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# Beta Regio, Venus: Evidence for uplift, rifting, and volcanism due to a mantle plume

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**Abstract**

Geophysical data have led to the interpretation that Beta Regio, a 2000 × 25000 km wide topographic rise with associated rifting and volcanism, formed due to the rise of a hot mantle diapir interpreted to be caused by a mantle plume. We have tested this hypothesis through detailed geologic mapping of the V-17 quadrangle, which includes a significant part of the Beta Regio rise, and reconnaissance mapping of the remaining parts of this region. Our analysis documents signatures of an early stage of uplift in the formation of the Agrona Linea fracture belts before the emplacement of regional plains and their deformation by wrinkle ridging. We see evidence that the Theia rift-associated volcanism occurred during the first part of post-regional-plains time and cannot exclude that it continued into later time. We also see evidence that Devana Chasma rifting was active during the first and the second parts of post-regional-plains time. These data are consistent with uplift, rifting and volcanism associated with a mantle diapir. Geophysical modeling shows that diapiric upwelling may continue at the present time. Together these data suggest that the duration of mantle diapir activity was as long as several hundred million years. The regional plains north of Beta rise and the area east and west of it were little affected by the Beta-forming plume, but the broader area (at least 4000 km across), whose center-northern part includes Beta Regio, could have experienced earlier uplift as morphologically recorded in formation of tessera transitional terrain.


*Keywords:* Venus; Tectonics; Volcanism; Geological processes

## 1. Introduction

Beta Regio is a well expressed 2000 × 2500 km topographic rise in northern mid-latitudes of Venus cut by Devana Chasma, a deep tectonic valley (Figs. 1 and 2). It is one of a few highlands on Venus considered to be formed by lithosphere uplift driven by a hot plume (e.g., McGill et al., 1981; Senske et al., 1992; Phillips and Hansen, 1994; Stofan et al., 1995; Stofan and Smrekar, 2005; Smrekar et al., 1997; Rathbun et al., 1999). Several geophysical modeling studies of the plume process based on gravity and topography data generally confirmed the possibility of such a process and placed some important constraints on it (e.g., Kiefer and Hager, 1991, 1992; Moresi and Parsons, 1995; Nimmo and McKenzie, 1996; Moore and Schubert, 1997; Solomatov and Moresi, 1996; Vezolainen et al., 2003, 2004; Kiefer and Swafford, 2006). The studied area is part of the major Beta-Atla-Themis volcanic anomaly suggesting mantle upwelling in this region (e.g., Crumpler et al., 1993). Debates about the role and in some cases even the existence of mantle plumes on Earth has led some researchers to refute the general existence of plumes on Venus (e.g., Hamilton, 2005). This argument concentrates, however, mostly on the mantle diapir origin of venusian coronae and does not address domical uplifts such as Beta, Atla or Western Eistla. Recently Stofan and Smrekar (2005) considered a variety of mechanisms that have been proposed as alternatives to plumes on Earth. None of them was found to be as likely as a simple mantle plume model for the formation of topographic rises and coronae. The mantle plume origin of topographic rises and coronae of different sizes was also supported by Hansen (2002, 2003).

This paper concentrates on the results of the geologic mapping of a significant part of Beta Regio and the adjacent areas (Basilevsky, 2007). In this sense it resembles the analysis of

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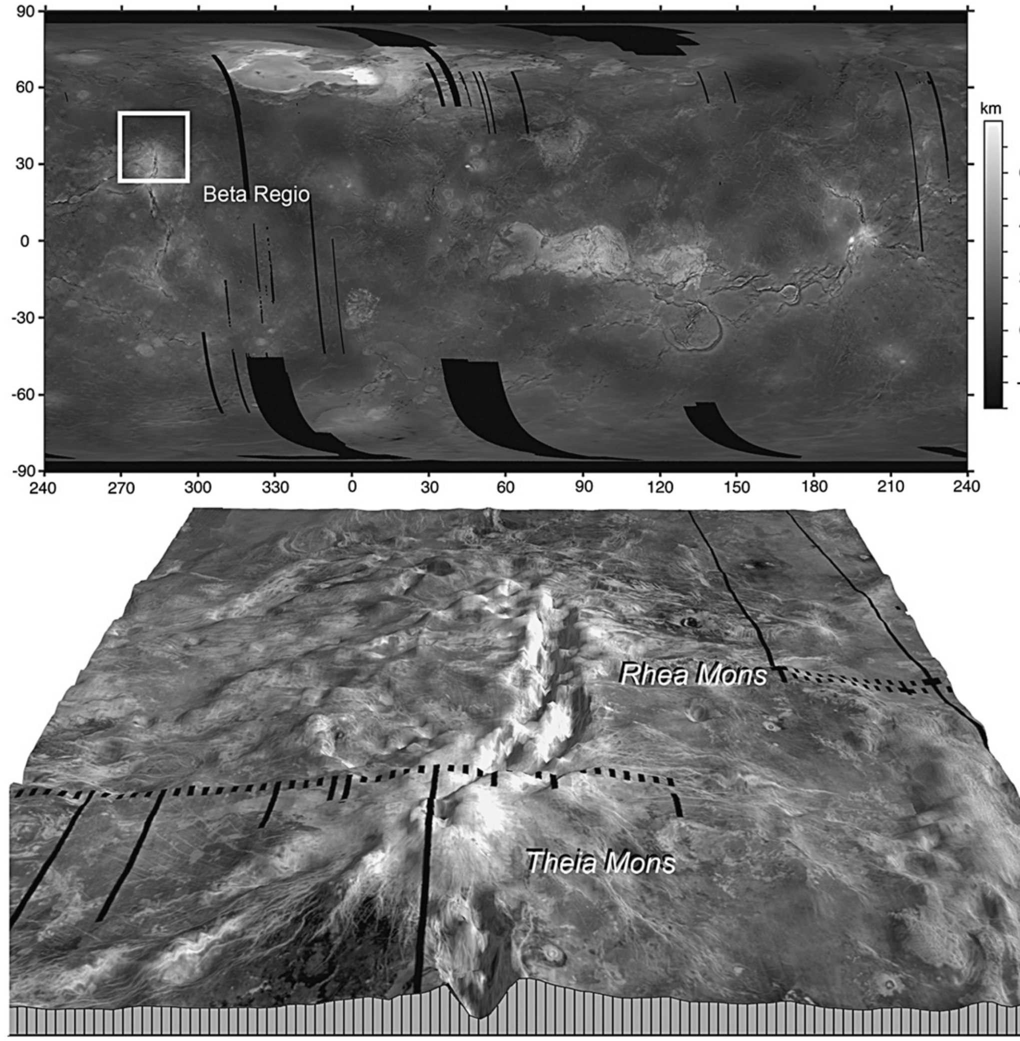


Fig. 1. Magellan-based global topography of Venus (top) and S to N perspective view of Beta Regio (bottom). White quadrangle in the top image outlines the study area.

Central Eistla Regio rise done by McGill (1998). Analysis of the mapping results has led us to documentation of observations indicating tectonic uplift of the Beta Regio structure, the establishment of a time sequence of material units and structures prior, during and possibly after formation of the uplift, and an estimation of the age of at least some of the uplift-related activities (Figs. 3 and 4). This geologic documentation and analysis is possible because of the lack of significant erosion and sedimentation on Venus, processes which seriously complicate deciphering of past episodes of the geologic history of Earth.

In our geologic mapping we used the traditional methods of geologic unit definition and characterization for the Earth (for example, American Commission on Stratigraphic Nomenclature, 1961) and planets (for example, Wilhelms, 1990) appropriately modified for radar data (Tanaka, 1994). We defined units and mapped key relations using the full resolution Magellan synthetic aperture radar (SAR) data and transferred these results to the base map compiled at a scale of 1:5 million (Figs. 2 and 3). Further discussion of these approaches and related issues can be found in Basilevsky and Head (2000a) and Hansen (2000).

## 2. Short history of Beta Regio studies

Beta Regio is one of the first features discovered on the surface of Venus in early Earth-based radar observations (e.g., Goldstein, 1965; Goldstein et al., 1978). In 1975 the Venera 9 probe landed on the north-eastern flank of the Beta rise (Moroz and Basilevsky, 2003). The gamma spectrometer measurements showed that in its contents of K, U, and Th, the surface material at the landing site is close to terrestrial basalts (Surkov et al., 1976). The Pioneer–Venus radar studies showed Beta Regio in global context. Together with later Earth-based radar observations they showed that Beta Regio is an area of interrelated rifting and volcanism (Masursky et al., 1980; McGill et al., 1981; Schaber, 1982; Campbell et al., 1984; Stofan et al., 1989). Devana Chasma was interpreted to be a part of a global system of rifts resembling terrestrial continental rifts (McGill et al., 1981; Schaber, 1982). It was found that Beta Regio has a prominent positive gravity anomaly, and that

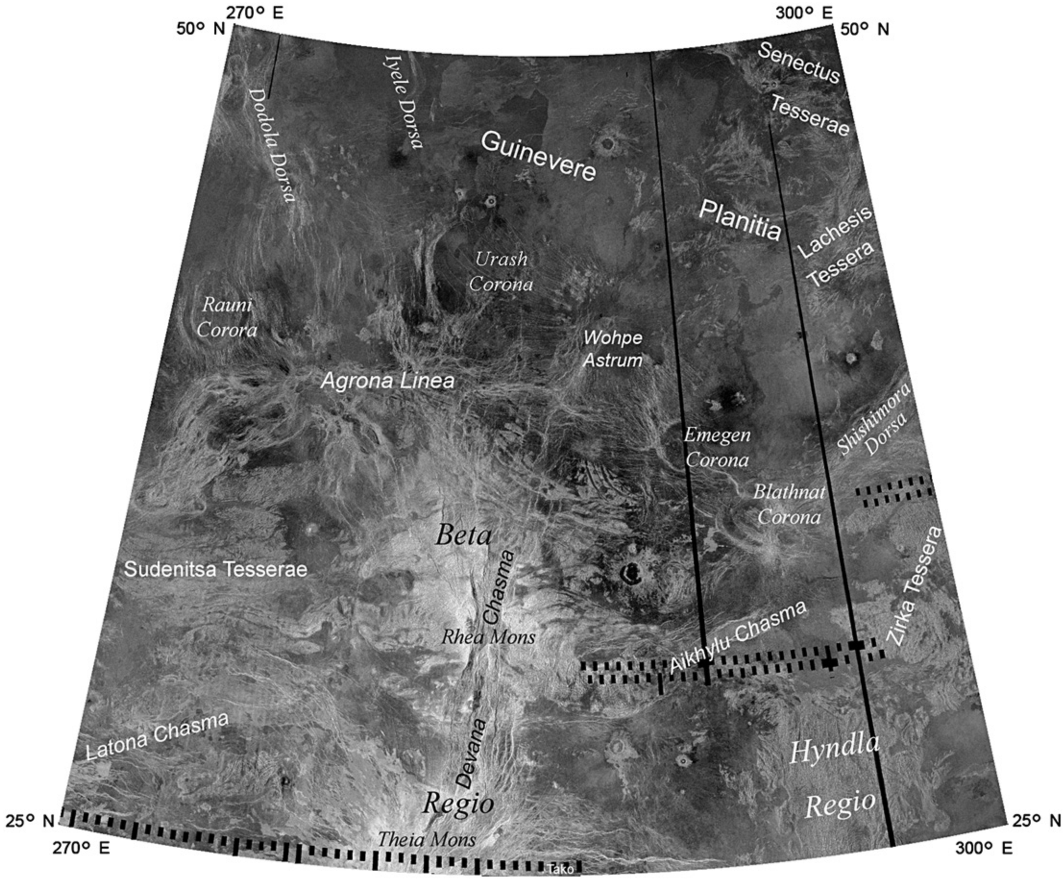


Fig. 2. Magellan SAR image of the V-17 quadrangle with the names of physiographic features according to http://planetarynames.wr.usgs.gov/.

the ratio of the anomaly to topographic height indicates that surface load compensation occurs at a depth of $\geqslant$400 km. This, in turn, was interpreted as evidence of dynamic support by a hot mantle plume (Phillips and Malin, 1983). The northern part of Beta Regio was covered by the Venera 15/16 radar survey (Barsukov et al., 1984; Kotelnikov et al., 1989). The analysis of the acquired SAR images having resolution 1–2 km suggested that the Beta rise is essentially a tectonic feature (Sukhanov, 1992).

