Rifts and large volcanoes on Venus: Global assessment of their age relations with regional plains

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Abstract. We report on the results of synoptic global mapping of rifts and large volcanoes on Venus and detailed mapping in six areas illustrating the relationships among these features. Rifts and large volcanoes were subdivided into old, transitional (for volcanoes only), and young features. The geologic event separating old features from young ones is the formation of wrinkle ridges on the regional plains. Global mapping showed that the postplains rifts dominate in the population of rifts both in terms of number of mapped segments and in area. The postplains volcanoes are more abundant in terms of number and area occupied than those that are transitional in age, and these, in turn, dominate over the old ones. These data show that in post-regional-plains time rifting and formation of large volcanoes are significantly more important processes than in the immediately preceding period. The time period during which regional plains were emplaced, and old (and partly transitional) large volcanoes formed, was much shorter than the postplains time. Therefore the mean rate of formation of large volcanoes during this first period was significantly higher than in the subsequent time. Similarly, the relatively short time duration of the plains-emplacement time indicates that the mean rate of old rifting was higher than in more recent time. This study shows prominent changes with time in the absolute rates and roles of rifting and large volcano formation. This supports the "directional" model of the geologic evolution of Venus during the last several hundred million years, as opposed to the "nondirectional" model, which predicts a more random occurrence of geologic processes throughout history.

1. Introduction

Rift valleys (chasmata) were first identified on Venus in Pioneer-Venus topography [Masursky et al., 1980; Schaber, 1982]. Magellan data confirmed that rift zones are widely distributed across the planet [e.g., Solomon et al., 1992; Senske et al., 1992; Crumpler et al., 1993]. Some later work distinguished two varieties of features of this sort [e.g., Hansen et al., 1997; Tanaka et al., 1997]: rifts and fracture belts. Both are long (hundreds to thousands of kilometers) belts of extensional structures (faults and graben), whose trends are generally parallel to the trends of the belts. Rifts (chasmata) are topographic troughs, while fracture belts typically stand hundreds of meters to more than a kilometer above the adjacent regional plains. Head and Basilevsky [1998] and Basilevsky and Head [2000] emphasized the age-stratigraphic differences between rifts, which crosscut the adjacent regional plains, and fracture belts, in which faults and graben are mostly embayed by the regional plains (although some of the individual belt-forming structures extend into these plains and cut them). Despite previously described differences between rifts and fracture belts, some workers reporting on the initial results of global mapping show them together, calling them either "fracture belts" [Senske et al., 1994] or "rifts" [Price, 1995]. In summary, a global assessment that separates rifts and fracture belts has not yet been done, and this task is the first goal of the present research.

The second goal of this research is a global assessment of large (>75-100 km in diameter) volcanic constructs also called "large volcanoes" [Head et al., 1992; Price, 1995; Crumpler et al., 1997; Crumpler and Aubele, 2000]. These are often associated with rifts, although edifices lacking such association are also known [e.g., Head et al., 1992]. Most large volcanoes are relatively young, showing superposition on the adjacent regional plains [Basilevsky and Head, 1995, 1998, 2000] and relatively low globally averaged crater density [Namiki and Solomon, 1994; Price and Suppe, 1994; Basilevsky et al., 1997]. Relatively old large volcanic constructs whose flows merge with the adjacent regional plains are also known (see, e.g., "source" of Baltis Vallis given by Baker et al. [1992]). The most complete summary of large volcanoes recently published by Crumpler and Aubele [2000] does not distinguish them in relation to age. In our work we determine age relations of large volcanoes in reference to the adjacent regional plains and document whether or not they are associated with rifts or fracture belts.

The third goal of this work is to assess whether there are changes in the roles of rifting and large volcano formation for the period of the history of Venus which includes the time of emplacement of regional plains (composing about 2/3 of the surface area of Venus) and subsequent time (up until the present).

On the basis of comprehensive and detailed mapping of the surface of Venus from Magellan data, Basilevsky and Head...
Table 1. Geologic units of Basilevsky and Head [1998, 2000] Used in This Work

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Label</th>
<th>Short description</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rифted terrain</td>
<td>RT</td>
<td>material of other units heavily deformed by faults and graben</td>
<td>structural unit; deformation is approximately contemporaneous with PI</td>
</tr>
<tr>
<td>Lobate plains</td>
<td>PL</td>
<td>radar-bright, locally dark material of lobate flows; forms plains and slopes of volcanic edifices; not deformed by wrinkle ridges</td>
<td></td>
</tr>
<tr>
<td>Plains with wrinkle ridges</td>
<td>Pwr</td>
<td>moderately dark, locally moderately bright plains-forming material; deformed by wrinkle ridges</td>
<td></td>
</tr>
<tr>
<td>Shield plains</td>
<td>Psh</td>
<td>moderately dark material forming small (2-15 km in diameter) shields, typically deformed by wrinkle ridges</td>
<td></td>
</tr>
<tr>
<td>Fracture belt</td>
<td>FB</td>
<td>material of other units heavily deformed by faults and graben</td>
<td>structural unit; deformation is roughly contemporaneous with Psh and Pwr</td>
</tr>
<tr>
<td>Plains with fractures and ridges</td>
<td>Pfr</td>
<td>moderately bright plains-forming material deformed by fractures and broad ridges</td>
<td></td>
</tr>
<tr>
<td>Densely fractured plains</td>
<td>Pfd</td>
<td>bright material heavily deformed by faults and graben</td>
<td></td>
</tr>
<tr>
<td>Tessera</td>
<td>Ti</td>
<td>bright material heavily deformed by compressional (ridges) and extensional (fauls and graben)</td>
<td></td>
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[1995, 1998, 2000] proposed that the history of Venus was characterized by a series of epochs, each represented by a dominant set of volcanic and tectonic processes and styles. Although many of the individual processes and styles were transitional between epochs, specific periods where certain styles dominated could be identified (e.g., tessera formation, shield plains emplacement, ridge belts, regional plains emplacement, wrinkle ridge formation, etc.) [Head et al., 1996; Head and Basilevsky, 1998]. Guest and Stefan [1999] assessed these analyses and defined the interpretation as a “directional history.” In contrast to this, they interpreted the Magellan data to indicate that “Venus has had a complex history in which most geologic processes operated in a nondirectional fashion to a greater or lesser extent throughout the planet’s history” (p. 55). In their view, for example, “there is evidence to suggest that coronae, rifts, wrinkle ridges, small and large edifices, and large flow fields have each formed throughout the portion of Venus’ history revealed by presently exposed rock units...” (p. 55) and that “the plains have been built up by lavas erupted in a number of different styles, each occurring throughout the history represented by the exposed stratigraphy of the planet” (p. 55). Guest and Stefan [1999] conclude that the history of Venus represents events and processes that occur essentially randomly throughout the history of Venus (“non-directional”), while Basilevsky and Head [1995, 1998, 2000] perceive differences in the relative importance of processes and events which have produced a not necessarily deterministic, but distinctive set of epochs in the geological record of Venus (“directional” history according to Guest and Stefan [1999]).

In the following parts of this paper we first show details of our approach in six typical areas studied in detail using digital format images and mapped at C1-MIDRP scale. In the mapping and descriptions of these areas we use geologic units suggested earlier by Basilevsky and Head [1998] and Basilevsky et al. [1997] (Table 1) and generally used (although under different names) by other workers (see equivalency chart and accompanying discussion by Basilevsky and Head [2000]). We map young and old rifts as RT (rifted terrain) and FB (fracture belts) correspondingly. We consider them as structural units although their difference in age (see section 2), and thus potential difference in materials, gives them a stratigraphical significance too. Then we present the comprehensive global map showing young and old rifts as well as young, transitional-in-time, and old volcanoes and describe the results of the global mapping. In the description and analysis of the regional and global geologic settings we also used the Venus surface altimetry gridded topographic data record (GTDR). Names of the areas studied and surface features were taken from the U.S. Geological Survey Web site (http://wwwflag.wr.usgs.gov/USGSFlag/Space/nomint/vgrid.html).

2. Approach and Procedure

In this study we classify rifts and volcanoes into young, transitional in age (only for volcanoes), and old. The geologic boundary separating “young” and “old” is the uppermost part of the Venustian regional plains. Regional plains are represented by two stratigraphically adjacent units: regional plains with wrinkle ridges (Pwr) and plains with shields (Psh) [Basilevsky and Head, 1995, 1998, 2000]. Regional plains with wrinkle ridges have a generally homogeneous radar backscatter cross section and few identifiable vents, whereas shield plains are characterized by abundant small edifices. For both units the presence of a network of wrinkle ridges is typical; these are considered to be a result of compressional deformation [Solomon et al., 1992; McGill, 1993; Kreslavsky and Basilevsky, 1998]. Among several hundred impact craters superposed on the regional plains, only seven are deformed by wrinkle ridges [Schaber et al., 1992, 1998] (http://wwwflag.wr.usgs.gov). Therefore deformation of the plains by the wrinkle ridges occurred within a very short time after the emplacement of regional plains. If formation of wrinkle ridges occurred over a longer period of time after emplacement of plains materials, the number of wrinkle-ridged craters should be much higher. If the mean surface age of Venus is T, the possible time gap between the emplacement of regional plains and formation of their wrinkle ridges was estimated to be from 1 to 13% of T [Basilevsky and Head, 1998, 2000; Collins et al., 1999]. Thus the network of wrinkle ridges on the regional plains forms a stratigraphic discontinuity separating materials of these plains from younger geologic units.

