectonic structures and features, and then examine their relationships to current and ancient topography. We conclude with a synthesis of the volcanic history of Venus, list insights that this provides and identify major outstanding questions.

2. Volcanic landforms on Venus and their typical associations

The specific morphology, dimensions of the occurrences, and relative importance of volcanic and tectonic processes permit the subdivision of the wide spectrum of landforms of Venus (Head et al., 1992; Crumpler and Aubele, 2000) into four broad categories: (1) vast and/or globally distributed volcanic units (plains), (2) local to regional volcanic features, (3) features that have both the volcanic and tectonic components (volcano-tectonic features), and (4) tectonized units/terrains, in which tectonic structures dominate the morphology. Several types of plains are globally important and the volcanic and volcano-tectonic features are often associated with these plains.

2.1. Volcanic plains

Volcanic plains are the most abundant volcanic features on Venus and occur throughout the global stratigraphic column of the planet (Fig. 1). The abundance of the secondary tectonic structures on the surface of the plains and the degree of their deformation define the following types of volcanic plains (Fig. 2).

2.1.1. Heavily tectonized plains (Fig. 2a and b)

Two units on Venus with the general aspects of volcanic plains have been so strongly deformed that tectonic structures clearly dominate and define the final morphology of the units.

Densely lineated plains (pdl, Atropos Formation, Fig. 2a; type localities are at: 67.2°N, 309.0°E; 43.8°N, 298.9°E): numerous densely packed, narrow (from a few hundred meters wide and down to the resolution limit), short (a few tens of kilometers long), and parallel (subparallel) to each other lineaments heavily dissect the surface of this unit (Fig. 2a). If the lineaments are wide enough they usually appear as fractures. As a rule, the lineaments of pdl are packed so densely that they completely erase the morphology of the precursor materials. In some occurrences of the plains,

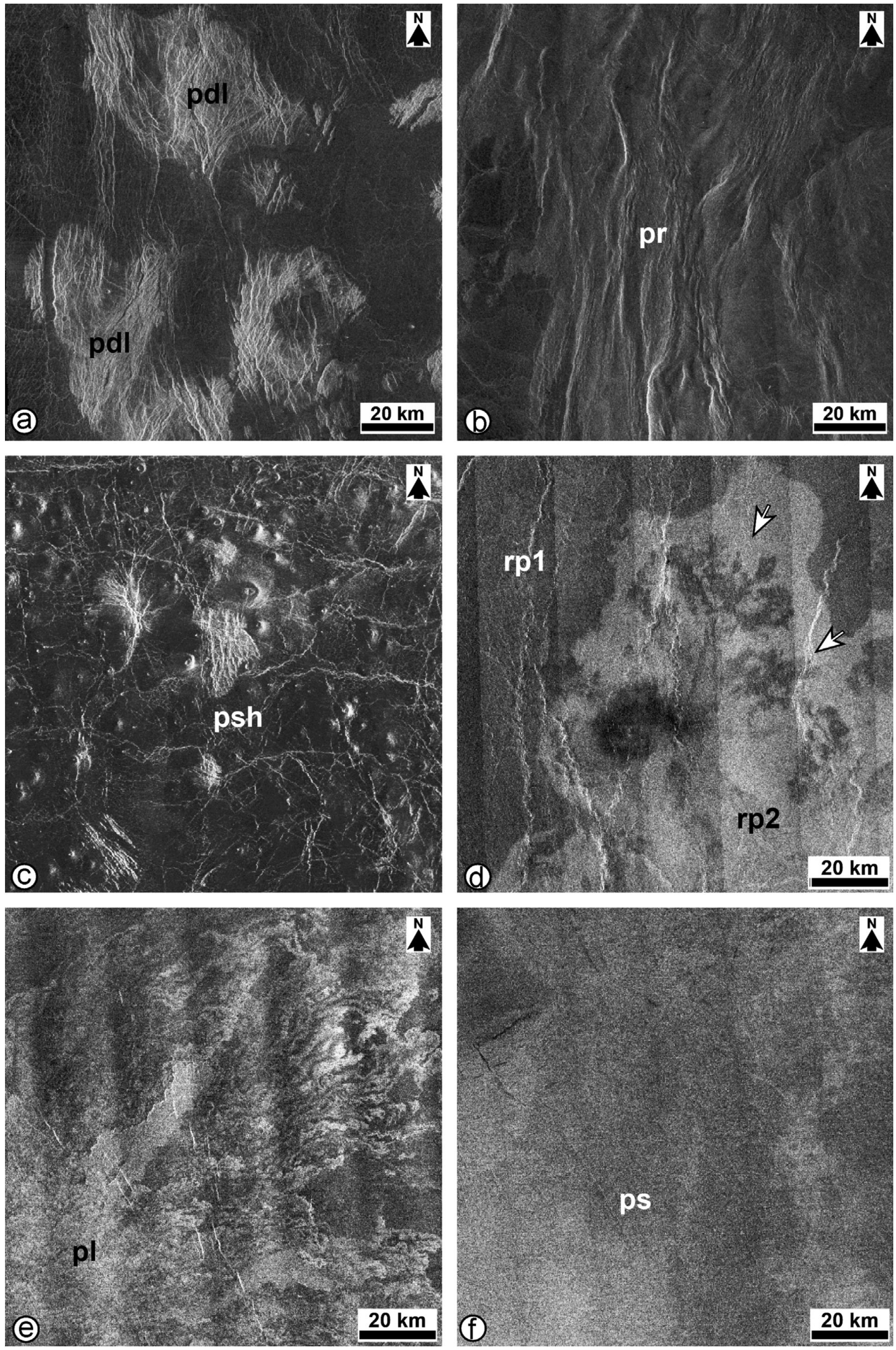

Fig. 2. (a–d) Examples of volcanic plains of Venus. (a) Densely packed and narrow fractures dissect the surface of densely lineated plains (pdl). Part of C1-MIDR 45N032, center of the image is at 42.5°N, 33.2°E. (b) The surface of ridged plains (pr) is deformed by broad curvilinear ridges that are absent in the surrounding units. Part of C1-MIDR 30N153, center of the image is at 35.4°N, 157.3°E. (c) Numerous small shield- and cone-like mounds interpreted as volcanic constructs populate the surface of shield plains (psh). Part of C1-MIDR 45N117, center of the image is at 38.7°N, 117.3°E. (d) Two sub-units of regional plains (rp_1 and rp_2) typically have different radar albedo that helps to distinguish these types of plains. The brightness of the lower sub-unit (rp_1) is moderate and uniform and the surface of the upper sub-unit (rp_2) is brighter and, in places, flow-like features (arrows) are seen on the surface of the unit. Part of C1-MIDR 15N180, center of the image is at 13.1°N, 171.8°E. (e and f) Examples of the weakly and non-deformed volcanic plains of Venus. (e) Numerous brighter and darker lava flows constitute lobate plains (pl). Part of C1-MIDR 15N266, center of the image is at 10.7°N, 263.9°E. (f) The surface of smooth plains (ps) appears homogeneous and has low- to moderate radar brightness. Part of C1-MIDR 00N300, center of the image is at 3.5°N, 308.1°E.

however, remnants of preexisting material (lava plains) are visible between the lineaments. Furthermore, their relatively flat and regionally smooth surfaces suggest a volcanic plains origin.

Small occurrences of densely lineated plains are often seen near each other and form broad clusters of outcrops. Neither the outcrops nor the pattern of lineaments in them indicate their possible relation to the visible or semi-buried radiating swarms of graben. This suggests that pdl mostly represent the results of pure tectonic deformation and agrees with the observations made by Ernst et al. (2003) who separated densely fractured plains (equivalent to our pdl) from the graben likely related to dikes.

Densely lineated plains occupy a small area of the global map, about 7.2×10^6 km^2 (1.6% of the mapped surface of Venus, Table 1) and are observed as slightly elevated and usually small (tens of kilometers across) patches. Occurrences of densely lineated plains do not form distinctive clusters and their arcuate patches are often associated with the rims of coronae and corona-like features.

Ridged plains (pr, Lavinia Formation, Fig. 2b; type localities are at: 64.8°N, 190.2°E; 39.3°N, 157.3°E): materials of ridged plains have the morphology of lava plains that are deformed by broad (5–10 km wide) and long (several tens of kilometers) linear and curvilinear ridges (Fig. 2b). Very often the ridges are collected into prominent belts, ridge belts (Barsukov et al., 1986; Frank and Head, 1990; Kruychkov, 1992; Squyres et al., 1992). Materials of ridged plains are interpreted to be volcanic plains deformed by contractional tectonic structures. Ridged plains and ridge belts occupy about 9.6×10^6 km^2 (2.1% of the mapped surface of Venus, Table 1) and usually form elongated occurrences hundreds to a few thousands of kilometers long and many tens (to a few hundred) kilometers wide.

Table 1
Areas of the main volcanic and tectonized units on Venus.

Unit	Area, 10^6 km^2	Percent of Venus surface
Volcanic units		
psh	84.5	18.5
rp$_1$	150.7	33.0
rp$_2$	44.8	9.8
pl	40.3	8.8
ps	10.3	2.3
Total	330.6	72.4
Tectonized units predating psh (exposed area)		
t	35.4	7.8
pdl	7.2	1.6
pr	9.6	2.1
gb	39.5	8.7
Total	92.8	20.4
Tectonized units synchronous to pl (true area)		
rz	24.5	5.4

2.1.2. Mildly tectonized plains (Fig. 2c and d)

These units, although they have been tectonically modified, still show the original morphology that indicates their volcanic nature.

Shield plains (psh, Accruva Formation, Fig. 2c; type localities are at: 29.4°N, 131.0°E; 11.9°S, 335.8°E): the characteristic features of shield plains are numerous small (from a few kilometers up to 10 km across) shield-like and cone-like mounds that are interpreted as volcanic edifices (Aubele and Slyuta, 1990; Head et al., 1992; Guest et al., 1992) (Fig. 2c). In many cases the volcanoes occur close to each other and form clusters listed in the catalog of the volcanic landforms of Venus (Crumpler and Aubele, 2000). The surface of both the shields, and plains between them, is morphologically smooth and sometimes is deformed by wrinkle ridges and fractures/graben. These structures, however, do not significantly modify the original morphology of shield plains.

The overall relief of the unit appears to be hilly due to the abundant shield features, and occurrences of shield plains tend to be slightly higher than the surrounding regional plains. Shield plains cover a significant portion of the surface of Venus, about 84.5×10^6 km^2 or 18.5% of the mapped area (Table 1) and typically occur as more or less equidimensional outliers several tens to hundreds of kilometers across (Fig. 3).

In general, the areal distribution of shield plains is broad and homogenous, but there are several large areas where the occurrences of the plains are less abundant or absent (Fig. 3). These regions correspond to the largest tesserae in Ishtar and Aphrodite Terrae (e.g., Fortuna, Ovda, Thetis Regions), Lakshmi Planum, the largest chasmata (e.g., Parga Chasma and canyons in Eastern Aphrodite), and some wide lowlands covered by regional plains (e.g., Sedna, Atalanta, Hellen Planitiae). The absence of the plains within the large tessera and in Lakshmi Planum is consistent with the presence of thickened crust in these regions (Grimm, 1994) that may have served as a rheological or crustal thickness barriers inhibiting formation of the plains (Ivanov and Head, 2008). Chasmata represent major zones of young extensional structures that may have destroyed occurrences of shield plains. The scarcity of occurrences of shield plains within the lowlands suggests that younger volcanic units may have buried shield plains in these regions, as concluded by numerous workers (see summary in Ivanov and Head (2004a, 2011)). In all seven landing sites (Table 2) where the chemical analyses of the surface material were taken either by landers of Venera or Vega series (Surkov, 1997), the composition of the rocks is consistent with varieties of terrestrial basalts (e.g., Nikolaeva and Ariskin, 1999). Analysis of the geology of the Venera-8 landing site has shown that the lander likely sampled the surface of shield plains (Abdrakhimov, 2001a).

Regional plains (rp): regional plains represent the most widespread material unit on Venus that occupies ~195.5×10^6 km^2 or 42.8% of the mapped surface of Venus (Table 1). Regional plains are composed of morphologically smooth, homogeneous plains materials of intermediate-dark to intermediate-bright radar backscatter. Narrow wrinkle ridges, which are clearly seen within extensive areas of regional plains, form pervasive intersecting networks that cut the surface of the plains (Bilotti and Suppe, 1999). Regional plains are defined by the characteristic morphology of their materials and, thus, belong to the class of true material units. A very important characteristic of regional plains is that volcanic edifices and sources of the plains are commonly not obvious at the resolution of Magellan data. The Venera 9, 10, and 13 and Vega 1 and 2 landers were probably landed on the surface of regional plains (Abdrakhimov, 2001b–f).

Regional plains are subdivided into two sub-units on the basis of the typical characteristics of their radar backscatter. The lower sub-unit of regional plains (rp$_1$, Rusalka Formation, Fig. 2d; type localities are at: 45.1°N, 143.6°E; 42.9°S, 162.3°E) has a morphologically smooth surface with a homogeneous and relatively low radar backscatter that can appear locally mottled. The lower sub-unit of regional plains is the most abundant and ubiquitous unit on Venus (about 150.7×10^6 km^2 or 33.0% of the mapped area, Table 1). Its extensive fields connect remote regions (Fig. 3) and they can be traced almost continuously around the globe. The lower sub-unit of regional plains preferentially makes up the floor of the lowlands surrounding the major tessera-bearing uplands and occurs between elevated regions composed of the heavily tectonized units and shield plains (Fig. 3).

The lower sub-unit of regional plains was mapped in all published geological maps of Venus (see review in Ivanov and Head (2011)). The areal abundance, similar morphologic characteristics almost everywhere, and its stable position in the local to regional stratigraphic columns, all together give the lower sub-unit of regional plains a position of extreme importance as a global-scale reference unit.

The upper sub-unit of regional plains (rp$_2$, Ituana Formation, Fig. 2d; type locations are at: 49.1°N, 161.3°E; 36.3°S, 163.4°E) is characterized by a morphologically smooth surface that is moderately deformed by numerous wrinkle ridges. The ridges appear to belong to the same family of structures that deform the lower member of the plains (Fig. 2d). The key difference between the upper and the lower sub-units of regional plains is radar albedo variation. In contrast to the uniform and relatively low albedo of rp_1, the upper sub-unit of the plains has noticeably higher albedo (Fig. 2d). Less frequently, this unit displays non-uniform radar albedo that consists of brighter and darker flow-like features. The upper sub-unit of regional plains covers about 44.8×10^6 km^2 or 9.8% of the mapped surface of Venus (Table 1) and occurs usually as equidimensional or slightly elongated patches of flow-like shape from tens of kilometers to several hundred kilometers across (Fig. 3). Boundaries between the two members of the regional plains vary from sharp to diffuse. Fields of the upper sub-unit of regional plains do not occur within the large tessera regions and tend to avoid large lowland regions, the surface of which is made up by the lower sub-unit of regional plains (Fig. 3). Occurrences of rp_2 surround some of large volcanic centers such as coronae and large volcanoes and form distal aprons of volcanic materials around them.

2.1.3. *Weakly or non-tectonized plains (Fig. 2e and f)*

Tectonic deformation (both contractional and extensional and that can be shown at the scale of the mapping) of these volcanic plains is either occasional or absent. This type of plains includes two units.

Lobate plains (pl, Bell Formation, Fig. 2e; type localities are at: 25.5°N, 48.0°E; 36.4°S, 88.6°E): occurrences of lobate plains usually have morphologically smooth surfaces that are occasionally disturbed by a few extensional features (fractures, graben). The most characteristic feature of lobate plains is their non-uniform albedo pattern consisting of numerous bright and dark flow-like features. The flows can be as long as several hundred kilometers and tens of kilometers wide. Lobate plains make up a significant portion of the surface of Venus, about 40.3×10^6 km^2 or 8.8% of the map area (Table 1) and their occurrences form distinct equidimensional fields from tens of kilometers up to many hundreds of kilometers across (Fig. 3). The presence of lobate plains is often a characteristic feature of many large volcanic centers on Venus. The plains are usually associated with the large dome-shaped rises (e.g., Beta, Eistla, Atla Regiones, and Lada Terra, Fig. 3). Large, high-standing, and plateau-shaped tessera regions (e.g., Fortuna, Ovda, etc.) lack significant occurrences of lobate plains. Within the BAT (Beta-Atla-Themis) region, especially along Parga Chasma, lobate plains are spatially associated with rift zones. The Venera-14 lander has probably landed on the surface of one of the occurrences of lobate plains (Abdrakhimov, 2001g).

Smooth plains (ps, Gunda Formation, Fig. 2f, type localities are at: 73.6°N, 171.4°E; 12.3°S, 268.0°E): the material unit of smooth plains has a morphologically smooth, tectonically undisturbed, and featureless surface. Areas of smooth plains are usually characterized by a low radar backscatter cross-section and appear dark. Smooth plains make up a small portion of the surface, about 10.3×10^6 km^2 or 2.3% of the mapped area (Table 1).

There are three types of geological settings of smooth plains. (1) Near and within volcanic regions (e.g., Bell Regio) where the plains are closely associated with fields of lobate plains. (2) Dark plains in spatial association with impact craters that may represent remnants of dark parabolas formed due to impact events (Campbell et al., 1992; Izenberg et al., 1994). (3) Patches of smooth plains within some large tessera regions (e.g., Ovda Regio) that are likely to have a volcanic origin.