Magellan observations provided the most complete and high-resolution data for Beta Regio including the 120–220 m/px SAR images (Saunders et al., 1992). The global Venus tectonic overview by Solomon et al. (1992) as well as a more regional study by Senske et al. (1992) confirmed the early interpretation of Theia Mons as a large shield volcano superposed on the Devana Chasma rift (e.g., Masursky et al., 1980). Rhea Mons was interpreted as an area of tectonically deformed terrain with inclusions of plains of possible volcanic origin. The southern half of Beta Regio was covered in the study of Ivanov and Head (2001a), who, based on the analysis of the Magellan data, geologically mapped a global geotraverse at 30° N latitude. Their work had a mostly stratigraphic and partly structural emphasis and thus is similar in approach to our V-17 mapping project. The V-17 area is in the central part of a broad region, within which Ernst et al. (2003) mapped graben–fissure systems.

## 3. Physiography

The Beta Regio quadrangle (V-17) extends from 25° to 50° north latitude and from 270° to 300° east longitude (Figs. 2 and 3). Its southern part covers a significant part of the generally domical rise of Beta Regio as well as the northern part of the less prominent and generally flat-topped rise of Hyndla Regio. The northern part of V-17 is occupied by the lowland plains of Guinevere Planitia, the majority of which is close to or below the 6051 km datum. Within the plains but close to the northeastern foot of the Beta rise there is a radiating system of radar-bright lineaments and grooves centered at Wohpe Tholus (informally called as Wohpe Astrum). The two summits of the Beta Regio rise, Rhea Mons, and Theia Mons, both reach altitudes more than +5 km above the datum. Rhea Mons is completely within the V-17 quadrangle while only the northern part of Theia Mons is within the quadrangle. From north to south the Beta Regio rise is cut by the very prominent topographic trough of Devana Chasma, the deepest parts of which locally reach the altitude levels of the Guinevere Planitia plains. At the eastern and western flanks of Beta Regio, correspondingly, there occur the troughs of Aikhylu Chasma and Latona Chasma, both much less prominent topographically than Devana Chasma. This cluster of chasmata resembles classical cases of the rift–rift–rift triple junctions on Earth (e.g., Condie, 1998). The northern base of the Beta rise is marked by the fracture belt of Agrona Linea.

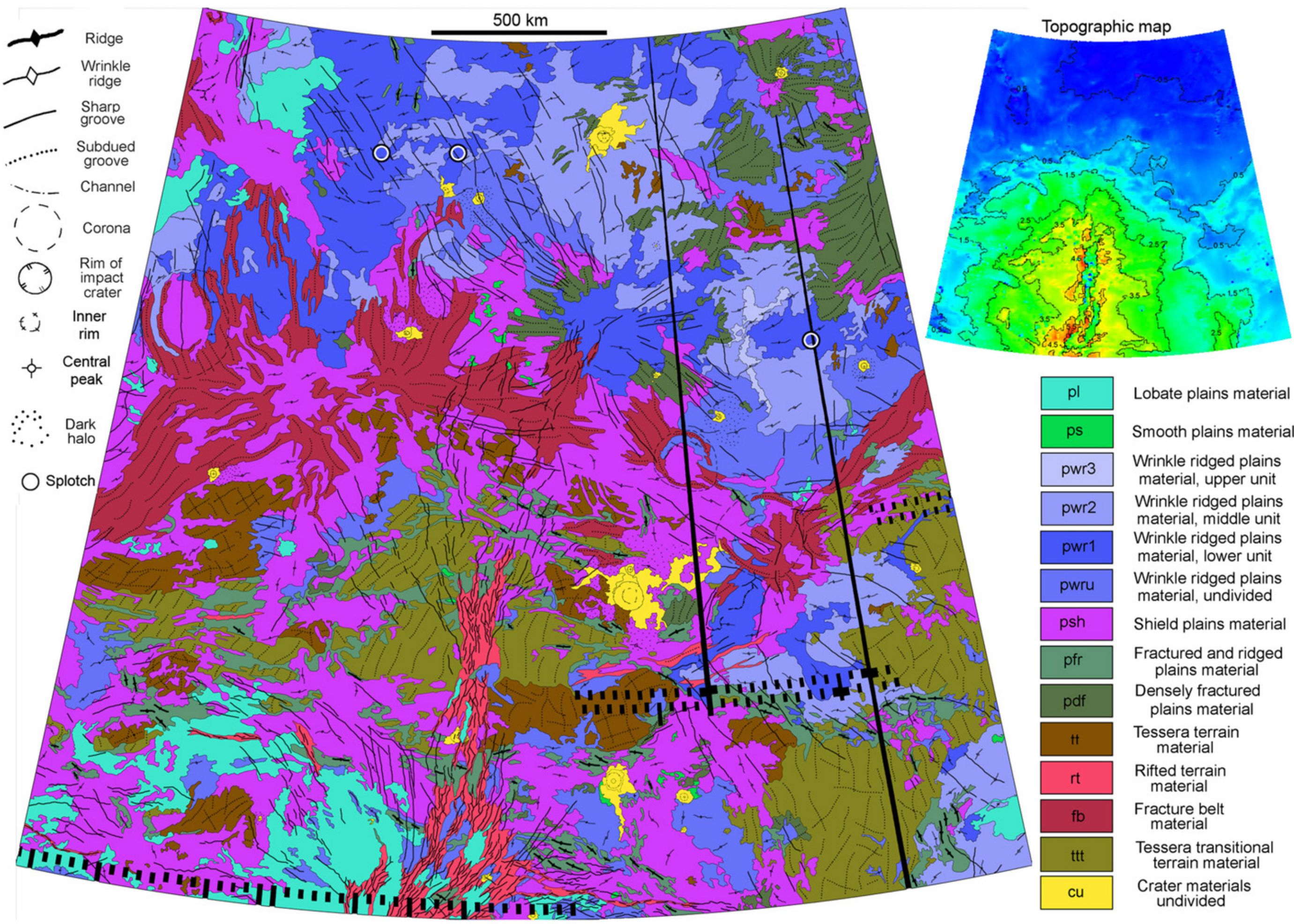


Fig. 3. Geologic map of the V-17 quadrangle and the color-coded Magellan-based schematic topographic map of the quadrangle (upper right). Because of the small size of this figure all three subunits of crater materials are shown with one color.

Both within the upland and lowland parts of the quadrangle there are several isolated massifs of tesserae: Senectus, Lachesis, Zirka, and Sudenitsa, and several unnamed tessera massifs (Fig. 2). Only a subset of them are blocks of tessera terrain, while others are composed of other geologic units that somewhat resemble normal tessera terrain (see below). Within the V-17 quadrangle there are also three topographically positive deformation belts: Dodona Dorsa, Iyele Dorsa, and Shishimora Dorsa, and four coronae: Rauni Corona, Emegen Corona, Urash Corona, and Blathnat Corona.

## 4. Geological units and their time sequence

Two geologic processes, volcanism and tectonism, have mostly determined the observed morphology of the region under study. Volcanism was found to be the dominant process of crustal formation on Venus (Head et al., 1992), in general, and in the formation of the observed geologic units in this map area, in particular. Tectonic activity has modified some of these materials (e.g., Solomon et al., 1992; Squyres et al., 1992) in a variety of modes, and in places deformation is so extensive, as in the case of tessera terrain, that the deformational features become part of the definition of the material unit (see also Tanaka, 1994; Scott and Tanaka, 1986; Campbell and Campbell, 2002; Hansen and DeShon, 2002; Ivanov and Head, 2004a; Stofan and Guest, 2003; Brian et al., 2005; Bleamaster and Hansen, 2005). Impact cratering has locally influenced some areas in the quadrangle but in general has not been an important process (Fig. 3). Aeolian processes and downslope mass movement did operate within the V-17 quadrangle region but their signatures here are insignificant (Greeley et al., 1992; Malin, 1992). Atmosphere–surface interactions are apparently visible within the V-17 quadrangle in the form of areas of high reflectivity and low emissivity above approximately +4 km altitude level (e.g., Klose et al., 1992).

Venus has a relatively small (∼1000) number of impact craters on its surface. This small number makes it possible only to estimate a mean surface age of the planet and mean ages of a few globally distributed geologic units (e.g., Schaber et al., 1992; Phillips et al., 1992; Namiki and Solomon, 1994; Price and Suppe, 1994). The most recent estimate of the mean surface age of the planet is ∼750 m.y., but values between 300 m.y. and 1 b.y. are considered possible (McKinnon et al., 1997). This estimate is practically equal to the estimate of the global mean for the so-called regional plains, which in the

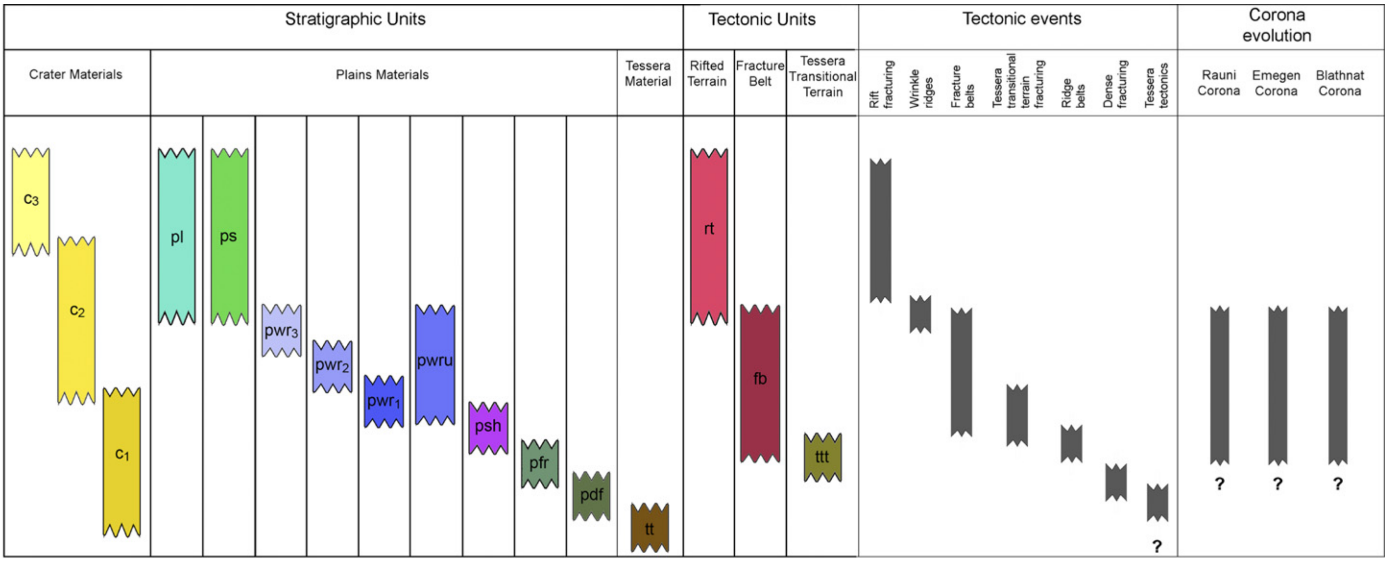


Fig. 4. Correlation chart of material and tectonic units for the V-17 quadrangle. The saw-like appearance of the upper and lower boundaries of the units symbolizes some uncertainty in the position of these boundaries in time.

stratigraphy described below correspond to the combination of units psh and pwr (Basilevsky and Head, 2000a, 2006).

It is also obvious that crater areal densities on different geologic units within the V-17 quadrangle cannot be used for estimating their relative ages (Miller and Kahn, 1962). Therefore, we focused on the analysis of crosscutting, embayment, and superposition relationships among the units and structures, and as an additional tool we used the degree of preservation of crater-associated radar-dark haloes. The latter approach provides the possibility of assessing if a given crater formed within the first or the second halves of post-regional-plains time (Izenberg et al., 1994; Basilevsky and Head, 2002a; Basilevsky et al., 2003) and then from the analysis of age relations between the crater and surrounding features, to assess their age.

