Geologic units on Venus: evidence for their global correlation

Alexander T. Basilevsky\textsuperscript{a, b, *}, James W. Head\textsuperscript{b}

\textsuperscript{a}V.I. Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow, Russia
\textsuperscript{b}Department of Geological Sciences, Brown University, Providence, RI 02912, USA

Received 31 March 1999; accepted 30 August 1999

Abstract

Detailed geologic mapping of approximately 30% of the surface of Venus has revealed a stratigraphic sequence that appears to be repeated in widely separated areas on the planet. This sequence shows a transition from oldest highly deformed terrain units, the tessera, to a series of widespread volcanic plains units, each with recognizable morphologic characteristics and interpreted eruption style, and finally to individual eruptive centers associated with edifices and rift zones. This sequence of events is accompanied by characteristic and repetitive patterns of tectonic deformation. In order to test the validity and broader applicability of this sequence, we compare it with local, regional, and global mapping published in 17 analyses by other authors. This comparison shows that the sequence of units, and thus the relative time sequence of the corresponding geologic events, is generally the same in virtually all of the widely distributed areas that have been studied, comprising about one-half the surface of Venus. We then address several alternative explanations for the observed sequence: (1) that the similar units and sequences correspond to events that occurred in different areas at different times (repetitive in different places but not time correlative); (2) that the sequences occurred generally synchronously in different places (repetitive and time correlative); or (3) that the situation is intermediate between the two cases. In order to distinguish among these possibilities, we analyze evidence for the lateral global continuity of units, the chronology of emplacement on the basis of the density of superposed craters, and the consistency of stratigraphic relationships based on these data. We find that this analysis supports the hypothesis that the individual sequences are repetitive in different parts of the planet, and generally time correlative between these locations. As a further test of this stratigraphy, we outline a global model for the geological evolution of Venus and assess the duration of emplacement of units, the timing and style of tectonic phases, and the volumes and implied fluxes of volcanic deposits. We find that the morphologically recognizable part of the history of Venus comprises only the last 10–20% of its total history. Emplacement of tessera-forming material and its deformation into tessera terrain are the major geologic events of the initial Fortunian time. Several stages of areally extensive volcanism occurred subsequently, burying vast areas of tessera and forming regional plains during Sigrunian, Lavinian, and Rusalkian times. The average global rate of volcanism was a few km$^3$ y$^{-1}$, and the emplacement of plains was accompanied by alternating episodes of contraction and extension. The last global-scale distributed tectonic episode, the formation of an extensive network of wrinkle-ridges, happened near the end of the Rusalkian Period, and marked the transition to the present stage of the history of Venus, the Atlian Period. Atlian times are characterized by a predominance of regional rifting focused at several broad rises, and localized rift-associated volcanism in the form of shield volcanic constructions and lobate volcanic plains-forming units, and is the longest time duration among the stratigraphic units considered, although the resulting tectonic and volcanic features and deposits cover only 10–20% of the surface of Venus. Comparison of this sequence of events with those revealed by continued geologic mapping of Venus will permit further testing and assessment so that a consistent and comprehensive documentation of the geological record can be presented and used to test models of the geodynamic evolution of Venus. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Working out models of local, regional and global stratigraphic sequences of geologic units is a well-known method of understanding the geologic history...
Fig. 1. A synoptic map of Venus showing the major areas of stratigraphic studies and photogeologic mapping reported in the literature and analyzed and compared in this study (Abdrakhimov and Basilevsky, 1998; Basilevsky, 1996, 1997; Basilevsky and Head, 1995a,b,c, 1996, 1997, 1998; Copp and Guest, 1995; DeShon and Hansen, 1998; Dohm and Tanaka, 1999; Head and Ivanov, 1996; Ivanov and Head, 1997, 1998a,b; McGill, 1994; Plaut, 1996; Rosenberg, 1995; Saunders, 1996; Senske, 1996; Stefan and Guest, 1996; Tapper and Guest, 1996; G. McGill, in Edmunds 1995; Price, 1995a, b; Senske, 1998; Senske et al., 1992, 1994; Solomon et al., 1992; Squyres et al., 1992). The latitude line with long teeth shows the southern boundary of our mapping north of 35°N. The lines with shorter teeth are the mapping boundaries of the geotraverse along 30°N (Ivanov and Head, 1997b, 1998a,b). Squares with solid boundaries outline the quadrangles mapped under the USGS geologic mapping program. Squares outlined with finer lines show sites of other studies. The background is the Magellan RMS map.

Fig. 2. Radar dark parabola (Cdp) associated with the crater Faustina (22.09°N, 4.69°E, D = 22 km). Cdp material is superposed (1) on lobate plains emanating from Gula Mons volcanic center to the west, (2) on plains with wrinkle ridges (Pwr) and (3) on densely fractured plains (Pdf). This area was earlier mapped by Senske et al. (1992) who identified (Table 1) several young plains units (our Pl), dark plains with wrinkle ridges (our Pwr) and ridged terrain (our Pdf). Area is about 800 × 950 km. Left, fragment of C2-MIDRP.30N026.1. Right, sketch map of this area. In this figure and in all others, North is at the top of the image.
of the planets (e.g., Wilhelms, 1987). In the case of Venus this work began with available local (e.g., Campbell et al., 1990) and regional (e.g., Kotelnikov et al., 1989) coverage, but global analyses were not possible until global SAR images with a resolution of 120–220 m of almost the entire surface of Venus were acquired by the Magellan mission (Saunders et al., 1992). Beginning in the early 1990s this work started partly as initiatives of individual researchers and groups, and as part of the NASA-funded Venus Geological Mapping Program coordinated by the US Geological Survey (Tanaka, 1994). This paper is derived from a presentation made at the Chapman Conference on Geodynamics of Venus on 4–6 September 1997, in Snowmass at Aspen, Colorado. Other talks presented there and mutual discussions at this conference helped us to understand areas of uncertainty and to clarify evidence related to the model of regional and global stratigraphy of Venus which we have been compiling since 1994 (Basilevsky and Head, 1994, 1995a,b,c, 1996a, b, 1998; Basilevsky et al., 1997; Head and Basilevsky, 1998a).

On the basis of these fruitful discussions, we emphasize that present geologic mapping at different scales by us and by other mappers covers a significant part of the surface of Venus (Fig. 1), strengthening the conclusions we made in our earlier work. In this paper we first describe evidence that the vast majority of terrains

---

**Fig. 3.** Lobate plains (Pl) in the form of digitate flows emanating from Gula Mons edifice. The flows are superposed on shield plains (Psh) and plains with wrinkle ridges (Pwr). This area was earlier mapped by Senske et al. (1992) who identified (Table 1) a few young plains units (our Pl), dark plains with wrinkle ridges (our Pwr), and mottled plains (our Psh). Area is about 220 × 260 km, centered at 25.5°N, 351.5°E. Left, fragment of C1-MIDRP.30N351;1. Right, sketch map of this area.

**Fig. 4.** Extended area of lobate plains (Pl) in northern Sedna Planitia superposed on three varieties of plains with wrinkle ridges (Pwr). Dark diffuse feature with brighter aureole in upper right is a splotch (S). On the Volcanic and Tectonic Map of Venus by Price (1995a, b) the area covered by the Pl, Pwr3 and Pwr2 units is shown as unit Pl1 while our Pwr1 unit was included here in her P1 unit. Area is about 220 × 220 km centered at 47.3°N, 347.5°E. Left, fragment of C1-MIDRP.45N350;1. Right, sketch map of this area.
seen in the Magellan images of Venus can be presented as a limited number of geologic units having specific, characteristic morphologies. These units typically show clear cross-cutting and overlapping relations, so their relative age sequence can be reliably established. In this paper we present new detailed examples of these stratigraphic relationships to illustrate what we believe to be their distinctiveness and clarity (Figs. 2–18). Our observations and photogeologic mapping in many areas of Venus, covering in total about 30% of the surface, combined with observations and mapping results of other workers, show that the sequence of units, and thus the relative time sequence of the corresponding geologic events, is generally the same in practically all of the widely distributed areas we have studied on Venus. We also show that the geologic units that we describe, and their sequence, are very similar to those of many other workers. Second, we address several alternative explanations for the observed sequence: (1) similar geologic units of the sequence correspond to a typical sequence of geologic events which occurred in different areas of the planet at different times; (2) geologic events which formed similar units in different areas of the planet occurred

Fig. 5. Localities of smooth plains (Ps) of amoeboid type south-west of Ohogetsu corona in Aino Planitia. The Ps unit is superposed here on plains with wrinkle ridges (Pwr) and on shield plains (Psh). The southwestern sector of Ohogetsu corona consisting of materials of two varieties of densely fractured plains (Pdf-a and Pdf-b) and of material of fractured and ridged plains (Ptr) is seen in the upper right (for details see Basilevsky and Head, 1998). Lobate plains (Pl) are seen in association with the corona. This area is part of quadrangle V46, mapped by Stofan and Guest (1996) (Table 1). Our Pwr unit corresponds to their uniform plains. The latter unit obviously embays the outer segment of the corona annulus made of Pdf-a material. Area is about 130 × 160 km, centered at 27.7°S, 85°E. Left, fragment of C1-MIDRP.30S081;1. Right, sketch map of this area.