We classify large volcanoes as young if lava flows comprising their flanking slopes are not wrinkle-ridged and if they show superposition on top of the neighboring wrinkle-ridged
regional plains. We classify large volcanoes as old if lava flows composing their flanking slopes are deformed by the wrinkle ridges which are part of the wrinkle ridge network deforming neighboring regional plains. At their distal ends these old flows often merge into the regional plains, so sometimes it is difficult to draw a boundary between them. We classify large volcanoes as “transitional in age” if part of the lava flows composing their flanking slopes are wrinkle-ridged and merge into the regional plains while other flows of the same volcano are not wrinkle-ridged and show superposition on the regional plains. Some volcanoes classified as young may have old wrinkle-ridged flows on their slopes which are now completely covered with young flows not deformed by wrinkle ridges. These volcanoes, if they exist, started their eruption before the end of emplacement of regional plains and their deformation by wrinkle ridges and thus are transitional in age. Similarly, some old volcanoes may have started their activities before the emplacement of regional plains. Later in the paper we discuss the significance of these potential parts of the population.

We classify rifts into two categories: young and old, which correspond to the categories of “rifts” and “fracture belts,” respectively, of Hansen et al. [1997] and Tanaka et al. [1997]. Young rifts are characterized by the presence of troughs cross-cutting the adjacent regional plains. Faults and grabens associated with young rifts cross-cut the materials of regional plains and the wrinkle ridges deforming them. Old rifts are represented by belts of fractures topographically standing above the adjacent regional plains. The majority of the fractures are embayed and covered by materials of regional plains although some of the fractures cross-cut the plains and the network of wrinkle ridges. The latter relationship implies continuation of some fracture belt activity into post-regional-plains time, and thus at least part of our old rifts could be classified as transitional in age. However, for the majority of the fracture belts it is obvious that their tectonic activity in the postplains time was minor, and this justifies the classification of rifts into only two age categories. The question of rifts that may be transitional in time requires additional detailed studies and is beyond the scope of the present paper.

In our study we used as a guide the "Tectonic and Volcanic Map of Venus" [Price, 1995], which shows, among other units, "rifts" and "volcanoes" (the latter are "large volcanoes"). Each of the rifts and volcanoes was studied by us in two ways. First, we analyzed synthetic stereo prepared by the U.S. Geological Survey through the combination of the Magellan C1-MIDR (225 m/pixel resolution) format synthetic aperture radar (SAR) images and altimetry (~10 km spatial resolution). This provided us with the ability to see a three-dimensional (3-D) view of each of the rifts, sorting them into (1) rift valleys (troughs, chasmata) cut into the adjacent regional plains and (2) fracture belts standing above the adjacent plains. Large volcanoes appear in this 3-D view as very prominent topographic highs clearly distinct from the surrounding regional plains. On regular (not stereo) Magellan products some of the volcanoes do not look as distinct. Second, we analyzed the age relations of both rift-forming fractures and volcano-forming flows with the adjacent regional plains which have been deformed by networks of wrinkle ridges. In this analysis we studied the appropriate Magellan SAR images (C1- and F-MIDRPs, F-MAPs) in the form of large-format hard copies and in digital format when the age relations being analyzed were not clear on the hard copies.

As a result of this approach, we have found that what is mapped by Price [1995] as rifts corresponds both to rift zones and fracture belts of other workers [e.g., Head and Basilevsky, 1998; Basilevsky and Head, 2000; Hansen et al., 1997; Tanaka et al., 1997]. For consistency, we did not add any new rifts to the those previously mapped, although some prominent features (e.g., Sigrun Fossae) obviously belong to the category of rifts (actually fracture belts), but are not shown on the Price [1995] map. These cases, however, are quite rare. The only change we made was removing the relatively small rift at 45°N,

![Figure 1](image_url). The location map for the six areas of detailed studies described in this analysis. The background is the Magellan-based altimetry of Venus.
190°E, which indeed is a cluster of wrinkle ridges. Also for consistency, we did not make any changes in relation to volcanoes although a very few of them may be classified as coronae rather than volcanoes (e.g., the feature centered at 11°S, 211°E).

3. Areas of Detailed Studies

These areas (Figure 1) represent typical examples of rifts and volcanoes classified according to their age. Area 1 (Figures 2-5) shows a young rift cutting an old rift with no rift-associated volcanism. Area 2 (Figures 6-9) represents an example of an old volcanic in association with an old rift. Area 3 (Figures 10-12) shows a transitional volcano apparently sitting on a now-flooded old rift. Area 4 (Figures 13-16) shows an example of a young volcano sitting on a young rift. Area 5 (Figures 17-20) shows another example of a young volcanic in association with a young rift. It differs from area 4 in that the late rifting cuts the volcanic slopes in arcuate troughs, producing a corona-like feature. Area 6 (Figures 21-23) represents an example of a young volcano lacking visible association with any rift. In describing these areas we concentrate on the analysis of age relations between rifts and large volcanoes, and regional plains, and on the association of faulting and volcanism. We also briefly discuss the presence of other geologic units in the areas analyzed.

3.1. Area 1 (15°S, 232°E)

This area is about 550 x 600 km and is located along the NE flank of Wawalag Planitia. Here a relatively young rift zone, a segment of Parga Chasma rift zone trending generally E-W, cuts an older unnamed fracture belt. The latter trends S-N in the southern part of the area and turns to the NW-SE in the northern part. Figure 2 shows the Magellan synthetic stereo images of the area. Figure 3 shows a perspective view. Figure 4 shows the image of the area and its photogeologic map at the C1-MIDR scale, and Figure 5 shows the details of the rift/fracture belt relations.

The geologic background of the area is represented by regional plains (Figures 2-5), mostly by plains with wrinkle ridges (Pwr) and locally by shield plains (Psh) [Basilevsky and Head, 1998, 2000; Basilevsky et al., 1997]. Pwr materials are generally smooth and homogeneously radar dark to diffusively mottled. The surface of Pwr is deformed by numerous wrinkle ridges ~1 km wide and a few tens of kilometers long. Psh plains, also wrinkle-ridged, have a radar brightness similar to that of Pwr but commonly slightly brighter. The typical character of Psh is the presence of numerous volcanic shields of ~3-5 up to ~15-20 km in diameter. Both Pwr and Psh plains are also locally deformed by narrow lineaments, probably fractures. Psh typically looks more deformed by the fractures than Pwr, and this locally emphasizes its embayment by Pwr, although some of the Psh shields may overlie the Pwr material. Altitudes of the surface of the regional plains vary from 750 to 1250 m above the mean planetary radius, with Psh plains typically sitting ~100-300 m higher than Pwr plains.

In the southern part of the area a segment of a fracture belt (FB) is observed trending N-S for ~250 km (Figures 2-5). It is ~200 km wide and consists of swarms of alternating subparallel grooves and ridges, evidently formed by fracturing. They trend parallel to the general trend of this segment of the belt. To the north the fracture belt and the regional plains are cut by the rift chasm, so the belt material is observed here in the form of blocks separated by the individual troughs of the rift zone. The trend of the subparallel clusters of FB-forming fractures here is generally SE-NW. Locally, the FB fracture clusters show arcuate trends forming a few of the corona-like features. The spacing of the FB-forming fracturing typically varies from 1 to 1.5 km. Most of the fractures of the fracture belt are embayed by the surrounding Pwr and Psh plains although some of the fractures cross the belt/plains boundary and cut the plains. This means that the material of the fracture belt was emplaced and deformed by the majority of the fractures before the regional plains were emplaced but some fracturing within the belt postdated the plains emplacement. Unit FB typically shows here altitudes from 1250 to 1500 m above the mean planetary radius, thus forming low highs among the regional plains.

The E-W trending rift zone cutting both the fracture belt and the regional plains represents topographically a system ~100-300 km long and 30-100 km wide of interconnecting and en
echelon troughs (Figures 2 and 3). It is mapped as a structural unit, RT. In the NE part of the area the rift troughs are arcuate, probably inheriting their orientation from the preexisting corona-like features formed at the time of FB, thus forming here a topographic feature named Beruth Corona. Floors of the rift troughs of the area are a few hundred meters to 1.5 km below the surface of the neighboring regional plains and the fracture belt blocks (see also Figures 2 and 3). The altitudes of the floor typically vary along the individual troughs by 500 m to –1 km. Floors and slopes of the rift troughs are fractured typically with 2-3 km average spacing of fractures (Figures 4 and 5). Rift-associated fractures also extend from the troughs into the neighboring regional plains and the fracture belt blocks. The rift fracture spacing is not spatially consistent and varies significantly. Trends of the majority of the fractures are roughly parallel to the trends of the rift troughs, although fractures transverse and oblique to the predominant trends are also abundant. Individual rift-associated fractures are a few tens of kilometers long. Some of them are a few hundred meters wide, with this width being rather constant along all the fracture length. Others show changes of their width from a few hundred meters to 1-2 km along the fracture. The fractures with varying width often show an anastomosing pattern.

No rift-associated volcanics are clearly observed within this area. Radar dark smooth subareas and small gently sloping shields of probable volcanic origin, observed on the floor of some rift troughs, cover the remnants of FB fracturing, are locally wrinkle-ridged, and are cut by the rift-associated fractures. They evidently belong to the Pwr and Psh varieties of the regional plains involved in the rifting. About 50 km NE of the crater Marie (see below), a subtle relatively bright 50 km long lobate flow is observed. It lacks obvious wrinkle ridges and probably belongs to relatively young volcanics of the PI unit (plains consisting of lobate flows) of Basilevsky and Head [1995, 1998, 2000]. This flow is ~150 km south of the rift zone and only ~25 km east of the fracture belt. The morphology of this unit implies flow from the belt toward topographically lower areas of the neighboring regional plains. It is deformed by a few fractures extending from the rift zone. Probably, this flow is related to the later stages of activity within the fracture belt rather than to the rift-associated activity.