In the V-17 quadrangle we have mapped 8 geologic material units and divided two of them into subunits (Figs. 3 and 4). Typically the mapped units and subunits maintain some specific morphology within the study area, but morphologic similarity alone was not considered as a sufficient basis for unit identification. Lateral correlations and age relations with other units and structures have always been used as a criterion. In the case of the crater materials unit, we used the degree of preservation of crater-associated dark halo to subdivide it into two subunits and one more subunit of crater materials has been identified based on age relations with other neighboring geologic units.

We have mapped tectonic structure independent of geologic units, but in some cases tectonic features are such a pervasive part of the morphology of the terrain that it becomes part of the definition of a unit at this scale. For example, our tessera unit (tt) and densely fractured plains unit (pdf) are so saturated with faults that at the Magellan SAR resolution the undeformed materials of these units are practically invisible. Their mapping on Venus as material units has been already accepted by the USGS, see for example, maps of Bleamaster and Hansen (2005) and Brian et al. (2005).

In some cases structures have been used as one of the steps in the unit identification even if the density of structures was not very great. For example, our unit of plains with wrinkle ridges (pwr) is characterized by these ridges in practically all of its mapped localities. The undeformed material of the unit is easily seen and it is obvious that wrinkle ridges are superposed on it. But the association of these ridges with this unit is so typical that we used their presence as a part of the unit definition. In this we also followed the examples of already published maps by Bridges and McGill (2002), and Campbell and Campbell (2002) (e.g., their ridged plains units). A situation similar to this is our unit of fractured and ridged plains (pfr): in most localities of it, broad ridges morphologically very different from wrinkle ridges are observed.

In some areas in V-17, there are structural zones in which it is possible to understand their age relations with neighboring units, but because of the high density of the structures it is difficult or impossible to judge what material is deformed within the zones. In these cases we identified tectonic units. Three tectonic units have been identified within V-17 (Figs. 3 and 4) and will be characterized below.

This approach of unit identification is followed by the vast majority of investigators mapping Venus (see review in Basilevsky and Head, 2000a) although in reference to specific units and structures, differences of opinion exist (for example, DeShon et al., 2000; Hansen, 2000; Ivanov and Head, 2001a, 2001b; Rosenberg and McGill, 2001; Bridges and McGill, 2002; Campbell and Campbell, 2002; Hansen and DeShon, 2002). Below we summarize the stratigraphic units and structures and their relations.

### 4.1. *Tessera material unit (tt)*

This unit is interpreted as the stratigraphically oldest unit in the quadrangle. It is embayed by most of the other units within the map area. Tessera terrain is relatively radar bright,

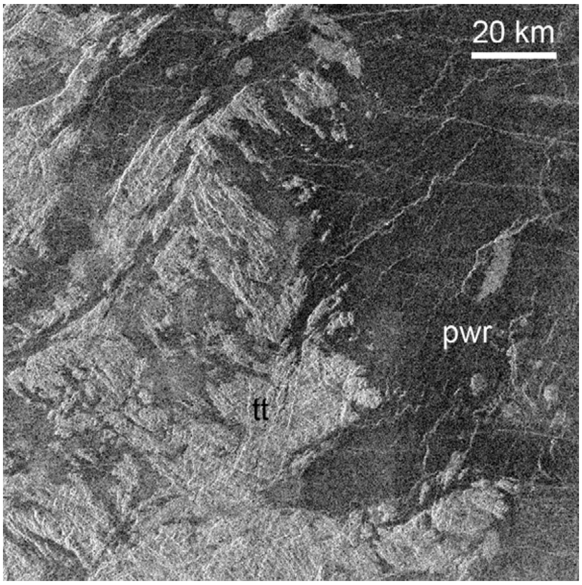


Fig. 5. Tessera terrain (tt) embayed by plains with wrinkle ridges (pwr). Image is centered at 34.5° N, 275.5° E.

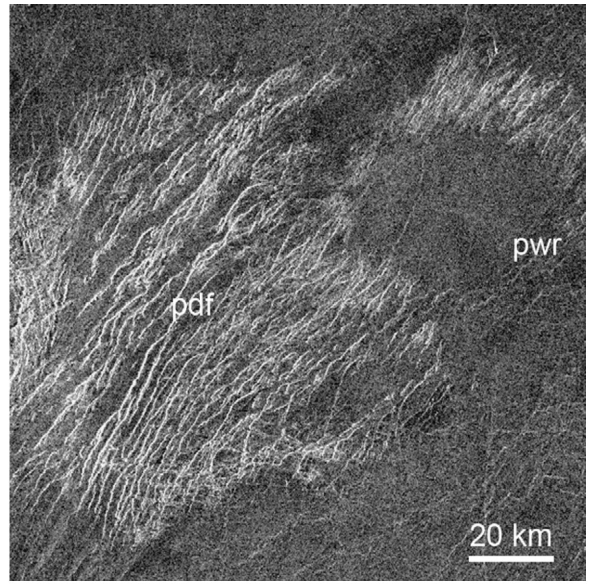


Fig. 6. Densely fractured plains (pdf) locally embayed by plains with wrinkle ridges (pwr). Image is centered at 44.5° N, 290° E.

consists of at least two sets of intersecting ridges and grooves (Fig. 5), and is a result of tectonic deformation of some precursor terrain (Barsukov et al., 1986; Basilevsky et al., 1986; Bindschadler and Head, 1991; Sukhanov, 1992; Solomon et al., 1992; Hansen et al., 1997). Within V-17, as within other regions of Venus, ridges and grooves on the tessera surface show a spectrum of spacing from a few hundred meters to several kilometers with wider features consisting of clusters of smaller ones. Tessera terrain is observed as outliers among the younger units (Fig. 3). Tessera terrain occupies ∼5% of the quadrangle, slightly smaller than the global abundance (8%) of this unit (Ivanov and Head, 1996).

### *4.2. Densely fractured plains material unit (pdf)*

This unit is next in the time sequence. It is characterized by relatively flat surfaces on a regional scale, and by swarms of parallel and subparallel lineaments, sometimes resolved as fractures (Fig. 6). Typical spacing of the lineaments is less than 1 km, although due to later emplacement of younger materials a greater lineament spacing is locally observed. The general flatness of unit outcrops suggests that it was plains. Based on analogy with the younger and less deformed plains of Venus it could be volcanic plains made of mafic lavas (Basilevsky et al., 1997; Basilevsky and Head, 2000a). Densely fractured plains are embayed by almost all younger material units except the youngest units pl and ps, with which they are not observed in direct contact. In rare occurrences where pdf plains and tessera are in direct contact the first one embays the second. Densely fractured plains predominantly occur in the north-eastern part of quadrangle composing Senectus and Lachesis Tesserae (Figs. 2 and 3). Small patches of pdf plains are also observed in other parts of the study area. Pdf plains occupy ∼5% of the quadrangle, close to, or slightly greater than its 3–5% global abundance estimated by Basilevsky and Head (2000a).

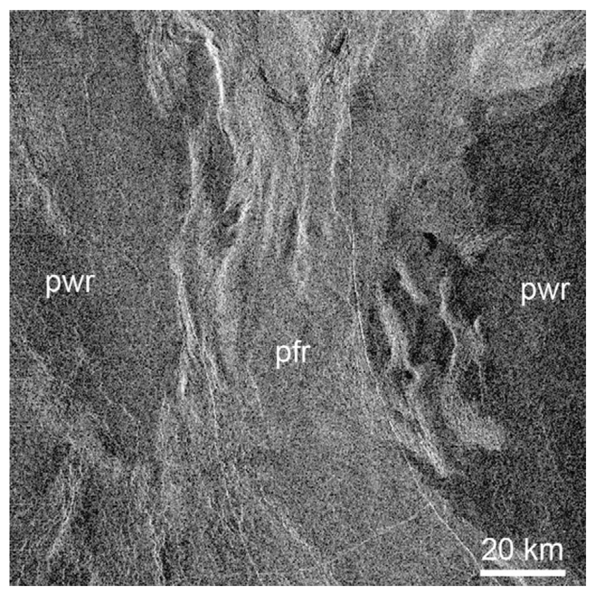


Fig. 7. Fractured and ridged plains (pfr) embayed by plains with wrinkle ridges (pwr). Unit pfr here is folded into broad ridges trending generally north. Image centered at 27° N, 297.5° E.

### *4.3. Fractured and ridged plains material unit (pfr)*

This unit is composed of medium-bright material with a predominantly smooth surface (Fig. 7). In this aspect, unit pfr is similar to the younger units pwr (middle subunit) and pl, that bear morphologic evidence that they are composed of mafic lavas. Thus it is logical to suggest that unit pfr is also composed of mafic lavas. But contrary to units pwr and pl, the pfr unit is commonly deformed by broad (3–10 km wide) ridges tens of kilometers long, thus forming so-called ridge belts (Fig. 3). Unit pfr embays the older units tt and pdf and is embayed by the younger units psh, pwr and pl. McGill and Campbell (2006) studied age relations between the ridge belts and sur-

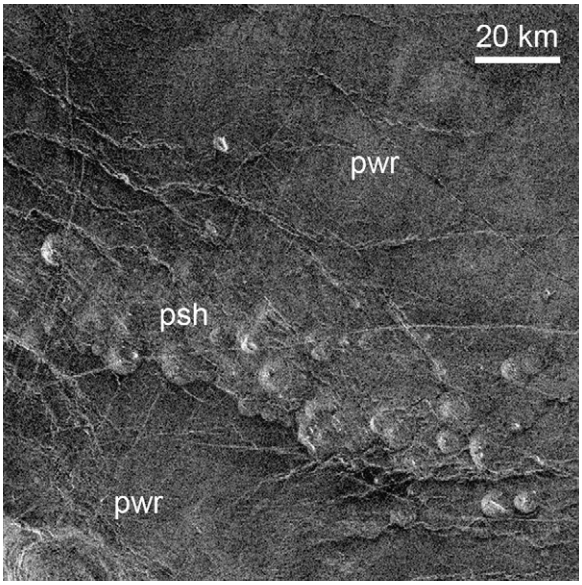


Fig. 8. Shield plains (psh) surrounded by plains with wrinkle ridges (pwr). The southern boundary of unit psh is sharp while the northern is gradual. Most shields appear deformed by wrinkle ridges. Image centered at 37° N, 292.5° E.

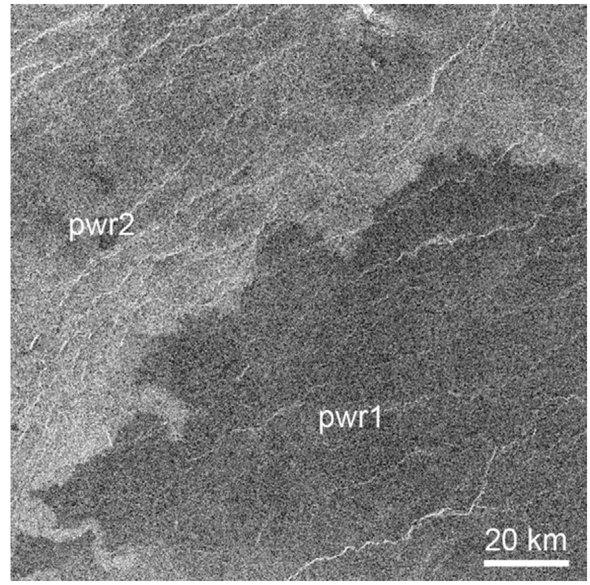


Fig. 9. The lower (pwr1) and the middle (pwr2) units of plains with wrinkle ridges of Guinevere Planitia. Both units are deformed by the same network of wrinkle ridges. Protuberances of pwr2 onto pwr1 are seen in the lower left. Image centered at 48° N, 283.5° E.