2.2. *Volcanic features*

The category of the local to regional volcanic features includes large and intermediate shield volcanoes, large flow fields, steep-sided and fluted/modified domes, festoon-like features, and narrow sinuous channels (Crumpler and Aubele, 2000; Magee and Head, 2001). The shield volcanoes (Fig. 4) represent noticeable topographic highs with a radiating pattern of flows that belong to either the upper sub-unit of regional flows (rp_2, 73 volcanoes or

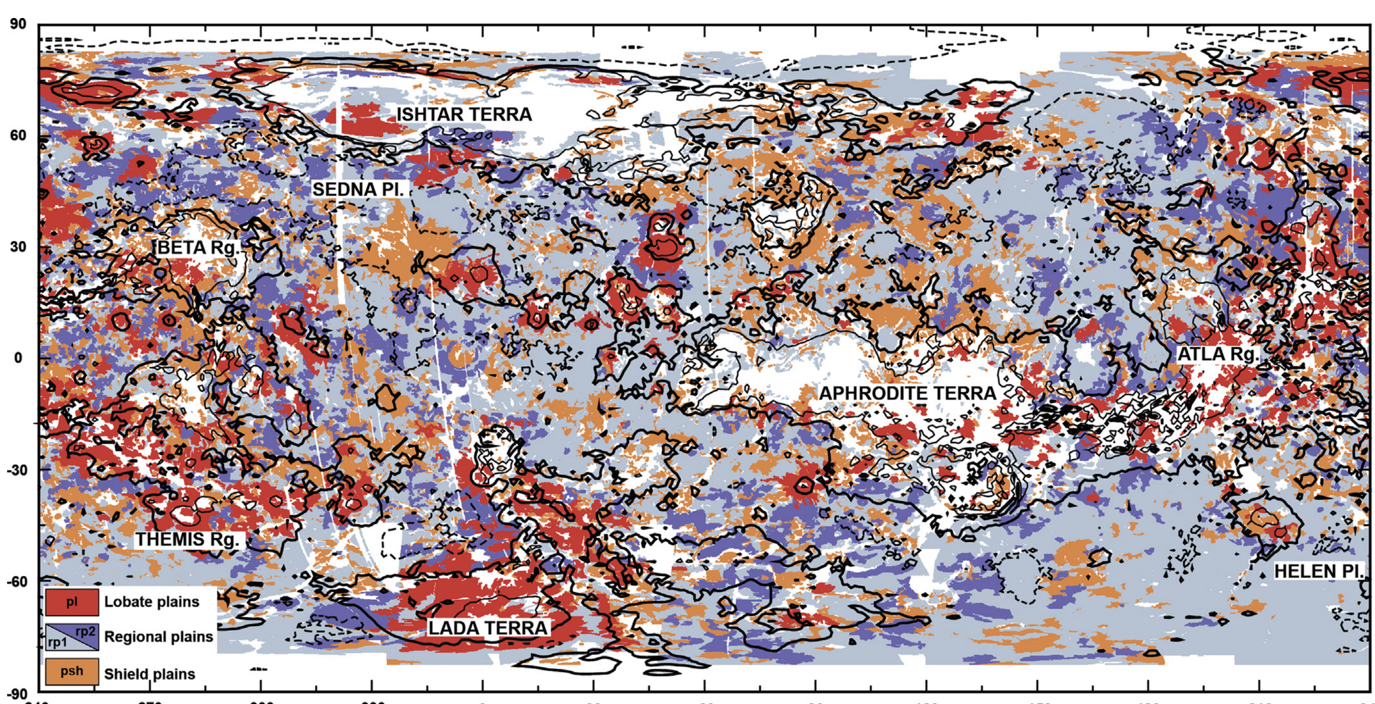

Fig. 3. The spatial distribution of the most abundant volcanic plains on Venus that cover about 70% of the surface of the planet. White spots (except for obvious data gaps) correspond to the major occurrences of the heavily tectonized units. Thick black line represents the 0 km contour line, the thinner lines indicate elevation −1 km (dashed line) and +1 km (solid line). The map is in simple cylindrical projection.

Table 2
Summary of data on chemical composition of materials on the surface of Venus.

Lander	Unit	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	K_2O	S	Cl	K	Th	U
V-8	psh											4.0 ± 1.2	6.5 ± 0.2	2.2 ± 0.7
V-9	rp_1											0.5 ± 0.1	3.7 ± 0.4	0.6 ± 0.2
V-10	rp_1											0.3 ± 0.2	0.7 ± 0.3	0.5 ± 0.3
V-13	rp_1	45.1 ± 3.0	1.59 ± 0.45	15.8 ± 3.0	9.3 ± 2.2	0.2 ± 0.1	11.4 ± 6.2	7.1 ± 0.96	4.0 ± 0.63	0.65 ± 0.4	< 0.3			
V-14	pl	48.7 ± 3.6	1.25 ± 0.41	17.9 ± 2.6	8.8 ± 1.8	0.16 ± 0.08	8.1 ± 3.3	10.3 ± 1.2	0.2 ± 0.07	0.35 ± 0.31	< 0.4			
Vg-1	rp_1											0.45 ± 0.22	1.5 ± 1.2	0.64 ± 0.47
Vg-2	rp_2	45.6 ± 3.2	0.2 ± 0.1	16.0 ± 1.8	7.74									
± 1.1	0.14 ± 0.12	11.5 ± 3.7	7.5 ± 0.7	0.1 ± 0.08	1.9 ± 0.6	< 0.3	0.40 ± 0.20	2.0 ± 1.0	0.68 ± 0.38					

Note: all major elements are in wt%, Th and U are in ppm; V—landers of the Venera series, Vg—landers of the Vega series.

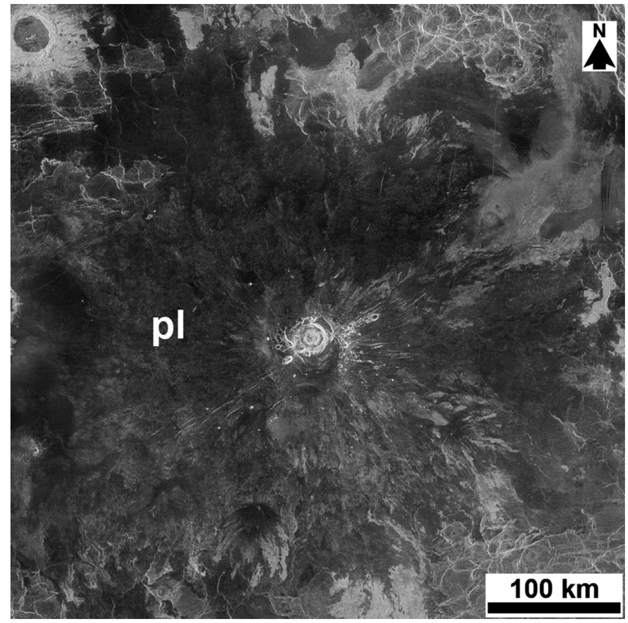

Fig. 4. An example of a large shield volcano on Venus. The summit of the volcano (center of the image) shows the presence of a relatively small caldera-like feature, from which numerous flows of lobate plains extend radially. Diameter of the volcano is about 400 km and its height is about 2 km. Thus, the average slope on the flanks of the volcano is about 0.6°. Part of C1-MIDR 15N026, center of the image is at 9.3°N, 29.3°E.

~34% of their population), or lobate plains (pl, 115 volcanoes, ~53%), or both (28 volcanoes, ~13%).

Dimensions of the shield volcanoes vary over a wide range, from ~20 to ~1000 km and the volcanoes associating with different types of volcanic plains have different size-frequency distributions. Shield volcanoes that occur as a part of the lower sub-unit of regional plains have a broad and indistinct peak between ~50 and ~250 km (Fig. 5). In contrast, the volcanoes that are associated with lobate plains show a very prominent peak in the distribution between ~300 and 600 km (Fig. 5). The number of shield volcanoes that show both rp_2 and pl units slightly increases toward the larger features (Fig. 5).

Steep-sided domes (Fig. 6) are rounded pancake-like features many hundreds meters high and tens of kilometers in diameter. The most common range of diameters is 10–30 km (Fig. 7). The prominent frontal scarp of the domes (Fig. 6) suggests that that their materials upon eruption were more viscous than basalts (Pavri et al., 1992; Fink et al., 1993; Ivanov and Head, 1999; Plaut et al., 2004). About 320 steep-sided domes were mapped during compilation of the global map; most of them are spatially associated with occurrences of shield plains (Fig. 8) and they tend to avoid the large expanses of regional plains. Detailed analysis of the stratigraphic position of the domes in the geotraverse along 30°N has shown that the materials of regional plains embay domes (Ivanov and Head, 1999). Thus, the domes are associated with shield plains not only spatially, but also stratigraphically.

There are three large (up to a few hundred kilometers across) volcanic flows on Venus that are characterized by pronounced frontal scarps and resemble in this respect the steep-sided domes. In contrast to the domes, festoons have a highly irregular planimetric shape and were formed by a series of eruptions of lavas that apparently were more viscous than basalt (Head et al., 1992; Moore et al., 1992; McColley and Head, 2004). Two of the festoons are within the lower-lying territories: one of the flows is associated with the fan of ridge belts and the other, Mahuea Tholus, occurs in Zhibek Planitia south of Eastern Aphrodite. In both cases, the festoons superpose regional plains and embay wrinkle ridges

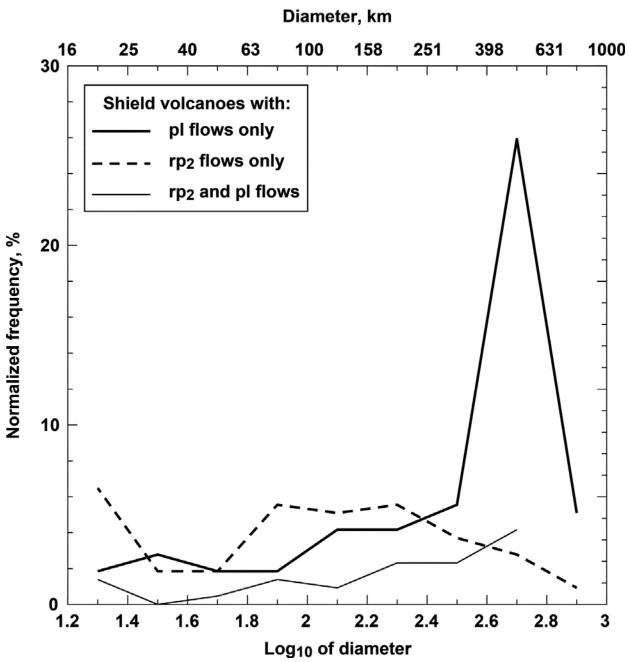

Fig. 5. The size-frequency distribution of the shield volcanoes that are associated with different types of volcanic plains. Diameters of the volcanoes vary over a broad range. Those volcanoes covered by lobate plains are predominantly concentrated within a relatively narrow interval of diameters (about 300–600 km). The list and dimensions of the volcanoes are from Crumpler and Aubele (2000).

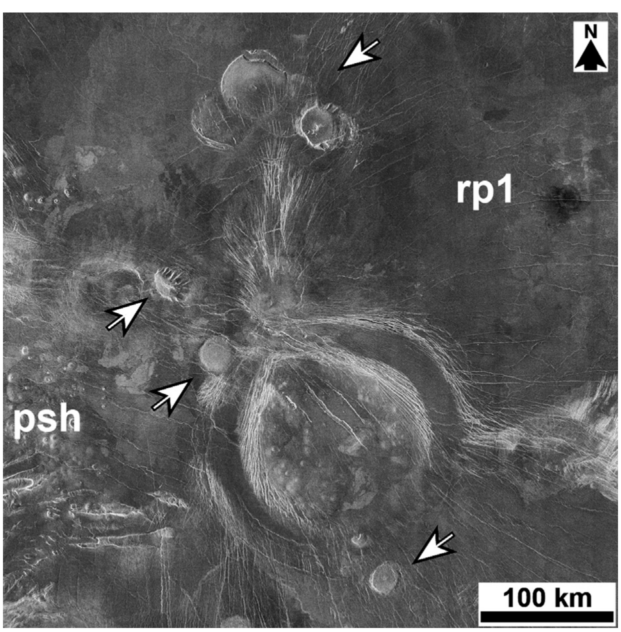

Fig. 6. Steep-sided domes (arrows). The image illustrates the prominent tendency of the domes to form clusters and groups of features. The group of domes shown is spatially associated with a corona and a branch of a groove belt extending northward of the corona. Edges of some of the domes are collapsed/fluted and embayed by regional plains. Part of C1-MIDR 30N315, center of the image is at 32.1°N, 312.3°E.

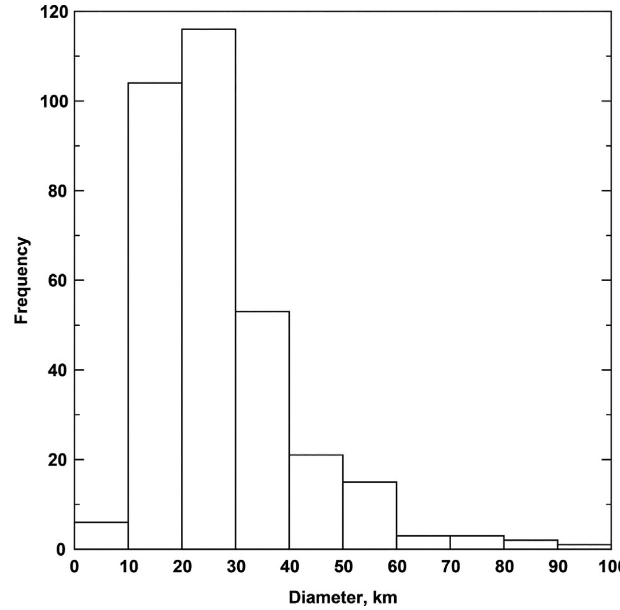

Fig. 7. The size-frequency distribution of the steep-sided domes. About 70% of these features have diameters between 10 and 30 km. The list of the domes and their diameters are taken from the global geological map (Ivanov and Head, 2011).

and, thus, stratigraphically correlate with the lobate plains. The third festoon, Ovda Fluctus, is within Ovda Regio where its material overlies the surface of tessera. The lack of contacts of the Ovda festoon with the other latter units prevents more specific assessment of its stratigraphic position.

The festoons as well as the steep-sided domes display features that suggest the higher viscosity of erupted materials, in a manner similar to the steep-sided Gruithuisen domes on the Moon (Wilson and Head, 2003). The festoons, however, occur at significantly different topographic levels (the lowest, Mahuea Tholus, is at ~0.2 km and the highest, Ovda Fluctus, is at ~3.5 km). The topographic positions of the festoons suggest that the ambient atmospheric pressure did not play a major role in the changing of the effective viscosity of the flows (e.g., the higher pressure may prevent dissolving of volatiles and lead to formation of highly vesicular and, hence, more viscous lavas (Head and Wilson, 1986). Thus, the shape of the festoons is more consistent with higher silica content of lavas that usually increases their viscosity. The Ovda festoon is, in fact, near the highest area of Ovda Regio where the tessera plateau should be the thickest (e.g., Grimm, 1994) and possess the deepest roots that may be partly eclogitized (e.g. Herzog et al., 1995). Remelting of such a material may cause formation of silica-enriched magmas and be responsible for the eruption of more viscous lavas (Hess and Head, 1990, 1996). Formation of viscous flows within the lower-lying terrains may be due to fractional differentiation in magma reservoirs and eruption of more evolved lavas. This mechanism appears to be more consistent with the formation of the steep-sided domes (e.g., Ivanov and Head, 1999; Head et al., 2009).