Two impact craters are observed in this area: the crater Darline (19.3°S, 232.6°E, D = 13 km) and the crater Marie (21.7°S, 232.4°E, D = 14.2) [Schaber et al., 1998] (http://www.flag.wr.usgs.gov). The crater Darline sits on the floor of a rift trough. The crater itself and its ejecta are super-
posed on most of the neighboring rift-associated fractures. One possible exception may be the NE trending fracture in the NE segment of the crater rim. It may either predate or postdate the crater formation. Ejecta associated with this crater is asymmetric and is extensive on the southern side of the crater and almost absent on the northern side, evidently a consequence of oblique impact. Absence of ejecta on the northern part of the crater makes the second option (the fracture predated the crater formation) very possible, but even if this fracture postdates the crater formation, the majority of the neighboring rift-associated fractures obviously predates the crater. Thus one can conclude that the formation of the crater Darline postdates either all or major episodes of rift formation in this place. No dark parabola is observed in association with the crater.
Darline, and this implies that rifting here occurred before the time $\sim 0.1 T$ from present, where $T$ is the mean age of the regional plains of Venus [Basilevsky and Head, 1998, 2000]. The crater Marie is superposed on the fracture belt and on pieces of regional plains locally seen in between the densely fractured parts of the belt. No radar dark parabola associated with this crater is observed.

So at area 1 the fracture belt (FB) represents the oldest of the observable geologic units. Emplacement of the material and major phases of its fracturing (old rifting) were postdated by emplacement of materials of regional plains, first, Psh plains, then, Pwr plains. Then, later phases of the FB fracturing and wrinkle ridge formation deformed the regional plains. After that, young rifting deformed both regional plains and the fracture belt. The young lava flow (P) in the SE part of the area shows no evidence of association with young rifting and may be associated with the waning phase of old rifting.

3.2. Area 2 (35°S, 226°E)

This area (Figures 6-9) is about 450 x 675 km and is located in the SE part of Wawalag Planitia, where a segment of an unnamed fracture belt stands above the wrinkle-ridded regional plains. The belt segment is separated into two fragments by an unnamed volcanic construct from which lava flows emanate. In their distal parts the flows merge into the Pwr variety of regional plains and, like the latter, are deformed by wrinkle ridges. This implies that the volcano is relatively old. Figure 6 shows a perspective view of this area. Figure 7 shows the image of the area and its photogeologic map at the C1-MIDRP scale. Figures 8 and 9 show the details of the relations among major geologic units of this area.

The geologic background of the area is represented by regional plains, plains with wrinkle ridges (Pwr), and shield plains (Psh) (Figures 6 and 7). Their morphologic characteristics are similar to those described above in area 1. The presence of wrinkle ridges is typical of both of these varieties of regional plains. In most places the age relations between Pwr and Psh are rather obvious, with Pwr embaying Psh (Figure 8) and forming kipukas composed of Psh. Altitudes of the surface of the regional plains vary from about 400 to 1200 m above the mean planetary radius, with Psh plains typically sitting $\sim 100$-300 m higher than Pwr plains. In several places of the area, outliers of tessera terrain (Tt) 5-10 to 50-80 km across are seen and are embayed by regional plains (Figure 9).

The fragments of the fracture belt (FB) observed in this area show a general NNE trend (Figure 7). They are not shown on the Price [1995] map, probably because of their relatively small sizes (150 x 300 and 120 x 200 km), so they are not shown on our global map. It is seen in the C1-MIDRP.30S225 mosaic that these fragments of the belt and the belt fragment described in area 1 are parts of a single fracture belt system now separated by Pwr and Psh plains into pieces standing apart. The FB unit here is characterized by swarms of alternating subparallel grooves and ridges, evidently formed by fracturing (Figures 7 and 8). As in area 1, they trend parallel to the general trend of the belt segments. Some places within the belt are densely fractured with a fracture spacing of 1 km. In many parts of the belt the subparallel swarms of fractures are not as dense. Their spacing is 2-5 km, while the width of the individual fractures is $\sim 1$ km, so the material in between the fractures is well seen. Judging by its morphology, it is evidently material of Psh plains (Figure 8). Some of these fractures appear to be partly buried by Psh material, while others cut it. At the boundaries of the FB fragments with Pwr and Psh units, it is seen that fractures of the fracture belt are mostly embayed by the neighboring Pwr and Psh plains but that some of the fractures cross the belt-planes.
boundary and cut the plains. This implies that formation of the fracture belt started before the emplacement of early varieties of the Psh material and continued to a minor extent until the emplacement of Pwr plains and even later. Unit FB typically shows altitudes from 800 to 1000 m above the mean planetary radius, thus forming low highs among the regional plains.

The volcanic construct separating the fracture belt into two pieces (Figures 6 and 7) has its summit altitude more than 1200 m above the mean planetary radius, and this is several hundred meters above the neighboring regional plains and fragments of the fracture belt. Two smaller edifices, 10 and 20 kilometers in diameter, are seen at the volcano summit (Figures 7 and 9). Flows forming slopes of this construct appear to be very similar to the surrounding Pwr plains, merging into the latter, and thus boundaries between the flows and the regional plains are not obvious in some places. The surfaces of the flows and the summit edifices are complicated with wrinkle ridges which belong to the same system of wrinkle ridges which deform the surface of regional Pwr and Psh plains. This implies that this volcanic construct was formed at approximately the same time as the regional plains formed. As it is mapped on Figure 7, the volcano, including its lava flow aprons, is about 120 x 250 km. Although in Figure 6 it appears to be a prominent topographic feature, its slopes are very gentle, typically not more than 1° at the scale of tens of kilometers.

This volcano is obviously associated with the fracture belt (Figure 7), but the belt is not shown on the map of Price [1995] because of its relatively small size, so it is not shown on our global map. This has an important implication: In the consideration of association of volcanoes and rifts based on analysis of the global map of rifts and volcanoes described below, the number of cases where such association exists is certainly underestimated.

In summary, the oldest of the observable geologic units of Area 2 is the material of tessera terrain (Tt). Next in the observable stratigraphic sequence is the fracture belt (FB) unit. The oldest part of its material and the early phases of its deformation (old rifting) predated emplacement of regional plains. The earlier member of the regional plains is Psh plains, and the later one is Pwr plains. The FB fracturing (old rifting) continued to some extent into the time of emplacement of regional plains, and waning phase of fracturing, even somewhat later. The large old volcano, which sits on the fracture belt, formed approximately simultaneously with the emplacement of Pwr.
3.3. Area 3 (39°N, 45°E)

This area is about 450 x 675 km, and a significant part of it is occupied by the volcanic construct of Api Mons. Flows from Api Mons are partly superposed on the surrounding regional plains and partly merge with the latter. The NW part of the area includes the tessera block which is the southernmost termination of Laima Tessera. Figure 10 shows a perspective view of this area. Figure 11 shows the image of the area and its photogeologic map at the C1-MIDRP scale. Figure 12 shows the details of the relations among some geologic units of this area.

As in the majority of other areas on Venus, the geologic background of this area is characterized by regional plains. In this area, only plains with wrinkle ridges (Pwr) are widely observed, while shield plains varieties (Psh) are not typical. The morphologic characteristics of the Pwr plains are similar to those in areas 1 and 2 (described above). They are relatively dark, locally mottled, with a network of wrinkle ridges superposed on them (Figures 10-12). The altitudes of the surface of the Pwr plains in the area vary from close to mean planetary radius in the NE and NW, to -400-1200 m above mean planetary radius in the SW, where a general rise to Bell Regio occurs.

Remnants of fracture belts are seen in the western and eastern parts of the area in the form of low-standing local highs 100-300 m above the adjacent Pwr plains. These remnants are up to 100-150 km long and 30-50 km wide (Figure 11). In their most well-preserved parts they show subparallel lineations with a spacing of ~1 km. However, within FB unit outcrops, local lows are typically partially filled with materials of Psh and Pwr type (best seen in the western part of the mapped outlier of FB ~150 km east of Api Mons summit area). As in other areas of Venus, some of the FB-forming fractures are covered by these materials, while others cut them.

The volcano Api Mons and its lava flow aprons are about 500 x 600 km across. Its summit, including the 100 x 150 km caldera-like feature, has an elevation of more than 1600 m above mean planetary radius and approximately the same height above the adjacent regional plains. The caldera walls and floor are composed of materials similar to Pwr and locally to Psh plains which are wrinkle-ridged (Figure 11). The slopes of the volcano are made of flows of two types: (1) those made of wrinkle-ridged material slightly brighter than typical regional Pwr plains of this area and (2) those made of slightly to significantly brighter material, lacking wrinkle ridges and having the prominent morphology of lobate flows (Figures 10 and 11). The wrinkle ridges at the Api caldera and on the volcano flanks have the same sizes and orientation as wrinkle ridges typical of the network of the surrounding Pwr plains, so they are obviously part of that network. This suggests that the caldera wrinkle ridges are not simply related to summit reservoir subsidence. We consider flows of the first type as a variety of Pwr plains and flows of the second type as a variety of lobate plains (Pl). So this volcano began to be active at the time of emplacement of regional wrinkle-ridged plains and continued to be active after the emplacement of the regional network of wrinkle ridges, at the time when lobate plains (Pl) formed [Basilevsky and Head, 1998, 2000; Basilevsky et al., 1997]. Api Mons slopes vary from 0.5° to 2° at the scale of tens of kilometers.

Two impact craters, Heloise (40°N, 51.9°E, D = 38 km) and Aisha (39.3°N, 53.3°E, D = 10.6 km) are seen in area 3.
Figure 9. (left) SAR image and (right) geologic map of the subarea covering the old volcano summit and its western slope in area 2. It shows the wrinkle-ridged surface of the volcano-related flows which embay outliers of the fracture belt (FB) and of tessera terrain (Tt). The white dotted line shows an approximate boundary of the volcano flow aprons. Lines with single hatch show the position of some wrinkle ridges. See text for description. Area is 75 x 85 km. Fragment of C1-MIDRP.30S225.1.