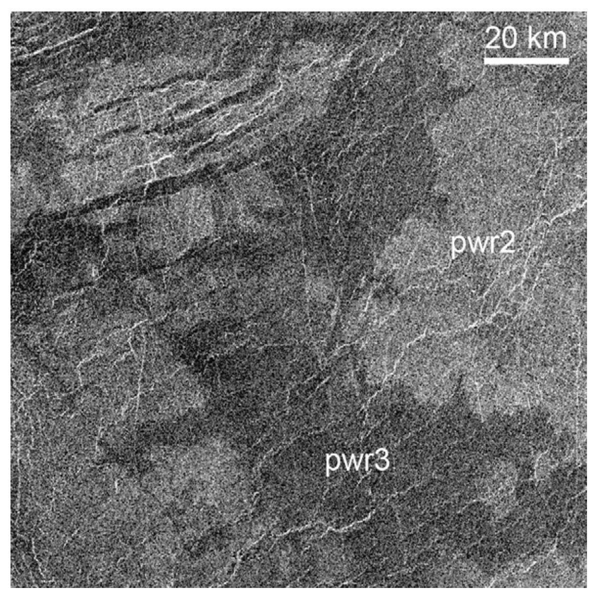


Fig. 10. Upper subunit of plains with wrinkle ridges (pwr3) embaying subunit pwr2 and filling troughs in it. Image centered at 40° N, 293° E.

rounding regional plains (correlative in this case to our units pwr and partly psh) in ten localities outside the V-17 quadrangle. In addition to traditional geologic analysis they considered the radar-scattering behavior of the ridge belt material and the surrounding plains and concluded that the belt material predates the regional plains. Unit pfr composes ∼5% of the V-17 area, similar to the 3–5% global abundance estimated by Basilevsky and Head (2000a).

### 4.4. Shield plains material unit (psh)

Next after the fractured and ridged plains is the material of shield plains. Typically it is of intermediate radar brightness and characterized by abundant, gently-sloping shield-shaped features a few kilometers in diameter, often with summit pits (Fig. 8). The shields are interpreted to be of volcanic origin (Aubele and Slyuta, 1990; Guest et al., 1992; Head et al., 1992; Aubele, 1994, 1995; Crumpler et al., 1997; Crumpler and Aubele, 2000). Although typically shield plains are embayed by plains with wrinkle ridges [globally, Kreslavsky and Head (1999); Ivanov and Head (2004b); and in this area, Ivanov and Head (2001a) and this study] and are wrinkle ridged, in a few places in the quadrangle, separate shields and shield clusters are locally superposed on wrinkle ridges. A similar situation is also observed in other areas of Venus (Addington, 2001; Ivanov and Head, 2004b). The psh unit is widely distributed mostly in the south-western half of the quadrangle and is locally present in its other parts. Its total abundance within V-17 quadrangle is ∼26%, significantly larger than the 10–15% estimates of global occurrence of this unit (Basilevsky and Head, 2000a).

### 4.5. Wrinkle ridged plains material unit (pwr)

Next is the unit represented by the material of wrinkle-ridged plains (pwr). This unit is composed of morphologically smooth, homogeneous plains material of intermediate-low to intermediate-high radar brightness complicated by narrow wrinkle ridges (Figs. 9 and 10). The unit with similar morphology occupying similar position in local stratigraphic columns is mapped in other regions of Venus under different names, e.g., ridged plains (Bridges and McGill, 2002; Campbell and Campbell, 2002) or regional plains (e.g., Brian et al., 2005). Within the study area as in other places on Venus, the wrinkle ridges typically are less than 1 km wide and tens of kilometers long, but locally they may be smaller or larger. The unit is interpreted to be plains of volcanic origin deformed by wrinkle ridges (Head et al., 1992; Basilevsky et al., 1997;

Basilevsky and Head, 1998, 2000a). The volcanic (lava) origin of the pwr plains globally and within V-17 is supported by flow-like morphology of one of the subunits of this unit (pwr2). The landing site of the Venera 9 lander (31.01° N, 291.64° E) is within the V-17 quadrangle and the majority of the landing ellipse is occupied by pwr plains so it is very probable that the interpreted basaltic composition for the surface material (Surkov et al., 1976) is characteristic of the unit pwr.

Within the study area we subdivided unit pwr into three subunits of different age (pwr1, pwr2, and pwr3) and in some places where we could not determine the correspondence of the pwr material to one of these subunits, one more subunit (pwru = undivided) was mapped (Fig. 3). The lower unit (pwr1) generally has a relatively low radar albedo (Fig. 9). The middle subunit (pwr2) generally has a relatively high radar albedo and lobate boundaries indicative of its superposition on pwr1 (Figs. 9 and 10). The upper subunit (pwr3) has been observed only in one locality, north-east of Emegen Corona, where it embays into gaps and graben within units pwr2 (Fig. 10). Its material is relatively dark, significantly darker than pwr2 and noticeably darker than pwr1. In its smooth and dark surface, subunit pwr3 resembles unit ps (see below), but differs from the latter in presence of wrinkle ridges forming a network in common with wrinkle ridges of the adjacent areas of subunits pwr1 and pwr2.

Unit pwr occupies ∼31% of the study area, significantly smaller than its global abundance (50–60%) estimated by Basilevsky and Head (2000a). Abundances of the pwr subunits within V-17 are as follows: pwr1 ∼11%, pwr2 ∼11%, pwr3 ∼0.2%, and pwru ∼9%. Pwr plains dominate in the north-eastern part of the V-17 area and form isolated fields in the rest of the study area. In the following description sometimes we call a suite of pwr + psh units as regional plains.

### *4.6. Smooth plains material unit (ps)*

This is one of the two youngest non-crater material units. Smooth plains material (ps) is smooth and radar dark (Fig. 11). It is observed in the form of fields of plains of 10 to 60 km across typically of planimetrically irregular outlines, and sometimes with rather long protuberances. Similar fields have been called by Head et al. (1992) as "amoeboids," and interpreted as specific lava flows. Pits about 1 km in diameter are seen sometimes within the ps fields and are probably volcanic vents. Smooth plains material is usually superposed on unit psh, and in some cases on units pfr, pwr and tectonic unit fb (see below). Two fields of ps plains are superposed by the 47 km crater Truth (28.68° N, 287.75° E) and the 22 km crater Nalkovska (28.14° N, 289.95° E), both having faint dark haloes. Within the V-17 quadrangle unit ps occupies only ∼0.15% of the area. Basilevsky and Head (2000a) did not estimate the global abundance of unit ps. They estimated only the combined global abundance (10–15%) of units ps and pl (see below). In the area of our study, unit ps forms about 20 fields. Nearly half of them are concentrated in the area north-east of Emegen Corona (Fig. 3).

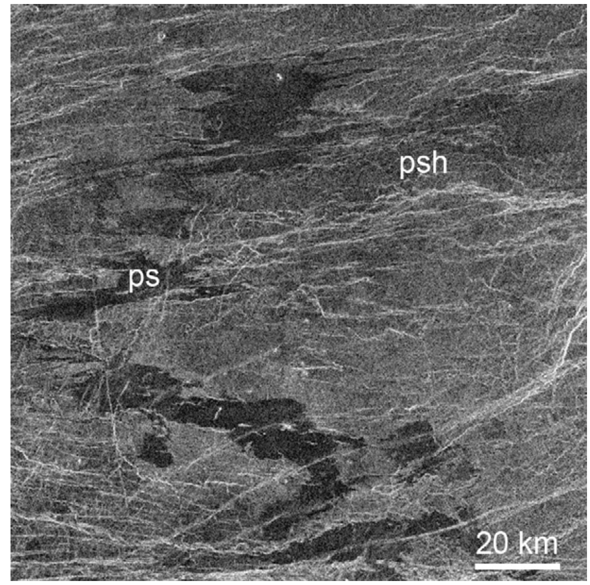


Fig. 11. Small fields of smooth plains (ps) among the wrinkle ridged and fractured shield plains (psh). Image centered at 40.3° N, 285° E.

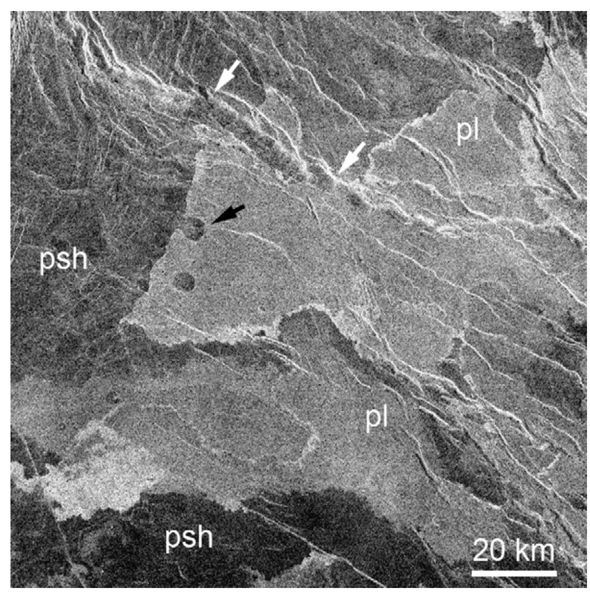


Fig. 12. Lobate plains (pl) on the western slope of Theia Mons. Pl lavas overlie and embay unit psh (black arrow shows one of the embayed shields). Both pl and psh units here are cut by rift-associated faults (white arrows). Image centered at 26.5° N, 177.5° E.

### *4.7. Lobate plains material unit (pl)*

The second of the two youngest non-crater material units, lobate plains material (pl), appears morphologically smooth at Magellan SAR resolution. It is mostly radar bright with darker subareas forming together a pattern of superposition of many individual flows (Fig. 12). The prominent flow-like texture and association with obvious volcanic constructs (within V-17 it is Theia Mons) prove that unit pl is composed of lavas (Head et al., 1992; Crumpler and Aubele, 2000). The Venera 14 landing site, although outside V-17, was located within a field of unit pl (Basilevsky et al., 1997; Basilevsky and Head, 2000a) and

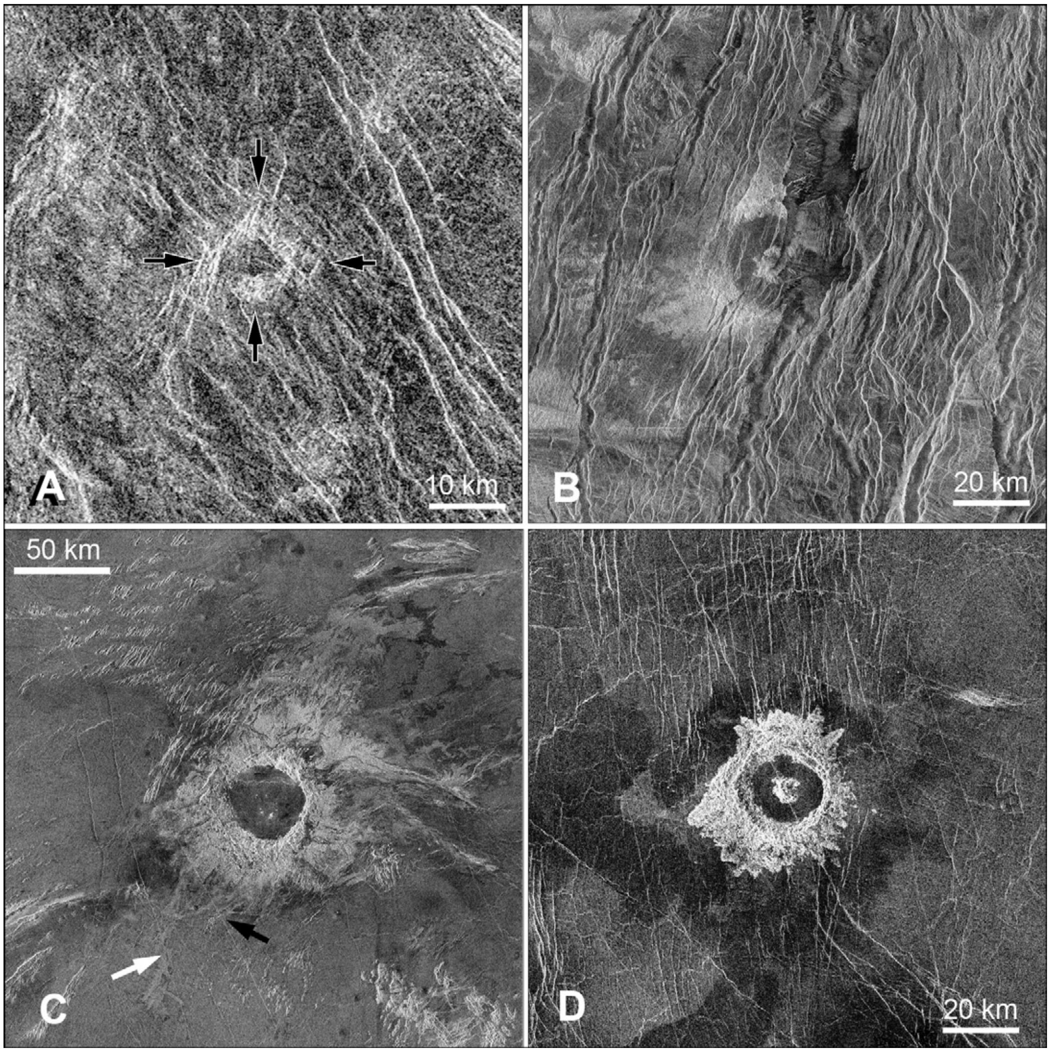


Fig. 13. Examples of impact craters in the Beta Regio quadrangle: (A) The crater Aigul ($D = 6$ km, 38.2° N, 280.4° E) represents subunit $C_1$, its rim protrudes through the psh lavas and is deformed by the pdf-style fractures; (B) The crater Balch (40 km, 29.9° N, 288.48° E) represents subunit $C_2$, has no radar-dark halo and is cut by graben of the Devana Chasma rift; (C) The crater Deken ($D = 48$ km, 47.13° N, 282.9° E) represents subunit $C_2$, has a faint radar-dark halo, and its floor is deformed by a wrinkle ridge; (D) The crater Zvereva ($D = 22.9$ km, 45.36° N, 283.12° E) represents subunit $C_3$, has a clear radar-dark halo, and is cut by a fault (see text).