Long, narrow, and sinuous channels (Fig. 9) represent another type of feature that are likely to have a volcanic origin. The channels are mostly associated with either the lower sub-unit of regional plains (rp_1) or with lobate plains. When channels occur in association with both subunits of regional plains (rp_1 and rp_2), there is evidence for embayment of the channels by material of unit rp_2 (Fig. 9a, see also Basilevsky and Head (1996)). A variety of hypotheses have been proposed to explain formation of the channels (Baker et al., 1992, 1997; Kargel et al., 1994; William-Jones et al., 1998; Lang and Hansen, 2006), including an exotic hypothesis attributing them to a fluvial origin (Jones and Pickering, 2003). The length-frequency distribution of the channels listed in the catalog of volcanic features of Venus (Crumpler and Aubele, 2000) displays two modes (Fig. 10) corresponding to shorter ($<$ ~150 km) and longer ($>$ ~150 km) channels. In comparison, the length distribution of lunar sinuous rilles is predominantly $<$ ~150 km (Hurwitz et al., in press). The longer features on Venus usually occur within the extensive areas of unit rp_1 (Fig. 9a),

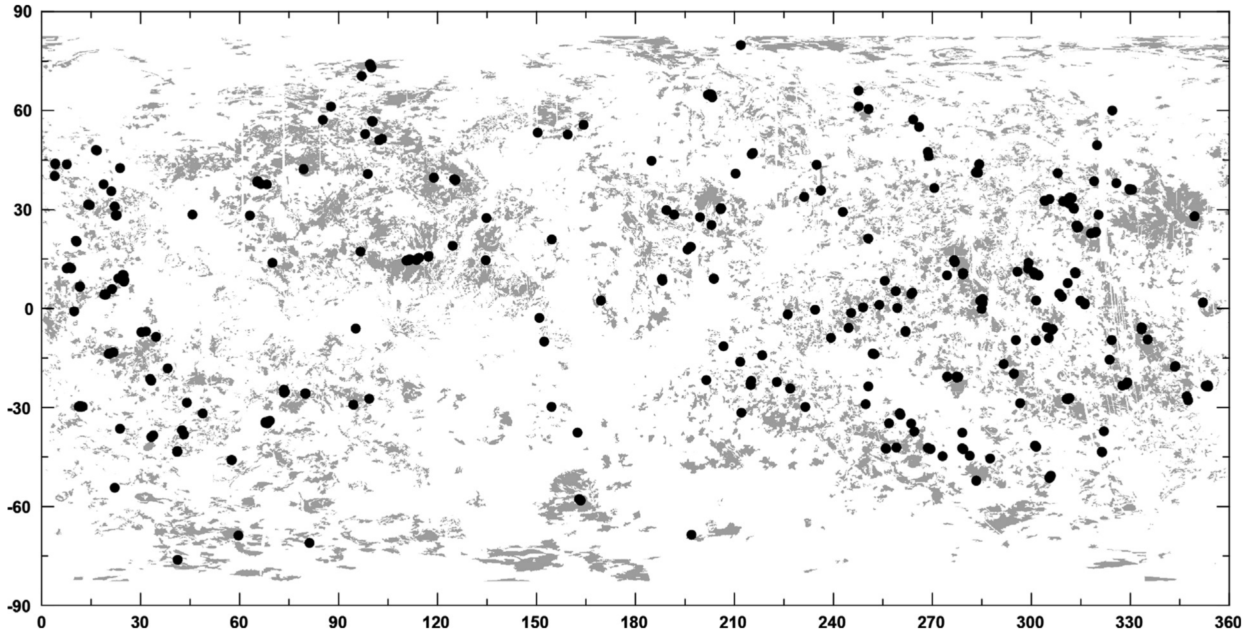

Fig. 8. The areal distribution of steep-sided domes (dots) in comparison with the occurrences of shield plains (gray areas). The close spatial association of the domes and shield plains is evident.

whereas the shorter channels are associated predominantly with fields of lobate plains (Fig. 9b).

2.3. Volcano-tectonic features

The class of volcano-tectonic features includes coronae and arachnoids, novae, and calderas (Crumpler and Aubele, 2000). These features consist of a volcanic component in form of lava flows and fields and a tectonic component that defines the shape of the features. The most abundant volcano-tectonic features on Venus are coronae (Fig. 11) (Barsukov et al., 1986; Pronin and Stofan, 1990; Stofan et al., 1992; Grindrod and Hoogenboom, 2006). In the catalog of these structures (Stofan et al., 1992, 2001a) there are 406 coronae of Type 1 (coronae with complete annulus) and 107 coronae of Type 2 (coronae with incomplete annulus). In our analysis we have used both of these lists.

All tectonically deformed units (except for tessera) contribute to the tectonic features of coronae. Among them, however, extensional structures strongly dominate: rims of about 70% of coronae are outlined by branches of groove belts and rims of about 20% consist of graben of rift zones (Table 3). This predominance of fractures and graben in corona rims suggests that coronae formed in extensional environments, which may be related to both the topographic evolution of the surface above the parent mantle diapir (Smrekar and Stofan, 1997) and intrusion of circular dikes (Ernst et al., 2003, 2007). The volcanic components of coronae postdate emplacement of the structures that form corona rims. Almost equally abundant volcanic features that are associated with coronae are shield plains (~36% of coronae, Table 3) and lobate/smooth plains (~35%, Table 3). Thirty-seven coronae (~7.4%) do not show evidence of volcanism because they are flooded by the lower subunit of regional plains and for ~22% of coronae the latest volcanic activity is in the form of flows of the upper sub-unit of regional plains (Table 3). Of those coronae that show flows of lobate plains as the latest volcanic activity, 73 coronae are associated with rift zones and 94 coronae are away of the rifts.

Arachnoids (Fig. 12) constitute another type of volcano-tectonic feature (Barsukov et al., 1986; Aittola and Kostama, 2000). These features usually are outlined by a broad and apparently low topographic rim, which may or may not be fractured, and by a radial pattern of wrinkle ridges. There are 265 arachnoids in the list of volcanic features (Crumpler and Aubele, 2000). Comparison of this list with the list of coronae (Stofan et al., 1992, 2001a) shows, however, that more than a half of arachnoids (147 features) were listed as coronae of either Type 1 or Type 2. The rest of arachnoids are predominantly associated with the upper sub-unit of regional plains and control the distribution of wrinkle ridges in the close vicinity of the arachnoids (Fig. 12). Thus, arachnoids likely existed before formation of the regional networks of wrinkle ridges.

Abundant tectonic structures characterize novae (e.g., Krassilnikov and Head, 2003) and the volcanic components of these volcano-tectonic features either subdued or absent (Fig. 13). When volcanic features are associated with novae, they represent flows of lobate plains that emanate from the graben of novae. This suggests that the graben are the surface manifestations of dikes (Mastin and Pollard, 1988; Grosfils and Head, 1995; Ernst et al., 1995, 2003; Studd et al., 2011) and novae may represent a specific class of radiating dike swarms (Davey et al., 2013).

About one hundred calderas (Fig. 14) are listed in the catalog by Crumpler and Aubele (2000). Calderas represent mostly broad (60–80 km) and shallow topographic depressions surrounded by swarms of concentric fractures. About 30% of these features were listed as coronae (mostly of Type 2). Calderas are approximately evenly associated with shield plains (~31% of the features), the upper sub-unit of regional plains (~41%), and lobate plains (~21%). About 7% of calderas occur within fields of unit rp_1.

Although the volcanic landforms on Venus display a great diversity (Head et al., 1992; Guest et al., 1992; Crumpler and Aubele, 2000), only four units of extensive volcanic plains, shield plains (psh), regional plains (rp, both the lower, rp_1, and upper, rp_2, sub-units), and lobate plains (pl), make up the major portion of the surface of the planet (Fig. 3). Together, these units cover up about 70% of the surface (~320×10^6 km^2, Table 1) and, thus, represent the most significant episodes of volcanic resurfacing during the observable geological record of Venus.

3. Age relationships among the main volcanic units

The main volcanic units on Venus demonstrate consistent relationships of relative ages among each other at the global scale.

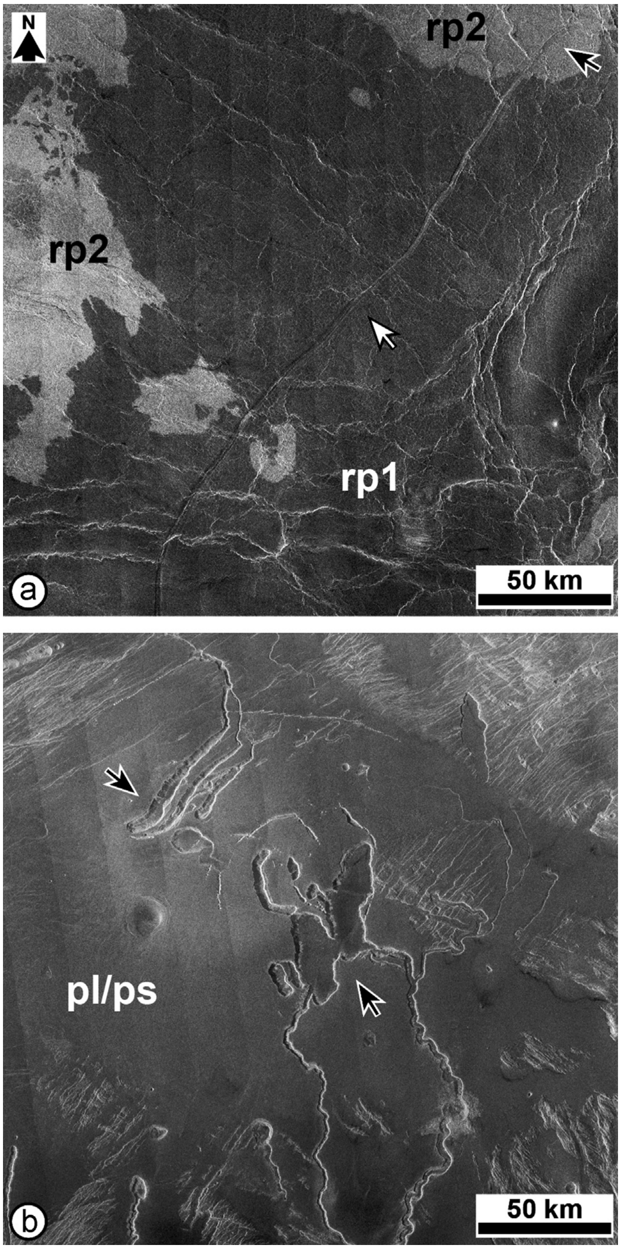

Fig. 9. Examples of narrow sinuous channels. (a) A channel (northern portion of Baltis Vallis) that is associated with the lower sub-unit of regional plains. The channel cuts the surface of unit rp_1 and appears as a prominent topographic feature (white arrow). Material of unit rp_2 almost completely fills the channels (black arrow). Part of C1-MIDR 45N159, center of the image is at 48.1°N, 161.3°E. (b) A group of channels that cut the surface of the younger volcanic plains (pl/ps). The channels appear to be much more sinuous compared with those in regional plains and begin in steep-sided and flat-floored depressions (arrows). Part of C1-MIDR 15S095, center of the image is at 11.7°S, 89.6°E.

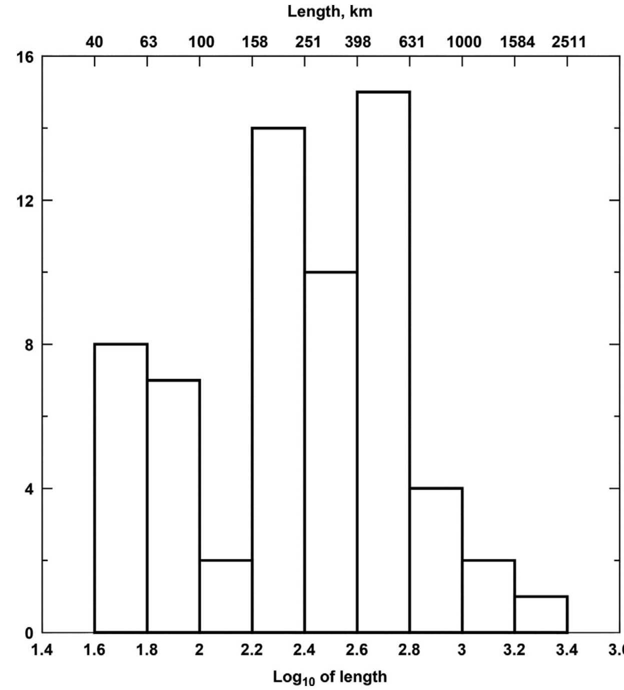

Fig. 10. The size-frequency distribution of the lengths of the sinuous channels (data are from Crumpler and Aubele (2000)). The histogram is bimodal. The upper mode mostly corresponds to the channels that occur in the lower sub-unit of regional plains (Fig. 9a). The channels that are associated with lobate plains (Fig. 9b) occur mostly in the lower mode of the histogram.

The most abundant volcanic units are shield plains and the lower sub-unit of regional plains (Table 1). Owing to the great abundances of these units, contacts between them are very frequent (Fig. 3) and can be studied in detail in many regions of Venus.

Morphometric analysis of individual volcanic constructs of shield plains at the contacts with regional plains has shown that the density, characteristic diameter, and height of the shields progressively decrease in the direction away from the edges of contiguous shield clusters toward the interiors of regional plains (Kreslavsky and Head, 1999). These characteristics of the contacts between psh and rp_1 strongly suggest embayment and partial burial of the older shield plains by younger regional plains. A more extensive list of criteria that included the morphometry characteristics described by Kreslavsky and Head (1999) was developed and applied to analysis of relative ages of shield plains and surrounding regional plains (rp_1) in the study by Ivanov and Head (2004a). In their study, the unit of shield plains was considered as consisting of two components: the small shields/cones and intershield plains. As it was shown earlier (Addington, 2001), these two components of shield plains often show overlapping relationships of relative age, which suggests their broadly synchronous formation.

In Ivanov and Head (2004a), three hypothetical cases were considered: (1) shield plains are older (Fig. 15a), (2) quasi-synchronous (Fig. 15b), and (3) younger (Fig. 15c) than the adjacent regional plains. Careful application of the entire set of criteria to each randomly selected occurrence of shield plains (Ivanov and Head, 2004a) has shown that in ~70% of analyzed cases regional plains represent an embaying unit and shield plains are older (Fig. 16). About 10% of analyzed shield fields appear to be synchronous to regional plains and ~10% of shield clusters post-date adjacent regional plains. The rest of the analyzed population shows either ambiguous or obscured age relationships with regional plains. Approximately the same proportions of the cases shown in Fig. 15a–c were found during the compilation of the global geological map.

These findings imply that the volcanic style of the small shields and related plains was not completely confined to the stratigraphic boundary introduced by regional plains (e.g., Basilevsky and Head, 1998, 2000a; Addington, 2001; Ivanov and Head, 2004a) and some groups of small shields continued to form after emplacement of unit rp_1 (Ivanov and Head, 2004a, 2005). In the global map, all occurrences of small shields that appear to be either synchronous to or younger than regional plains were mapped as a specific unit of shield clusters (Fig. 1, Boala Formation).

The surface of this unit (Fig. 17) is morphologically similar to that of shield plains (compare Figs. 2c and 17). In contrast to psh,

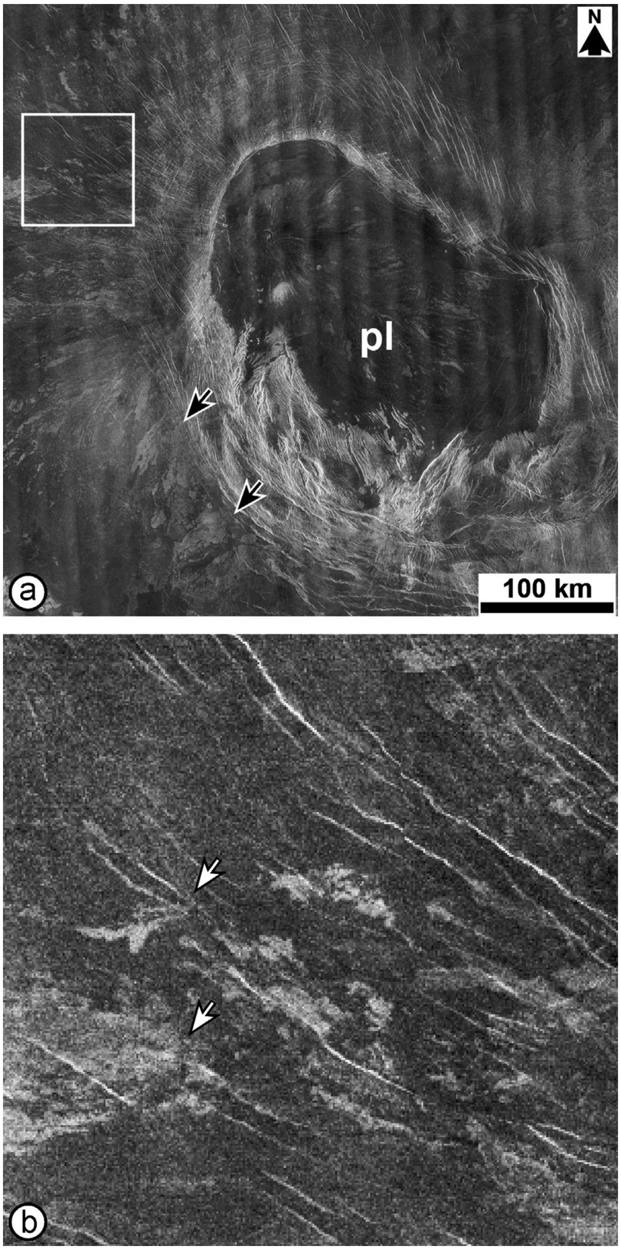

Fig. 11. An example of a corona. (a) The feature is outlined by an elevated rim that consists of densely packed grooves. The corona is a source of volcanic flows that constitute lobate plains (pl). Some flows (black arrows) begin near the rim. White frame indicates the portion of the image shown in Fig. 9b. Part of C1-MIDR 15N266, center of the image is at 9.4°N, 262.2°E. (b) Enlargement of the image (white frame in Fig. 9a) showing a series of NW-trending graben radiating away from the corona. White arrows show lava flows that emanate from the distal ends of the graben These graben are likely to be the surface manifestations of dikes.

Table 3
Stratigraphy of the tectonic and volcanic components of coronae.

Unit	Number of coronae	Percent of coronae
Tectonic component		
rz	85	19.9
gb	295	68.9
pr	20	4.7
pdl	28	6.5
Unknown[a]	85	19.9
Volcanic component		
pl/ps	175	34.9
rp_2	110	22.0
Absent[b]	37	7.4
psh	179	35.7
Unknown	12	2.4

Note: coronae are of Type 1 and Type 2.

[a] Tectonic component is unknown for coronae of Type 2.

[b] Unit rp_1 embays tectonic component of coronae and no other types of volcanic activity is associated.