Figure 10. A perspective view of area 3 looking to the north. The transitional-in-age volcano Api Mons is seen at the center of the area. Its older wrinkle-ridged flows merge into the adjacent regional plains. The younger flows are easily visible because of their higher radar brightness. A block of very bright terrain at the upper left part of the image is the southmost termination of Laima Tessera. Area is 450 x 675 km.
[Schaber et al., 1998]. The crater Heloise is heavily flooded by Pwr plains, so only its rim is preserved (Figure 11). The crater Aisha is located ~100 km SE of Heloise and has prominent ejecta but no associated radar dark parabola. It appears to be superposed on the wrinkle-ridged flows of Api Mons and may be partly embayed by its younger flows.

As it is seen in the C1-MIDRP 45N053 mosaic, the outcrops of FB in the eastern part of area 3 described above represent the western termination of a 150 x 300 km outlier of the fracture belt embayed by Pwr and partly by Psh plains. The inlier itself, and the FB fractures in it, trend NW in the direction of Api Mons. It appears that Api Mons volcano sits on the fracture belt and is completely covered in this place by the Api flows. The inlier of the fracture belt in area 3 is not shown on the map of Price [1995], obviously because of its relatively small size, and thus is not shown on our global map. This example further underlines the fact that consideration of the association of volcanoes and rifts based only on analysis of the global map of rifts will lead to an underestimation of the number of cases in which such association exists.

In summary, the oldest geologic unit in area 3 is the material of tessera terrain (Tt). Next in the observable stratigraphic sequence is the fracture belt unit (FB). It is observed in the form of a few outliers among the regional plains. Regional plains are represented here mostly by Pwr plains. The oldest part of FB material and the early phases of its deformation (old rifts) predated emplacement of regional plains. Later, waning phase of old rifts partly deformed Pwr plains. Approximately simultaneously with emplacement of the regional Pwr plains, a significant part of the volcanic construct Api Mons formed. Then its flanks as well as the regional plains were deformed by wrinkle ridges. Eruption of younger lava flows (Pl) after the episode of wrinkle ridge formation continued the construction of Api Mons.

3.4. **Area 4 (25°N, 264°E)**

This area is about 450 x 900 km and lies within Asteria Regio (Figures 13-16). It is crosscut by the N-NE-SW diagonal. Its northeastern segment of the segment of Hecate Chasma rift system [Hamilton and Stofan, 1996]. In the central part of
Figure 12. (left) SAR image and (right) geologic map of the subarea in area 3 showing relations of old, wrinkle-ridged lavas and (superposed on them) young, not wrinkle-ridged lava flows on the NE slope of the volcano, with the Pwr regional plains. The white dotted line shows the approximate boundary of the volcano flow aprons. Lines with single hatch show the position of some wrinkle ridges. See text for description. Area is 150 x 165 km. Fragment of C1-MIDR3-45N053-1.

Figure 13. A perspective view of area 4 looking to the north. The young volcano Polik-mana Mons is seen at the center of the area. It sits on the NE trending Hecate-Latona system of young rifts. The volcano flows are superposed on the adjacent regional plains. Area is 450 x 900 km.
the area a large volcano, Polik-mana Mons, sits on the rift. Its lava flows partly cover rifted terrain and extend hundreds of kilometers north and south, covering and embaying regional Pwr and Psh plains and inliers of more ancient tessera terrain and fracture belts. Figure 13 shows a perspective view of this area. Figure 14 shows the image of the area and its photo-geologic map at the C1-MIDRP scale. Figures 15 and 16 show the details of the relations among the major geologic units of this area.

Regional plains of this area are represented by both plains with wrinkle ridges (Pwr) and shield plains (Psh). They occupy a comparatively small percentage of the area being flooded by the younger flows of Polik-mana Mons volcano (Figure 14). The presence of wrinkle ridges is typical of both of these varieties of regional plains. The morphologic characteristics of Pwr plains are similar to those in areas 1-3, as described above. Psh plains contain numerous small shields, as in previously described areas, but in contrast to areas 1-3, the shields are
typically smaller and less prominent. In some places in area 4, SE of the volcano, for example, Pwr plains embay Psh plains (Figure 14). These Psh plains locally show the presence of FB-type fracturing, while Pwr plains here are much less fractured, and this makes the embayment relations obvious. Altitudes of the surface of the regional plains in area 4 vary from about 1 to 2 km above mean planetary radius.

Remnants of the fracture belt unit are seen in the western part of the area (Figures 14 and 15). In their most well-preserved parts they show subparallel structural lineations with spacing of ~1 km. Typically, however, local lows within the FB outcrops are partially filled with the materials of Psh type. As in other areas of Venus, some of the FB-forming fractures are covered by Psh materials, while other fractures cut the latter. The FB infills stand only a few hundred meters above the adjacent Pwr plains.

The volcano of Polik-mana Mons, including its lava flow aprons as it is mapped in Figure 14, is ~500 km in diameter. Its
summit, with an 80 km caldera-like feature, stands more than 5.4 km above mean planetary radius and ~3.5 km above the adjacent regional plains. The walls and floor of the caldera-like feature are composed of materials similar to lobate plains (PI) but which locally resemble Psh plains. Material of the caldera floor is slightly fractured. The slopes of the volcano are composed of flows which become more prominent downslope. Within ~100 km downslope from the caldera-like feature these flows are significantly more heavily fractured than the feature floor, but farther downslope they become less fractured. The volcano lava flows are not wrinkle-ridged, and they are clearly superposed on varieties of Pwr and Psh regional plains. Thus this is a typical young volcano. Although the steepness of the slopes at the scale of a few kilometers locally reaches ~10° close to the summit caldera, over most of the volcanic construct slopes at the scale of a few kilometers to a few tens of kilometers vary from 0.5° to 2°.

The volcano of Polik-mana Mons sits on a NE-SW trending rift zone which is one of the segments of the Hecate Chasma rift system. Part of the rift NE of the volcano has its own name, Latona Chasma. The topographic trough of the rift zone is 50-100 km wide and within the area described is at least 1000 km long. Its floor is 1-3 km lower than the adjacent plains. Depth varies along the trough by 1-2 km. The rift-associated fractures extend from troughs and cut the regional plains and partly the younger volcanics, clearly showing that this is a young rift. The fracturing is generally the most dense on the trough floor and slopes, where spacing of the fractures and graben varies from 1 to 5 km. These densely fractured zones are shown in the map of Figures 14 and 16 as rifted terrain (RT). The individual fractures have widths from the limit of the image resolution (a few hundred meters) to 1-2 km. Graben are 1-5 km wide. Most rift-associated structures of this area change their width along the structure and have an anastomosing morphology. Densely fractured rift zones cut the slopes of the volcano, but its topmost part and caldera-like feature are only slightly fractured. Thus the latest episodes of the Polik-mana Mons activity were not followed by significant rift-associated tectonic activity.

In summary, the oldest geologic unit in area 4 is material of tesseran terrain (T). Next in the observable stratigraphic sequence is the fracture belt unit (FB). It is observed in the form of a few outliers in the western part of the area, mostly among the regional plains. The regional plains are represented here by Psh and Pwr plains. The oldest part of FB material and the early phases of its deformation (old rifting) predated emplacement of regional plans. Later, waning phase of old rifting partly de-

Figure 17. A perspective view of area 5 looking to the north. The construct of the young volcano is seen at the upper center of the image. It is cut circumferentially by arcuate rift troughs, which form a roughly oval feature named Odudva Corona. The rift troughs belong to the NE trending Parga system of young rifts. The volcano flows are superposed on the adjacent regional plain. Area is 450 x 675 km.
forms Pwr plains. Next in the sequence is rifted terrain (RT) formed by the young rifting, which is responsible for the formation of the adjacent parts of Hecate and Latona Chasmata. Volcano Polik-mana Mons sits on the young rift zone and is partly deformed by the rift-associated fracturing.

### 3.5. Area 5 (11°S, 211°E)

This area is about 450 x 675 km and is crossed along its NE-SW diagonal by one of the segments of the Parga Chasma rift zone (Figures 17-20). A large volcanic construct sits in this zone, and its extended lava flows cover the adjacent regional plains. This construct is cut around its central part by arcuate rift troughs, thus forming a roughly oval tectonic feature ~150 km in diameter, which is listed in the USGS web site as OkuJura Corona. Figure 17 shows a perspective view of this area. Figure 18 shows an image of the area and its photogeologic map at the C1-MIDRP scale. Figures 19 and 20 show the details of the relations among the major geologic units of this area.

The regional plains of this area are represented by plains with wrinkle ridges (Pwr) and shield plains (Psh), having morphologic characteristics typical of many other areas of Venus, including those described above. These plains are rather abundant in the southern and western parts of the area. In most localities of area 5, for example, SE of the volcano, Pwr plains embay Psh plains (Figures 18 and 19). Altitudes of the surface of the regional plains in area 5 vary from about 1 to 1.5 km above the mean planetary radius. In several places in this area there are outliers of moderately radar bright material embayed by both varieties of regional plains (Figures 18 and 19). On the basis of its stratigraphic position and morphological characteristics we consider it as a variety of the Pfr unit of Basilevsky and Head [1995, 1998, 2000].