X-ray fluorescence analysis of the surface material at the site showed a composition close to tholeitic basalt (Surkov, 1997). Unit pl embays and is superposed on all other non-crater material units except unit ps with which unit pl is not in contact. Within unit pl, at the flanks of Theia Mons, there are two craters with faint haloes. These are the 13-km impact crater Raisa (27.5° N, 280.3° E) and the 11 km crater Tako (25.11° N, 285.27° E). The faint halo of crater Raisa is seen on the nearby "windows" of pwr plains and on one of the pl flows, while another pl flow significantly floods the crater. Crater Tako is superposed on pl lavas. Unit pl is locally cut by some young fractures, mostly by those associated with the Devana Chasma rift. Unit pl occupies ~5% of the V-17 area. This is about half or smaller than the combined global abundance of units pl and ps estimated by Basilevsky and Head (2000a) as 10–15%. Within V-17 most of unit pl is on the slopes of Theia Mons (Fig. 3).

### 4.8. Impact crater material unit (C)

Within the V-17 quadrangle there are 25 impact craters and three splotches (Schaber et al., 1992, 1998). Based on age relations of the craters with regional (psh + pwr) plains and on the degree of preservation of the crater-associated radar-dark halo, we subdivided the craters into three age subunits: a lower one ($C_1$)—pre-regional-plains craters; a middle one ($C_2$)—post-regional-plains craters with a faint or no halo; and an upper one ($C_3$)—post-regional-plains craters with a clear halo (Fig. 13). According to Basilevsky and Head (2002a), craters with a faint or no halo were formed within the first half of the post-regional-plains time period, while craters with clear haloes formed in the second half of this period. Below we use this halo type vs age dependence to date some geologic units and features.

Among the 25 craters of the V-17 quadrangle, one was classified as representing the lower unit $C_1$ (crater Aigul, Fig. 13A),

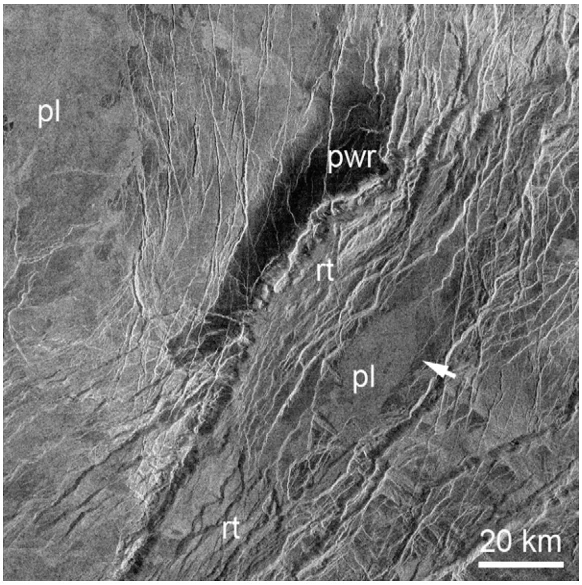


Fig. 14. Area of the rifted terrain tectonic unit (rt) which is part of Devana Chasma close to the summit of Theia Mons volcano. Rift-associated fractures cut units pl and pwr east of Devana Chasma and locally are flooded by pl lavas inside the Devana Chasma. Image is centered at 27° N, 282° E.

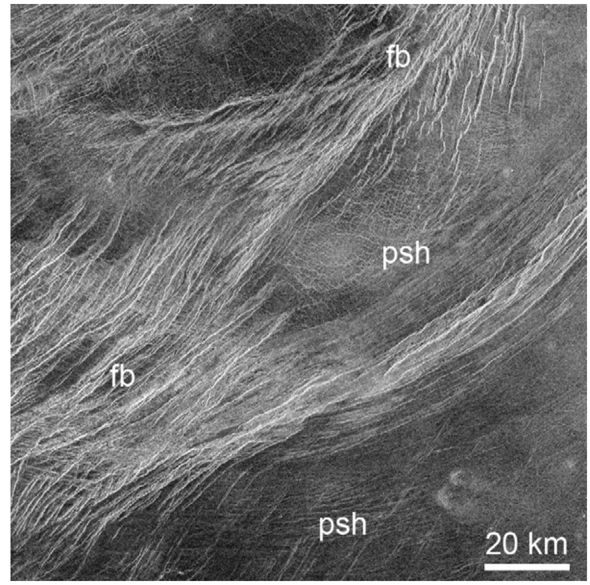


Fig. 15. Area of the fracture belt tectonic unit (fb), part of the Agrona Linea system of fracture belts. Unit fb is embayed by the psh unit (center of the image), and locally part of fb structures cut unit psh (upper right). Image is centered at 37.5° N, 275° E.

twelve as the middle unit $C_2$ (Figs. 13B and 13C), and twelve as the upper unit $C_3$ (Fig. 13D). Splotches, which are radar-dark spots without a visible crater inside (Schaber et al., 1992), are similar in their darkness to the clear crater haloes, so we consider them as contemporaneous to subunit $C_3$.

## 5. Structures and structural units

Tectonic features, observed and mapped within the quadrangle, show evidence that some are of extensional origin while others are contractional. Long and short linear fractures and sometimes paired and facing scarps interpreted to be graben are seen in practically all parts of the quadrangle. Their highest concentration is within and nearby Devana Chasma. The places saturated with fractures and graben have been mapped as tectonic unit ***rifted terrain (rt)***. Rift faults are typically several tens of kilometers long, with the longest being 100–150 km long. Fractures and graben of the rifted terrain are typically of variable width, ranging from about a hundred meters (limit of resolution) to several kilometers (Fig. 14). A few graben, including one which cuts the 40 km crater Balch (Fig. 13B), are up to 15–20 km wide. Quite often the widths of individual faults are variable. The rt fractures and graben are planimetrically anastomosing and this, together with variability in their width, makes the morphology of this unit very distinctive and recognizable. The rt faults deform all material units of the quadrangle including the youngest ps and pl units. Locally the rt faults are flooded by the pl lavas. The latter is especially typical of Theia Mons. The morphology of the rt faults (open fracture and graben) in combination with their anastomosing planimetric pattern and variable width imply an extensional origin. The rt tectonic unit occupies ∼2.5% of the quadrangle area, mostly in the N–S trending axial zone of Beta Regio rise (Fig. 3).

Young fractures and graben cutting practically all material units of the study area are also seen without any direct association with the Devana Chasma rift. These faults typically are long (tens to a few hundred kilometers), planimetrically linear or slightly arcuate, with their width being a few hundred meters to 1 km along the fault (Fig. 13D). These fractures are broadly contemporaneous with the structures of tectonic unit rt.

Five impact craters show clear age relations with young faults. Four of them, Deken (41.13° N, 288.48° E), Zvereva (45.36° N, 283.12° E), Balch (29.9° N, 282.91° E), and Sanger (33.77° N, 288.56° E), are cut (themselves or their ejecta) by relatively young faults. The fifth crater Olga (26.1° N, 283.8° E) is partly superposed on the young faults and is cut by another part of them. Craters Balch, Deken and Olga belong to subunit $C_2$, while craters Zvereva and Sanger, to subunit $C_3$. The faults that cut craters Deken and Zvereva are part of the Wohpe Astrum radiating system. The faults in contact with craters Balch, Olga and Sanger are structures of the Devana Chasma rift zone.

Within the quadrangle there are linear zones saturated with faults, which themselves are linear, or arcuate, or slightly anastomosing. These faults are typically tens of kilometers long and several hundred meters wide. Their trends are parallel or oblique to the trends of these zones so the faults are often mutually intersecting (Fig. 15). These zones have been mapped as a *tectonic unit of* ***fracture belts (fb)***. The fracture belts whose faults are often represented by open fractures and graben are considered in the literature as zones of extensional deformation close in origin to the zones of rifted terrain (Hansen et al., 1997; Banerdt et al., 1997; Basilevsky and Head, 2000b, 2002b). Structures of the tectonic unit fb cut material units tt, pdf and pfr. They are embayed by units psh and pwr but some of the fb faults cut psh and pwr. Lavas of the pl and ps units, when in contact, embay fracture belts, but in some cases the fb faults may be

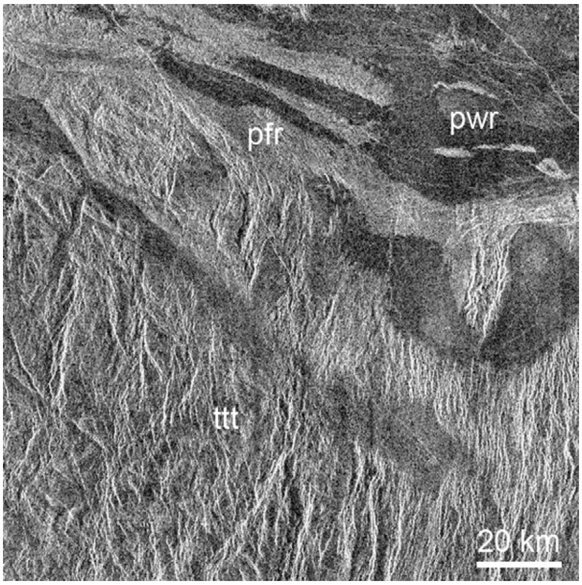


Fig. 16. Tessera transitional terrain (ttt) formed by fracturing of unit pfr. Both ttt and pfr are embayed by plains with wrinkle ridges (pwr). Image is centered at 28.5° N, 295° E.

the source of small fields of pl lavas. Within the V-17 quadrangle fracture belts occupy ∼9% of the area, being concentrated within the 35–40° latitude zone forming Agrona Linae and Shishimora Dorsa (Fig. 3). Contrary to the rt unit, the V-17 fracture belts are not associated with topographic troughs. Fracture belts associated with the northern base of Beta are at the +0.5 to +1.5 altitude range. Those which make up Dodola Dorsa and Shishimora Dorsa stand a few hundreds meters above the adjacent regional psh + pwr plains.

In the southern half of the V-17 quadrangle, areas of terrain are observed that somewhat resemble tessera in morphology. In a number of localities it is seen that this terrain is formed at the expense of fracturing of the material unit pfr (Fig. 16) and locally at the expense of the material unit pdf. A portion of the fractures of this terrain resemble fractures and faults of tectonic unit rt in their variable width, while others with less variable width resemble faults of tectonic unit fb. In contrast to units rt and fb, this type of terrain typically forms planimetrically equidimensional areas rather than linear zones. The typical length of fractures is a few tens of kilometers. Areas with similar morphology have been identified by Ivanov and Head (2001a) as a tectonic unit known as tessera transitional terrain; we also mapped these areas as tectonic unit ***tessera transitional terrain (ttt)***.

The major distinctions of tessera transitional terrain from normal tessera, which allowed Ivanov and Head (2001a) and then us to consider it as separate unit are: Normal tessera is so densely deformed that it is impossible to say what is the nature of its precursor terrain while tessera transitional terrain is less densely deformed so Ivanov and Head and later we could conclude that this structural unit was formed due to faulting of units pdf and pfr. These latter units are younger than tessera, so ttt being formed at their expense is even more young than tessera. Thus, the difference both in age (tt is older than ttt) and in morphology (ttt is less deformed compared to tt) is the basis to identify and map them separately.