Fig. 6. Smooth plains (Ps) of the type for which association with impact craters is typical. This Ps dark material, which evidently derived from the ejecta of the crater Bonnevie located upwind (36.1°S, 127°E, D = 91 km), is superposed on plains with wrinkle ridges (Pwr) and a fracture belt (FB) of Aino Planitia. This area is part of quadrangle V47 mapped by Senske (1996) (Table 1). In this locality our Ps unit is his dark homogeneous plains, and our Pwr unit is his mottled plains. Senske (1996) mapped the fracture belt as a tectonic structure. Area is about 220 × 300 km centered at 43.8°S, 116.2°E. Left, fragment of C1-MIDRP.45S117;201. Right, sketch map of this area.
generally synchronously around the planet so the established sequence of events represents general changes in the geologic history of Venus recognized morphologically; or (3) the situation is intermediate between options (1) and (2).

2. Description of geologic units

In distinguishing our units we followed the recommendations of The Venus Geologic Mappers’ Handbook (Tanaka, 1994), which, in turn, inherits experience of the geologic mapping of the Solar System planets and satellites summarized in Wilhelms (1990). Mapping Venus (or other planets) is based on photogeologic analysis of images of the planets. So we have to use as distinctive characteristics of the units mostly their surface morphologies: observable surface brightness or darkness, smoothness or roughness, their patterns, and the presence or absence of characteristic

Fig. 7. Two subunits of Pwr plains in Atalanta Planitia. Brighter material of the Pwr2 subunit displays the morphology of an extensive lava flow, superposed on the darker Pwr1 plains. About 400 km south-west of this area similar-looking Pwr2 material partly fills the Baltis Vallis channel incised into the Pwr1 plains. An inlier of smooth plains of the amoeboid type is seen among the Pwr2 plains (upper center). This area is a part of quadrangle V5 mapped by Rosenberg (1995) (Table 1). Our Pwr2 unit corresponds to her bright plains, our Pwr1 unit to her dark plains, and our Pfr unit to her undifferentiated plains. Area is about 80 × 90 km centered at 55.5°N, 182°E. Left, fragment of C1-MIDRP.60N180;1. Right, sketch map of this area.

Fig. 8. Shield plains (Psh) embayed by plains with wrinkle ridges (Pwr) at the northwestern flank of Cailleach corona in Aino Planitia. Fracturing of Psh not extending outside this unit makes the embayment very obvious. This area is part of quadrangle V46, mapped by Stofan and Guest (1996) (Table 1). Our units Pwr and Psh seem to be generally mapped by them as a single uniform plains unit. In this given locality our Psh unit seems to be a part of their corona unit. Area is about 130 × 150 km centered at 47.3°S, 84°E. Left, fragment of C1-MIDRP.45S074;201. Right, sketch map of this area.
landforms (shields, ridges, grooves, etc.). The most important thing in this analysis is a study of contact relations between units and this was an emphasis of the present work.

Described below are 11 units. Eight of them, from the materials of Radar-dark parabolas to materials of Tessera terrain, are geologic/stratigraphic units with rather clear boundaries and certain age relations among most of them. One, undivided crater materials, is stratigraphically through-going from oldest to the youngest parts of the stratigraphic column. Two units, Rift terrain and Fracture Belts, are tectonic ones being specific analogs of the densely faulted parts of the rift zones on Earth. We describe, first, the sequence of the geologic/stratigraphic units in the order from younger to older ones because the younger units are less modified by superposed processes and thus can be a clue to understanding the nature of the older ones. Then we describe the undivided crater materials, and, finally, the tectonic units. This description is based on our pre-

Fig. 9. Fractured and ridged plains (Pfr) embayed by plains with wrinkle ridges (Pwr) and shield plains (Psh) in Navka Planitia. Pfr plains embay kipukas of densely fractured plains (Pdf). This area is a part of quadrangle V42 mapped by Plaut (1996) (Fig. 1). In the area shown here, our Pwr unit is his undifferentiated plains, our Psh and Pdf units are small parts of his deformed plains, the latter corresponding mostly to our fractured and ridged plains (Pfr). Small inliers of our Pdf unit are too small to be shown on his map. Area is about 90 × 100 km centered at 10.5°S, 317.5°E. Left, fragment of C1-MIDRP.15S317;1. Right, sketch map of this area.

Fig. 10. A fragment of the Pandrosos Dorsa ridge belt system in Atalanta Planitia. The belt is made of fractured and ridged plains (Pfr) embayed by plains with wrinkle ridges (Pwr) and lobate plains (Pl). Small areas of shield plains (Psh) are present here, being superposed on the Pfr unit and embayed by the Pwr unit. This area is a part of V5 quadrangle mapped by Rosenberg (1995) (Table 1). Our Pl unit is her digitate flows, our Pwr unit is part of her dark plains, our Psh unit is her shield fields, and our Pfr unit is mostly her undifferentiated plains. Area is about 200 × 200 km centered at 53.2°N, 216°E. Left, fragment of C1-MIDRP.60N208;1. Right, sketch map of this area.
vious studies (Basilevsky and Head, 1994, 1995a,b,c, 1996, 1998; Basilevsky et al., 1997; Head and Basilevsky, 1998a). Areas covered by the units are our estimates, supported by quantitative measurements made by Ivanov and Head (1998a,b) for the geotraverse along 30°N, which appears to be a representative sample of the surface of Venus.

Some of the mentioned morphologic elements may be directly or indirectly related to tectonic structures. In this study tectonic structures are a part of the unit’s description and even used as a part of the unit’s name (e.g., densely fractured plains). At first glance this appears to be a violation of the rules: “Because structures commonly cut across several rock units, the Stratigraphic Code does not allow for mapping of units on the basis of their structural modification alone.” (Wilhelms, 1990). But let us look on the authoritative recommendation. The important thing, which is overlooked by many, is the last word of the quoted sentence: “alone”. In our approach structures are not the only (alone), but only one of the characteristics of any unit. In practice, the USGS programs of geologic mapping of the planets show numerous examples of tolerance and usefulness of involvement of structures into identification and definition of a unit. For example, Carr (1975) shows on the geologic map of the Tharsis quadrangle of Mars “Fractured plains material”. Wilhelms (1997) mapping the Jovian satellite Ganymede identifies “Dark lineated material”, which is considered to be a result of structural defor-

Fig. 11. Densely fractured plains (Pdf) embayed by plains with wrinkle ridges (Pwr) and shield plains (Psh) in Eistla Regio. The latter are clearly embayed by the Pwr plains. This area was studied and schematically mapped by Senske et al. (1992) (Table 1). Our Pwr unit evidently corresponds to their dark plains, our Psh unit corresponds to their mottled plains, and our Pdf unit corresponds to their ridged terrain. Area is about 125 × 140 km centered at 19.3°N, 3.4°E. Left, fragment of C1-MIDRP.15N009;1. Right, sketch map of this area.

Fig. 12. Inlier of tessera (Tt) embayed by plains with wrinkle ridges (Pwr) in Rusalka Planitia. This area is a part of quadrangle V37 studied by DeShon and Hansen (1998) (Table 1). Our Pwr unit here is one of their two units of the Rusalka Planitia plains. Tessera is considered by these authors to be the oldest unit of the area. Area is about 180 × 220 km centered at 6.5°S, 159.5°E. Left, fragment of C1-MIDRP.00N163;1. Right, sketch map of this area.
The requirement for distinguishing a unit is to determine its distinctiveness, characteristics and age relations with other units, in practice, with areally neighboring units. The characteristics that define units are determined by their observed morphology which sometimes includes structures.

The youngest unit of the sequence is represented by the materials of impact craters having associated radar-dark parabolae (Cdp) (Fig. 2) and, contemporaneous to them, surface spots (Sp) and streaks (Ss) of eolian materials. Radar-dark parabolae, observed around about 50 craters, are believed to be relatively fine-grained ejecta from the craters with which they are associated. Being injected into the upper atmosphere, these small particles are transported to the west by the E–W zonal wind, thus forming parabolae with their apex to the east (Campbell et al., 1992). Radar-dark parabolae occupy a total of about 8% of Venus’ surface, while the areal distribution of other components of this unit is significantly smaller. The discoverers of the dark parabola craters found that these craters are among the youngest features of the Venusian surface (Campbell et al., 1992). A special
study of the geologic position of the dark parabola craters confirmed that in most cases analyzed, they are the youngest geologic formations of the area, although in a very rare case, young rift-associated volcanics postdate these craters (Basilevsky, 1993). The upper-most position of radar-dark parabolas in the relative age sequence of units is generally accepted by the researchers. Schultz (1992) notes also that the presence of the dark parabola is not only a function of relative age, but also a function of impact direction. So craters as young as those mapped as Cdp, but having no associated dark parabola, may also be present on Venus as a small part of the undivided crater materials unit (Cu; see below).

Next oldest in the sequence are materials of lobate (Pl) and smooth (Ps) plains occupying in total about 10–15% of the surface. The age relations between them are not clear but both Pl and Ps plains clearly overlie other units except for the majority of Cdp. Lobate plains (Figs. 3 and 4) are typically associated with young rift zones (see below) and comprise slopes of large volcanoes, or form fields of lobate generally.