The volcanic construct and its lava flow aprons occupy an area more than 500 km across. Its summit is heavily fractured with a radial pattern and is shown in maps of Figures 18 and 20 as radially fractured terrain (RF), which is a structural member of the material unit composing the volcanic construct. In its most densely fractured parts the fracture spacing is ~1 km. These radial fractures are seen up to distances of 80-100 km from the summit center of radiation. Farther outward they are
covered by radiating lava flows. At least part of these flows evidently originate from the radial fractures at some distance from the summit area. The lava flows observed on the slopes of this volcano have typical lobate morphology, lack wrinkle ridges, and clearly overlap both varieties of regional plains, Pwr and Psh. This is why this volcano is considered as a young one. The altimetric data show that the center of the fracture radiation is inside the summit depression, being ~0.5 km lower than the highest parts of the construct. These highest parts form the horseshoe-shaped feature ~80 km in diameter (Figure 17). The highest parts of this feature stand ~3 km above the mean planetary radius, that is, ~1.5-2 km above the adjacent regional plains. If we ignore the rift-associated topography, slopes of this volcanic construct are 0.5°-2°.

The rift zone of this area consists of interconnecting and en echelon-arranged topographic troughs generally trending NE-SW. Around the volcano summit the topographic troughs are planimetrically arcuate, forming a feature named Odudova

Figure 19. (left) SAR image and (right) geologic map of the subarea at the SE apron of the unnamed volcano in area 5. It shows the relatively dark Pwr plains embaying Psh plains, which, in turn, embay Pfr plains. Young lavas of the volcano apron (Pl) cover Pwr and Psh plains and are cut by a long rift-associated fracture. Lines with single hatch show position of some wrinkle ridges. See text for description. Area is 110 x 115 km. Fragment of C1-MIDRP.15S215;1.

Figure 20. (left) SAR image and (right) geologic map of the subarea in area 5 showing the radially fractured summit (RF) of the unnamed volcano and lobate flows (Pl) of its NW slope. The image also shows arcuate troughs (RT) of the young rift which cuts the volcano slope. See text for description. Area is 150 x 165 km. Fragment of C1-MIDRP.15S215;1.
Figure 21. A perspective view of area 6 looking to the north. The twin young volcano is seen at the center of the image. Its flows are superposed on the adjacent regional plains. Area is 450 x 675 km.

Corona. On the geologic maps shown in Figures 18 and 20, only areas of heavy rift-associated fracturing are shown as rifted terrain (RT). These heavily fractured areas are typically on the floors and especially on the walls of the troughs. Rift-associated fracturing here clearly postdates regional plains and even the younger volcanics, so this rift is classified as young. At the same time, in many places in the troughs their floors are not heavily fractured, preserving the typical morphology of the adjacent regional plains. These places are shown in the maps as regional plains. Radially fractured terrain (RF) on the summit of the volcanic construct described is cut by a young rift unit (RT). It is especially obvious on the synthetic stereo, which shows the abrupt cutting of the radially fractured slopes of the volcano by the rift-associated topographic trough. The most heavily deformed areas of rift-associated fracturing have fracture-to-fracture spacing of ~1 km. The majority of fractures in these areas are densely packed in parallel clusters and have approximately the same width and maintain a relatively constant width along their lengths. In this respect they are very similar to structures typical of more ancient units of fracture belts and even densely fractured plains of Head and Basilevsky [1998] and Basilevsky and Head [1998, 2000]. However, their frequent localization at the steepest parts of walls of the trough cutting regional plains and their wedge-like planimetric form controlled by the trough geometry suggest that they are part of the young rift zone that predates the regional plains. The areas of dense fracturing and the adjacent geologic units are often deformed by generally wider (up to 1-3 km) fractures with 2-10 km spacing. These are anastomosing, and their width along the individual structures typically varies from the limit of resolution to 1-3 km. All of these characteristics of the area 5 rift zone indicate that it should be classified as a "young rift."

Within the oval feature of Oduduva Corona the fractures radiating from the center of the volcanic construct are typically cut by rift-associated fractures, although opposite relations are also observed. Superposition of the large-scale rift activity with formation of topographic troughs on the radial fractures is especially obvious in the synthetic stereo. The rift-associated fractures also often cut the radiating volcanic flows, while the latter typically cover the radial fractures or originate from them. Relatively small (3-10 km across) areas of moderately radar dark material with a smooth surface are locally seen in the rift trough floors and radially fractured volcano summit, thus indicating the presence of minor postfracturing lava eruptions or accumulations of eolian debris. Thus one may conclude that major stages of volcanic activity forming the observed construct predated significant rift activity in this area.

SW of the volcano there is an impact crater named Izakay (12.3°S, 210.9°E, D = 10.2 km). The crater itself and its butterfly-like ejecta blanket obviously overlap the rift-associated
fractures. The crater shows no associated radar dark deposits characteristic of relatively young craters. This implies that, at least in the crater vicinity, the rifting activity was not very recent.

In summary, the oldest geologic unit in area 5 is material of tessera terrain (Tt). Next in the observable stratigraphic sequence is the unit of deformed plains which is probably correlative with the Pfr unit of Basilevsky and Head [1998, 2000]. It is observed in the form of outliers in several places of the area, mostly among the regional plains. The latter are represented here by the Psh and Pwr plains, both deformed by wrinkle ridges. Next in the sequence are the materials composing vol-
cano Polik-mana: lobate flows (Pl) of the volcano flanks and the structural member (RF) of the volcano summit. Young rifted terrain (RT) postdates the volcano construct.

3.6. Area 6 (18°N, 303°E)

This area is about 450 x 675 km and lies within Undine Planitia ~1000 km SE of Beta Regio (Figures 21-23). The dominant terrain here is regional plains, within which there is a twin unnamed volcano whose flows are obviously superposed on the regional plains. No young or old rift zones are observed in this area or in its close vicinity. Figure 21 shows a perspective view of the area. Figure 22 shows an image of the area and its photogeologic map at the C1-MIDRP scale. Figure 23 shows the details of the relations between the volcano flows and regional plains.

Regional plains of this area are represented by three varieties of plains with wrinkle ridges (Pwr1, Pwr2, Pwr3) and shield plains (Psh). Pwr plains here, as in many other areas of Venus, are smooth, homogeneous to slightly mottled in radar brightness, and deformed by wrinkle ridges (Figure 22). The oldest of them (Pwr1) is relatively dark. Intermediate in age (Pwr2) is intermediate in brightness. The youngest (Pwr3) is relatively bright. The boundaries between these three members of Pwr plains are very prominent here. The age relations among these three varieties of regional plains are based on the embayment of the flow-like morphology of the younger unit in relation to the older one. The Pwr1 unit dominates in the eastern part of the area, Pwr2 dominates in the central north and central south, and Pwr3 dominates in the west. The areal distribution of Pwr subunits appears obviously independent relative to the position of the twin volcano which sits in the center of the area. So the twin volcano seems to show no spatial inheritance from the volcanism which formed the Pwr lava fields. Psh forms a few fields, the largest of which is in the SW corner of the area. This is the eastern part of the 150 x 200 km feature known as Grizodubova Patera. Psh material of this area is more fractured than adjacent fields of Pwr1 and Pwr3 units and is clearly em- bayed by them. Two fields of Psh material in the eastern part of the area are embedded by Pwr1 plains although locally a few Psh type shields clearly postdating Pwr1 unit are seen here. Altitudes of the surface of the regional plains in area 6 typically vary from about 0.3 to 0.5 km above mean planetary radius. The altitudes of Psh plains on the eastern flank of Grizodubova Patera reach 0.8 km above mean planetary radius. In the SE corner of the area, the northern part of a 40 x 80 km block of tessera terrain (Ti) is seen (Figure 22).

The twin volcano has two summits ~90 km apart (Figure 22). Each of them is more than 1.2 km above mean planetary radius and ~800 m above the surrounding regional plains. Lava flows around these two summits form a common field about 300 x 350 km in dimension. The flows are relatively bright although some of them are less bright than the Pwr3 unit. The twin volcano flows have typical lobate morphology, have no wrinkle ridges on them, and are clearly superposed on the Pwr plains (Figure 23). Thus we classify this volcano as a young one. As mentioned above, neither old nor young rifts are observed in reasonable proximity to this volcano. So it should be considered as “not associated with rifts.” The lower parts of the twin volcano slopes are very gentle, <0.5° on the scale of tens of kilometers. The upper parts of volcano slopes are steeper, up to 3°-5°. These are the steepest values of the volcano slopes observed in the example areas studied, but even they are gentle, comparable to the slopes of terrestrial shield volcanoes such as Mauna Kea.

In summary, the oldest geologic unit in the area is material of tessera terrain (Ti), forming the relatively small massif in the SE part of the area. Next in the observable stratigraphic sequence are regional plains: Psh plains and above them three subunits of Pwr plains. All varieties of regional plains are deformed by wrinkle ridges. The volcanic construct formed by lobate flows (Pl) is clearly superposed on the Pwr plains.
4. Global Assessment of the Volcanoes and Riffs

A global map of rifts and volcanoes on Venus was compiled (Plate 1) as a result of the procedure described above for the analysis of Magellan data products (see section 2). The map shows rifts subdivided into (1) young, superposed on regional plains and (2) old, embayed and partly flooded by the regional plains. The volcanoes (>75-100 km in diameter) are subdivided into (1) young, with flows on their slopes superposed on the regional plains; (2) transitional, composed of flows both superposed on the regional plains and contemporaneous with the plains; and (3) old, made of flows contemporaneous with the regional plains. As we mentioned above (see section 2) the geologic event marking the upper boundary of the regional plains was emplacement of wrinkle ridges. Thus, in the photo-geologic analyses we considered the age relations of deformation and/or material units with formation of wrinkle ridges. The following description starts with the characteristics of rifts, then follows with the characteristics of the volcanoes, and then considers the associations of the volcanoes with rifts.