The morphologic similarity of ttt structures to those in the rt and pdf tectonic units implies that they are also of extensional origin. In some localities, structures of the tectonic unit ttt are superposed on broad ridges typically deforming material unit pfr and they do not extend into the neighboring material units psh and pwr. Tectonic unit ttt occupies ∼10% of the quadrangle area composing the southern part of Sudenitsa Tesserae, Zirka Tessera, Hyndla Regio, and a significant part of Rhea Mons (Fig. 3).

A specific variety of structures is characteristic of the material unit pdf (Fig. 6). They are typically very linear, densely packed and parallel to each other. In the northeastern part of the V-17 quadrangle, where the pdf unit occupies rather large areas, it is seen that the unit is a mosaic of subareas; within each subarea structures are parallel to each other, while in different subareas the orientation of the structures is different. The pdf faults are typically several tens of kilometers long and a few hundred meters to 1 km wide. We did not find in the literature any work devoted to the origin of these specific venusian structures. They are typically so narrow that Magellan images do not show details of the morphology of individual pdf structures. Locally we could suggest that some of them are open fractures. This in combination with typical local parallelism suggest that they are probably extensional faults, perhaps with involvement of shear.

The most abundant contractional structures within the V-17 quadrangle are wrinkle ridges typically deforming material units pwr and psh and locally also observed on unit pfr. The wrinkle ridges are typically a few tens of kilometers long and several hundreds meters wide (Figs. 6–10). They usually form networks with ridge to ridge spacing varying from 3–5 km (typical for subunit pwr3 and locally for psh) to 10–15 km (typical for subunits pwr1 and pwr2). An origin of wrinkle ridges by compressive stress (that explains their positive topography) is commonly accepted by many researchers (Plescia, 1991; Watters, 1991; Solomon et al., 1992; Banerdt et al., 1997, Bilotti and Suppe, 1997, 1999; Watters and Robinson, 1997). Wrinkle ridges are common on the plains of Venus and the orientation of their networks is indicative of the orientation of stresses forming them. This, in turn, may be indicative of the presence of topographic/geoid swells at the time of wrinkle ridge formation.

Another type of contractional structure within V-17 is represented by ridges which are wider than wrinkle ridges and are not as sinuous as is typical of wrinkle ridges, but rather slightly arcuate. Typically they form ridge belts but locally single ridges are observed. These ridges usually deform material unit pfr (Fig. 7) and locally the material unit pdf. The ridges in these belts have the same morphology as those observed and described in other areas of Venus (Kryuchkov, 1990; Solomon et al., 1992; Hansen et al., 1997). Ridges are usually 3–5 km wide (sometimes up to 10 km) and a few tens of kilometers long. The ridge belts of V-17 quadrangle are significantly flooded by the material units psh, pwr and pl and thus are observed as elongated islands up to 100–200 km long and 10–

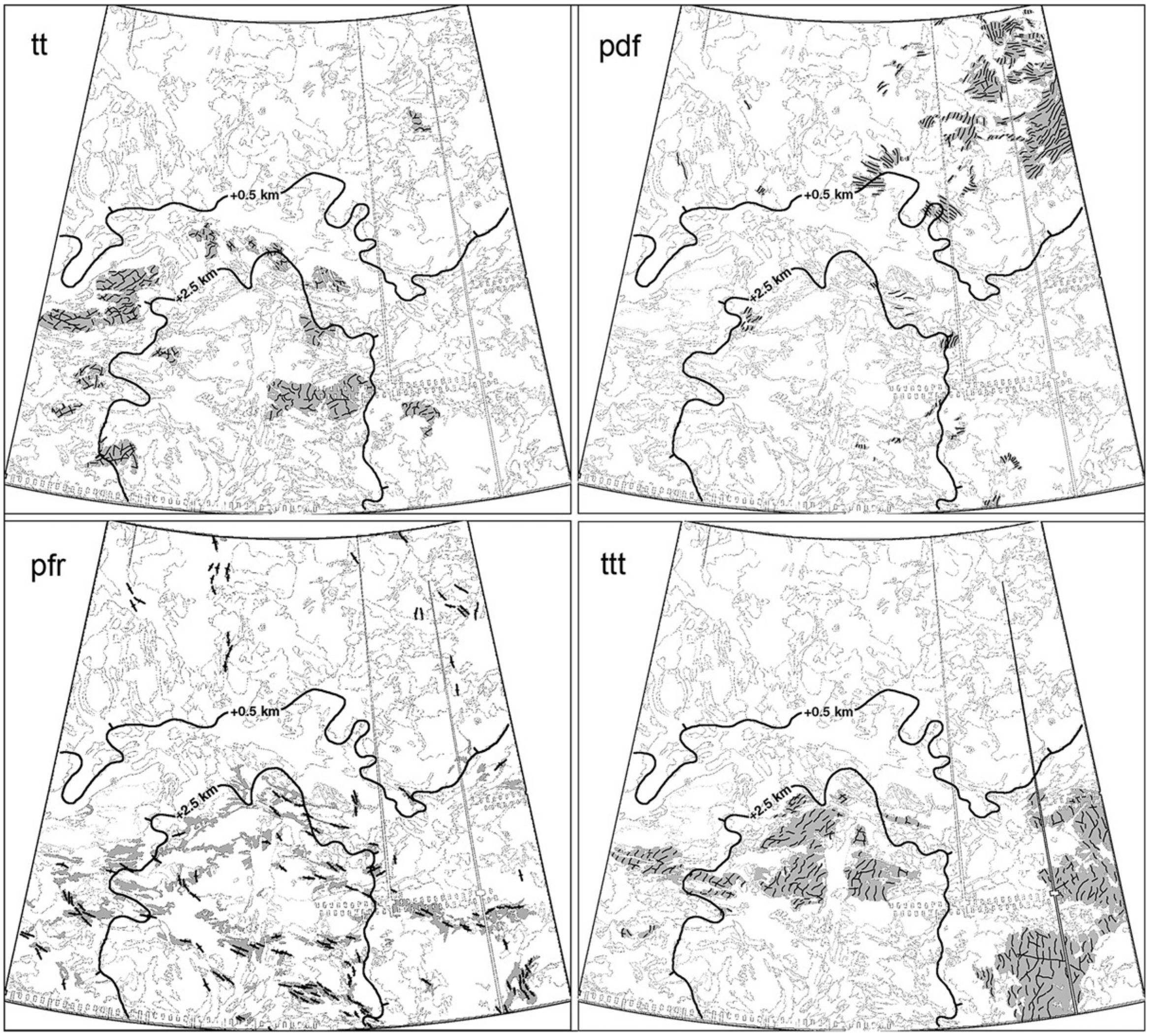


Fig. 17. Thematic maps showing areas occupied by the mapped material and tectonic units tt, pdf, pfr, and ttt as well as the dominant structural trends.

50 km wide. Within the ridge belts, ridges form clusters with 3–15 km ridge to ridge spacing while some rather extended areas of the pfr unit lack ridges.

A combination of contractional (ridges) and extensional (grooves) structures is typical for tessera-forming deformation. The matrix of tessera terrain in V-17 is ridge-and-groove ensembles, in which ridges and grooves abut each other with practically no horizontal surfaces between them (Fig. 5). Ridge-to-ridge or groove-to-groove spacings vary in these ensembles from a few hundred meters to several kilometers with wider features often consisting of clusters of smaller ones. Typically there are two dominant trends of structures with 60° to 90° angles between them. Sometimes structures criss-cross each other. In other cases, tessera is a complicated mosaic of 10–20 km blocks within some part of which one trend dominates while in other blocks another trend dominates. Locally structural trends within tessera are noticeably arcuate to almost ring-like The densely packed ridge-and-groove matrix of tessera terrain probably formed due to compressive stresses while the flat-floored grooves are graben (Basilevsky et al., 1986; Bindschadler and Head, 1991; Sukhanov, 1992; Bindschadler et al., 1992a,1992b; Solomon et al., 1992; Hansen and Willis, 1996; Ivanov and Head, 1996; Hansen et al., 1997).

## 6. Analysis of spatial and altitudinal distribution of material units and structures

The results of our geologic mapping are presented here in the form of a geologic map (Fig. 3) and several thematic maps showing the presence of material units and structures as well as the dominant structural trends (Figs. 17 and 18). Also on the thematic maps are shown the +0.5 km and +2.5 km altitude contour lines correspondingly outlining the position of the base and summit part of the Beta Regio structural uplift. In cases where structures are numerous, the maps show only a representative part of them. When structures are short, we artificially made them longer to emphasize their trends. Below is a short description of the maps following the order from older to younger units and some analysis.

Fig. 17 (upper left) shows the major areas occupied by tessera terrain and the major tessera-forming structures. Structural trends, which are mostly outlined by graben (which are

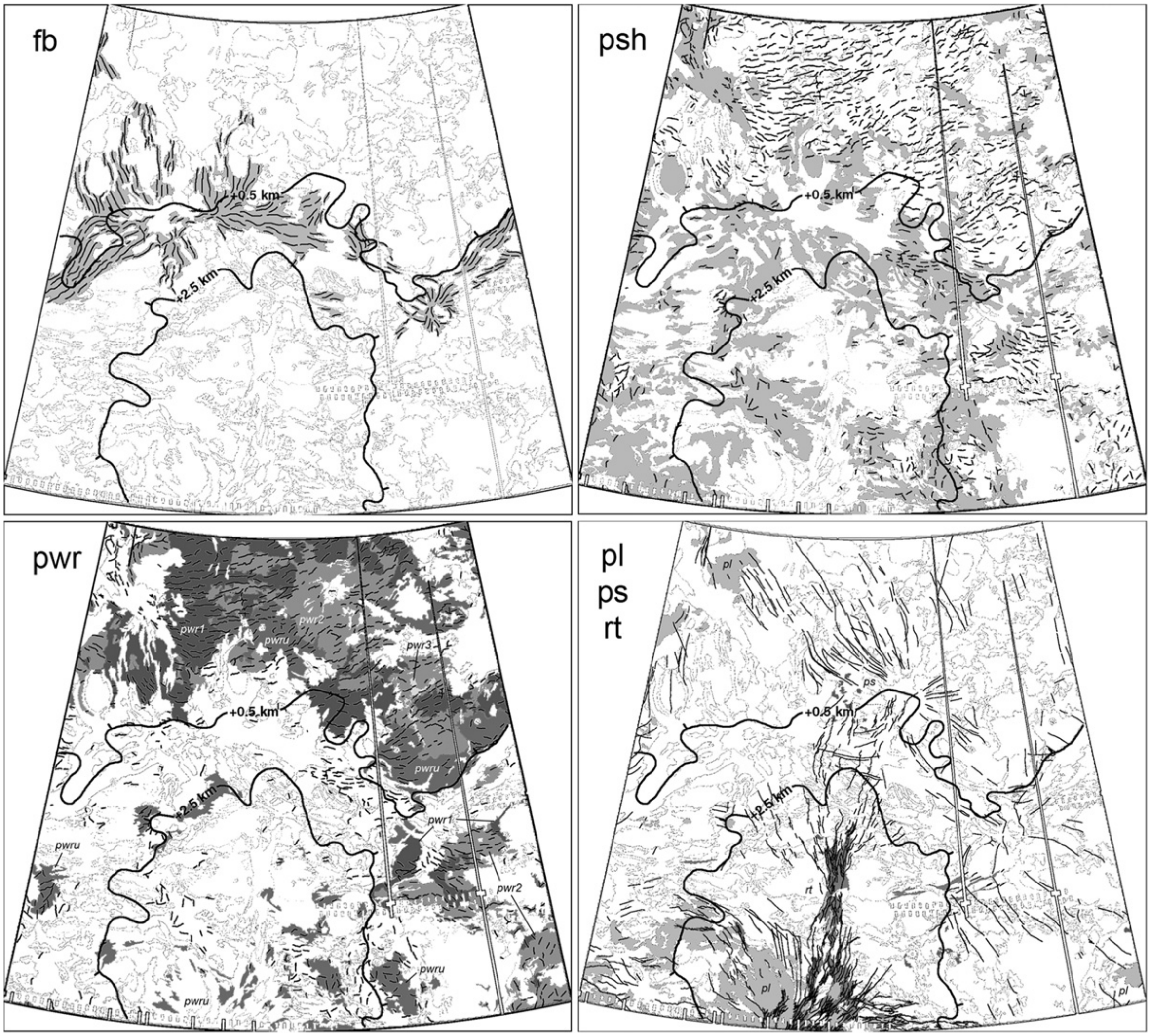


Fig. 18. Thematic maps showing areas occupied by the mapped material and tectonic units fb, psh, pwr, pl, ps, and rt as well as the dominant structural trends.

part of tessera-forming structures), are rather variable showing neither consistency within different tt subareas nor with the planimetric geometry of the Beta rise.