Fig. 15. Western central part of Maxwell Montes composed of mountain belt material (M) embayed by the fractured and ridged plains (Pfr) folded in a ridge belt in general alignment with the Maxwell massif. Pfr material is embayed by plains with wrinkle ridges (Pwr). This image shows a distinction between the ridge belts and mountain belts shown on synoptic maps of Venus as a combined unit (Senske et al., 1994; Price, 1995a, b). White dots show so called 'snow line' which is considered to mark the limits of high-altitude weathering. Although weathering of this sort affects here mostly unit M, some high-standing areas of Pfr and Pwr units are also affected. Area is about 150 × 155 km centered at 64.5° N, 358.5° E. Left, fragment of C1-MIDRP.60N014;1. Right, sketch map of this area.

Fig. 16. Undivided crater materials unit (Cu) exemplified by the 72-km crater Markham (4.1° S, 155.6°) superposed on plains with wrinkle ridges (Pwr). The crater has hummocky ballistic ejecta and extended outflows. The latter are identified by some mappers as a separate unit (e.g., Plaut, 1996). Area is about 225 × 240 km. Left, fragment of C1-MIDRP.00N163;1. Right, sketch map of this area.
elongated lava flows emanating from rifts. Quite frequently they are associated with coronae. Typically material of lobate plains is relatively bright although darker flows are also observed and some bright flows have relatively dark rims. Superposition of flows of different brightness gives a characteristic morphology to fields of the majority of lobate plains.

Smooth plains are present in two varieties: (1) relatively small featureless radar-dark areas typically with a visible source in the form of shallow-sloped shields with summit craters (Fig. 5); their boundaries with the neighboring units are sharp, sometimes showing finger-like margins, which was the basis for Head et al. (1992) to call them amoeboids; and (2) radar-dark or intermediate in brightness featureless areas often associated with impact craters (Fig. 6); their boundaries with the neighboring units are usually diffuse, but in some cases they may be sharp.

Materials of lobate plains and the first variety of smooth plains are obviously mafic lavas (Head et al., 1992). This is supported by observation that Venera 14 landed in the area dominated by lobate plains.
(Abdrakhimov and Basilevsky, 1998; Weitz and Basilevsky, 1993) and showed a basaltic composition of the surface material (Barsukov, 1992). The second variety of smooth plains are evidently mantles of fine-grained crater-ejecta debris partly reblown by wind. As it was mentioned, Pl/Ps materials clearly overlap all other units except Cdp. They are not deformed by wrinkle ridges which are typical features of the areally most extensive regional plains. Moreover, in most cases a superposition of the Pl/Ps materials on those plains is very evident. Sometimes Pl/Ps materials are deformed by rift-associated faults.

The next oldest are materials of plains with wrinkle ridges (Pwr) occupying 50–60% of the surface of Venus. Their surface appears homogeneous to mottled in radar brightness and looks smooth if one ignores the network of wrinkle ridges (Fig. 7; see other examples of Pwr in Figs. 5, 8, 11, 12 and 16). Wrinkle ridges are 1–2 km wide and several tens of km long with ridge to ridge spacing of a few to 30–40 km (Bilotti and Suppe, 1999; Kreslavsky and Basilevsky, 1998). Usually Pwr plains can be subdivided into two subunits. The stratigraphically upper one (Pwr2) consists of lobate lava flows which differ from the lower Pwr unit in higher radar brightness. In the latter and in flow-like morphology they resemble Pl plains. Pwr2, however, differs from flows of the Pl plains due to the presence of wrinkle ridges and also in more planimetrically equidimensional morphology typical of the Pwr2 flows. As it was shown by Ivanov and Head (1999a, b) Pwr2 plains tend to occupy lows among the stratigraphically lower Pwr1 subunit. The Pwr1 subunit consists of homogeneous or mottled plains of intermediate radar backscatter and show no discernible flows. In several regions the canali-type channels (Baker et al., 1992, 1997) are incised in Pwr1 plains (e.g., Basilevsky and Head, 1996a, b). On the Magellan images the Pwr2 flows typically appear brighter than Pwr1, although sometimes darker flows deformed by wrinkle ridges and clearly superposed on typical Pwr1 plains are also observed. In some areas of Venus mapped in considerable detail, more than two subunits of the Pwr plains can be identified (see, for example, Basilevsky, 1997). Based on the characteristic flow-like morphology of Pwr2 material, it is obviously made of mafic lavas. Material of the Pwr1 plains is evidently made of mafic lavas too. Geochemical measurements of Venera 9, 10, 13 and Vega 1 and 2 (Barsukov, 1992) which landed at the areas with predominance of Pwr plains (Abdrakhimov and Basilevsky, 1998; Weitz and Basilevsky, 1993) support this conclusion. Because of their vast areal abundance, Pwr materials form a background on which other units are usually seen, either overlapping upon the Pwr unit (Cdp, Pl/Ps), or embayed by Pwr materials (almost all others). The wrinkle ridge network superposed on the Pwr plains is considered to be caused by moderate contractional deformation (Banerdt et al., 1997; Bilotti and Suppe, 1999; Kreslavsky and Basilevsky, 1998; McGill, 1993; Solomon et al., 1992).

Material of shield plains (Psh) is close in its stratigraphic position to that of Pwr plains, but generally older (Fig. 8). In our early discussions of Venus stratigraphy (Basilevsky and Head, 1995a,b,c), what is now considered as Psh was part of a broader undivided Pwr unit. Detailed local mapping by McGill (1992), Ivanov (1993), and Aubele (1995, 1996) showed, however, that they could be distinguished and that they occupied a generally unique stratigraphic position. Psh material as currently defined is composed of clusters of volcanic shields 3–15 km in diameter, with typically gently-sloping flanks (a few degrees (Kreslavsky and Head, 1999)), and inter-shield areas of plains, which together occupy a total of about 10–15% of the surface. In many cases it is seen that Psh plains are embayed by the material of Pwr plains and are deformed by the wrinkle ridge network, in common with the neighboring Pwr plains. In some cases the age relationships of the Psh and Pwr units look ambiguous and in some cases a few clusters and separate shields of the Psh type clearly postdate some Pwr plains and the wrinkle ridge network. Thus in future work, and in some local areas, the Psh unit may be subdivided into subunits. The morphology of the Psh plains is evidence that their materials are composed of mafic lavas. Steep-sided volcanic domes a few tens of kilometers in diameter are sometimes observed in association with Psh plains and are thought to be possibly genetically related (Ivanov and Head, 1997, 1998a,b, 1999b). The distinctive dome morphology is evidence of the high viscosity of lavas and may indicate silicic composition or high abundance of vesicles (Head et al., 1992; Pavri et al., 1992). Gamma-spectroscopy measurements by Venera 8, which landed in an area with a predominance of Psh plains and presence of a steep-sided dome (Basilevsky, 1997; Basilevsky et al., 1992; Weitz and Basilevsky, 1993) showed the geochemically evolved composition of the surface material (Barsukov, 1992; Basilevsky et al., 1992).

Next oldest is the relative time sequence is material of fractured and ridged plains (Pfr), which is of intermediate radar brightness (Figs. 9 and 10). These plains are locally deformed by fractures and broad ridges. Sometimes the ridges are arranged in clusters, thus forming ridge belts (RB). Pfr/RB material is typically present in the form of elongated islands embayed by the surrounding plains with wrinkle ridges (Pwr). It occupies an area comprising ~3–5% of the surface. Wrinkle ridges of Pwr plains sometimes enter into the neighboring Pfr/RB materials. In some areas a superposition of clusters of Psh-type shields on Pfr/RB islands is seen. If one ignores fractures and broad
ridges, the material of fractured and ridged plains and ridge belts looks similar to the materials of plains with wrinkle ridges. The relatively smooth surface provides evidence that it may also be made of mafic lavas, and the similarity of style and orientation of structures suggests that in some places wrinkle ridges may represent decreased levels of deformation. Broad ridges typical of Pfr/RB are considered to be formed by contractional deformation, while fractures observed in some localities of this unit are due to extensional strain (Solomon et al., 1992; Banerdt et al., 1997). Sometimes fractures deforming Pfr/RB material are so densely clustered that undeformed primary material is very rare. In some areas of Venus these clusters of dense fractures form fracture belts (FB) which have a characteristic morphology and are large enough to be mapped as a separate unit (see below).

Another variety of relatively old, densely fractured material, and commonly stratigraphically older than those described above, forms densely fractured plains (Pdf) (Fig. 11). This unit occupies about 3–5% of the surface. It differs from the FB unit in that it is not formed at the expense of Pfr/RB material, but is embayed by it. Pdf plains typically form small kipukas (e.g., islands of older terrain surrounded by relatively younger units) with a densely fractured surface scattered among Pwr plains. The fractures are about 1 km wide and are arranged typically in a subparallel manner. The fractures are so densely packed that the primary undeformed material is commonly not observed. But if one ignores the fracturing, one may conclude on the basis of the regional topography that the precursor terrain was plains, probably made of mafic lavas. In an initial version of the Venus stratigraphy model (Basilevsky and Head, 1995a,b,c), we did not distinguish Pdf and FB units, considering both of these now-subdivided varieties of densely fractured terrain as a single Pdf unit. So part of what we called at that time Pdf, is now considered unit FB. The morphology of the dense fracturing of the Pdf type suggest extensional (Banerdt et al., 1997) and perhaps shear faulting.