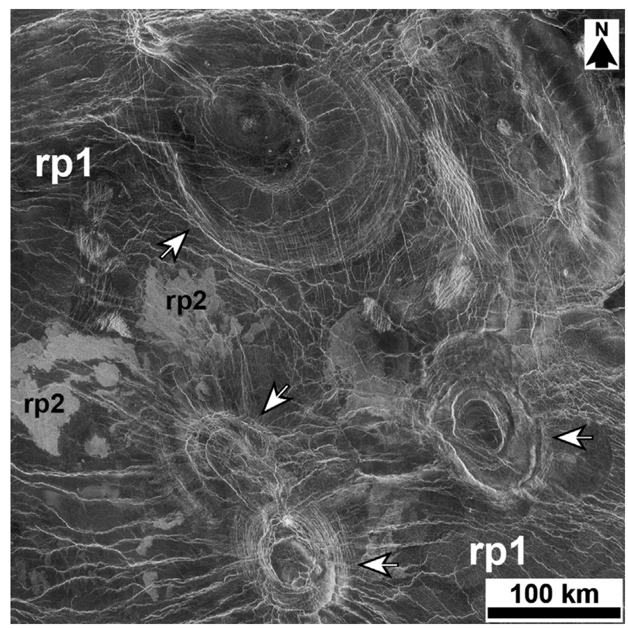

Fig. 12. Examples of arachnoids. These circular and elliptical features (arrows) are surrounded by topographic rims that, at some arachnoids, are cut by swarms of concentric fractures. Wrinkle ridges within the lower sub-unit of regional plains (lower portion of the image) are converging toward the arachnoids. Graben radiating from these structures appear as the sources of the flows of unit rp_2. Part of C1-MIDR 45N011, center of the image is at 40.0°N, 19.2°E.

however, shield clusters are mostly tectonically undeformed and often display small lava flows superimposed on the surrounding regional plains (Fig. 17). Shield clusters cover about 3.3×10^6 km^2 or 0.7% of the mapped surface of Venus, but they are distinctive and mappable features that play an important role in the understanding of the history of volcanism on Venus. The scarcity of the shield clusters implies that although the volcanic style responsible for formation of small edifices seems to continue through a large portion of the visible geologic history of Venus, the rate of the small shield volcanic activity has dropped significantly (more than an order of magnitude) after emplacement of regional plains.

Shield plains underlie both subunits of regional plains (rp_1 and rp_2) and, thus, represent the lower stratigraphic boundary of regional plains. The tectonic episodes of wrinkle ridge formation apparently establish the upper time limit of emplacement of regional plains. Wrinkle ridges cut the surface of both subunits of regional plains and shield plains as well (Fig. 2c and d) and no compelling evidence for embayment of wrinkle ridges by materials of regional plains was documented either on regional geological maps (e.g., Bender, et al., 2000; Bridges and McGill, 2002; Campbell and Campbell, 2002; Ivanov and Head, 2005) or during compilation of the global geological map (Ivanov and Head, 2011). In all maps (except the map V-25 (Young and Hansen, 2003) the unit with the characteristic morphology of regional plains (rp_1) occupies the middle stratigraphic position and is shown as superposed on heavily tectonized units (such as tessera) and embayed by undeformed lava plains and flows.

The units rp_1 and rp_2 often display diffuse boundaries between them probably because of the diffusing of the contact by post-emplacement eolian activity. In regions where the contacts are

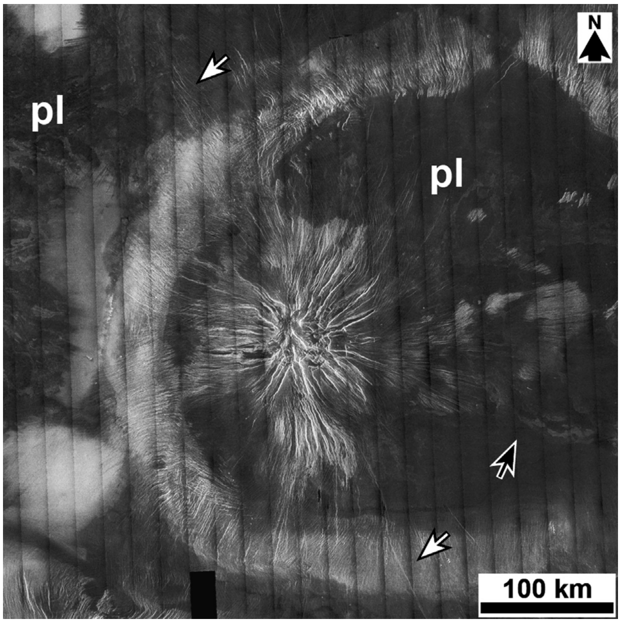

Fig. 13. An example of a nova. The star-like pattern of grooves defines the nova, which is completely inside the rim of Pavlova Corona (radar-bright circular feature). Lobate plains (pl) embay both the nova and the corona rim. Some of narrow graben radiating from the nova cut both the rim and the embaying plains (white arrows). To the east of the center of the nova, flows of lobate plains seem to emanate from the graben of the nova (black arrow). Part of C1-MIDR 15N043, center of the image is at 14.5°N, 39.0°E.

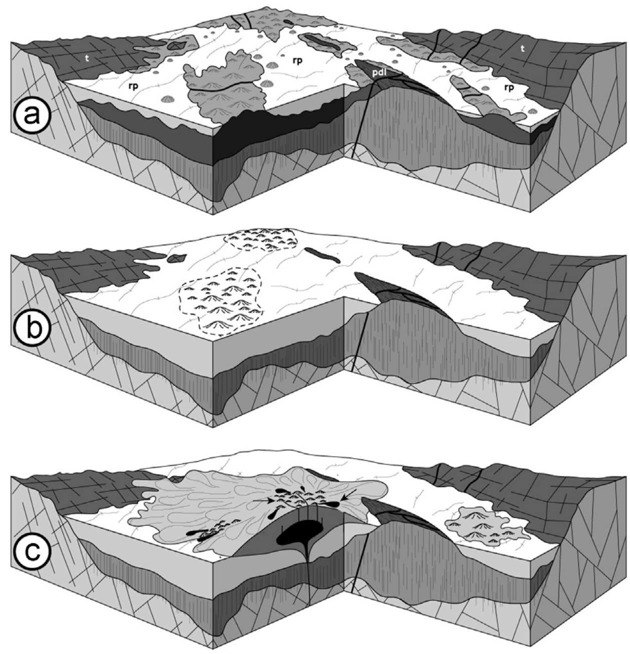

Fig. 15. A sketch illustrating three possible age relationships of small shields and regional plains: (a) shields are older, (b) shields are contemporaneous, and (c) shields are younger that regional plains. The shields and intershield plains from the first example were mapped as shield plains and the other shields were lumped into a unit of shield clusters in the global geological map (modified from Ivanov and Head (2004a)).

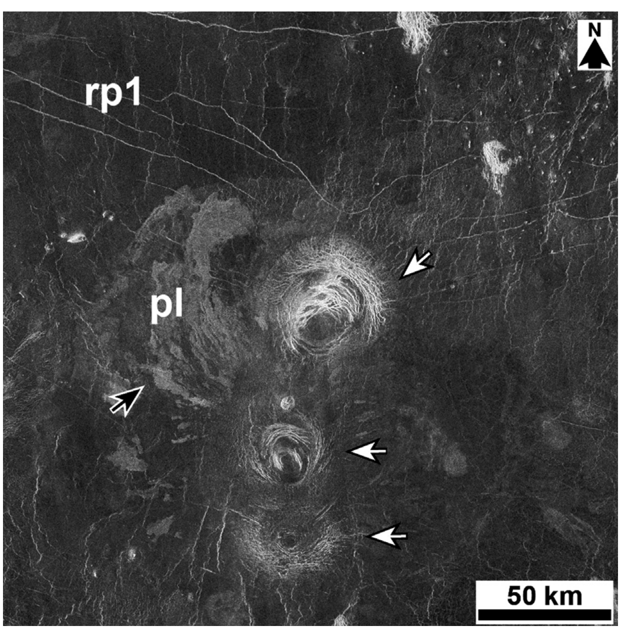

Fig. 14. Examples of calderas (white arrows). Calderas are circular topographic depressions outlined by swarms of concentric fractures. Some of the calderas appear as the sources of lobate plains (black arrow). Part of C1-MIDR 30S225, center of the image is at 30.5°S, 224.5°E.

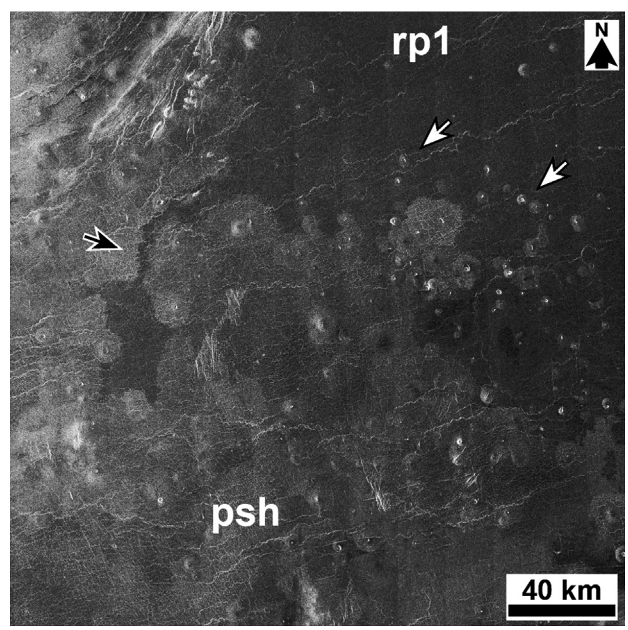

Fig. 16. Relative age relationships between shield plains (psh) and regional plains (rp_1). Material of regional plains penetrates into shield plains (black arrow) and separates individual shields from the main exposure of shield plains (white arrows). This is strong evidence for the older relative age of shield plains. Part of C1-MIDR 30N351, center of the image is at 33.0°N, 352.1°E.

clean and sharp, it is seen that material of the upper sub-unit (rp_2) either penetrates into local lows (e.g., fractures, lava channels) of the lower sub-unit (Fig. 18) or embay local highs of unit rp_1. These relationships are observed at the global scale and indicate the relatively young age of unit rp_2.

The characteristic albedo pattern and usually sharp and well-defined boundaries between the individual flows of lobate plains (Fig. 2e) permit very detailed stratigraphic subdivisions of materials that form the plains. In some geological maps, a large number of units (many tens of them e.g., (Brian et al., 2005) that make up the tops of the regional stratigraphic columns and correspond to different distinctive volcanic centers and/or phases of volcanism that have been mapped. Although this approach is appropriate for mapping of specific regions, it is impractical for global geological mapping because this would create many hundreds (if not thousands) of units overlapping each other at local scale. In the global map we combined all morphologically similar and

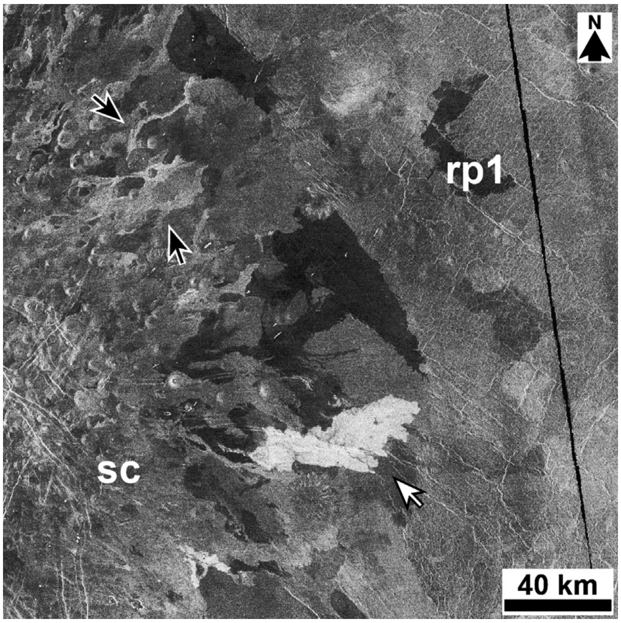

Fig. 17. An example of shield clusters (sc). This unit is characterized by numerous small shield- and cone-like volcanic constructs similar to those in shield plains. In contrast to psh, the constructs of shield clusters often represent the sources of small lava flows (white arrows), some of which superpose the surface of regional plains (black arrow). Part of C1-MIDR 15S317, center of the image is at 8.9°S, 309.8°E.

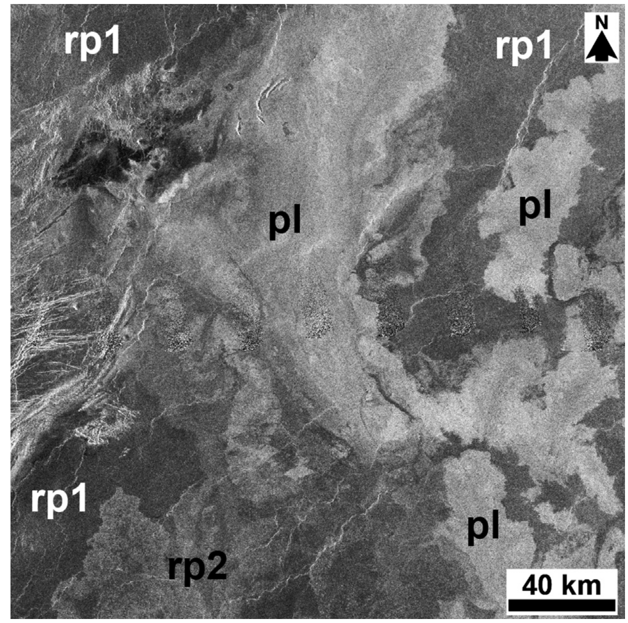

Fig. 19. Relative age relationships between lobate plains (pl) and two sub-units of regional pains (rp_1 and rp_2). Wrinkle ridges cut the surface of regional plains and are embayed by the flows of lobate plains. Part of C1-MIDR 45S350, center of the image is at 51.5°S, 350.8°E.

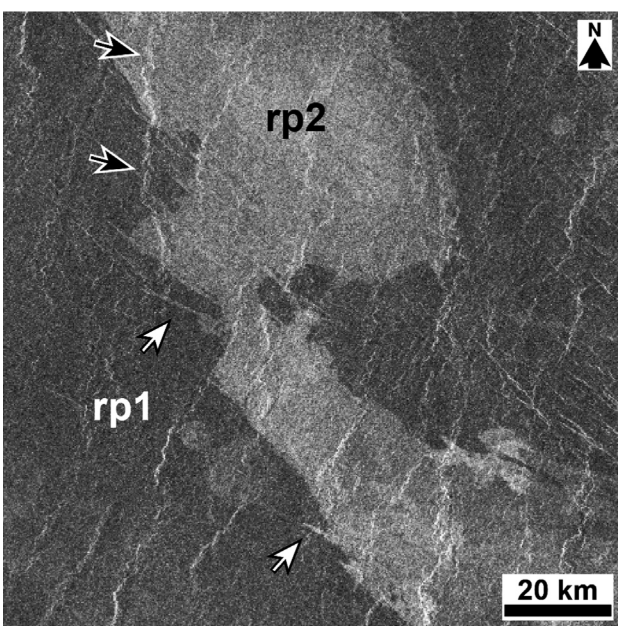

Fig. 18. Relative age relationships between the lower- (rp_1) and the upper (rp_2) sub-units of regional plains. The flow-like occurrence of unit rp_2 is brighter and outlined by a sharp boundary. Material of this unit penetrated into narrow fractures that cut the surface of the lower sub-unit (white arrows). Black arrow indicates a wrinkle ridge that cuts both sub-units of regional plains. Part of C1-MIDR 45S350, center of the image is at 38.4°S, 350.2°E.

tectonically undeformed flows into one composite unit of lobate plains (Fig. 2e). In all places where lobate plains occur in contact with either shield plains or the sub-units of regional plains, flows of lobate plains embay wrinkle ridges that deform materials of regional plains and overlap their surfaces (Fig. 19). These relationships clearly indicate that lobate plains are younger.

The above analysis of the age relationships among the main volcanic units is based on the observation, documentation, and interpretations of the relationships along the unit contacts in virtually all regions of Venus (e.g., Ivanov and Head, 2011) and, thus, it establishes a firm foundation. This is important because it helps establish that the global succession of volcanic units proceeded from shield plains through regional plains to lobate plains.

4. Age relationships of the main volcanic and tectonic units

We define tectonized units/terrains as those in which the surface was strongly modified by tectonic structures that largely erased the characteristic morphologic signatures of underlying material units. Two of such heavily deformed units (densely lineated plains, pdl, and ridged plains, pr) have been described in Section 2.1. Three more types of terrain are included into the category of tectonized units as follows.

Tessera (t, Fortuna Formation, Fig. 20a; type localities are at: 33.0°N, 98.8°E; 8.5°S, 126.0°E) represents one of the most heavily tectonized terrains (e.g., Barsukov et al., 1986; Bindschadler and Head, 1991; Sukhanov, 1992), the surface of which is cut by several sets of intersecting contractional (ridges) and extensional (graben and fractures) structures. Elevated occurrences of tessera are mostly equidimensional or slightly elongated and vary in size from a few tens of kilometers up to a few thousands of kilometers (Ivanov and Head, 1996). Tessera occupies about 35.4×10^6 km^2 (7.8% of the mapped surface of Venus, Table 1) and tends to occur within several extensive provinces (Fig. 21).