Fig. 17 (upper right) shows the major areas occupied by densely fractured plains (pdf) and the major pdf structures. It is seen that pdf structural trends show a prevalence of north-eastern orientations and the partial star-like pattern when they are part of Wohpe Astrum (41° N, 288° E). No correlation is observed between the pdf structural trends and the planimetric geometry of the Beta rise.

Fig. 17 (lower left) shows the major areas occupied by ridged and fractured plains (pfr), and the relatively broad ridges deforming them. Clusters of these broad ridges form the ridge belts. The ridges of Iyele Dorsa in the V-17 north and their continuation to the south both have N–S trends, but the majority of ridge belts and single ridges show a slightly variable north-western orientation. No correlation of the ridge and ridge belt trends with the Beta rise geometry is observed.

The major areas occupied by tessera transitional terrain (ttt) and the fractures deforming them are shown in Fig. 17 (lower right). Comparing this map and the previous one shows that the ttt localities are mostly in spatial association with areas occupied by the pfr unit. Major trends of the ttt fractures are often transverse to the trends of the ridge belts but some structures show different trends. No correlation of ttt fracture trends and the Beta rise geometry is observed.

Fig. 18 (upper left) shows the areas occupied by fracture belts (fb) and major trends of the fb structures. A significant part of the fb tectonic unit approximately follows the +0.5 km contour line outlining the northern part at the base of the Beta Regio rise. To the east, the fracture belt trend changes its orientation so that it becomes perpendicular to the base of the Beta rise. Another cluster of fb structures approximately perpendicular to the base of Beta is in the north-western part of the quadrangle (Dodola Dorsa). The fb structures outline all four coronae of the quadrangle: Rauni, Emegen, Urash, and Blathnat. They are also part of the radiating structures forming Wohpe Astrum.

The areas occupied by wrinkle-ridged regional plains (psh + pwr) and the major trends of wrinkle ridges are shown in Fig. 18 (upper right and lower left). Orientation of trends of wrinkle ridges varies significantly within the quadrangle. North of Beta, within the Guinevere Planitia plains it shows some parallelism with the orientation of the base of northern Beta. But in other places it shows no obvious relationship with the planimetric geometry of the Beta rise. In this respect the Beta rise differs significantly from several large topographic rises (e.g., Western Eistla or Laufey Regio) around which the wrinkle ridge networks show an alignment parallel to the rise boundaries (Basilevsky, 1994; Bilotti and Suppe, 1997, 1999; Brian et al., 2004).

Areas occupied by the rifted terrain tectonic unit (rt) and major post-regional-plains faults are shown in Fig. 18 (lower right). Shown also are areas occupied by the post-regional-plains units ps and pl. The map shows that the rt unit is in the N–E axial zone of the Beta rise and that the faults feathering from the rt unit zone show north-western and north-eastern trends radiating to the north from Theia and Rhea Montes. In the center-northern part of the quadrangle a significant part of the young (i.e., post-regional-plains) faults radiate around Wohpe Astrum. Within the quadrangle there are also young faults that show no obvious association with either the Beta uplift, or with Wohpe Astrum, but they are not abundant. In areas where young pl and ps lavas are observed, young faults are often present. This is especially typical for Theia Mons. However young faults of Rhea Mons and the majority of other areas show little if any association with young lavas.

The combined analysis of the geologic map (Fig. 3) and thematic maps given in Figs. 17 and 18 shows that in the structural sense the V-17 area is dominated by the Beta Regio uplift. It is very prominent in topography being more than +5 km above the neighboring Guinevere Planitia plains. In its structural pattern the Beta uplift is outlined by the Devana Chasma axial rift zone and by the fracture belts of Agrona Linea embracing its northern base.

Other structures of the area are significantly smaller than the Beta structure. Figs. 2, 3, 17, and 18 show several centers of radiating fractures, all mapped earlier by Ernst et al. (2003). The most prominent are the following four, centered at 34.5° N, 293.5° E; 39° N, 277° E; 40° N, 279.5°, 42° N, 287.5°. The first three of these are part of the fracture belt. The fourth one, Wohpe Astrum, is composed of several generations of structures. Its NE and SE sectors have abundant faults associated with pdf. Its SW sector is partly made of structures associated with fb. Young, post-regional-plains Wohpe Astrum structures radiate in almost all directions.

Swarms of ridge belts trending mostly NW and going through the Beta structure with no alignment with it, as well as swarms of wrinkle ridges are also seen in Figs. 3, 17, and 18. The wrinkle ridges are mostly of variable orientations, except at the very northern part of V-17, where WSW trends obviously dominate. Trends of ttt, pdf and tt structures are seen in relatively small windows, and appear rather variable and with almost no orientation heritage with time.

## 7. Discussion and scenario of geologic history

Our study has resulted in identification and mapping of eight material units, two of them subdivided into subunits, and three tectonic units (Figs. 3 and 4). This sequence of units is essentially the same as sequences of units identified and mapped by other researchers in other regions of Venus. We have also found it possible to distinguish three subunits of different age ($C_1$, $C_2$, and $C_3$) among the impact crater materials (on Fig. 3 because of its relatively small size they are shown undivided). This was accomplished based on the degree of degradation of the crater-related radar dark haloes (Basilevsky and Head, 2002a; Basilevsky et al., 2003) and using the analyses of age relations between craters and other units and structures. This approach provided the possibility to date several geologic events of the region:

South-west of the $C_2$ crater Deken (Fig. 13C) its ejecta outflow buries an adjacent graben (see white arrow) and is then cut by other graben (black arrow), both radiating from Wohpe Astrum. This suggests that at least part of the Wohpe faults formed during the first half of the post-regional-plains time. Another fault radiating from Wohpe Astrum cuts the $C_3$ crater Zvereva. The latter relationship implies that faulting related to Wohpe Astrum continued into the second half of this time.

Superposition of the $C_2$ crater Olga on the Devana rift fractures indicates that during the first half of the post-regional-plains time the rift was already active while deformation of the ejecta outflow of the $C_3$ crater Sanger by faults branching from the Devana rift suggests that rifting activity continued into the second part of this time. This observation and conclusion, made earlier by Basilevsky and Head (2002a), was recently confirmed in relation to the crater Sanger by Matias and Jurdy (2005).

Superposition of the $C_2$ craters Truth, and Nalkowska on two fields of smooth plains and also the $C_2$ craters Raisa and Tako on pl lavas associated with Theia Mons implies that these two ps fields and these localities of the Theia lavas formed within the first part of post-regional-plains time. Matias and Jurdy (2005) showed that ejecta outflows associated with crater Truth flowed south in agreement with the current dip of this area suggesting that the southward areal dip did exist here at the time of the crater formation. For craters Sanger, Truth and Nalkowska these authors measured also the dip of the crater floor, considering it as evidence of post-impact dip of the area. This consideration is based on assumption that an impact crater floor is initially absolutely horizontal.

Our mapping revealed that the general time sequence of units mapped within V-17 is the same as in other regions of the planet, with tessera material (tt) at the bottom of the stratigraphic column and materials of the lobate (pl) and smooth (ps) plains at the top. What makes the studied area different from many other regions of Venus are: (1) differences in the abundance of some units and structures, and (2) the presence of the Beta topographic rise. Within the V-17 region, the abundance of pwr plains (∼31%) is about half the global abundance of this unit, while the abundance of psh plains (∼26%) is about twice the global abundance (Basilevsky and Head, 2000a). Within V-17, the tectonic unit ttt—tessera transitional terrain (∼10%) is unusually abundant, being rather rare in other regions of Venus (Ivanov and Head, 2001a). Similarly, tectonic unit fb (∼9%), is characterized by an abundance 2–3 times greater than the global abundance (Basilevsky and Head, 2000a). We interpret these relationships to indicate that the presence of the Beta rise reflects the activity of a large mantle plume, which was responsible for the topographic rise and Theia Mons pl volcanism and influenced emplacement of the Devana Chasma rift and the Agrona Linea fracture belts (see below).

The results of the geologic analysis and mapping made it possible to outline a scenario of the geologic history of the region studied:

The earliest morphologically documented geologic events of the region were emplacement of tessera material (tt) and its heavy deformation. The morphology of tessera terrain within V-17, as elsewhere, implies intensive contractional and extensional deformation. Structural trends of tt-forming deformation are variable suggesting local rather than regional control of deformation patterns. The major areas where tessera terrain is observed are in the southern part of V-17, but smaller islands of tessera are also seen in the north among the younger units (Fig. 17). This suggests that tessera terrain material may be present everywhere in the quadrangle underlying the younger material units.

Next in time sequence were emplacement and heavy deformation of the material of densely fractured plains (pdf). If one ignores the fracturing, the unit represents a plains-forming material suggesting that these were primarily mafic lavas. The fracturing in pdf is dense, probably extensional, and may also be characterized by local shear. Fracturing is subparallel within subareas tens of kilometers across, and changes orientations within the largest outcrops, which are 100–300 km across. The latter relationship, as in the case of tessera-forming deformation, suggests local rather than regional control of deformation. The structural pattern of the pdf unit is obviously different from that of the tt unit and this implies a significant change in deformation style. Major areas where the pdf unit is observed are concentrated in the NE part of V-17. Smaller outliers of the unit are seen, however, in other areas of the quadrangle (Fig. 17), so one may infer that the densely fractured plains material is rather widespread in the quadrangle underlying the younger material units.

The next phase was emplacement of the material of fractured and ridged plains (pfr) and its deformation into rather broad contractional ridges, forming so-called ridge belts. This deformation is modest, so there is no doubt that the unit consists of a plains-forming material suggesting that the pfr plains are composed of basaltic lavas. Trends of ridges in pfr, although variable, show a certain consistency, suggesting regional rather than local control of deformation. On the basis of these relationships, we conclude that since the time of pdf fracturing, the deformation style changed significantly: widespread but locally controlled extensional deformation changed into widespread but regionally controlled contractional deformation. It is important to note that the ridge belts of V-17 show no alignment with the planimetric geometry of the Beta topographic rise. This implies that at the time of ridge formation, the Beta topographic rise either did not yet exist, or was not yet high enough to produce topographic stresses affecting the trends of ridge belts.

The pfr unit is more abundant in the southern half of V-17, but its small elongated islands are also seen among the younger plains in the north (Figs. 3 and 17) suggesting that this material is rather widespread in the quadrangle, especially in its northern part, underlying the younger material units. Altitudes of the pfr outcrops within the Beta rise are much higher (up to +4.5 km) than the outcrops within Guinevere Planitia (close to the datum), This is certainly a result of the later Beta-rise-forming uplift. Because altitudes of the pfr outcrops within Hyndla Regio and Zirka Tessera, the areas not affected by the Beta uplift, are also higher (although not significantly so) than those in Guinevere Planitia, one may suggest that the Hyndla and Zirka areas also were uplifted.

Following pfr ridging there were two deformational episodes: extensional fracturing which transformed large areas of the pfr unit into tessera transitional terrain (ttt) and also extensional fracturing, which formed the fracture belts (fb). The first episode appears to be at least partly earlier than the second one. In rare cases where the ttt unit is in contact with fb (in the eastern part of the quadrangle), fb faults seem to cut the ttt unit. Also the ttt unit is obviously embayed by psh + pwr regional plains, and while although the fb unit is generally embayed by these plains too, some fb unit faults enter into the plains and cut them. The ttt structural pattern implies little or no predominant stress orientation (Fig. 17), while the fb structures are organized in prominent linear belts, a significant number of which are in alignment with the northern base of the Beta rise (Fig. 17). These observations lead us to suggest that following the contractional deformation, which formed the ridge belts, the tectonic environment in the region again changed and the net stress came to be tensional.