The oldest member of the sequence is the material of tessera terrain (Tt) (Figs. 12–14). It is radar bright and has crosscutting sets of ridges and grooves of evident tectonic nature. First identified on images taken by the Venera 15/16 spacecraft with a resolution of 1–2 km, tessera showed ridge and groove spacing of about 5–20 km (Barsukov et al., 1986; Sukhanov, 1992). Higher resolution (120–220 m) Magellan images show that these ridges and grooves are typically fractured with a spacing of about 1 km and down to the limit of image resolution. Tessera forms islands and large contiguous regions surrounded by various, mostly Pwr, plains. The total area occupied by tessera is about 8% of the surface (Ivanov and Head, 1996). Tessera is embayed by materials of all other units (Basilevsky and Head, 1994, 1995a,b,c, 1996, 1998; Basilevsky et al., 1997; Head and Basilevsky, 1998a) and this is a basis for considering it as the oldest member of the sequence. Tessera-forming deformation is interpreted to involve an early phase of contraction and crustal shortening, followed by a later stage of crustal extension (Solomon et al., 1992, Ivanov and Head 1996; Gilmore et al., 1998). An alternative interpretation suggests that tessera deformation changed from extension to later contraction and then again to extension (Hansen and Willis, 1996). The compositional nature of tessera material is unknown.

Close in stratigraphic position to tessera terrain is the material of the mountain belts (M) (Fig. 15) surrounding Lakshmi Planum. These belts morphologically merge through the gradual change of their subparallel patterns into adjacent tessera. The pre-plains age of the belts is directly established by their emplacement by the surrounding plains of the Pwr and Pfr units (Basilevsky and Head, 1995d; Pronin, 1998). These mountain belts are thought to be formed by contractional deformation (Basilevsky, 1986; Crumpler et al., 1986; Keep and Hansen, 1994; Pronin, 1986; Vorder Bruegge et al., 1990). The compositional nature of the material of unit M is unknown. Variations in the surface radar reflectivity/emissivity in the Maxwell mountain massif were interpreted as indirect evidence of the compositional inhomogeneity of this part of the mountain belts (Basilevsky, 1995).

The unit that appears to occur throughout the stratigraphic column is undivided crater materials unit (Cu) (Fig. 16). This unit includes the materials of all parts of impact craters (walls, floors, central peaks, inner rings) and crater ejecta (including outflows) (Herrick et al., 1995; Schaber et al., 1992). The total number of craters on the surface of Venus is about 1000 (Schaber et al., 1995). They cover altogether ~1–2% of the surface. Materials of the dark parabola craters (Cdp) are not included in unit Cu. The stratigraphic position of unit Cu is very broad. Individual craters belonging to this unit may be contemporaneous with any of the units described above, from Pl/Ps to Tt. Less than 100 of the craters composing unit Cu are superposed on the unit Pl/Ps; more than 650 on Pwr+Psh regional plains; about 80 on tessera terrain, and the rest on other units.

The youngest of two tectonic units is represented by the material of Rift zone terrain (RT) which occupies not more than a few percent of Venus. The rift zones form belts of a few hundred to several thousand km long and up to a few hundred km wide often called chasmata (Crumpler et al., 1993; Hansen, 1997; Senske et al., 1992; Solomon et al., 1992). The structures forming rift zones are normal faults and graben (Fig. 17) implying an extensional environment of defor-
<table>
<thead>
<tr>
<th>Examples</th>
<th>Our units</th>
<th>Alternative unit names by other researchers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar dark parabolas (CdP)</td>
<td></td>
<td>Diffuse deposits</td>
</tr>
<tr>
<td>Lobate plains (PI)</td>
<td></td>
<td>Digitate plains, flows, Lobate flows</td>
</tr>
<tr>
<td>Smooth plains (Ps)</td>
<td></td>
<td>Smooth, Dark homogeneous plains</td>
</tr>
<tr>
<td>Rifted terrain (RT)</td>
<td></td>
<td>Rift zones, Deformation belts</td>
</tr>
<tr>
<td>Plains with wrinkle ridges (Pwr)</td>
<td></td>
<td>Pwr2: Bright plains, Pwr1: Dark, Reticulate plains, Uniform plains, Smooth plains</td>
</tr>
<tr>
<td>Shield plains (Psh)</td>
<td></td>
<td>Shield fields, Dome fields, Mottled plains</td>
</tr>
<tr>
<td>Fracture belts (FB)</td>
<td></td>
<td>Fracture belts, Lineated tessera</td>
</tr>
<tr>
<td>Fractured and ridged plains (Pf) and Ridge belts (RB)</td>
<td></td>
<td>Ridge belts, Tectonic belts, Textured terrain, Deformed plains</td>
</tr>
<tr>
<td>Densely fractured plains (Pdf)</td>
<td></td>
<td>Lineated plains, Rridged plains</td>
</tr>
<tr>
<td>Tessera terrain (Tt) and Mountain belts (M)</td>
<td></td>
<td>Tessera. Complex ridged terrain, Complex lineated terrain, Mountain belts</td>
</tr>
</tbody>
</table>

Fig. 19. A relative time sequence of geologic units presented in this analysis. Unit names used by other researchers are given for comparison. This table ignores established or possible unit overlaps. The latter are shown on the correlation diagram (see Fig. 20).
mation. They are typically anastomosing with variable widths of individual faults that makes them very distinctive from the dense subparallel fracturing typical of the Pdf unit. RT overprints practically all stratigraphic units. Some faults of certain rift zones even postdate the dark-parabola craters (Basilevsky, 1993). So RT material consists of a mixture of deformed materials of all other units.

Another tectonic unit is the material of Fracture Belts (FB) (Fig. 18). The FB unit localities occupy altogether about 3–5% of the surface. These belts were described already in the early stage of the Magellan data analysis (Solomon et al., 1992) but their stratigraphic significance was not clear at that time. FB-forming fractures, when in contact with the Pfr unit, criss-cross it. When in contact with Pwr plains, most of the belt fractures are embayed with plains material, but some of the fractures extend into Pwr plains deforming them. So the FB unit is evidently made of the deformed Pfr/RB (and may be partly contemporaneous with them) and older (Pdf, Tt) materials and may also include the deformed materials of younger (Pwr, Psh) units. As it is mentioned above, in our early stratigraphic models (Basilevsky and Head, 1995a,b,c) we described FB as part of Pdf unit. Usually it is easy to distinguish Pdf and FB units when they are in direct contact with undeformed Pfr/

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Correlation of units of this work and units of other mappers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>This work</strong></td>
<td><strong>Solomon et al., 1992</strong></td>
</tr>
<tr>
<td>Cdp</td>
<td>Diffuse deposits</td>
</tr>
<tr>
<td>Pwr2</td>
<td>Bright plains</td>
</tr>
<tr>
<td>Pwr1</td>
<td>Dark &amp; Var. pl.</td>
</tr>
<tr>
<td>Psh</td>
<td>Textured/mottl. pl.</td>
</tr>
<tr>
<td>FB</td>
<td>Fractured belts</td>
</tr>
<tr>
<td>Pfr/RB</td>
<td>Textured terrain</td>
</tr>
<tr>
<td>Pdf</td>
<td>Rridged terrain</td>
</tr>
<tr>
<td>Tt</td>
<td>Tessera</td>
</tr>
</tbody>
</table>

Fig. 20. Correlation diagram for the geologic units presented in this analysis.
fractures deforms the neighboring Pwr plains. The morphology of fracture belts suggest their formation is due to extensional faulting so they may be old zones of rifting (Banerdt et al., 1997).

The described sequence of geologic units, from younger to older (Cdp → Pl/Ps + RT → Pwr + Psh → Pfr/RB + FB → Pdf → Tt; see for clarity Figs. 19 and 20) is observed with different degrees of completeness in all areas studied by us and our co-authors, a total covering more than 30% of the surface of Venus (Abdrakhimov and Basilevsky, 1998; Basilevsky, 1996, 1997; Basilevsky and Head, 1995a,b,c, 1996, 1997, 1998; Head and Ivanov, 1996; Ivanov and Head, 1993, 1996, 1997, 1998a,b, 1999a).

3. Stratigraphic sequences determined by other workers

How closely do these units and this stratigraphic sequence compare to that observed by other workers in the same regions and other parts of Venus? In this section we review the results of geologic mapping available in the literature and compiled by other workers, individuals who are not our co-authors, nor affiliated with our research groups, nor who have used our stratigraphic model in their studies (Table 1). Thus, their mapping efforts can be viewed as independent from ours. For this same reason we do not treat the work of Ivanov (1993), Kryuchkov (1996, 1997), Marchenko (1994), Pronin (1997, 1998), Aittola and Raitala (1998) in this analysis. Unfortunately many of the works considered below are preliminary results published as LPSC abstracts. Of course it would be better to deal with the results published in the form of thoroughly reviewed USGS geologic maps. However it is not practically possible because the process of publication of the USGS maps has not been completed. Meanwhile a discussion of regional and global stratigraphies is worthwhile now, when the USGS mapping program is in progress.