4.1. Rifts

The compiled map (Plate 1) shows very obviously the three global-scale disrupted zones first described by Schaber [1982]: (1) the longest (21,000 km), the NE trending Aphrodite-Beta zone; (2) the second longest (14,000 km), the NW trending Themis-Atla zone; and (3) the shortest (6000 km), the Beta-Phoebe zone trending S-N. The first zone intersects the second one at Atla Regio (centered at 4°N, 200°E) and also intersects the third one at Beta Regio (centered at 30°N, 285°E). Young rifts dominate over old rifts in these three zones, in terms of both length and area. The map also shows a discontinuous zone ~7000 km long (not described by Schaber [1982]), consisting of NE and NW trending segments of both young and old rifts, trending generally E-W along latitudes 55°-60°S and connecting (with gaps) the southern terminations of the Aphrodite-Beta and Themis-Atla zones. These four zones approximately outline a great-circle arc inclined at 30° to the equator referred to by Phillips et al. [1981] as the Equatorial Highlands. In addition, three isolated relatively small rifts are seen on the map: (1) the young Guor Linea rift centered at 18°N, 5°E; (2) the old rift centered at 10°N, 80°E; and (3) the young rift of Ix Chel Chasma centered at 10°S, 70°E.

According to Price [1995], rifts occupy 36.5 x 10⁶ km², that is, 7.9% of Venus’s surface. This estimate is based on synoptic mapping in which the smallest details shown on the map are ~100 km across, and hence generalization due to combining separated relatively small neighboring rifts into broader and longer zones is inevitable. In areas 1-6, which we mapped in more detail, these broad zones split into separate troughs, bands of densely fractured rift terrain, and less fractured plains and other terrains in between. So estimates of the area occupied by rifts depend on what is shown as the rifts (e.g., topographic troughs or areas of dense (how dense?) rift-associated fracturing) and on the scale of mapping. It is obvious that more detailed studies should lead to smaller values for estimated rifted area.

In the synoptic view (Plate 1) the young rifts form a system of the four extended zones described above, consisting in total of ~60 interconnected, sometimes crisscrossing, generally linear and arcuate segments of several hundred kilometers to ~2000 km long (Table 2). Their widths vary from 100-200 to 500-800 km. A few relatively small young rifts standing separately from this large system are also observed. The total area of young rifts is 31.1 x 10⁶ km², that is, 85.3% of the total area of the synoptically mapped riffs. Old rifts (fracture belts) are represented by ~25 linear and arcuate fragments ranging from 700 to 1500 km long and typically 100-200 km wide. Old rifts occupy 5.4 x 10⁶ km², that is, 14.7% of the total area of rifts. So the area occupied by old rifts is significantly smaller than that of young rifts. Most of the mapped old rifts are spatially associated with young rifts, both following the trends of young rifts and being transverse to them. Significant areas of old rifts standing far from the young rifts are not observed. The old rifts are mostly observed north of Beta, southwest of Aphrodite, and southeast of Themis at the terminations of three major rift zones [Schaber, 1982] and within the fourth zone running along latitudes 55°-60°S.

4.2. Large Volcanoes

According to Price [1995], large volcanoes occupy 19.5 x 10⁶ km², that is, 4.2% of Venus’s area. It is obvious that more detailed mapping will not significantly change this estimated area. The total number of large volcanoes shown on the map is 109 (Table 3). On the slopes of 74 of them (68%) there are flows postdating wrinkle-ridged regional plains. These young volcanoes occupy 15.8 x 10⁶ km², that is, 81% of the total area of large volcanoes. On the slopes of 18 volcanoes (16.5%) there are flows, some of which postdate the regional plains and some of which are contemporaneous with them. These transitional-in-age volcanoes occupy 2.6 x 10⁶ km², that is, 13.5% of the total area of large volcanoes. Flows on slopes of 17 volcanoes (15.5%) are wrinkle-ridged. Flows postdating wrinkle ridges are not seen here. These old volcanoes occupy 1.1 x 10⁶ km², that is, 5.5% of the total area of large volcanoes. So areas occupied by young volcanoes strongly dominate over those that are transitional in age, while the latter dominate over old ones. The map (Plate 1) is too synoptic for accurate measurements of diameters of volcanoes, but the general trend is clearly seen. Young and transitional-in-age volcanoes vary in diameter from 75-100 km to more than 500-700 km. The sizes of the majority of old volcanoes are near the lower limit of this range.

For more systematic assessment of sizes of large volcanoes we used the catalogue of volcanic centers of Crumpler and Aubelle [2000]. Their large volcanoes correspond in the lower size limit of those mapped by Price [1995] and now shown in Plate 1. Crumpler and Aubelle [2000] list 168 large volcanoes. Among them, 126 are shown on the Price [1995] map, and 42 are not. As discussed above, if one counts volcanoes on the

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Table 2. Characteristics of Rifts

<table>
<thead>
<tr>
<th>Rifts</th>
<th>Area, 10⁶ km²</th>
<th>Number of Mapped Segments</th>
<th>Segment Length, km</th>
<th>Segment Width, cm</th>
<th>Topography</th>
<th>Typical Fracture Spacing, km</th>
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<tr>
<td>Young</td>
<td>31.1</td>
<td>~60</td>
<td>Hundreds to 2000</td>
<td>100-200 to 500-800</td>
<td>troughs</td>
<td>~1-10</td>
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<tr>
<td>Old</td>
<td>5.4</td>
<td>~25</td>
<td>700-1500</td>
<td>100-200</td>
<td>elongated highs</td>
<td>~1</td>
</tr>
<tr>
<td>Total</td>
<td>36.5</td>
<td>~85</td>
<td></td>
<td></td>
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</table>
Table 3. Characteristics of Large Volcanoes

<table>
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<tr>
<th>Volcanoes</th>
<th>Area, (10^6) km(^2)</th>
<th>Number (Percent)</th>
<th>Diameter Range, km</th>
<th>Mean Diameter, km</th>
<th>Show Association With Rifts</th>
<th>No Association With Rifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young</td>
<td>15.8</td>
<td>74 (68%)</td>
<td>100-1000</td>
<td>400</td>
<td>46 (62%)</td>
<td>28 (38%)</td>
</tr>
<tr>
<td>Transitional</td>
<td>2.6</td>
<td>18 (16.5%)</td>
<td>100-800</td>
<td>300</td>
<td>10 (56%)</td>
<td>8 (44%)</td>
</tr>
<tr>
<td>Old</td>
<td>1.1</td>
<td>17 (15.5%)</td>
<td>100-500</td>
<td>220</td>
<td>8 (47%)</td>
<td>9 (53%)</td>
</tr>
<tr>
<td>Total</td>
<td>19.5</td>
<td>109 (100%)</td>
<td>100-1000</td>
<td>350</td>
<td>64 (59%)</td>
<td>45 (41%)</td>
</tr>
</tbody>
</table>

map, their number is 109. Of those, eight volcanoes are absent in the list of Crumpler and Aubele [2000]. So 126 volcanoes from the list are shown on the map as 101 features. The difference in numbers (126 against 101) is because some spatially close volcanoes with adjoining lava fields have been mapped by Price [1995] as a single feature. Area 6 (section 3.6, Figures 21-23) is an example of such a situation.

Of these 126 volcanoes, 85 (67.5%) belong to the category of young volcanoes, 22 (17.5%) belong to the transitional ones, and 19 (15%) belong to the old ones. It is obvious that the proportions of young/transitional/old in the sample of 126 listed volcanoes are practically the same as in the sample of 109 mapped volcanoes. The size distribution of young, transitional and old volcanoes is shown in Figure 24. The diameters of young volcanoes vary from 100 to 1000 km, and the mean value is \(\approx 400\) km. Diameters of volcanoes that are transitional in time vary from 100 to 800 km, and the mean value is \(\approx 300\) km. The diameters of old volcanoes vary from 100 to 500 km, and the mean value is \(\approx 220\) km. Thus the increase in diameters from old to transitional and further to young volcanoes is obvious. It is not clear, however, to what extent it may be a real increase of volcano size and to what extent it may be an effect of the progressive embayment by regional plains.

We have investigated the nature of those 42 features in the Crumpler and Aubele [2000] list which have not been mapped by Price [1995]. For this analysis we used the same procedure as we applied to the study of volcanoes mapped by Price [1995]. Of those 42 features, 18 are coronae and arachnoids having associated lava flows, and they were mapped by Price [1995] as different varieties of coronae. The other 18 features are apparent volcanic centers. Their edifices are topographically low, which is probably the reason why they were not included by Price [1995]. The other four volcanoes are topographically prominent, and the reason why they were missed is not obvious. Two features listed by Crumpler and Aubele [2000] as volcanoes appear to be more tec tonic than volcanic centers with no prominent lava flows. Among the 18 coronae previously mentioned, the ages determined for the associated volcanic activity are eight young, nine transitional, and one old. Among the 18 low volcanoes previously mentioned, the ages determined are 14 young, four transitional, and none old. Among the four missed relatively prominent volcanoes, one is determined to be young, two are transitional, and one is old. In summary, if we add \(18+4=22\) volcanoes from the list of Crumpler and Aubele [2000] to those mapped by Price [1995], this extended sample of volcanoes shows the proportions young/transitional/old which are practically the same as those found for the sample of 109 volcanoes of Price [1995].

Among eight volcanoes mapped by Price [1995] but not included by Crumpler and Aubele [2000], four are young, and four are old. Six of the eight are smaller than 150 km in diameter, and most have topographically low edifices. These characteristics are probably the reason why these eight volcanoes are not included by Crumpler and Aubele [2000]. These comparisons show that in spite of noticeable difference between authors, the map of Price [1995] and the list of Crumpler and Aubele [2000] are generally consistent.