The slightly earlier ttt structural pattern shows no alignment with the Beta rise geometry and probably resulted from uplift more areally extensive than the now-observed Beta rise. We see outcrops of tessera transitional terrain at distances to 1000–2000 km from the Beta rise boundaries to the west (Sudenitsa Tessera), south (Nedolya tessera), and east (Zirka Tessera). Meanwhile a significant part of the later fb pattern within V-17 does show alignment with the northern base of the Beta rise. The alignment shows the Agrona Linea fracture belt, which is only part of the much longer system of fracture belts extending at least from about 30° N, 250° E to 40° N, 305° E (Basilevsky and Head, 2000b; Cherkashina et al., 2004; Ivanov and Head, 2001a). This system is significantly longer than the east–west dimension of the Beta rise and probably formed as a result of a larger-scale regional or even global tectonic phase(s). Thus, the formation of the Agrona Linea belt was a part of that large-scale tectonic activity but its arcuate alignment along the base of Beta was determined by the initiation of the Beta uplift. As mentioned above, the majority of structures of the Agrona Linea belt are embayed by units psh and pwr, so the morphologically recorded initiation of the Beta uplift occurred in the late stages of pre-pwr time.

Next in time was the emplacement of the shield plains unit (psh). The unit morphology suggests that it was formed due to eruption of mafic lavas from numerous spatially scattered edifices (Head et al., 1992; Ivanov and Head, 2004b). Compared to pfr-forming volcanism, which primarily produced smooth plains, the psh eruption style was obviously different. Shield plains of the study area are typically wrinkle ridged. Within

V-17, the major areas of the psh unit are within the Beta rise and are found in association with fracture belts and densely fractured plains. Although the psh plains typically are embayed by the younger pwr, pl and ps units and underlie them, it is impossible to be sure how widespread the unit is beneath them. Kreslavsky and Head (1999) and Ivanov and Head (2001a, 2001b, 2004a) showed abundant evidence that shield plains underlie much of the regional and global plains with wrinkle ridge units. The abundance of the psh unit within V-17 is about twice its global abundance. Ivanov and Head (2001a) interpreted this relationship to mean that by the end of the time of emplacement of psh, the Beta rise had reached sufficient elevation that pwr lavas flooded lows around the regional high, preferentially preserving the earlier psh unit within the high.

Emplacement of plains with wrinkle ridges (pwr) generally followed that of psh plains although locally they were overlapping in time. Pwr plains are considered as part of the volcanic plains (e.g., Head et al., 1992). Its volcanic nature is inferred on the basis of its smooth plains-like surface and embayment relationships, the morphology of unit pwr2, which forms extensive, relatively bright flows, and the presence within the pwr unit of the Omutnitsa Vallis channel, which belongs to the category of features interpreted to be formed by lava flow and thermal erosion (Baker et al., 1992, 1997). The abundance of the pwr1 and pwr2 subunits are approximately the same ($\sim$11%), but keeping in mind that subunit pwr2 is almost certainly underlain by subunit pwr1, one can conclude that areas influenced by volcanic floods during pwr2 time became significantly smaller compared to pwr1 time. The very small area of subunit pwr3 appears to continue this trend.

Pwr and psh plains were deformed by wrinkle ridges considered to be formed due to modest contractional deformation (Plescia, 1991; Watters, 1991; Solomon et al., 1992; Banerdt et al., 1997, Bilotti and Suppe, 1997, 1999; Watters and Robinson, 1997). Within the V-17 quadrangle they form a single network which deforms the psh unit and the pwr subunits with no evidence of different generations of ridges separated by the material (sub)units. The orientation of wrinkle ridges within the V-17 quadrangle is generally not in alignment with the planimetric geometry of the Beta rise. This implies that at the time of wrinkle ridging, the Beta topographic rise was not high enough to produce topographic stress sufficient to influence the trends of ridge belts.

Formation of the suite of smooth (ps) and lobate (pl) plains was next in time. The morphology of both of these suggests that they were formed due to eruption of mafic lavas (see, e.g., Head et al., 1992). In the case of the smooth plains these were eruptions of small volumes of very liquid lavas penetrating into narrow faults and gaps. This type of volcanism seems to be a continuation of the volcanic style typical of subunit pwr3. Eruptions of lavas forming lobate plains were mostly associated with the Theia Mons volcano sitting on the Devana Chasma rift zone. These were eruptions forming rather extended fields of relatively radar-bright lavas. This partly resembles the volcanic style typical of subunit pwr2. As it was mentioned above, a few fields of ps plains are superposed by the impact craters Truth and Nalkovska, which have faint radar-dark haloes. This implies that these particular lava fields were emplaced within the first half of post-regional-plains time. A similar age constraint is seen for the lobate plains lavas superposed by the ejecta of the craters Raisa and Tako, which have a faint associated halo. These observations, however, do not exclude the possibility that pl and ps volcanism continued into the second half of the post-regional-plains time.

Following the episode of contractional wrinkle ridging, there was a phase of extensional tectonism probably extending up to the present time. It was generally contemporaneous with the emplacement of units pl and ps. During this phase the Devana Chasma rift zone, and the linear extensional faults not directly related to the rift, were formed. Devana Chasma coincides with the N–S axis of the Beta rise. This, however, does not necessarily mean that Devana Chasma rifting occurred solely due to the Beta uplift although it is a possibility (e.g., Rathbun et al., 1999; Kiefer and Swafford, 2006). Venus, however, has several other large young rifts, e.g., Parga and Hecate Chasmata, not associated with Beta-like domical topographic rises. Thus it is possible that we observe here a combined effect of regional Beta uplift and a global phase of rifting. In this case the regional uplift of the Beta Rise could be determining the spatial localization on the rise axis, and contribute to the formation of the broader extensions of the Devana rift zone. In contrast to the segment of the Devana rift associated with the Theia Mons volcano, the segment, which includes Rhea Mons and faults feathering from the latter, show no associated volcanism. We have no observations specifically suggesting how soon after the wrinkle ridging phase the rifting started. Deformation of the faint-halo crater Olga by Devana rift faults and deformation of the ejecta outflow of the clear-halo crater Sanger by faults feathering from the Devana rift, however, suggest that the rift was active at least for some time intervals within the first and second parts of the post-regional-plains period. Results of geophysical modeling suggest that the Beta uplift continues today (see, e.g., Leftwich et al., 1999; Kiefer and Peterson, 2003; Vezolainen et al., 2003, 2004).

In summary, we see evidence of the growth of the Beta rise since the time of emplacement of fracture belts composing Agrona Linae, which is in alignment with the northern base of the rise. The growth continued into psh/pwr time favoring emplacement of pwr lavas outside the uplift, but by the end of that time the uplift apparently had not reached sufficient prominence to control the orientation of post-pwr wrinkle ridges. The major phase of growth of uplift occurred during the ps/pl time when it became prominent enough to determine localization of the emplacement of the Devana Chasma rift zone. During the same ps/pl time the Theia Mons volcanic construct started and continued to form. Before the time of the morphologically recorded beginning of the Beta rise, the study area was probably involved in much broader scale uplift in association with which the pfr plains were irregularly fractured and locally transformed into tessera transitional terrain (Ivanov and Head, 2001a, and this work). Concerning even earlier time, we can say only that in and around the study area there were episodes of deformation responsible for structures observed in tessera terrain, densely

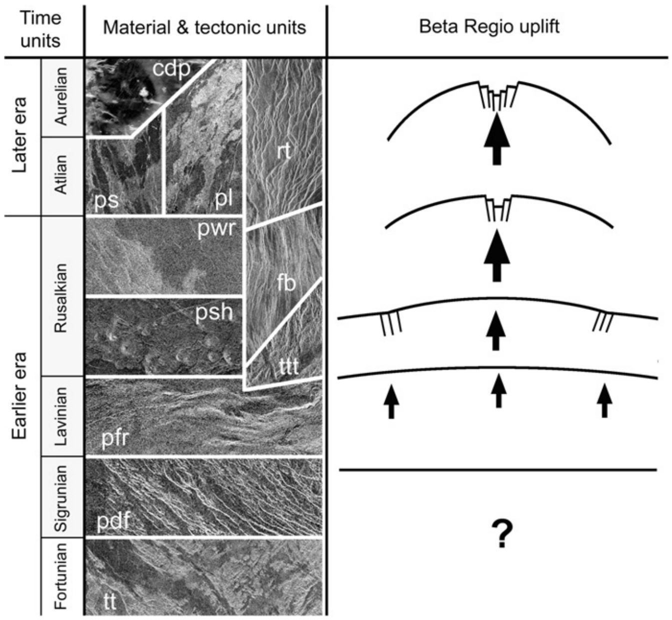


Fig. 19. A stratigraphy of Beta Regio and the inferred formation and evolution of the Beta rise. Time units are from Basilevsky and Head (2000a, 2002b). All images of the material and tectonic units (except cdp) show those outcropping within the V-17 quadrangle. Within the study area we did not find any Aurelian dark parabola crater (shown is image of the crater Stuart) but we cannot exclude that in this recent time some pl/ps volcanism was ongoing here.

fractured plains and ridge belts. A diagram representing this history is shown in Fig. 19.

Stofan et al. (1995) summarized predictions of the plume hypothesis. The major prediction suggests that the mechanical effect of plume rise (topographic uplift) should precede the plume-associated volcanism. Our analysis of the geology of Beta Regio shows that both the noticeable uplift and the volcanism were occurring during the post-regional-plains time and it is not possible to reliably distinguish which one started first. However, if one considers the geometric control of the essentially pre-pwr fracture belt of Agrona Linea described above as the mechanical effect of the rising plume, and note that the rise-associated lavas of Theia Mons are post-pwr in age and only locally deformed by the rise-associated rift structures, one can conclude that the sequence of geologic events in the study area is in agreement with the plume hypothesis prediction.

## 8. Conclusions

On Earth, very active processes of erosion, and a laterally moving and deforming lithosphere, often make documentation and assessment of suspected mantle plumes difficult. The lack of significant erosion on Venus, and the very well-preserved record of geological processes and sequences of events, permit the assessment of the origin and evolution of Beta Regio, long considered a prime candidate for a mantle plume on Venus. The geologic mapping of the V-17 quadrangle, which includes a significant part of the Beta Regio rise, and the resulting analysis have led to an understanding of the key characteristics of the geologic evolution of this region. Our results are consistent with models suggesting that the dominant structure of this region, the Beta rise, formed due to uplift caused by a hot mantle diapir (e.g., Kiefer and Hager, 1991, 1992; Stofan et al., 1995; Nimmo and McKenzie, 1996; Moore and Schubert, 1997; Vezolainen et al., 2003, 2004; Stofan and Smrekar, 2005). The major geologic manifestations of the mantle diapir activity are: (1) formation of the topographic rise and (2) construction of Theia Mons volcano. Formation of the Devana Chasma rift zone may be directly caused by plume activity (e.g., Rathbun et al., 1999; Kiefer and Swafford, 2006) but rifting here may also be partly supported by a global tectonic phase. The Beta rise could be one of the two driving forces of rifting and to have determined localization of the rift emplacement on the N–S axis of the rise.

We see signatures of the early stage of the Beta uplift in the formation of the Agrona Linea fracture belts; this happened some time before the emplacement of regional plains and their wrinkle ridging. On the global scale the mean age of regional plains is close to the mean surface age of the planet, that is somewhere between 300 m.y. and 1 b.y. (McKinnon et al., 1997). We see evidence that Theia rift-associated volcanism occurred during the first part of the post-regional-plains time (relations of lavas with craters Raisa and Tako) and cannot exclude that it continued into later time. We also see evidence that the Devana rifting was active during both the first (relations with crater Olga) and the second (relations with crater Sanger) parts of post-regional-plains time. And finally, geophysical modeling shows that the uplift may be active at the present time (e.g., Leftwich et al., 1999; Vezolainen et al., 2004). This suggests that the duration of plume activity was as long as several hundred million years, and may still be ongoing. The regional plains north of the Beta rise and the area east and west of it were little affected by the Beta-forming plume, but the broader (at least 4000 km across) area, whose center-northern part includes Beta Regio, could have experienced the earlier uplift morphologically recorded in formation of tessera transitional terrain.

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