1. One of the first geologic maps based on the analysis of Magellan data was made by George McGill for a portion of the plains of southern Guinevere Planitia (Fig. 32 in Solomon et al., 1992). Six stratigraphic units were identified from younger to older: (1) C — Impact crater materials; (2) Pa — Radar-bright plains with rare or no wavy bright lines (considered by McGill to be wrinkle ridges); (3) Pb — Radar-dark plains with rare wrinkle ridges; (4) Pc — Plains of variable radar brightness with wrinkle ridges; (5) Pd — Finely textured to mottled plains with low domes and abundant wrinkle ridges; and (6) T — Tessera materials. This short description, as well as a comparison of the McGill map with the Magellan image of this area, and the fact that one of us (ATB) recently compiled a geologic map of the Venera 8 landing site (Basilevsky, 1997), which is next to the area mapped by McGill in the north, all made it possible for us to correlate the units of McGill with ours. Unit C is completely equivalent to our undivided crater materials unit (Cu), units Pa, Pb, and Pc together correspond to the subunits of our plains with wrinkle ridges (Pwr); at the Venera 8 site there are also three subunits of Pwr with similar characteristics. Unit Pd clearly correlates with our shield plains unit (Psh), and Unit T corresponds to our tessera terrain material (Tt). In summary, the units of McGill (in Solomon et al., 1992) correlate with our units very well and their relative time sequence is the same as proposed by us (e.g., Basilevsky and Head, 1994, 1995a,b,c; Basilevsky et al., 1997b).

2. Another example of geologic mapping and stratigraphic studies of that time is represented by the work of Senske et al. (1992) on the geology of several topographic rises: Western Eistla, Beta and Atla Regiones. The most detailed stratigraphy was worked out for Western Eistla. The youngest units are seven plains units composing the slopes and outskirts of Sif and Gula volcanoes. Next older in age are Coronae, shown as one unit. Next oldest are Domed plains and Volcanic centers, other than Sif and Gula Montes. Even older are Dark plains (with sinuous ridges). And the group of oldest units in the area include Mottled plains, Tesserae, and Ridge terrain. The last two are interpreted by Senske et al. (1992) to be the oldest “in this part of the planet”. The units mapped by Senske et al. in Beta and Atla Regiones and their time sequences are generally similar to those of Western Eistla.

The unit descriptions given in this work and comparison of the map with the Magellan images of Western Eistla made it possible for us to correlate the units of Senske et al. (1992) with our units (Table 1). The seven plains units composing Sif and Gula volcanoes are obvious equivalents of our lobate and smooth plains (Pl/Ps) (see Figs. 2 and 3). We can not find correspondence of the Coronae of Senske et al. (1992) to any single unit in our geologic units sequence because our stratigraphic studies show that coronae are typically made of several geologic units formed through several stages of geologic activity from relatively young Pl units to rather old Pd ones (Basilevsky and Head, 1998; Basilevsky et al., 1997b). The Domed plains are not explicitly described, but on the C1-MIDRP-30N351;1 image this unit appears to be a variety of our lobate plains agreeing with the interpretation of Senske et al. that it is a part of the Sif Mons edifice (see their Fig. 2b). As is shown through the examination of the appropriate Magellan images,
“Volcanic centers other than Sif and Gula Montes”, include different things. Of three mapped localities, one centered at 25.5°N, 355.5°E corresponds to the 200 × 300 km corona Nissaba and consists of a mixture of our Pwr and Pl plains. Another locality centered at 21.5°N, 3.0°E corresponds to a field of lobate plains heavily obscured by the material of a dark parabola associated with the crater Faustina. The third locality of this unit is centered at 24°N, 6.5°E and is an occurrence of our Pwr2 unit. The Dark plains of Senske et al. (1992), described by these authors as having homogeneous radar-dark texture and bearing sinuous ridges, are evidently correlative with our lower subunit of plains with wrinkle ridges (Pwr1). Mottled plains having large abundances of small domes and shields and bearing abundant wrinkle ridges are correlative with our shield plains (Psh). Tesserae correlate with our tessera terrain. What is described by Senske et al. (1992) as Ridged terrain has densely spaced ridge-and-groove morphology typical of our densely fractured plains (Pdf) (see Fig. 11 of this paper as well as the image and our map of this area in Fig. 13a,b in Basilevsky and Head, 1995a). In summary, most of the geologic units of Senske et al. (1992) find evident correlates to our units and their relative time sequence are very close to each other (Table 1).

3. Another example of photogeologic analysis and mapping of that period is the work of Squyres et al. (1992), devoted to analysis of plains tectonism in Lavinia Planitia. In a stratigraphic sense, they identified four units (Table 1). The youngest is digitate plains consisting of complexes of digitate to locally lobate flows. The next oldest are regional plains with two subunits: dark plains and mottled plains. The first are darker, have more uniform radar backscatter, and have fewer superposed wrinkle ridges than mottled plains. The latter are moderately bright with mottled texture, generally have abundant superposed wrinkle ridges, and in places include small shields or domes. The next oldest is textured terrain, which is relatively bright, and forms inliers of plains and ridge belts embayed by regional plains. The oldest is described as complex ridged terrain. In addition to these units, Squyres et al. (1992) identified three major types of tectonic features: wrinkle ridges deforming regional plains, ridge belts composed of textured terrain, and fracture belts. The latter deform mottled plains and older units but not dark plains and digitate plains materials.

Based on descriptions of the units and illustrative figures given by these authors, comparisons of their sketch maps with the map of that area compiled by Head and Ivanov (1996) and Ivanov and Head (1999a), and with comparison to the appropriate Magellan images, we correlated units of Squyres et al. (1992) with the ones we previously mapped (Table 1). Their digitate plains is a correlative of our lobate plains (Pl) with an admixture of our younger subunit of plains with wrinkle ridges (Pwr2). Their Dark plains are our plains with wrinkle ridges (Pwr1) subunit. Mottled plains is mostly our shield plains (Psh) and their fracture belts correspond to our fracture belts (RB). Their Textured terrain corresponds to our fractured and ridged plains (Pfr) and ridge belts (RB) (see Fig. 18). Inliers of their complex ridged terrain in this area are made of both our densely fractured plains (Pdf) and tessera (Tt). In summary, the geologic units of Squyres et al. (1992) find evident correlates to our units. In addition, their relative time sequence is practically the same as ours (Table 1).

4. Senske et al. (1994) compiled a synoptic geologic map of Venus identifying sixteen geologic units and suggesting stratigraphic relations among them. These results were recently quoted in Tanaka et al. (1997) referencing Senske et al. (in preparation). The youngest units of Senske et al. are Bright and Dark diffuse deposits associated with impact craters. They are not shown on the map. Next older in time are Digitate plains (lava flow fields) generally associated with coronae. Next oldest are Volcanic edifices, Shield/dome fields and Fracture belts. Lower in the relative time sequence of Senske et al. are Ridge belts (including a subunit of Mountain belts). Even lower are Bright, Dark, and Mottled plains and Ridged and fractured terrain of coronae. Below these are very widespread Reticulate plains that typically contain abundant wrinkle ridges. Stratigraphically lower are Lineated plains, and the lowest in their sequence is Complex ridged terrain that is a synonym for Tesserae used by many of the Magellan Science Team.

Based on the short descriptions of the units given by these authors, and on comparisons of their map with the Magellan images, one may correlate their units with ours (Table 1). Their Dark diffuse deposits are correlative to our dark parabolas. We see on Magellan images what they call Bright diffuse deposits but do not map them because major units are easily seen through them. Digitate plains of Senske et al. (1994) are a mixture of our lobate plains and our Pwr2 unit. Volcanic edifices are correlative with those portions of our lobate plains unit which compose the flanks of large volcanoes. Shield/dome fields are evidently correlative with our shield plains, probably to the younger varieties of them. Fracture belts are our Rift zones and Fracture Belts which we map as tectonic units. Ridge belts are equivalent to our ridge belts. Mountain belts are equivalent to our mountain
belt systems. Bright and dark plains are not shown by these authors on the published version of their map, so in order to correlate them with our units we must rely only on the short description of them given in Senske et al. (1994). Based on this description, bright plains may be a mixture of our lobate plains and Pwr2 unit, and dark plains may be a correlative of our smooth plains. Mottled plains are a mixture of our plains with wrinkle ridges (Pwr) and shield plains (Psh). The Ridged and fractured terrain of coronae is evidently a mixture of our plains with wrinkle ridges (Pwr), fractured and ridged plains (Pfr), fracture belts (FB) and densely fractured plains (Pdf). Reticulate plains are evidently equivalent to our plains with wrinkle ridges (Pwr). Lineated plains are a mixture of our densely fractured plains (Pdf) and fracture belts (FB). Complex ridged terrain is clearly equivalent to what we map as terrae terrain. So taking in mind the very synoptic character of the Senske et al. (1994) mapping that forces the combining of subunits into broader general units, we consider that their units have a rather good correspondence to ours and that their unit time sequence is generally close to ours (Table 1). The major difference is that these authors see ridge belts as a unit postdating the most widespread regional plains with wrinkle ridges while we see abundant evidence that in most places ridge belts are embayed by these plains (see Figs. 9 and 10).