Analysis of the map shown in Plate 1 provides the possibil-

![Figure 24. Frequency distribution of young, transitional-in-age, and old large volcanoes of Venus. Sizes used for preparation of this diagram are from Crumpler and Aubele (2000).](image-url)
ity of determining which volcanoes are in spatial association with rifts and which are not. Of course, as it was demonstrated by the examples of areas 2 and 3 (sections 3.2 and 3.3, Figures 6-9 and 10-12), relatively small rifts are not shown on the map, so in this approach we underestimate the number of cases in which volcano-rift associations exist. This underestimation seems to be unimportant for young rifts and more important for old rifts because, by definition, the latter are embayed and thus partly covered by the regional plains. Of 74 young volcanoes, 46 (62%) show association with young rifts, and 28 (38%) do not (Table 3), although in some infrequent cases the decision as to whether they are rift-associated or not is unclear. Of 18 transitional volcanoes, eight (44%) show association with young rifts, two (12%) show association with old rifts, and 8 (44%) show no association with mapped rifts. Of 17 old volcanoes, two (12%) show spatial association with young rifts, 6 (35%) show association with old rifts, and 9 (53%) show no association with rifts. Thus, if we discuss associations only among mapped features, the majority of young volcanoes, about half of the transitional volcanoes, and slightly less than half of the old volcanoes show associations with rifts. If we summarize all 109 volcanoes considered, 64 of them (59%) show spatial association with the mapped rifts and 45 (41%) do not.

5. Discussion

The results obtained in this study show that young rifts and young large volcanoes, both postdating wrinkle-ridged regional plains, represent the majority of the mapped rifts and volcanoes. The majority of young volcanoes show association with young rifts. Transitional-in-age volcanoes formed by flows both younger than regional plains and contemporaneous with them are significantly less abundant than young volcanoes. Slightly more than half of the transitional-in-age volcanoes show association with young or old rifts. Old volcanoes are close in number to transitional ones but typically have noticeably smaller sizes. Slightly more than half of them show no apparent association with the mapped rifts. Below, we discuss the implications of these observations.

In this work we determine the age of rifts and volcanoes in relation to the end of emplacement of regional plains and their deformation by a wrinkle ridge network. The question of whether this relative time boundary, being very prominent in each region, marks some specific global-wide boundary in absolute time or not is a subject of debate. Some workers [e.g., Guest and Stefan, 1999] believe that the geologic evolution of Venus follows a so-called nondirectional trend and the geologic boundaries of this sort correspond to different periods of time in different regions of Venus. In the early analysis of the Magellan data this approach was represented by the work of Phillips et al. [1992]. As we have shown in our previous work [Basilovsky et al., 1997, Basilovsky and Head, 1998, 2000; Head and Basilovsky, 1998], there is abundant evidence that some events in the geologic history of Venus, including emplacement of regional plains and their deformation by the wrinkle ridges, were quasi-synchronous around the planet. In the early analysis of the Magellan data a similar conclusion concerning the emplacement of the majority of volcanic plains of Venus was reached by Schaber et al. [1992]. Recent work by Solomon et al. [1999, and references therein] also supports a globally contemporaneous phase of wrinkle ridge formation.

5.1. Riffs

The observations described above reveal an apparent increase in the role of rifting in the period of the geologic history of Venus which postdates emplacement of regional plains and their deformation by wrinkle ridges. This is certainly correct simply because in postplains time rifting is the dominant form of tectonism in both abundance and prominence, while other young tectonic structures (some fractures on plains in and without connection to some coronae) are very minor in abundance and prominence [e.g., Head and Basilovsky, 1998; Price and Suppe, 1994]. However, in the period immediately preceding this postplains time, rifting also occurred. These old rifts are observed and mapped as fracture belts (Plate 1). The true role of rifting at that time is not clear because an unknown portion of old rifts is completely flooded by regional plains. Was that old rifting more areally widespread compared to the young rift system? What was the general planimetric geometry of the old rift system(s)? Were those old rifts the loci of sources of volcanism forming regional plains with wrinkle ridges, which are the major component of the regional plains? A specific global mapping analysis of all remnants of the fracture belts is needed to address these questions.

Young and old rifts have noticeably different topographic expression, as described above: rifts are troughs, while fracture belts typically stand hundreds of meters to more than a kilometer above the adjacent regional plains [e.g., Hansen et al., 1997; Tanaka et al., 1997]. However, this is a difference at the present time when depressions inside old rifts were probably flooded by regional plains, and what we see now is a biased sample of those parts of old rifts which stood high enough not to be flooded. Many young rifts have high-standing portions typically on their flanks [e.g., Solomon et al., 1992; Hansen et al., 1997; Tanaka et al., 1997], so what we see now as fracture belts may be analogs of these elevated portions of old rifts. The general topographic similarity of pristine old rifts with young rifts can be seen in those areas where old rifts cut the older terrain not flooded by the regional plains. Figure 25 shows an example of such a situation.

The detailed study of a few typical areas showed another difference between old and young rifts. In the best preserved parts of the fracture belts the fracture-to-fracture spacing is ~1 km, and fracture width is approximately the same from fracture to fracture and along one fracture. The younger rifted terrain sometimes shows this type of fracturing, but almost always it is characterized by anastomosing fractures of variable width having larger (2-10 km) spacing. This change in style of rift-associated fracturing may reflect an increase in the Venustian lithosphere thickness with time [Banerdt et al., 1997, and references therein].

5.2. Large Volcanoes

The observations described above also imply a noticeable increase in the role of volcanic eruptions forming large volcanic constructs in the period which postdates emplacement of regional plains and their deformation by wrinkle ridges. This is certainly clear simply because in postplains time the large volcanoes are the most significant volcanic structures. Smaller in size are the so-called intermediate volcanoes, which, although more numerous than the large ones, cover less area than the large volcanoes. This is evident from the following calcula-
Figure 25. A Magellan synthetic stereo image (left and central images, fragment of C1-MIDRP.15N077;1) and the geologic map (right image) of the 220 x 250 km area in Akhtamar Planitia centered at 11°N, 81.5°E. The images show the ridge belt made of the Prf material which is embyayed by three varieties of regional plains: Psh, Pwr1, and Pwr2. This area is unusual in that the older unit of plains with wrinkle ridges (Pwr1) here has a radar brightness slightly higher than the younger one (Pwr2). The fracture belt (FB) in this area enters from the plains into the older Prf material. It is well seen that the FB unit is embyayed by the regional plains and cut into the ridge belt. The topographic range within the part of the FB belt which is surrounded by regional plains is smaller than in the part cutting the ridge belt (Prf) and isolated from regional plains. This is probably due to filling of the depressions within FB by the materials of regional plains.

Discussion: The mean diameter calculated from sizes of 85 young large volcanoes is ~400 km, while the mean diameter of intermediate-size volcanoes catalogued by Crampler and Aubele [2000] is close to 30 km. These authors listed 289 intermediate-size volcanoes. Even if all of them were young (this is certainly an exaggeration), their total area is less than the area of two "average" large volcanoes. Volcanism contributing to the plains continued into post-regional-plains time in the form of extended lava flows not deformed by wrinkle ridges and commonly not forming noticeable volcanic constructs [Roberts et al., 1992; Magee and Head, 2000]. A prominent example of this activity is the Mylitta F��us lava field, which covers ~300,000 km² [Head et al., 1992; Roberts et al., 1992; Crampler et al., 1997]. Although some of these flows are very large, the total area occupied by these flows is 8.7 x 10⁶ km², that is, only ~1.9% of Venus’s surface and more than twice less than area occupied by large volcanoes [Price and Suppe, 1994, 1995].

Formation of large volcanic constructs also occurred in the period immediately preceding this postplains time, but formation of large volcanoes at this time was certainly subordinate to the floods forming the regional plains. This is evident from the fact that even the combined area of old and transitional large volcanoes is 0.8% of the total surface of Venus (see estimates in section 3), while regional plains occupy ~70-75% of the surface of this planet [Basilevsky and Head, 1998, 2000]. However, it does not mean that the absolute intensity of large volcano formation at that time was lower than in the postplains period, and the following estimates show that it might, in fact, be higher if we keep in mind the durations of the appropriate time periods.

As was recently estimated by Collins et al. [1999] from the number of craters embayed by the global suite of regional plains, the combined duration of the preplesn surface exposure and duration of the plains emplacement is 0.6-9% of T at the 98% confidence level, where T is the mean surface age of Venus. It is important to note that this average time span estimate holds true whether the plains were emplaced globally synchronously or not. The estimates of Collins et al. [1999] are in agreement with the results of Basilevsky et al. [1999], who showed that in the area north of 35°N (21% of Venus’s surface) ~80-97% of the craters superposed on the units predating regional plains, also postdate the regional plains. It follows from the results of these two studies that the time interval between the formation of these older units and the end of emplacement of regional plains was from a few percent to ~20% of T. This time span estimate also holds true whether the plains were emplaced globally synchronously or not.

Because regional plains occupy 70-75% of Venus’ surface and the remaining part is composed of units older than the regional plains and units younger than the regional plains in approximately equal proportions [see Basilevsky and Head, 1998, 2000, Price and Suppe, 1994], the mean surface age of T represents well the duration of the postplains period on this planet [Basilevsky and Head, 1998, 2000]. The work of Basilevsky et al. [1999] referenced above confirms this conclusion at least for the area of 21% of Venus surface where crater density for the Plains with wrinkle ridges (Pwr) is the same as the total crater density for the whole area. T shows the average duration of the time between the end of emplacement of regional plains and the present, regardless of how mutually close in time the termination of regional plains emplacement occurred around the planet. Thus this estimate also holds true whether the plains were emplaced globally synchronously or not.