Groove belts (gb, Agrona Formation, Fig. 20b; type localities are at: 36.2°N, 271.7°E; 40.2°S, 353.2°E) represent a structural unit, which is formed by densely packed extensional structures. Fractures and graben of the belts almost completely obscure the morphology of underlying materials at the scale of the mapping. Groove belts occupy about 39.5×10^6 km^2 (8.7% of the mapped surface of Venus, Table 1) and occur as zones of hundreds to thousands of kilometers long and a few hundred kilometers wide that are seen throughout a major portion of the surface of Venus (Fig. 21). Inside the belts the swarms of fractures are often

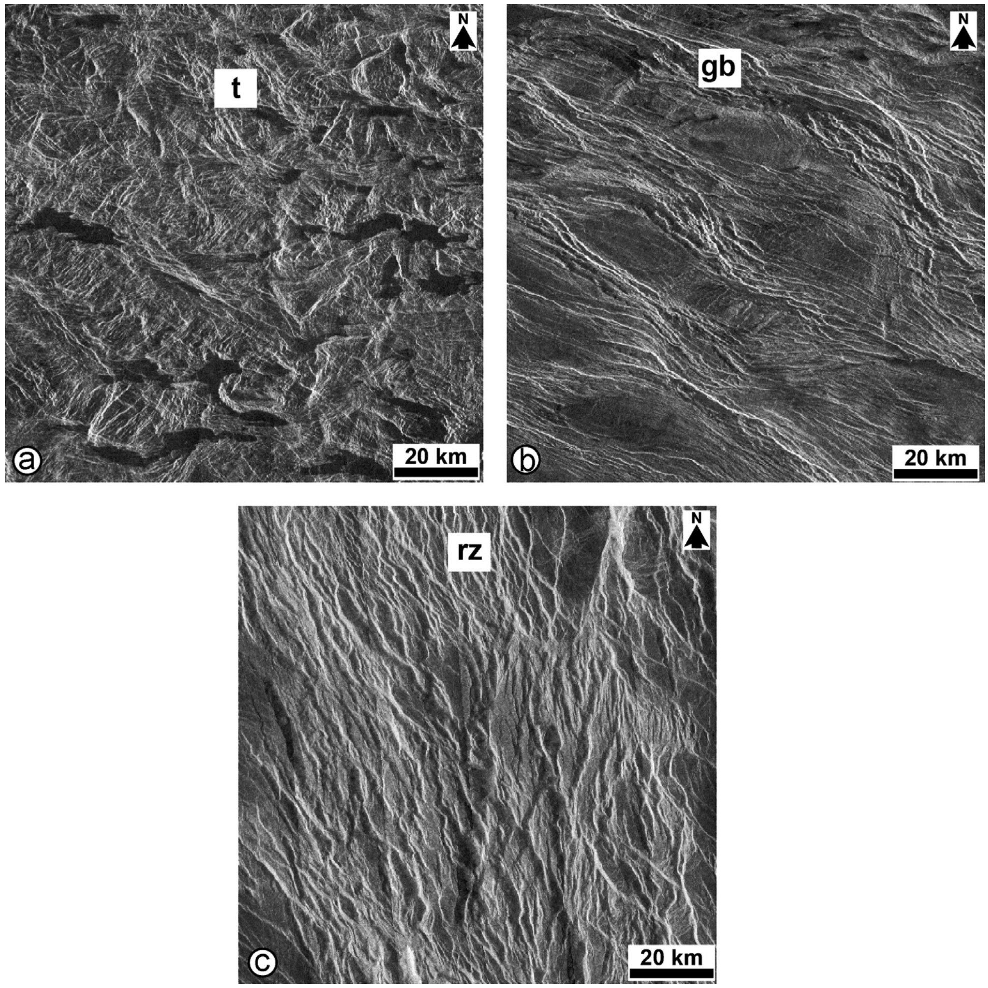

Fig. 20. Examples of the heavily tectonized units. (a) Tessera (t) is characterized by multiple sets of intersecting structures that almost completely erase the morphology of preexisting terrain. Part of C1-MIDR 30N081, center of the image is at 35.4°N, 81.6°E. (b) Swarms of narrow curvilinear graben form groove belts (gb). The graben cut underlying materials and eliminate most of their morphologic characteristics. Part of C1-MIDR 45S350, center of the image is at 40.8°S, 341.7°E. (c) Rift zones (rz) also consist of multiple extensional structures that are wider and longer than the grooves of groove belts. Part of C1-MIDR 15N197, center of the image is at 9.4°N, 204.6°E.

anastomosing and form elliptical and circular features (Fig. 20b). In many places, the swarms of graben/fractures comprise either rims of coronae or the star-like pattern of novae and may be underlain by dike swarms (Grosfils and Head, 1995; Ernst et al., 1995, 2003; Studd et al., 2011).

Rift zones (rz, Devana Formation, Fig. 20**c; type localities are at: 11.1°N, 198.7°E; 1.1°N, 287.7°E)** form another structural unit consisting of numerous and densely packed extensional structures. Rift zones represent broad (hundreds of kilometers) and long (thousands of kilometers) swarms of graben, and flat-floored troughs. On average, structures of rift zones are broader, longer and somewhat less densely packed than structures of groove belts. Rift zones occupy about 24.5×10^6 km^2 or 5.4% of the mapped surface of Venus (Table 1) and occur as prominent belts near the equatorial zone of Venus (Fig. 21).

The pervasive sets of tectonic structures usually present clear relationships of embayment and crosscutting that greatly help to determine the relative ages of the tectonized units.

Practically everywhere on Venus contacts of tessera with surrounding volcanic plains are very sinuous due to penetration of materials of plains into tessera massifs (Fig. 22a). All tectonic structures of tessera are abruptly truncated by the contact with the plains and none of the structures extends into the plains either as morphologic or topographic features (Fig. 22a). These characteristics of the contacts of tessera provide compelling evidence that both emplacement of tessera materials and their tectonic modification were completed before formation of the younger vast volcanic plains. The higher topography of the tessera massifs (Ivanov and Head, 1996) prevents their flooding by successive plains units that were able only to embay the high-standing massifs.

The characteristic features of densely lineated plains are sets of narrow parallel lineaments. At the contacts with any of the main volcanic units, the lineaments abut against a smooth and sharp boundary with the plains that, thus, are younger and overlay densely lineated plains (Fig. 22b). The typically low relief of the occurrences of unit pdl (Ivanov and Head, 2001) suggests that their survivability to flooding can be sensitive to the thickness of the later volcanic plains.

Similar relationships of embayment are seen globally at the contacts of ridged plains with the main volcanic units. The ridges (either individual or collected into belts) of unit pr are truncated at the contact with the surrounding plains and do not continue further into the adjacent plains (Fig. 22c). This situation is analogous to that at the contacts of tessera with the embaying plains (Fig. 22a) and unequivocally indicates that the tectonic episode(s) of the broad ridging predated emplacement of vast volcanic plains. The radar backscatter cross-section of ridged plains is noticeably higher than that of the surrounding regional plains (McGill and Campbell, 2006). Clear differences in the radar albedo, together with embayment relations, provide additional

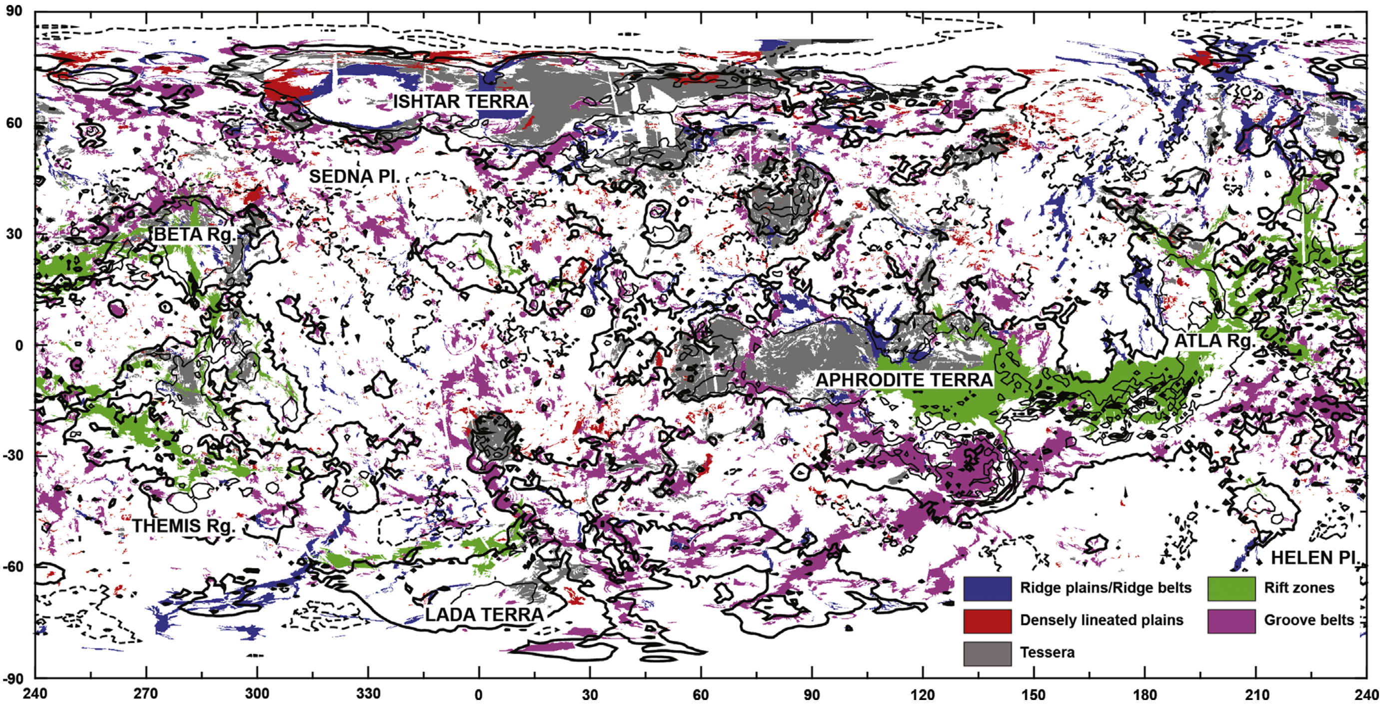

Fig. 21. The spatial distribution of tectonized units on Venus. Rift zones are organized into a few compact zones and are not as pervasive as the older tectonized units. White spots (except for obvious data gaps) show the major occurrences of the main volcanic units. Thick black line represents the 0 km contour line, the thinner lines indicate elevation −1 km (dashed line) and +1 km (solid line). The map is in simple cylindrical projection.

evidence for the older ages of ridged plains/ridge belts relative to regional plains (e.g., McGill and Campbell, 2006).

Structures of groove belts usually cut tessera, densely lineated plains and ridged plains/ridge belts, which indicate that groove belts formed later than these units. The abundance of groove belts on Venus (Table 1) allows tracing these relationships in many areas and everywhere the belts appear to be younger. Vast plains units such as shield plains and regional plains embay groove belts (Fig. 22d). It should be noted, however, that a few fractures of gb sometimes cut materials of the plains. This suggests that, although the waning stages of tectonic activity at the belts were contemporaneous with formation of some of the volcanic units, the main episode of groove belt formation occurred before emplacement of the vast plains.

Thus, the absolute majority of the tectonically deformed terrains on Venus (Table 1 and Fig. 21) predate emplacement of both shield and regional plains. The tectonized terrains/units make up about 20% of the surface of Venus and this is the minimum estimate of their abundance because the younger volcanic plains certainly have buried some portion of the tectonized units.

Fractures and graben of rift zones cut all tectonic units, shield plains, and both sub-units of regional plains and, thus, are younger. Rift zones occur in close spatial association with lobate plains (Fig. 22e). Structures of rifts both cut the plains and are embayed by their material (Fig. 22e), which indicates the partly contemporaneous formation of the rifts and these young volcanic plains. These embayment and crosscutting relationships define rift zones as an individual group of tectonized terrains/units that is stratigraphically distinct from the other tectonized units. Although rift zones form very prominent and extensive features of Venus (Fig. 21), their abundance is almost four times smaller compared with the combined exposed area of the older tectonized units (Table 1). This difference in the abundances means that rift zones have resurfaced a much smaller portion of Venus upon their formation and, thus, they represent a less significant episode of tectonism.

5. Topographic configuration of the main tectonized and volcanic units

Comparison of the global geological and topographic maps of Venus reveals a pronounced correlation between the material/structural units and topography. Most of the tectonized units are either associated with (tectonized belts) or form (largest tessera regions) the topographic highs that are hundreds to thousands of kilometers long. Although densely lineated plains do not form regional highs, they tend to occur within elevated areas. Owing to the virtual lack of erosion on Venus, the high frequency variations of topography (at the scale of kilometers-tens of kilometers) characterize the surface of all tectonized terrains. The main volcanic units do not show the high-frequency topographic variations of topography and represent topographically smooth surfaces that are undulating at the scale of a few hundreds of kilometers (Komatsu and Baker, 1994; Stewart and Head, 1999) (Fig. 23a and b). The contacts between different vast volcanic plains are usually poorly distinguishable topographically but occurrences of shield plains either produce local topographic highs or occur on flanks of highs formed by the tectonic units (Fig. 23a and b).

The stratigraphic position of the tectonized units (see Section 3) divides them into two groups. The first group consists of units predating the vast volcanic plains (psh and rp) and includes tessera, densely lineated plains, ridged plains, and groove belts (Fig. 22a–d). The second group includes rift zones, the structures of which cut shield and regional plains and are contemporaneous with emplacement of lobate plains (Fig. 22e).

A significant topographic step of several hundreds of meters and higher usually occurs at the contact between the older tectonized units with shield and regional plains and emphasizes the embayment of the tectonized terrain by the vast plains (Fig. 23a and b). In contrast, such steps are absent at the contacts between the broadly contemporaneous lobate plains and rift zones (Fig. 23c) and the flows of lobate plains can occur either at higher

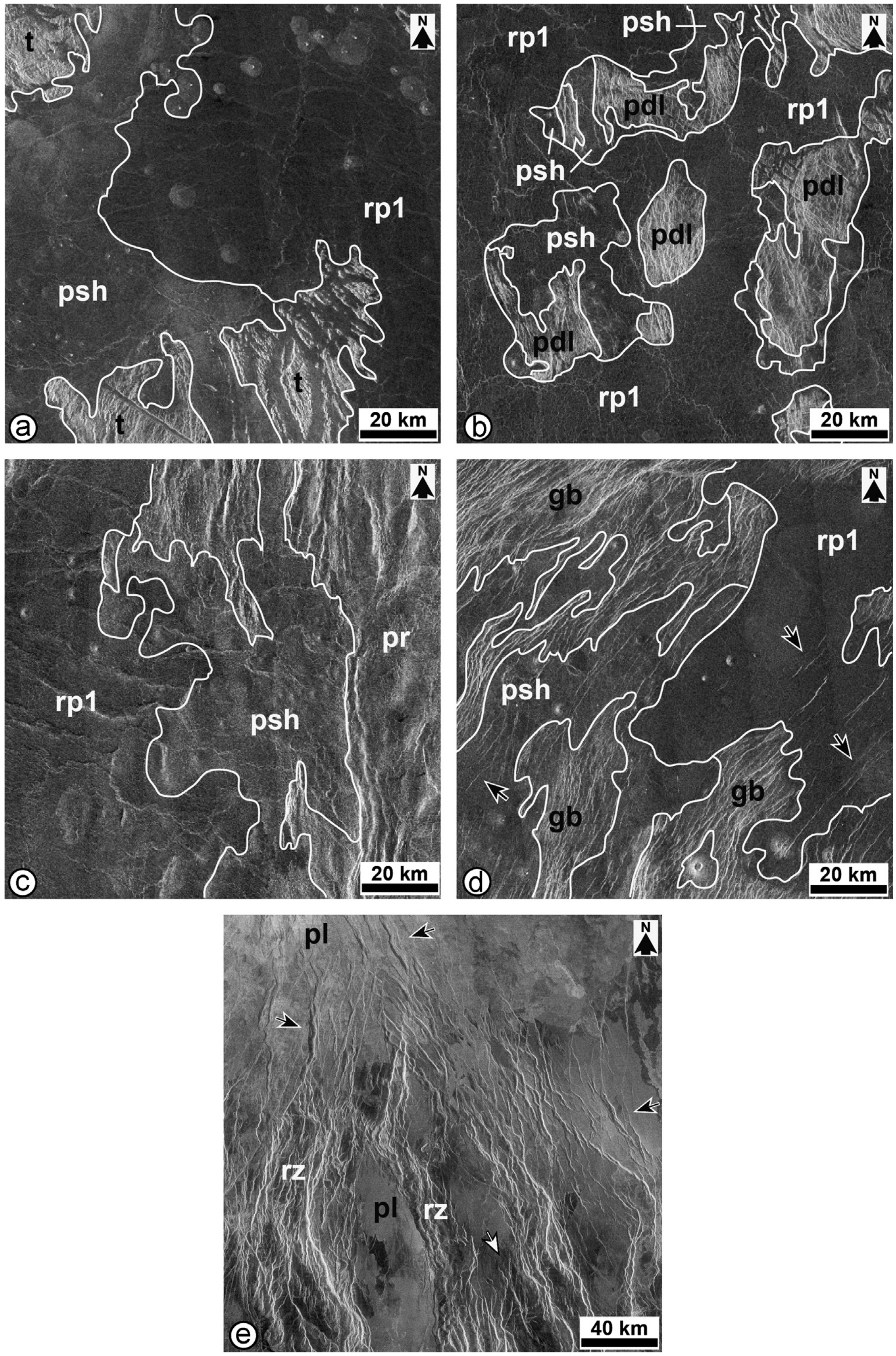

Fig. 22. (a–d) Relative age relationships between the older tectonized units and the vast volcanic plains (psh and rp_1). In the cases shown in images (a), (b), and (c), the surface of the vast volcanic plains is mildly deformed and materials of the plains completely superpose all structures of the tectonized units. (d) At the contact of groove belts with either psh or rp1, a few graben of the belts cut the surface of the plains (black arrows) but the absolute majority of the structures of groove belts are embayed by the vast volcanic plains. (a) Part of C1-MIDR 45N117, center of the image is at 47.3°N, 127.6°E. (b) Part of C1-MIDR 45N032, center of the image is at 40.9°N, 34.7°E. (c) Part of C1-MIDR 45N159, center of the image is at 37.5°N, 156.4°E. (d) Part of C1-MIDR 00N146, center of the image is at 3.0°N, 146.7°E. (e) Relative age relationships between the structures of the younger tectonized unit, rift zones (rz), and lobate plains (pl). Graben of rift zones both cut lobate plains (black arrows) and are embayed by the plains (white arrow). This relationships indicate broadly contemporaneous formation of rift zones and lobate plains. Part of C1-MIDR 15N283, center of the image is at 21.2°N, 281.5°E.

topographic levels on flanks of rift zones or topographically low on the floor of the rift valleys (Fig. 22e).