5. Price and Suppe (1994) and Price (1995a, b) suggested a model of the global stratigraphy of Venus (Table 1). Their youngest unit is Large volcanoes. Stratigraphically lower are Coronae and Rift zones. Below this are four units of plains: P11, highly lobate plains such as Mylitta Fluctus; P12, plains with distinct but less dramatic flow morphology; P13, plains with subtle lobate appearance; and Ps, smooth plains with no discernible flow morphology. This subdivision of plains units is based on the conclusion of Arvidson et al. (1992) that the morphological prominence of the plains-forming lava flows is degraded with time due to surface weathering and infill by eolian deposits. Their model also has a Shield plains unit which they correlate in stratigraphic level to the entire interval from P11 to Ps. They also map Fold belts, which they propose are stratigraphically correlative with P13 and Ps units. The lowest unit of their stratigraphic sequence is Terrae, which is shown on their correlation chart as partly overlapping in relative time with their Ps unit.

The large volcanoes of the Price and Suppe model obviously correspond to part of our lobate plains. Their Coronae, as in the case of the stratigraphic model of Senske et al. (1992) do not find a simple correlation with our model. In our model rift zones are interpreted to be young, as they are in the Price and Suppe model (see Fig. 17). Basilevsky et al. (1994) undertook a specific study to compare the Price (1995a, b) map units with units of our model. This comparison was made for a rather large area (40°–80°N, 140°–260°E) and showed that the P11 to Ps units of Price (1995a, b) are mixtures of our several plains units. In the sequence from P11 to Ps, the role of our younger (P1/Ps and Pwr2) plains units systematically decreases while the role of the older units (Pwr1, Pfr/RB and Pdf) increases. The Shield plains of Price and Suppe correspond to our shield plains (Psh). The only difference is that their model emphasizes the wide stratigraphic range of this unit while we, accepting the possibility of that rather broad range, emphasize that the majority of Psh materials studied by us are older than Pwr plains. The Fold belts of Price and Suppe correspond to two different units of ours: ridge belts (RB) and mountain belts (M). Although the latter certainly have a structural component correlative to that of our ridge belts, and may have some material component correlative to that of our ridge belts, the predominant part of our M material is interpreted to be older than our RB material and stratigraphically close to our terrae material (see Fig. 15) (Basilevsky, 1995; Basilevsky and Head, 1995a, b, c; Basilevsky et al., 1997b). Terrae, the oldest unit of Price and Suppe, is correlative to our terrae terrain material (Tt), also the oldest. So if one ignores the obvious difference in the two models in terms of the subdivision of plains, their sequences of geologic units and ours are rather close (Table 1). The differences are in their approach to coronae as a single geologic unit of relatively young age, and in the interpretation of the stratigraphic position of ridge belts and mountain belts.

6. McGill (1994) reported the results of photogeological studies of the Sappho Patera quadrangle (Table 1). Eighteen geologic units were identified. Eight of them (Af, Ah, Aflh, Am, Sf, Sh, Sfh, and Sm) are flows and small summit shields of Anala Patera and Sappho Patera, all essentially devoid of wrinkle ridges. Four units compose regional plains: Uf, moderately bright with wrinkle ridges; Pr2, moderately bright to moderately dark with wrinkle ridges; Pr, like Pr2 but with a higher density of wrinkle ridges, and locally abundant shield fields; Prl, like Pr but with an even higher density of wrinkle ridges. Two units are older than regional plains: Pb, very bright, deformed with a single fabric trend; t, terrae terrain, considered to be the oldest in the area. Also identified are: C, undifferentiated impact crater materials; Pd, very dark local plains with no wrinkle ridges; f, digitate flows associated with coronae; and Pc, moderately bright terrain associated with
Nehalennia and other coronae.

The descriptions of the units given in this paper, as well as comparison of the McGill map with the Magellan images of this area, made it possible to correlate units of McGill (1994) with ours (Table 1). Units Af, Ah, Ahf, Sf, Sh, Shf, and f are correlative with our lobate plains (Pl); unit Pd, with our smooth plains (Ps); units Am and Sm with the younger part of our shield plains. The regional plains of McGill (1994) are correlative with our plains with wrinkle ridges (Pwr), with an admixture of shield plains (Ps). Unit Pb corresponds to our densely fractured plains (Pdf) and unit t is our tessera. Unit Pc is densely fractured terrain of coronae probably consisting of our Pdf and Fb components. Unit C is our undifferentiated crater materials. In summary, all units of McGill (1994) have correlative to our units and their time sequence is the same as ours (Table 1).

7. Copp and Guest (1995) published the preliminary results of their geologic mapping of the V31 Sif and Gula quadrangle (0N–25°E, 330°E–0°E). Six major units were identified: Sif Mons unit, Gula Mons unit, Smooth plains unit, Mottled plains unit, Homogeneous plains unit, and Coronae unit. Minor units include: Edifice fields, Crater units and Volcanic centers, along with other volcanic and tectonic features not named in the paper. Outcrops of Complex ridged terrain are also mentioned.

Short descriptions of the geologic units given in the paper, as well as comparison of the Copp and Guest map with the Magellan images of this area, and with the geologic map of the Venera 8 landing site, published by Basilevsky (1997), which partly overlaps the V31 area at the south, made it possible for us to correlate units of Copp and Guest (1995) with ours (Table 1). Sif Mons and Gula Mons units, interpreted by Copp and Guest as the youngest major units, are obviously correlative with our lobate plains (see Fig. 3, this paper). Smooth plains are obviously correlative with our Pwr1 unit. Mottled plains correspond mostly to our shield plains. Homogeneous plains units are correlative with the Pwr1 unit, with a minor admixture of the Pwr3 unit of the Venera 8 site. Copp and Guest (1995) observe the embayment of Mottled plains by the material of Smooth plains, and this agrees with our observed stratigraphic sequence. However they consider Homogeneous plains to be the oldest among the major plains units and this does not agree with our interpretation of the relations of these units. Coronae, as we mentioned above, are not considered by us as a single unit. Edifice fields, corresponding to clusters of the Psh-type shields that we mapped, are considered by Copp and Guest to be superposed on both Mottled and Smooth plains, a conclusion which is not evident to us on the basis of examination of these data. Volcanic centers correspond mostly to our Pwr2 unit and we agree with Copp and Guest that they are superposed on Mottled and Smooth plains. Their Crater unit obviously corresponds to our Cu unit. Complex ridged terrain considered by Copp and Guest as the oldest unit of the area is correlative with our tessera terrain (Tt). So all of the units of Copp and Guest (1995) except Coronae have unequivocal correlative with our units. In addition, their time sequence, with minor exceptions, is similar to that which we outlined (Table 1).

8. Edmunds (1995) reported on the results of the geologic mapping of the Sekmet Mons area (C1-MIDRP-45N244) (Table 1). Ten geologic units are identified and arranged in a time sequence in the map legend, from youngest to oldest: (1) Fsd, Summit domes and dark flows; (2) Fsu, Summit flows; (3) Fe, Eastern flow field; (4) Fd, Digitate flows; (5) Fsh, Sheet flows; (6) Df, Dome fields; (7) Rb, Ridge belts; (8) Pm, Mottled plains; (9) Ps, Smooth plains; and (10) T, Tesserae. The paper also mentions that, based on superposition relations, the Dome field unit (Df) seems to be associated with the emplacement of mottled plains (Pm), and not the smooth plains (Ps).

Comparison of the Edmunds map with the Magellan images of this area is not easy because the patterns of their legend do not completely match the patterns on the map. Correlation of the units proposed by Edmunds with the image and thus with our units is, however, possible. It is evident that the upper five units of Edmunds (1995) are correlative with our lobate plains (Pl). Dome fields are correlative with our shield plains (Psh), probably with its younger part because no wrinkle ridges are seen on these dome fields. Edmunds' Ridge belts are correlative with our ridge belt units (Pfr/RB). Mottled plains are a mixture of our lobate plains (Pl) and plains with wrinkle ridges (Pwr). Smooth plains correspond to our smooth plains (Ps) and Tesserae correspond to our tessera terrain (Tt). So the units of Edmunds (1995) have definite correlative with our units. However, the time sequence of units Rb (our Pfr/RB), Pm (our P1+Pwr) and Ps (our Ps) interpreted by Edmunds (1995), differs from ours. In our version of the relative time sequence, RB is older than the two other mentioned units. According to the map of Edmunds (1995), the unit Rb is not in direct contact with unit Pm, so differences between this and our interpretations is understandable. Less understandable is the lower stratigraphic position of Edmunds' unit Ps in relation to unit Rb, because at the eastern part of the area of this mapping there are good examples of embayment of ridge belts by
9. Rosenberg (1995) reported on the preliminary results of the geologic mapping of the Pandrosos Dorsa Quadrangle (V5). Her mapped units include: digitate flows (df), bright plains (Pb), dark plains (Pd), mottled plains (Pm), hazy plains (Ph), undifferentiated plains (Pu), and tesserae (t). Rosenberg (1995) concluded that units df, Pb, Pd, and t, form a stratigraphic sequence (from younger to older). The age relations of Pu, Pm and Ph are considered to be indeterminate. Coronae and impact craters are also mapped as geologic units (Co and C, respectively).