Combining the estimates discussed above shows that the
time duration of emplacement of the regional plains was very short compared to the time since emplacement of regional plains (the latter is \( T \)), from less than 1% to 10% of \( T \). As shown above, among the population of large volcanoes, ~68% are young, ~17% are transitional in age, and ~15% are old. These observations demonstrate that about \( 1/3 \) (15+17=32%) of the population of large volcanoes were active during the regional plains emplacement within the time period which was by a factor of 10-100 shorter than the time during which the remaining 2/3 of the large volcanoes formed. This obviously shows that the mean rate of activity of large volcanoes during regional plains emplacement was significantly higher (by an order of magnitude and maybe more) than in the subsequent time (Figure 26). We cannot determine on the basis of our analysis if the rate of large volcano formation in post-wrinkle-ridge time was declining, rather constant, or pulsating. The option of declining rates appears to be the most likely, although the rate of that decline may be more prominent than is shown of Figure 26.

As we mentioned in section 2, some old volcanoes might start their activity before the emplacement of regional plains. Guest and Stofan [1999] show an example of a rather large volcano obviously emplaced by regional plains and thus forming and being active prior to the emplacement of regional plains. However, these even older volcanoes are evidently not abundant. This follows both from the work of Guest and Stofan [1999] and from our observations. None of the 17 old and 18 transitional-in-age volcanoes studied by us showed any part of their constructs being emplaced by regional plains. This observation is meaningful because later flows of the volcanoes are typically shorter than the earlier ones, an observation that is clearly shown by the examples of the transitional-in-age volcanoes whose older flows are only partly covered by the younger ones. In addition, this relationship is clearly shown in detailed mapping of many individual volcanic edifices [e.g., Keddie and Head, 1994, Figure 2b]. So among 35 mapped old and transitional volcanoes, those which might start their activities in pre-regional-plains time are probably rare. If so, we may consider most, if not all, 35 old and transitional volcanoes as having formed during the emplacement of regional plains. So we tentatively conclude that the rate of formation of large volcanoes during regional plains emplacement was significantly larger than in the subsequent time.

This conclusion is certainly correct if we consider the number of volcanoes formed per unit time. However, if we consider the area and volume of volcanic products erupted in the form of large volcanoes per unit time, we should take into account that young volcanoes are systematically larger than the old ones. As it was shown above, the area occupied by young volcanoes is ~81% of the total area occupied by the large volcanoes of Venus. Transitional volcanoes occupy 13.5% and the old ones occupy 5.5% of that area. If the percentage of transitional volcanoes is divided equally between young and old volcanoes, the resulting young to old proportion is ~7:1. The larger volcanoes probably also have thicker lava accumulations, so the proportion of masses of young and old volcanics in the population of large volcanic constructs may be even greater relative to the young ones. So if we measure the mean rate of volcanism-producing large volcanoes in terms of volumes of the volcanics produced, we come to the following conclusion: If the
duration of the regional plains emplacement was closer to its lower estimate (~1% of T), this rate during the regional plains emplacement was an order of magnitude larger than in more recent time. If the duration of the regional plains emplacement was closer to its upper estimate (~10% of T), this rate during the regional plains emplacement was comparable to that in more recent time.

It was mentioned above that in the population of large volcanoes of Venus, young volcanic constructs are generally larger in size than intermediate ones, which, in turn, are larger than old ones. Partly, this might be due to covering of the old volcano lava aprons by lavas of regional plains generally contemporaneous with them. However, this contradicts the observation mentioned above that none of the old and transitional volcanoes show embayment by regional plains. Moreover, examples of young constructs that are large in diameter and topographically very prominent, such as Maat Mons and Teppe Mons, are not known among the subpopulation of old volcanoes. This provides evidence that the trend among large volcanoes of increasing size from old features toward young ones is at least partly a characteristic of the process. Detailed study is required, however, to distinguish a trend related to increased volcanic activity from one related to edifice loading and flexure [e.g., McGovern and Solomon, 1997]. If increasing size from old large volcanoes toward young ones is indeed a characteristic of the process, it might be due to the growth of lithosphere thickness with time suggested by some models [e.g., Grimm, 1994; Grimm and Hess, 1997; Phillips and Hansen, 1994]. The suggested increase of lithosphere thickness may be also a cause of the decrease in the volcano production rate with time.

5.3. Association of Volcanoes With Rifts

As demonstrated by the analysis of the map of rifts and volcanoes (Plate 1), the spatial association of volcanoes with rifts is seen for 62% of young volcanoes, 56% of transitional volcanoes, and 47% of the old ones. Although the decrease of this percentage from young to old volcanoes is obvious, it is not large and may be due to burial of some old rifts by regional plains, rather than due to a real change in the association with time. Indeed, volcanoes sitting on the rifts are topographically higher than the structural components of rifts; hence there is a preference toward burial of rifts compared to rift-associated volcanoes. Keeping this in mind, we may suggest that in the population of large volcanoes formed at least partly at the time of the regional plains emplacement (these are old and transitional volcanoes), the percentage of volcanoes associated with rifts might be approximately the same as in the population of postplains (young) volcanoes.

The percentage of the rift-associated volcanoes in the population of large young volcanoes may be underestimated because of the synoptic character of the mapping. However, it is quite obvious that young large volcanoes showing no association with rifts, at least with observable rifts, do exist (area 6 is an example, as is Sapas Mons [Keddie and Head, 1994]) and compose a noticeable part of the population. We can tentatively estimate that among the young volcanoes about 2/3 of them are rift-associated and about 1/3 are not. Assuming that the same proportion was typical for large volcanoes formed at the time of the regional plains emplacement and that the majority of those volcanoes were not completely buried by the relatively thin [Collins et al., 1999] plains-forming lavas, then using volcanoes as possible indicators of the buried rifts, one may suggest that the network of rifts at that time was not dense.

As discussed in section 4, the numbers of large volcanoes associated with young rifts (54) and those associated with old rifts (eight) are approximately proportional to the mapped areas of young (31.1 x 10^4 km^2) and old (5.4 x 10^4 km^2) rifts. These general proportions do not imply, however, a globally homogeneous distribution of rift-associated large volcanoes along rifts. Regional inhomogeneities are clearly visible on the map (Plate 1). These include a general concentration of large volcanoes within the Beta-Atla-Themis region (earlier described by Head et al. [1992] and Crumpler et al. [1997]), especially at the intersections of the rift zones [Schaber, 1982], and a deficit of large rift-associated volcanoes in the Aphrodite region and within the previously mentioned (in section 4.1) fourth rift zone connecting the southern terminations of the Aphrodite-Beta and Themis-Atla zones. If we add those large volcanoes, which are cataloged by Crumpler and Aubele [2000] but not shown on this map, to volcanoes shown in Plate 1, the deficit remains. The map also shows a concentration of large volcanoes within the region of 0°-40°N and 340°-70°E (16 volcanoes, young, transitional and old). In addition, the more scattered presence of large volcanoes is observed within the area of 40°-70°N and 220°-310°E (13 volcanoes, also of different age). These two regions have practically no mapped rifts. So, except in one case (Gula Mons), large volcanoes in these regions show no association with the mapped rifts. Summarizing, the majority of large volcanoes shows an association with rifts, implying that rifting favors this type of volcanism; however, this association is not mandatory.

6. Conclusions

This study has shown, through synoptic mapping, the distribution in space and time of rifts and large volcanoes of Venus. These features were subdivided into old, transitional in time (for volcanoes only), and young. The geologic event separating old features from young ones is the formation of wrinkle ridges on regional plains. We favor the model that this geologic event marks a global, quasi-synchronous event in the geologic history of Venus, although this question is not fully resolved. Mapping has shown that the postplains rifts dominate over the preplains rifts both in the number of mapped segments and in area. The postplains volcanoes dominate over transitional-in-age ones, which, in turn, dominate over the old ones. These trends occur in both the number of volcanoes and their areas. These data show that the roles of rifting and formation of large volcanoes in post-regional-plains geologic time are significantly more important than in the immediately preceding period of time.

This, however, does not mean that absolute rates of rifting and volcanism producing large volcanoes were higher in the postplains time. Because the time period when both regional plains were emplaced, and old and transitional large volcanoes formed (transitional were not completed), was much shorter than the postplains time period, the rate of formation of large volcanoes, if measured in number of volcanoes formed per unit time, was significantly higher during the first period than in the subsequent one. If we measure the rate of formation of large volcanoes in areas or volumes of old and young volcanics formed per unit time, the rate for old volcanoes was still significantly higher than for young ones. It might not be significantly higher, but comparatively, only if the duration of the regional plains emplacement was close to its maximum estimate. If some part of the volcanoes which we classified as “young”
have an older “core” hidden beneath young lavas, the estimates of the formation rate for old volcanoes would be even greater.

The study has also shown that an unknown number of old rifts have been buried by the volcanism forming the regional plains. However, even without a knowledge of that number it is evident that, as in the case with large volcanoes, the relatively short time duration of the plains-emplacement time makes the rate of old rifting higher than in more recent time.

All of this leads to the conclusion that emplacement of regional plains on Venus occurred in concert with rather intense rifting and formation of large volcanoes. When the regional plains emplacement was over, the absolute rates of rifting and formation of large volcanoes significantly decreased. This was a change obviously directional in time. In addition, because rifting and formation of large volcanoes become almost the only active tectonic and volcanic processes in the postplains time (despite a decrease in their absolute rates), their relative roles became dominant (Figure 27). Thus this study shows prominent changes with time of the absolute rates and roles of rifting and large volcano formation. This supports the idea of the “directional style” of geologic evolution of Venus during the last several hundred million years [Basilevsky et al., 1997; Basilevsky and Head, 1998, 2000], in contrast to the idea of “nondirectional” evolution [Guest and Stefan, 1999].

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