The topographic configuration of the vast volcanic plains correlates well with their stratigraphic position. In many regions on Venus, shield plains occur near outcrops of the older and elevated tectonized terrains and form a “transition” zone between them and expanses of regional plains (Fig. 23a). On the average, shield plains are characterized by the higher elevations compared with the both sub-units of regional plains (Table 4). This difference at the global scale is illustrated by the hypsograms of units psh, rp_1

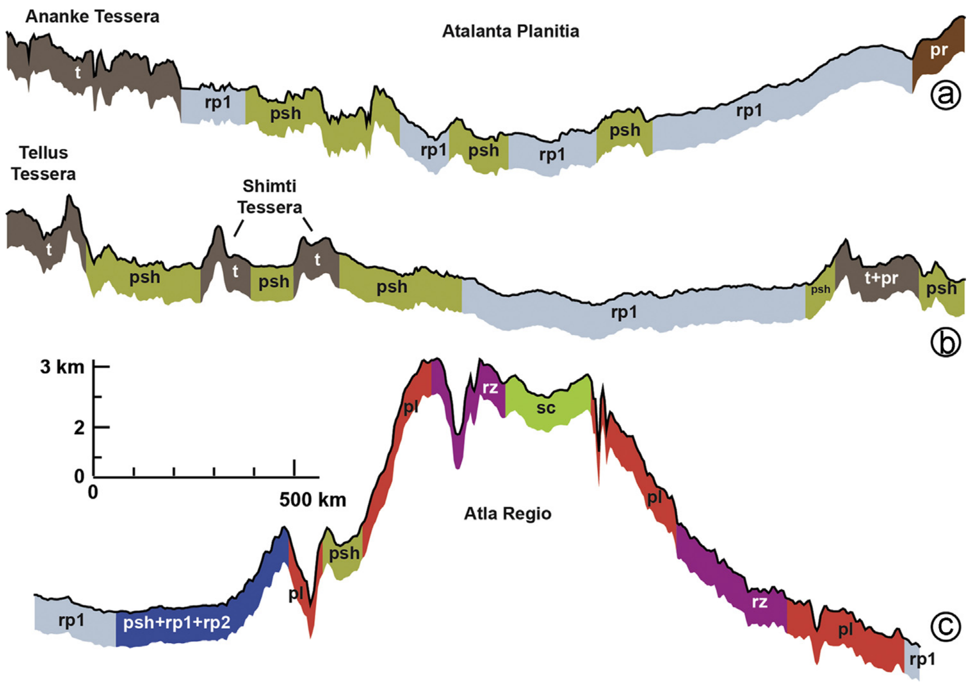

Fig. 23. Regional topographic profiles that illustrate the topographic position and configuration of the major volcanic and tectonic units on Venus.

Table 4
Topographic characteristics of main volcanic and tectonized units on Venus.

Unit	Mean elevation (m)	St. deviation (m)	1st Decile (m)	9th Decile (m)
Volcanic units				
psh	−130	660	−820	630
rp_1	−380	650	−1070	280
rp_2	−430	560	−1070	280
pl	340	820	−520	1280
Tectonized units predating psh				
t	1340	1370	−270	3430
pdl	−130	880	−1020	780
pr	50	870	−920	1130
gb	130	720	−670	980
t+pdl+pr+gb	550	1200	−670	3080
Tectonized units synchronous to pl				
rz	890	1050	−370	2180
Total hypsogram	0	970	−920	1180

and rp_2 (Fig. 24a). The mode of the hypsogram of shield plains almost exactly coincides with the total hypsogram mode (Ivanov and Head, 2011) suggesting that the plains represent a "typical" topographic level on Venus. The hypsogram of the lower unit of regional plains (Fig. 24a) is clearly shifted toward the lower elevations (Table 4) reflecting the preferential association of this unit within the regional lowlands (Fig. 3). Because of this, the areal distribution of the plains mimics the general pattern of long-wavelength topography (the X-pattern of lowlands) known since the Pioneer-Venus mission (Pettengill et al., 1980; Masursky et al., 1980) (Fig. 3). The upper sub-unit of regional plains (rp_2) tends to occur at even lower elevations compared with the lower sub-unit (rp_1, Table 4) and its hypsogram is slightly shifted to the left (Fig. 24a).

Although shield plains often form an outer zone between regional plains and the tectonized units and occur at relatively higher topographic levels (Fig. 24a), sometimes within vast expanses of regional plains there are isolated occurrences of shield plains at the lower elevations. For example, within Atalanta Planitia fields of shield plains completely surrounded by regional plains are seen at different topographic levels (Fig. 23b) (Ivanov and Head, 2004b). These outliers of shield plains form local highs that stand above and are embayed by the adjacent regional plains. These relationships suggest that shield plains underlie some portions of regional plains.

Lobate plains are almost exclusively associated with prominent topographic highs, e.g., large volcanoes (Figs. 23c, and 3). The materials of lobate plains flow down the regional slope and overlay the surface of the surrounding shield and regional plains. In only in a few cases do the distal portions of the lobate plains lava flows extend below the zero contour line (Fig. 3) and the hypsogram of the plains is shifted toward the higher elevations (Fig. 24b and Table 4). Rift zones as well as lobate plains are strongly associated with elongated regional highs mostly in the equatorial zone of Venus and around the BAT region (Crumpler et al., 1993) (Fig. 21). Due to this, the hypsogram of rift zones is strongly shifted toward the higher elevations (Fig. 24b and Table 4). The rift valleys, however, represent very prominent elongated depressions that can be several kilometers deep.

6. Discussion

The definition, description, and documentation of the tectonized and volcanic units and the global-scale analysis of their relative age relationships and topographic configuration (Ivanov and Head, 2011) permit addressing of several important problems of the geologic history of Venus. (1) What is the stratigraphic position of volcanic landforms on Venus? (2) What is the possible structure of the observable part of the geologic history of the planet? (3) What style of volcanic activity the volcanic landforms suggest and/or indicate? What is evidence for the changes of volcanic styles and evolution of volcanism? (4) What constraints do the topographic configuration and stratigraphic position of the volcanic landforms place on the history of the long wavelength topography?

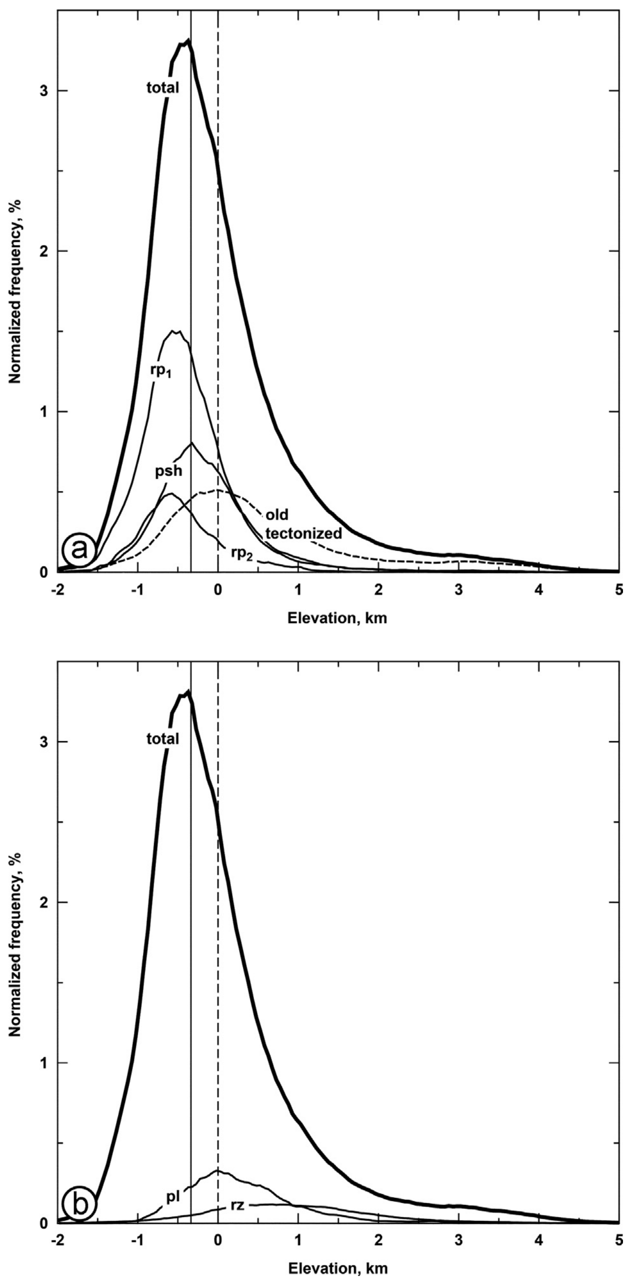

Fig. 24. The global-scale hypsograms of the major volcanic and tectonized units summarizes the topographic characteristics of the units shown in Fig. 23.

6.1. Tectonically and volcanically dominated regimes of resurfacing on Venus

Surface units and terrains whose morphology is related to either tectonic and/or volcanic processes, comprise the absolute majority of the surface of Venus (~99.5%). The scale and abundance of tectonic structures and, thus, their importance in the morphological appearance of the terrain types that make up the surface of Venus divide the entire spectrum of the morphologically defined units (except impact craters) into two principal populations: (1) units, the surface of which clearly show their volcanic origin and where tectonic structures played a subordinate role, volcanic units (Figs. 2c–f and 2) units/terrains, in which tectonic structures are the primary features that largely overprint the morphologic characteristics of underlying materials, tectonized units (Figs. 2a, b and 20).

The regional and global-scale classification, definition, and documentation of a variety of morphologies (Basilevsky and Head, 1995a,b; Hansen et al., 1997; Guest and Stofan, 1999; Ivanov and Head, 2011) reveal that such units as tessera (t), densely lineated plains (pdl), ridged plains/ridge belts (pr), groove belts (gb), and rift zones (rz) compose the class of tectonically dominated units on Venus. The observable morphology of these terrains/units (Figs. 2a, b and 20) clearly reflects the leading role of tectonic deformation that strongly affected the older materials, perhaps of volcanic origin.

The observation of extreme importance is that extensive and mildly deformed volcanic plains (shield plains and regional plains) embay the majority of the tectonized units and are cut by structures of rift zones everywhere on Venus where these units are in contact. Such a stratigraphic position of the tectonized units relative to the vast volcanic plains divides them into the older (t, pdl, pr, gb) and younger (rz) groups.

The total area of the older tectonically dominated units is ~92.8×10^6 km^2, or ~20.4% of the surface of Venus (Table 1), which is the minimum estimate of their abundance. Thus they comprise at least 80% of all heavily tectonized terrains on Venus. The older tectonized units are broadly distributed on the surface of Venus and occur in many regions of the planet (Fig. 21). Both the abundance of the older tectonized units and their global-scale areal distribution imply that tectonics played an important role during the earlier episodes of the geologic history of Venus.

In terms of their state of tectonic modification, the vast plains units (shield plains and regional plains) are in sharp contrast to the tectonized units (compare Figs. 2c, d and 20). About the only structures that deform the surface of the volcanic units are low and narrow wrinkle ridges that seem to form regionally to globally extensive networks (Bilotti and Suppe, 1999). Wrinkle ridges are much less prominent features than the structures of the tectonized units and do not erase or obscure the morphologic signatures of the underlying volcanic plains. The plains occupy ~280×10^6 km^2 (over 60% of the surface of the planet, Table 1), occur in almost every region of Venus (Fig. 3) (Ivanov and Head, 2011), and when they are in contact with the older tectonized units they always embay and are partly superposed on them (Fig. 7a–d). Only a few graben that constitute groove belts cut the surface of the surrounding plains but the absolute majority of the graben are embayed by the volcanic units (Fig. 22d).

The sharp stratigraphic transition from the heavily deformed units to the mildly tectonized extensive volcanic plains occurred at the global scale (Figs. 3 and 21) and in no area on Venus is the reverse age relationships observed (deformation of either shield or regional plains by structures of the tectonized units). These facts indicate that a tectonically driven regime dominated the earlier stages of the geologic history of Venus. The existence of such a regime (Head et al., 1994) does not exclude volcanism; indeed, the emplacement of materials of the densely lineated plains and the ridged plains suggests volcanic activity at these times. Tectonic deformation during this period, however, clearly overcame the intensity of volcanism, strongly modified and deformed the emplaced volcanic materials and largely erased evidence for the sources of the plains.

Sharp contacts of the vast volcanic plains with the tectonized units, lack of transitional morphologies (e.g., the absence of intense tectonic deformation within either shield or regional plains), and the always-younger age of the volcanic plains suggest that the tectonically dominated regime changed to a regime of predominantly volcanic activity and volcanic resurfacing at the middle stages of the geologic history of Venus (Fig. 25).

The flows of lobate plains (a volcanic unit) and graben of rift zones (a tectonized unit) formed broadly contemporaneously and superpose and/or cut regional plains in all localities where these

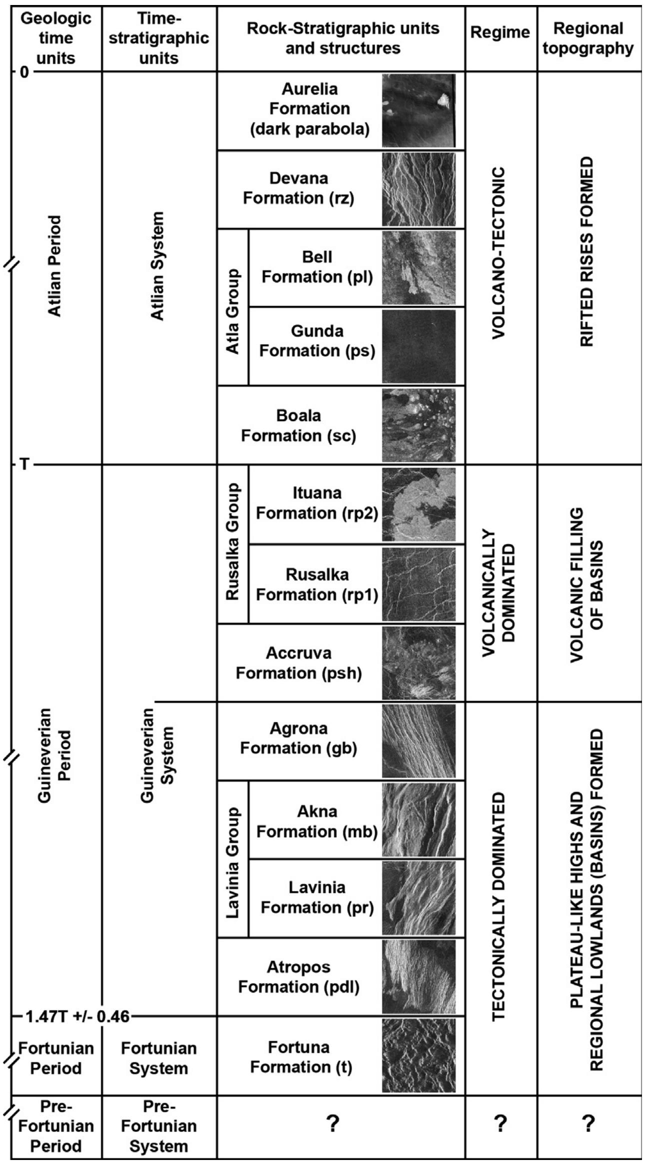

Fig. 25. The stratigraphy and geologic history of the observable portion of the geologic history of Venus. The major endogenous regimes and episodes of evolution of the long-wavelength topography are shown.

units are in contact (e.g., Fig. 19). Lobate plains and rift zones have roughly comparable abundances (Table 1) and both postdate regional plains. This means that a volcano-tectonic regime of resurfacing has characterized the later episodes of the visible geologic history of Venus (Fig. 25) and about 14% of the surface of the planet was renewed during this time. The total area affected by lobate plains and rift zones is, thus, about six times smaller than that resurfaced during the earlier tectonically and volcanically dominated regimes. This implies a significant drop of endogenous activity on Venus after emplacement of regional plains.

6.2. *Constraints on the history of resurfacing: relationships of impact craters and regional plains*

Regional plains represent the most widespread volcanic unit of Venus (Table 1) and, thus, the characteristics of the interaction of materials of the plains with impact craters are very important for understanding the history of resurfacing on the planet.