Comparison of the Rosenberg map with the Magellan images of this area made it possible for us to correlate her units with ours (Table 1), with the exception of units Pm and Ph, which are not shown on the published version of the map. Her digitate flows are our lobate plains (Pl), bright plains are our plains with wrinkle ridges, mostly the Pwr2 unit (see Fig. 7), but in some cases the Pwr1 unit too. Her dark plains unit is a mixture of our unit Pwr1 and smooth plains (Ps) of the amoeboid type. Her tesserae are our tessera terrain (Tt). Her undifferentiated plains correspond to our ridge belts (RB). Ridge belts are mentioned by Rosenberg (1995) as a terrain but she believes that “it does not necessarily represent a single stratigraphic rock unit” and consists “of one or more of the plains materials (Pd, Pb, Pm, Ph)”.

10. Plaut (1996) reported on the geologic mapping of the Navka Planitia quadrangle (V42). He distinguished nine geologic units (Table 1): (1) Lobate flow materials (fb) and (2) Lobate flow materials of Ushas Mons (flu), both considered to be the youngest in the sequence; (3) Undifferentiated plains (pu), moderately deformed by wrinkle ridges; (4) Mottled plains (pm), slightly deformed by wrinkle ridges; (5) Deformed plains (pd); (6) Deformed plains, corona/caldera (pdc); (7) Complexly lineated materials (cl), placed at the bottom of the stratigraphic column; (8) Impact crater materials (ci); and (9) Fluidized impact crater materials (cif).

Comparison of the Plaut map with the Magellan images of this area made it possible for us to correlate his units with ours (Table 1). The Lobate flow materials of Plaut (1996) are mostly our lobate plains (Pl), with some admixture of the Pwr2 unit. Lobate flow materials of Ushas Mons are our lobate plains. Undifferentiated and Mottled plains are varieties of our plains with wrinkle ridges (Pwr). Deformed plains are our Pfr/RB unit (see Fig. 9). Deformed plains of coronae are a mixture of our shield plains (Psh) and densely fractured plains (Pdf). Complexly lineated materials are correlative with our tessera terrain materials (Tt). Impact crater materials and Fluidized Impact crater materials are correlative with our undifferentiated crater materials (Cu). In summary, the units of Plaut (1996) find correspondence to our units, and the relative time sequence determined by him agrees with ours (Table 1).

11. Saunders (1996) reported on the preliminary results of his photogeologic analysis and mapping of the western part of Ovda Regio (Table 1). The earliest unit of this area is Complex Ridged Terrain (CRT), forming the highlands of western Ovda. Then, according to Saunders (1996), localized uplift and fracture belt formation occurred and later evolved into the large-scale plains-forming volcanic episode. Subsequently the plains and the highlands uplifted relative to the marginal plains. The latest volcanic eruptions formed rilles that trend down slope to the north and south, away from the Ovda highlands.

The short description given by Saunders (1996), combined with the analysis of Magellan images of this area, show that his CRT unit is our tessera terrain (Tt). His fracture belts are our fracture belts (FB) and densely fractured plains (Pdf). His Large-scale volcanic plains are mostly our plains with wrinkle ridges (Pwr) and the latest rille-forming eruptions mentioned by Saunders produced what we call lobate plains (Pl). In summary, the specific geologic units and corresponding geologic events of Saunders (1996) find correlative to our units and corresponding events, and the time sequence determined by him agrees with ours (Table 1).

12. Senske (1996) reported on the preliminary results of the geologic mapping of Juno Dorsum quadrangle (V47) (Table 1). A total of eight units have been identified, with the youngest considered to be Dark digitate plains (pdd). Close to it in stratigraphic position are Bright digitate plains (pdb)
and Bright plains (pb). Lower in the sequence are Mottled plains (pm) and Dark homogeneous plains (pdh). Below are extensive Dark plains (pd), and wrinkle ridges have been mapped in many places of this unit. Even lower in the stratigraphic column are Lineated plains (pl) having sets of parallel lineaments. Unit pl is typically embayed by the adjacent pd plains although some lineaments of the pl unit extend into pd plains. At the bottom of the local stratigraphic column is Complex ridged terrain (crt). The surface geology of the Juno Dorsum quadrangle is strongly affected by the radar-dark material associated with the 91-km crater Bonnevie (36.1°S, 127.0°E), and this is probably why many units of Senske (1996) are radar dark.

The short description given by Senske (1996) and analysis of the Magellan images of this area show that his pd and pdh units are equivalent to our lobate plains (Pl). His pb unit corresponds to our Pwr2 unit, with an admixture of our Pl plains. His pm unit corresponds mostly to our plains with wrinkle ridges (Pwr), mottled due to the influence of the Bonnevie crater ejecta material. His pdh unit is correlative with our smooth plains, partly those of amoeboid type, and partly those associated with impact craters (see Fig. 6). His pd unit corresponds to our plains with wrinkle ridges. His pl unit is mostly our densely fractured plains (Pdf) unit, with an admixture of our fracture belts (FB) unit. The crt unit of Senske (1996) corresponds to our tessera terrain (Tt) unit. In summary, the units of Senske (1996) find correlative to our units and the time sequence of units determined by him generally agrees with ours (Table 1).

13. Stofan and Guest (1996) reported on the preliminary results of their photogeological analysis of the Aino Planitia quadrangle (V46) (Table 1). Dominating this region is a low-lying uniform plains unit, characterized by wrinkle ridges and numerous small volcanic edifices. This unit embays several small outcrops of highly deformed terrain and high-standing regions of more deformed, mottled plains. The uniform plains also embay a rift segment located on the western margin of the quadrangle. Juno Chasma rift cuts across the plains and is superposed by Kunapipi Mons volcano. Eight coronae are in the area under study. They are interpreted to have a complex evolution and appear to postdate formation of the uniform plains.

It is difficult to compare the results of Stofan and Guest (1996) with our approach in the same way as in most of the examples described above because the map given in this work shows only physiographic features and does not show the geologic units. Geological units are only mentioned in the text in a very brief way. The descriptions given in a previous paragraph are close to direct quotations from their text. The large feature considered by these authors to be relatively young is Kunapipi volcano, which is made of our lobate plains (Pl). Their next stratigraphically older unit down in the sequence, uniform plains, are mostly our plains with wrinkle ridges (Pwr), with admixture of shield plains (Psh) (see Fig. 8). Outcrops of highly deformed terrain mentioned by them are inliers of our tessera terrain (Tt) and fractured and ridged plains (Pfr). We could not reliably identify what terrain Stofan and Guest (1996) called the “high-standing regions of more deformed, mottled plains”. The westernmost “rift segment” mentioned by them is composed of our Pfr and Tt units. We agree with Stofan and Guest (1996) that this terrain is embayed by the regional plains. So generally we find reasonable correspondence of their units and their time sequence with ours (Table 1). We agree with these authors that the coronae of this area had a complex evolution. But we disagree that in all cases this evolution appear to postdate formation of the uniform plains (see Fig. 5). We have studied in detail two coronae of this area, Aramaiti and Ohogetsu, and found that a significant part of the corona-forming deformation occurred here before the emplacement of our Pwr, their uniform plains (Basilevsky and Head, 1998).

14. Tapper and Guest (1996) reported on the preliminary results of the geologic mapping the Scarpellini quadrangle (V33) (Table 1). They identify six major geologic units. The youngest is Volcanic Centers. Volcanic Centers are superposed on the Scarpellini Regional Plains (P) which is the most extensive unit in the mapped area. Stratigraphically lower are four units which have no contacts between them but all are embayed by the regional plain: Bright Mottled Plains, Mottled and Lineated Plains, Lineated Tessera and Tessera.

The short descriptions given by Tapper and Guest (1996), together with reference to the Magellan images of this area, show that their Volcanic Centers are partly our lobate plains (Pl) associated with fractured terrain of the FB and Pdf type, and partly with clusters of shields of the Psh type. The Scarpellini Regional Plains are our plains with wrinkle ridges (Pwr). Bright Mottled Plains are our shield plains (Psh) with inclusions of our Pdf unit. Mottled and Lineated Plains are our shield plains (Psh) with inclusions of the Pwr unit. Lineated Tessera is the unit most resembling our fracture belts (FB), and their tessera corresponds to our tessera terrain (Tt). Thus, the units of Tapper and Guest (1996) find correlative with our...
units and the time sequence of units generally agrees with ours (Table 1).