Regional plains, although globally extensive, do not seem to have a great thickness. Several lines of evidence suggest that. (1) The low-relief occurrences of densely lineated plains that should be sensitive to volcanic flooding are broadly distributed within regional plains (Ernst et al., 2003; Ivanov and Head, 2011). A layer of greater thickness, for example, a few kilometers would effectively hide exposures of densely lineated plains. (2) Polygonally organized fractures that may have been formed due to thermal contraction of a cooling volcanic layer are rarely seen within regional plains (Smrekar et al., 2002) but sometimes occur within fields of lobate plains (Johnson and Sandwell, 1992). The characteristic dimensions of the polygons outlined by fractures appear to require a larger thickness of volcanic units that may reach a few kilometers (Johnson and Sandwell, 1992). (3) The average slope of the surface of regional plains and the older underlying units are small and close to each other, which implies a rather small thickness (~500 m) of regional plains in a zone along the contacts with the older units (Collins et al., 1999). (4) In places, graben that predate emplacement of regional plains are still recognizable on their surface, which also indicates a small thickness of the plains, a few hundred meters (DeShon et al., 2000). (5) Near the contact with shield plains, kipukas of small volcanoes are seen within regional plains suggesting the thickness of the plains in these areas to be less than 100–200 m (Kreslavsky and Head, 1999).

Despite the apparently small thickness, regional plains show little (if any) evidence for the presence of the ghost craters (craters that are completely buried by overlying materials). On Mars and Mercury these features are quite common and recognizable on the surface even if the thickness of overlying lava plains is estimated to be 0.5–1.5 km (Ivanov et al., 2005; Klimczak et al., 2012). The virtual lack of ghost craters on Venus requires that any craters formed prior to emplacement of regional plains were concentrated exclusively in regions where the overlying regional plains may be as thick as several kilometers. This is highly unlikely and strongly suggests that the previous cratering record was erased prior to formation of regional plains and the plains were emplaced onto the surface that was largely free of craters. Thus, the observable population of craters very likely represents a production one (Schaber et al., 1992), which is completely consistent with the spatial distribution of craters, which is indistinguishable from completely random (Phillips et al., 1992; Strom et al., 1994; Hauck et al., 1998).

Phillips et al. (1992) have argued that the visible population of craters on Venus formed in equilibrium with emplacement of volcanic plains. Indeed, the results of volcanic embayment of craters can be much less evident than their tectonic modification. For example, young mare materials embay the eastern portion of the rayed crater Lichtenberg on the Moon (Schultz and Spudis, 1983). In contrast to the volcanically flooded surfaces on Moon, Mars, and Mercury where the obviously flooded craters are common, the vast plains on Venus, however, show a very small number of such craters, ~6% of the total population (Schaber et al., 1992, 1998).

The scarcity of truly embayed impact craters on Venus strongly limits the possible variety of the modes of emplacement of the vast volcanic plains and leaves room only for a “delicate”, Lichtenberg-type embayment, the results of which may be very difficult to see at Magellan resolution (e.g., Herrick and Rumpf, 2011). Regional plains represent the most widespread unit on Venus and most of impact craters occur within the plains. If materials of regional plains embay a large proportion of the craters in a manner similar to Lichtenberg it would imply formation of the plains by numerous very thin and morphologically indistinguishable lava flows. The lack of sources of the plains materials and huge areas covered by them (up to a few millions of square kilometers) seem not to be consistent with such a mode of formation and suggests instead the emplacement of regional plains due to massive volcanic flooding of large provinces.

In contrast to regional plains, the stratigraphically younger and much less widespread lobate plains (Table 1) were obviously formed by superposition of successive lava flows (e.g., Keddie and Head, 1995; Magee and Head, 2001). In places where impact craters are either within or in contact with the fields of lobate plains, the craters quite often are obviously embayed by materials of the plains (about 50% of craters interacting with lobate plains are truly embayed (Ivanov, 2009). This example suggests that the successive emplacement of lava flows of lobate plains that are much smaller in extent than the questionable flows of regional plains usually results in the undoubted embayment of impact craters.

Thus, the small proportion of impact craters obviously embayed by materials of regional plains (~3% of all craters that are either within or in contact with regional plains) disfavors the proposed prolonged, equilibrium-like, formation of the plains (e.g., Phillips et al., 1992; Herrick and Rumpf, 2011). Instead, the geologically rapid formation of the plains (e.g., Schaber et al., 1992; Strom et al., 1994; Collins et al., 1999) is more consistent with the state of volcanic modification of impact craters.

6.3. *Constraints on the history of the long-wavelength topography*

The shape and the topography and gravity signatures define two major groups of topographic highs on Venus (e.g. Sjogren et al., 1983; Smrekar and Phillips, 1991). The first group includes the plateau-like elevated regions that are spatially associated with the large tessera regions (e.g., Ovda and Thetis Regiones). The equidimensional (dome-shaped) and elongated rifted uplands constitute the second group.

Analyses of the modern topographic and gravity signals have shown that the large tessera-bearing regions are compensated at relatively shallow depth (Herrick et al., 1989; Smrekar and Phillips, 1991; Grimm, 1994) and their relief is supported isostatically by the greater thickness of the crust (Grimm, 1994). At the same time, tessera, as a distinctive morphologic terrain, appears as the oldest stratigraphic unit that is embayed/cut by all other materials and structures. This tight correlation of the topographic configuration and the stratigraphic position strongly suggests that the major plateau-like topographic features (sometimes referred to as crustal plateaus (Hansen et al., 1999, 2000)) formed near the beginning of the visible portion of the geologic history of Venus during the tectonically dominated regime of resurfacing (Fig. 25) and that they have remained high since that time. The other, older tectonized units (e.g., ridge belts and groove belts) also represent noticeable (although lower than tessera) zonal topographic highs (Fig. 23a and b) that extend for thousands of kilometers (Fig. 21) and contribute to the long-wavelength topographic pattern.

Thus, during the earlier tectonic episode of the geologic history of Venus, a significant portion of the regionally to globally important topographic highs was formed. In the sense of the filling of topographic depressions, volcanism on Venus plays a similar role to erosion on Earth: fluid products of volcanic activity flow down the regional slopes and accumulate within the depressions. The regionally important lowlands and highlands should, thus, control the spatial distribution of the main volcanic units.

The older shield plains are concentrated slightly lower the zero contour line (Fig. 3); about 70% of the area of the plains is below this elevation. The mode and the shape of the central 50% of the shield plains hypsogram mimic the mode and the distribution of the total hypsometric curve (Fig. 24a). This suggests that shield plains tend to occur within a 'typical' elevation range of Venus. In some lowlands, however, shield plains are seen in stratigraphic windows at low elevations where shield plains likely underlie the cover of regional plains (Fig. 23b). Such a topographic position of these windows suggests that the surface upon which shield plains emplaced subsided after their formation. Alternatively, the extensive lowlands may have existed before formation of shield plains. The map of spatial distribution of regional plains (rp_1) shows that this unit preferentially occurs at lower elevations (Fig. 3) and about 80% of regional plains is below the zero contour line (Fig. 24a). This clear association of regional plains with the lowland regions suggests that the lowlands (1) were formed before emplacement of the plains, (2) largely controlled their spatial distribution, and (3) have served as the sites of the preferential accumulation of regional plains.

The correlation of the older tectonized units and the vast volcanic plains with regional topographic pattern strongly suggests that the major features of the long-wavelength topography of Venus that include the plateau-like highs and the lowlands have been formed prior to emplacement of the lower sub-unit of regional plains (rp_1).

The defining features of lobate plains and rift zones postdate formation of regional plains and are closely associated with the second class of the regional highs, the dome-shaped rises (Figs. 3 and 21). The rises are characterized by large gravity anomalies (Esposito et al., 1982; Konopliv et al., 1999; Lawrence and Phillips, 2003) and high geoid-to-topography ratio (Smrekar and Phillips, 1991) interpreted as evidence of dynamic support of topography by active mantle upwelling (e.g., Phillips et al., 1981; Phillips and Hansen, 1998). The extensional structures of rift zones are consistent with, and suggestive of, fracturing due to growth of the rises and the flows of lobate plains on flanks of the rises imply that they represent the large centers of volcanism.

These stratigraphically youngest features of lobate plains and rift zones match perfectly the gravity and topography signatures of the rises and strongly suggest that they were active during the latest episodes of the geologic history of Venus (Fig. 25). The latest (observable) flows of lobate plains on the flanks of the rises flow down the regional slope and the graben of rift zones are localized mostly along the crest areas of the rises (Fig. 23c). These topographic characteristics of lobate plains and rift zones suggest that the rifting and late volcanism are associated with the mature stages of the development of the rises.

When did the rises begin to form? The regional pattern of wrinkle ridges can be used as an indicator of the regional stress fields (Sandwell et al., 1997; Bilotti and Suppe, 1999). The swell-push model developed in Sandwell et al. (1997) predicts that the older topographic and geoid highs can affect orientation of the younger wrinkle ridges arranging them circumferentially around the highs. The pattern of the spatial distribution of wrinkle ridges indicates that the best correlation between the regional trends of the ridges and the topographic rises is observed southward of eastern Aphrodite Terra (Bilotti and Suppe, 1999) where it is consistent with the swell-push model (Sandwell et al., 1997) and may suggest that the geoid high in the rifted eastern Aphrodite Terra existed before formation of the family of wrinkle ridges to the south, in Aino Planitia. Another region of the regional alignment of wrinkle ridges around a topographic rise is to the south of Themis Regio (Bilotti and Suppe, 1999). The other pronounced rises such as Beta and Atla are not characterized by the circumferential orientation of the ridges around them (Bilotti and Suppe, 1999), which may suggest that the rises formed largely after emplacement of wrinkle ridges. Eistla Regio shows a complex pattern of the ridges in its surroundings and only some of them are arranged circumferentially around Sif and Gula Montes (Basilevsky, 1994), whereas the others are chaotically oriented (Bilotti and Suppe, 1999). This may suggest that the development of the rise of Eistla Region partly overlapped with formation of the ridges.

Two specific features of the upper sub-unit of regional plains (rp_2) may also provide constraints to the relative ages of the dome-shaped rises: (1) unit rp_2 is cut by wrinkle ridges and (2) flow-like occurrences of rp_2 indicate their source regions or direction to the source. In some areas on Venus, flows of unit rp_2 that clearly indicate their source (e.g., Ituana Corona (Young and Hansen, 2003)) appear as the result of the latest volcanic activity and are not associated with significant topographic features. Yet in some other regions (e.g., Lada Terra, Atla Regio, etc., Fig. 3), flows of unit rp_2 occur on flanks of the rises and flow down the regional slope in concert with the younger flows of lobate plains (Ivanov and Head, 2006). This topographic position and the relationships with lobate plains suggest that the flows of the upper sub-unit of regional plains may represent the earlier phases of volcanism that began when the rises at least partly existed.

In many areas on Venus, however, the flows of lobate plains flowing down from the rises are superposed directly on the surface of either the lower unit of regional plains rp_1, or shield plains, psh, (Fig. 3) and embay outcrops of the older tectonized units. In these regions, the surface of the vast volcanic plains (rp_1 and/or psh) is usually tilted away from the rise suggesting that the rise began to form after emplacement of the plains.

Thus, the alignment of wrinkle ridges and the topographic configuration of the upper sub-unit of regional plains and lobate plains suggest that the beginning of formation of the rises somewhat overlapped the late stages of formation of regional plains. The later evolution of the rises caused emplacement of lobate plains on their flanks and deformation of their crest areas by rift zones. Volcanism probably accompanied the rises since the beginning of their formation, whereas tectonic deformation appeared only when and if the rises have reached a certain height.

6.4. Changes in volcanic styles

Densely lineated plains (pdl) and ridged plains (pr) provide evidence for volcanic activity during the earlier, tectonically dominated regime of resurfacing. The surface of these plains, however, is significantly deformed (Fig. 2a and b) and successive plains heavily embay their occurrences. This situation precludes an interpretation of the style of volcanism responsible for emplacement of the material component of units pdl and pr.

The characteristically low relief of the occurrences of densely lineated plains suggests that the later volcanic plains could relatively easily cover them. However, outcrops of unit pdl are widely distributed over the surface of Venus (Fig. 21) and tend to be away from large tessera regions (Ivanov and Head, 2011). This suggests that (1) source areas of densely lineated plains were probably also broadly distributed in the areas between the large tessera massifs and (2) that the thickness of the embaying plains was relatively small and they were not able to completely hide the occurrences of densely lineated plains from view. Some regional lowlands, the surface of which is covered by regional plains (e.g., Helen, Aino, Laimdota, Imapinua, and Zhibek Planitiae), lack occurrences of pdl and this suggests that the thickness of regional plains in these regions is greater.

Occurrences of ridged plains (Fig. 21), especially when they are in the form of ridge belts, have much higher relief than patches of densely lineated plains (Ivanov and Head, 2011). Thus, fragments of unit pr should be less sensitive to later embayment and flooding. The original distribution of ridged plains, however, is largely obscured by contractional structures, and materials of the plains were certainly displaced during their formation. The surfaces of both the weakly-ridged facies of ridged plains and the ridges of ridge belts are morphologically smooth, distinctly different from that of shield plains, and originally may have been resembled the surfaces of regional plains and lobate plains. This suggests that the style of volcanism during formation of the material component of ridged plains was different from that typical of shield plains.

The main volcanic units (plains) that were emplaced at the later portion of Guineverian Period and during the Atlian Period have obviously different morphology and this indicates different volcanic styles during their formation. The consistent stratigraphic relationships of the main volcanic units and associated volcanic features (Figs. 16, 18 and 19) allow tracking of the evolution of volcanism on Venus.

Shield plains started the volcanically dominated episode of the observable geologic history of Venus and predate regional plains and lobate plains (Fig. 25). Their occurrences are seen over the majority of the surface of the planet (Fig. 3), which suggests that these plains were of global importance. The most obvious features of shield plains are small (typically several kilometers across) and very abundant (~500,000 shields on the exposed surface of psh) volcanic constructs (Fig. 2c). The great abundance of the constructs implies that their sources were fairly pervasive and nearly globally distributed while the small sizes of the shields suggest that supply of magma in their sources was restricted. Another important feature of shield plains is that the steep-sided domes are spatially and stratigraphically associated with the plains (Fig. 8) (Ivanov and Head, 1999, 2001). The shape of the domes suggests that upon eruption their materials were more viscous than basalt, which may have three possible explanations (e.g., Head et al., 1992; Pavri et al., 1992): (1) materials of the domes were saturated with crystals, or (2) materials of the domes were saturated with bubbles and represented a 'volcanic foam', or (3) materials of the domes had higher silica content. The hypothesis that the domes formed by the low-rate eruption of common basaltic lavas (Gregg, and Fink, 1996; Stofan et al., 2000) is not consistent with either typical dimensions of the domes or their morphology (Ivanov and Head, 1999). The spatial and stratigraphic proximity of the steep-sided domes to shield plains constrains the above possibilities and favors the explanation that the apparent high viscosity of lavas of the domes was due to enhanced silica content (Ivanov and Head, 1999), for example, because of partial re-melting of basaltic crust (e.g., Hess and Head, 1990).

Fields of shield plains often occur in association with coronae (Table 3) and may be genetically linked with evolution of these volcano-tectonic features. Shield plains at coronae superpose their tectonic structures but are embayed by the surrounding regional plains. These relationships suggest that if the corona-associated occurrences of shield plains represent a specific phase of the corona volcanic activity, then this phase corresponds to the earlier stages of evolution of coronae. Alternatively, shield plains near and/or in the interiors of coronae may represent exposures of the regionally to globally extensive unit of shield plains that is not genetically related to formation of coronae, but rather accompanies their formation in time.

The small size of the constructs of shield plains and their association with the steep-sided domes are most consistent with shallow crustal melting and differentiation of magma in reservoirs and/or partial melting of the crustal materials. Many of calderas (Crumpler and Aubele, 2000) occur within fields of shield plains and represent broad and shallow topographic depressions surrounded by an annulus of fractures (Fig. 14). No lava flows are seen in association with these calderas. These features obviously were formed due to subsidence of the surface, which may be due to removal of materials from the shallow magma reservoirs and, thus, is consistent with the mode of formation of shield plains, which apparently requires the presence of numerous, distributed and shallow reservoirs.

The most significant occurrences of shield plains are fairly large, many hundreds of kilometers across (Fig. 3), and are surrounded by smaller outcrops of psh embayed by regional plains. This suggests that the true occurrences of the plains that existed before emplacement of the overlying regional plains were even greater. The large dimensions of the fields of psh and their broad distribution over the surface of Venus is not consistent with isolated mantle plumes and requires much more extensive, globally distributed shallow heat sources that could be provided if large regions of the crust were underplated by exposure to hot fertile mantle.

The lower sub-unit of regional plains (rp_1) postdates emplacement of shield plains and forms very broad and morphologically homogenous surfaces that are distinctly different morphologically from the preceding shield plains. Two important features characterize this unit and provide the keys for the understanding of its mode of formation. (1) The sources of lavas are not visible at the resolution of Magellan SAR, which is in sharp contrast to either older shield plains or younger lobate plains. (2) Regional plains are very abundant and ubiquitous: the exposed surface of rp_1 itself comprises about one third of the surface of Venus (Table 1) and the unit occurs almost everywhere on the planet (Fig. 3). These features strongly suggest that regional plains formed by voluminous volcanic eruptions from broadly, near global, widely distributed sources, during which individual lava flows coalesced into essentially large volcanic flow units and buried the source regions. The absence of noticeable volcanic constructs (except for a few small shield that may be contemporaneous to emplacement of regional plains (Ivanov and Head, 2004a)) suggests that eruptions of materials of the plains were extremely voluminous and relatively short-lived.

Sinuous channels (Baker et al., 1992; Komatsu and Baker, 1996) that are associated with the lower sub-unit of regional plains belong to the population of the longer features (Fig. 10) and are not typical of the upper subunit of regional plains (rp_2). Formation of the longer channels seems to be consistent with the mode of emplacement of the unit rp_1 if the channels were cut, for example, by channeled flows of hotter lava (e.g., komatiites) (e.g., William-Jones et al., 1998), although a variety of hypotheses were proposed to explain formation of the channels (Baker et al., 1992, 1997; Kargel et al., 1994; William-Jones et al., 1998; Lang and Hansen, 2006).

The style of volcanic activity of regional plains resembles that of terrestrial flood volcanism that is often related to pressure-release melting in the head of a mantle plume (e.g., Condie, 2001 and references therein; Bryan and Ernst, 2008). One of the characteristic features of flood volcanism is the geologically short duration of the main volcanic phase. For example, the major portion of the Columbia River Flood Basalt province was emplaced during about 3 myr (Hooper, 1988) and the Siberian Traps (Zolotukhin and Al'mukhamedov, 1988) province was largely completed during 1 myr (Sharma, 1997). In the Central Atlantic Magmatic Province, the main phase of volcanism lasted for about 0.6 myr and consisted of four magmatic episodes (Blackburn et al., 2013). After the main phase, the volcanic activity may continue but at much lower level (e.g., Hooper, 1988).

The principal difference between regional plains on Venus (rp_1) and terrestrial large igneous provinces (LIPs) is their scale (Head and Coffin, 1997; Hansen, 2007). The area of the largest LIPs on Earth, e.g., Siberian traps, Ontong Java Plateau, etc., is about $2–2.5 \times 10^6$ km^2 (the total area of the largest recognized LIPs on Earth is about 24.8×10^6 km^2 (Coffin and Eldholm, 1994, 2001; Ernst and Buchan, 2001) whereas the surface of regional plains on Venus is about 150×10^6 km^2 (Table 1). It is obvious that such an extensive volcanic province on Venus cannot be reconciled easily with the melting in the head of one plume or a series of plumes. However, the decompression melting of a fertile mantle layer that may had been replaced delaminated portion of lithosphere and underplated the crust may have caused formation of shield plains at the earlier stage followed by the subsequent massive lava outpouring and emplacement of regional plains.

If such characteristics of the mode of flood volcanism as the short duration of the main phase and the prolonged volcanic activity at much lower level are applicable to formation of regional plains, they may explain an important feature of the crater record of Venus. The small number of craters obviously embayed by regional plains (Schaber et al., 1992; Ivanov, 2009) may correspond to the period of massive but short-lived eruptions and the larger number of craters that may be embayed but are not recognizable at the resolution of Magellan data (Herrick and Rumpf, 2011) may have been formed during the waning stages of volcanic activity related to emplacement of regional plains. In this case, however, the possible prolonged phases of emplacement of regional plains should cause formation of volcanic flows/fields that are not recognizable at the current resolution of available images.

Large and radar-bright flows that are deformed by wrinkle ridges characterize the upper sub-unit of regional plains (rp_2, Fig. 2d). Usually, the flows of rp_2 clearly indicate the source areas of the plains and are represented by individual features such as large and intermediate volcanoes and some coronae. About 47% of the population of the volcanoes (Crumpler and Aubele, 2000) shows lava flows deformed by wrinkle ridges and in about 22% of coronae (Stofan et al., 1992) the upper sub-unit of regional plains represents the latest recognizable volcanic activity.

The distinct volcanic flows of unit rp_2 and their clear association with individual sources mark the other change of volcanic style on Venus, from the massive and broadly distributed eruptions to more localized volcanic activity at fewer specific centers.

The style of volcanism that caused formation of the youngest extensive volcanic units, lobate plains, was distinctly different from those of shield plains and regional plains. The definitive features of the plains, numerous radar-darker and -brighter flows (Fig. 2e), are not observed either in unit psh or rp_1. Because the brightness on the SAR images depends largely upon the roughness of the surface (e.g., Ford et al., 1993), the darker flows should have a smoother surface, which is consistent with pahoehoe lavas, and the brighter flows likely represent blocky a'a lavas. The interleaving darker and brighter flows typical of unit pl (e.g., Roberts et al., 1992; Keddie and Head, 1995) suggest that during the entire period of formation of lobate plains in each specific region where the plains occur the duration of individual eruptions and the eruption rates have changed from one episode of activity to the other.

The second characteristic feature of lobate plains is that the plains are associated with discrete regions and do not form continuous fields comparable in size to the expanses of regional plains (Fig. 3). This type of areal distribution implies that the sources of lobate plains were discrete and the plains formed in different areas at different times. The results of regional geological mapping in areas with abundant occurrences of lobate plains provide strong evidence for that (e.g., Brian et al., 2005). The relationships of flows of lobate plains with impact craters (Basilevsky and Head, 2000b), interpretations of characteristics of their thermal emissivity (Smrekar et al., 2010), and radar properties (Bondarenko et al., 2010) as well as modeling of the concentrations of sulfur dioxide in the atmosphere (Bullock and Grinspoon, 2001), together suggest that lobate plains formed during a prolonged time span since after emplacement of regional plains at time *T* (the mean age of the surface (Basilevsky and Head, 1998)) until geologically recent times. The long-lasting activity of the sources of lobate plains is also suggested by the fact that their material embays about 50% of all impact craters associated with lobate plains (Ivanov, 2009).

The discrete character of the sources of lobate plains is in good agreement with the observation that lobate plains are associated with such individual features as large and intermediate volcanoes and coronae (e.g., Keddie and Head, 1995). Flows of the plains clearly indicate that these features are the sources of unit pl. The majority of the volcanoes (~66% of their population) show flows of lobate plains that make up at least the surface of the volcanoes.

About 45% of coronae that source lobate plains are associated with rift zones and the plains and rifts represent the youngest and most broadly contemporaneous features of these coronae. About 55% of coronae with lobate plains are not associated with rift zones and their tectonic components (usually branches of groove belts) are embayed by the lower sub-unit of regional plains. Lobate plains that superpose unit rp_1 at these coronae clearly represent their latest activity and may indicate either a delayed phase of volcanism or reactivation of the corona magmatic systems due to new batches of melt supplied to the corona-related magma reservoirs. Some coronae and novae are surrounded by radiating graben that show relatively small, pl-type flows emanating from them. These graben are strongly indicative of the presence of dikes propagating away from the central reservoir and could be formed due to overpressurization of the reservoir by new pulses of magma (Lister and Kerr, 1991; Head and Wilson, 1992; Menand and Tait, 2002).

Finally, lobate plains predominantly occur within the regional dome-like highs where the plains closely associate with rift zones (Figs. 3, 21 and 23c). These associations suggest that emplacement of lobate plains was related to active rifting (e.g., Baker et al., 1972) that caused upward warping and fracturing of the surface due to rising of mantle plumes/diapirs in some regions or along specific zones.

In summary, lobate plains continue the trend started by the upper sub-unit of regional plains and show a strong tendency to be sourced from distinct individual magmatic centers and interconnecting rift zones. These characteristics of the volcanism during the late volcano-tectonic regime of resurfacing (Fig. 25) are consistent with the hotspot-like activity likely related to interaction of mantle plumes with the thicker crust/lithosphere (e.g., Smrekar and Parmentier, 1996; Solomatov and Moresi, 1996; Smrekar et al., 1997; Phillips and Hansen, 1998; Jellinek et al., 2002; Johnson and Richards, 2003; Anderson and Smrekar, 2006).

6.5. *Estimates of volume of main volcanic units*

The volume of the main volcanic units on Venus is a very important quantity that characterizes the amount of volcanic activity as function of time. Both areas and thickness of the units are essential for the volume assessment and both require assumptions to be made. The areas of the units (except for lobate plains, which is on top of the global stratigraphic column and, thus are represented by true exposures) is assumed to be equal to the sum of the total area of exposures of a specific unit and areas of all units that are stratigraphically higher (e.g., the estimates area of shield plains is equal to the area of the unit exposures, 84.5 km^2 (Table 1), plus exposed areas of rp1, rp_2, and pl (Table 5). This approach almost certainly leads to overestimations of the unit areas and, thus, is an upper bound for the area values in Table 5.

The lack of robust constraints on the thickness of the units imparts an additional uncertainty to the volume estimates. Here we use the stratigraphic position of the units, their topographic configurations, and typical associations in order to make reasonable estimates of the thickness of the units.

Numerous exposures of heavily tectonized units (e.g., pdl), which predate the emplacement of shield plains, are seen within the occurrences of shield plains and suggest that the thickness of the plains is rather small. An average distance between the exposures of the tectonized units is on the order of several tens of kilometers and they form local highs that are several meters high.

Table 5
Estimates of volume of the main volcanic units.

Unit	Exposed area, 106 km^2	Max area, 106 km^2	Volume, 106 km^3, at specific thickness (km)					
			0.1	0.2	0.3	0.4	0.5	
psh	84.5	320.3	32	64				
rp1	150.7	235.8				94	118	
rp2	44.8	85.1	9	17				
pl (plains)	40.3	40.3			12		20	
pl (large volcanoes)[a]								8.5
pl (large volcanoes)[b]								17

[a] Volume of the visible portion of large volcanoes.
[b] Volume of the visible and subsurface portions of large volcanoes.

Both the spatial distribution of the older units and their topographic configuration suggest that the thickness of the overlying shield plains is about a few hundred meters. Another piece of evidence for the small thickness of shield plains is the absence of embayment of individual volcanic constructs by materials of intershield plains within the occurrences of shield plains. This suggests that the thickness of the intershield plains should be noticeably less than the typical height of the shields, a few hundred meters (Guest et al., 1992; Laxson et al., 1997; Kreslavsky and Head, 1999). Thus, we have assumed that values between 100 and 200 m may represent reasonable estimates of the thickness of shield plains (Fig. 26).

The thickness of the lower subunit of regional plains (rp_1) at the contact with shield plains was estimated to be about 150 m (Kreslavsky and Head, 1999) and where embayed shields are covered, the thickness of regional plains is likely to be larger than about 400 m (Kreslavsky and Head, 1999). Width of the zones where the kipukas of shields are seen among the embaying regional plains is usually less that about 10% of the dimensions of the occurrences of regional plains. Thus, the reduced thickness at the edges of regional plains likely does not play an important role in the estimates of the average thickness of the plains. Measurements of the regional slopes of terrains surrounding the extensions of regional plains have led Collins et al. (1999) to the conclusion that the thickness of regional plains probably does not exceed about 500 m. According to these findings, we have selected values of 400–500 m as the most likely estimate of the average thickness of the lower subunit of regional plains (Fig. 26).

Wrinkle ridges, which belong to the same family of structures that cut the lower subunit of regional plains, deform the upper subunit of regional plains (rp_2, Figs. 2d, 18, and 19). When ridges cross the fields of rp_2, they do not show recognizable changes of either their width or planform (Figs. 2d, :18 and 19), which suggests that the thickness of the plains is small and did not affect the morphology of wrinkle ridges. In some regions on Venus, there are swarms of ghost-like graben covered by a veneer of the upper subunit of regional plains (see discussion in Ernst et al. (2003) and Hansen and Young (2007)). The graben are still recognizable on the surface and suggest a small thickness of fields of unit rp_2, about 50 m (DeShon et al., 2000), at their margins. Thus, as a possible estimate of the thickness of the upper subunit of regional plains we have chosen values from 100 to 200 m (Fig. 26).

When lobate plains are in contact with wrinkle ridges, the plains embay and bury the ridges whose height is seen to be a few hundred meters. This introduces one possible constraint on the thickness of lobate plains. For the occurrences of lobate plains that are not associated with large volcanoes we have selected a value of 300 m for the thickness of the plains. For large volcanoes, we assumed that a layer of the same thickness (~300 m) makes up

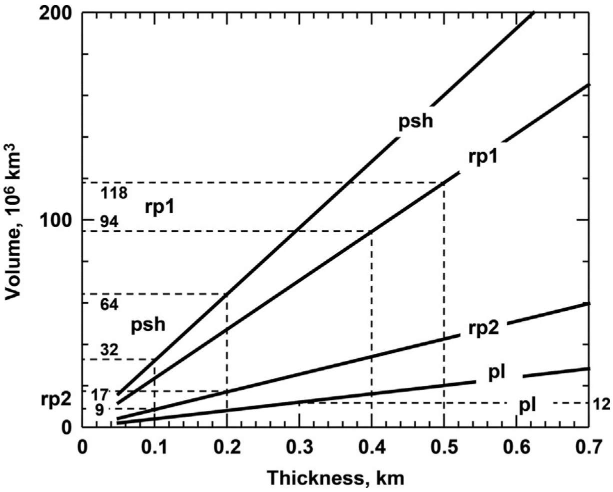

Fig. 26. Estimates of volumes of the main volcanic units on Venus.

their uppermost portion. Thus, we believe that a value of 300 m may represent a reasonable thickness estimate for the exposed lobate plains (Fig. 26). Lobate plains typically make up flanks of large shield volcanoes and, thus, these structures may contribute significantly to the total volume of the plains. The volcanoes represent large topographic highs and can be approximated by cones (e.g., Stofan et al., 2001b). We have measured the average slopes of the flanks of large volcanoes that have been selected at random and represent about 10% of the population of these structures listed in the catalog of volcanic landforms on Venus (Crumpler and Aubele, 2000). The mean value of the slopes is about 0.2° (±0.1°, one sigma) and the cone approximation in this case gives the total volume of large volcanoes to be about 8.5×10^6 km^3. The volume of the volcanoes, however, may be twice as large if they possess a significant subsurface component (McGovern and Solomon, 1997).

Table 5 and Fig. 26 summarize our approximate estimates of the volume of the main volcanic units on Venus. The data in the table show that both shield plains and the lower subunit of regional plains are the major contributors to the volcanic resurfacing on Venus. The combined volume of these units may vary from about 130 to 180×10^6 km^3. The much smaller volume of the upper subunit of regional plains shows a significant drop in volcanic activity by the end of the volcanically dominated regime. The total volume of volcanic materials erupted during this regime (psh +rp_1+rp_2) is estimated to be from about 140 to 200×10^6 km^3 (Table 5). In sharp contrast to this, the total estimated volume of lobate plains is about an order of magnitude smaller, ~20–30×10^6 km^3 (Table 5 and Fig. 26), which corresponds to a volcanic resurfacing rate from ~0.03–0.04 km^3/yr (if the mean age of the surface, T, is 750 myr (McKinnon et al., 1997) through 0.04–0.06 km^3/yr (T=500 myr (Schaber et al., 1992; Phillips et al., 1992)) to 0.06–0.09 km^3/yr (T=300 myr (Strom et al., 1994)). These values of the flux are about an order of magnitude smaller that the average intraplate volcanic flux on Earth (e.g., Head et al., 1996).

7. Conclusions

Our analysis of the abundances, the areal and temporal distributions, and topographic configurations of the major volcanic units and features shown on the global geological map of Venus allow us to draw the following conclusions.

1) The main volcanic units (plains) embay the older tectonized units/terrains everywhere on Venus. This suggests a major change from the tectonically to volcanically dominated regimes at the earlier stages of the geologic history. At the later stage, both tectonics and volcanism operated broadly synchronously and were about equally important in the resurfacing.
2) The older volcanic units (psh, rp_1) tend to occur topographically lower areas, fill the regional lowlands, and embay the older and elevated tectonized units. These relationships suggest that a significant portion of the long-wavelength topography (the plateau-like highlands and regional lowlands) was produced at earlier stages of the geologic history and has remained stable since that time.
3) The varied volcanic landforms demonstrate certain types of spatial and stratigraphic associations (e.g., steep-sided domes and psh, long channels and rp_1) that are related to the mode and style of their formation.
4) Different styles of volcanism characterize specific groups/associations of volcanic landforms. Shield plains and associated steep-sided domes are consistent with shallow crustal melting and melt differentiation. Regional plains and the longer channels suggest voluminous eruptions due to massive decompression melting and high-effusion rate, but likely short-lived, eruptions. Lobate plains and related features may indicate multistage voluminous eruptions from large and discrete sources repeating during long time intervals.
5) The stratigraphic position of the specific groups/associations of volcanic landforms illustrates the evolution of the styles of volcanism through the visible geologic history of Venus.
6) The visible portion of the geologic history of Venus is characterized by pronounced evolutionary trends suggested by the progressive changes of volcanic styles, the role of volcanism and tectonics in resurfacing, and the history of the long-wavelength topography. This means that the geological evolution of Venus during the period of its history represented by the surface record was strongly non-linear and this requires the investigating of geodynamic models that are consistent with these conclusions.
7) Several important problems related to the evolution of volcanism on Venus still remain. What is the nature and mode of origin of tessera material? Is there any evidence, additional to the high D/H ratio (de Berg et al., 1991), for the presence of water in the geological past of Venus? What are the sources of material of regional plains? Is there evidence for individual flows on the surface of regional plains and what it may imply for the mode of formation of this unit? How do the small-scale topographic details correlate with morphology and what it may tell us about evolution of the local-scale topography? What is the thickness of the most important (psh, rp, pl) volcanic units? These problems can be addressed in the future with the help of in-situ measurements of composition (e.g., Venera-D mission planned by Russian Space Agency and EVE mission proposed to European Space Agency (Chassefiere et al., 2012)), high-resolution SAR images (meter scale) and topographic data (MOLA-scale resolution).

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