15. DeShon and Hansen (1998) presented preliminary results on the geologic mapping of the Diana-Dali quadrangle (V37) (Table 1). Although this given publication emphasizes mostly the tectonic evolution of this area, some information on the mapped geologic units and their stratigraphic sequence is also provided. The youngest materials mentioned by these authors are some of "lava flows associated with corona and fracture zone formation", and cited as overlying plains units. Among the plains units, four varieties are identified: two units in Rursalka Planitia, both bearing wrinkle ridges, and two south of Latona corona, unit A bearing NW-trending fractures and no wrinkle ridges, and unit B bearing wrinkle ridges. DeShon and Hansen (1998) mentioned also lava flows "covered by plains units". Ridge belts are briefly described in the paper but their time relationships with the plains units are not explicitly given in the paper. The oldest unit of the area is reported to be represented by the tessera inlier in the northwest part of the quadrangle.

It is difficult to compare the results of DeShon and Hansen (1998) with our approach because the map given in this work shows mostly physiographic features and structures and only one geologic unit (tessera). Nevertheless from the given description and reference to Magellan images of this area, it is evident that the lava flows overlying plains units are our lobate plains (Pl), two plains units in Rursalka Planitia and unit B south of Latona are correlative to our plains with wrinkle ridges (Pwr), and the tessera inlier is made of our tessera terrain material (Tt) (see Fig. 12). It is not clear to us where lava flows covered by plains mentioned by these authors are located and we could not identify which specific plains were mentioned by them as unit A. In any case, however, we have found a general correspondence of their geologic units to ours and a similarity in the time sequence of these units with our unit sequence (Table 1).

16. Dohm and Tanaka (1999) reported on their analysis of the geologic mapping of the Metis Regio (V6) quadrangle (Table 1). They have identified 29 rock-stratigraphic units, forming four groups, from oldest to youngest: (1) Tessera; (2) Coronae and densely fractured plains materials, fracture and ridge belts; (3) Widespread moderately fractured and wrinkle-ridge plains materials; and (4) Large volcanic constructs, domes and flows. Although the individual units are not described in the paper, the general unit sequence of these authors is very close to our stratigraphic model. Indeed Dohm and Tanaka (1999) conclude that "the geologic sequence in V-6 agrees with previous studies of global and local stratigraphies that apply to this area (e.g., 1–4)". The latter are: Tanaka et al. (1997); Basilevsky et al. (1997); Basilevsky and Head (1998); and Stofan and Head (1990).

17. Senske (1999a,b) in two companion papers reports on the photogeologic analysis of the Tellus and Phoebe regions with emphasis on examination of the relationship between plains and tessera (Table 1). For Tellus Regio he considers impact craters and the localized occurrences of shield plains as the youngest unit found in the area. As stratigraphically lower he describes digitate plains and two varieties of homogeneous plains. Even lower are the most widespread regional plains which "embody tessera, lineated plains and in some places deformation belts". The tessera material is considered as the oldest in this area although the possibility of some continuation of tessera-forming activity in later time is mentioned. Lineated plains are somewhat younger (shown on the correlation chart as partly overlapping with tessera). Deformation belts (ridges) are mapped as two units, one is older and other is younger than the regional plains. Comparison of the Senske (1999a) map and the Magellan images of this area show that his time sequence of the units is very close to ours. His shield plains correspond to our younger variety of Psh. His digitate plains is a mixture of our Pl and Pwr2 plains. His homogeneous plains are part of our Pwr2. His regional plains is our plains with wrinkle ridges, mostly Pwr1. His deformation belts are our Pfr/RB. His lineated plains are a mixture of our Pdf and FB. And his tessera is considered by us as tessera too. The major disagreement between Senske and us is his interpretation that one of two varieties of deformation belts is younger than regional plains.

Considering Phoebe Regio, Senske (1999b) describes essentially the same units as in Tellus Regio. The differences with Tellus are as follows: There are two units of lobate flows which are considered as the youngest among volcanics. Shield plains, homogeneous plains and mottled plains (a new unit, a mixture of our Pl, Pwr and Psh units) are described as predating the lobate flows but postdating regional plains. Of the two deformation belt units, one (the younger) represents faulted rift zones (our RT unit), another — ridge belts (our Pfr). The latter is shown as postdating lineated plains and almost contemporaneous with regional plains. The unit time sequence of Senske (1999b) is generally close to ours (Table 1). Again the major disagreement is in relations between the regional plains and the deformation (ridge) belt: Senske shows Ridge Belts (his db2) to be of the same age.
as Pwr (his regional plains) although many examples of clear embayment of Pfr/RB by Pwr plains are observed by us in this area (Fig. 13).

In summary, we have reviewed the available results of seventeen different efforts of geologic mapping made by individual mappers and teams and compared their results with the appropriate images they used for photogeological analysis and with the results of our analysis of some of these and other regions (Table 1). The synoptic map showing the locations of the major areas studied by us and others is shown in Fig. 1. We found that the geology of these regions, which were partly new to us, was represented by these workers as consisting of a limited number of geologic units. We have found that the geologic units of other mappers (Table 1) can be easily correlated with our units (Fig. 19). Most of them are direct analogs of our units but only named differently. Some of the units of other workers are mixtures or combinations of our units. In many cases this is evidently because the published versions of their maps (often one page or less) are too synoptic to show the detailed breakdown or subdivisions. This is certainly the case for the ‘coronae’ units in several of the works considered above. In some cases other workers distinguished more than one unit within our one unit. This typically happened in two types of cases: (1) either when mappers considered lava flows of approximately the same age, but emanating from different sources, as separate units; or (2) when the unit was modified by surficial processes, noticeably changing the unit morphology. In the latter cases, because we could see the primary features of the unit through these changes we did not introduce the modified area as a new unit. In most cases there is a good and unequivocal correspondence of the geologic units of other mappers with our units (Table 1).

We have also found that the relative time sequence of the units of other mappers are commonly the same or very close to our sequence (Table 1; Figs. 19 and 20). Although most of the mappers did not map surficial deposits correlative with our dark parabolas, the young stratigraphic position of them was often mentioned in the text. All the mappers considered lobate lava flows as the youngest units of their area. In most cases these are correlative with our lobate plains (Pl). In some relatively rare cases, the mappers included in this unit(s) wrinkle ridged flows, which we consider as the upper part of our plains with wrinkle ridges (Pwr2). In some areas correlatives to our smooth plains were distinguished and their relatively young stratigraphic position was recognized. The most widespread regional plains, correlative with our plains with wrinkle ridges (Pwr), were found by other mappers to be in the middle part of the local stratigraphic columns, corresponding to the place where they occur in our column. Many of the mappers identified varieties of mottled plains and shield fields correlative with our shield plains (Psh), often putting them stratigraphically above the regional plains. Although we agree that some shield fields of the Psh type are rather young, we believe that in many cases their emplacement predated the Pwr plains. Another area of disagreement is the stratigraphic position of the ridge belts composed of our Pfr unit. We see many convincing cases of their embayment by material of regional plains with wrinkle ridges (Pwr) but some mappers put this unit or event (ridge belt formation) stratigraphically above the regional plains. In some regions other mappers identified lineated plains, correlative with our densely fractured plains (Pdf) and fracture belts (FB), and recognized their low stratigraphic position, which agrees with our interpretation. Finally, in all regions where tessera was mapped, the individual mappers considered it to be the oldest unit, in a manner similar to our interpretation. In summary, not only do the geologic units of other mappers find appropriate counterparts to our map units, but the sequence of units of other mappers are generally similar to ours (Table 1).

These considerations strengthen the case that local stratigraphic columns in all areas of Venus studied by us, and by other researchers working independently from us, are very similar. This could be interpreted to mean that either: (1) similar geologic units of the stratigraphic sequences of different areas correspond to a typical sequence of geologic events which occurred in different areas of the planet at different times; or (2) geologic events which formed similar units in different areas of the planet occurred rather synchronously around the planet, so the established sequence of events represents the sequence of the geologic history of Venus recorded in the morphological units. Alternatively, a third option might exist in which the situation is intermediate between options (1) and (2). We see two approaches which may help to distinguish among these three options. The first is to look at estimations of the absolute age of geologic units which occupy different positions in the stratigraphic column(s). Another approach is to consider the interpretation a planet-wide consistency of the local stratigraphic columns to see if it appears to have geological consistency. We treat each of these approaches separately and then summarize our observations and conclusions.

4. Planet-wide consistency of local stratigraphic columns

As described in sections 2 and 3, a typical sequence of up to eleven major geologic units (Cdp → Pl/ Ps + RT → Pwr + Psh → Pfr/RB + FB → Pdf → Tt; see for clarity Figs. 19 and 20) is observed in all areas studied by us, as well as in many areas studied by other
workers (see Fig. 1; Table 1). The areas studied by us include thirty-six 1000 × 1000 km sites randomly distributed around the planet (Basilevsky and Head, 1995a,b,c), a 5000 × 5000 km region around Baltis Vallis (Basilevsky and Head, 1996), quadrangles V16 and V55, each about 2500 × 2500 km size (Basilevsky, 1996; Head and Ivanov, 1996), a 1500 × 3000 km area around the Venera 8 landing site (Basilevsky, 1997), an 1800 × 1800 km area around the Venera 13 and 14 sites (Abdrakhimov and Basilevsky, 1998), areas of six stereoscopically studied coronae covering in total about 1 million km² (Basilevsky and Head, 1997; 1998), a geotraverse along 30°N covering about 11% of Venus (Ivanov and Head, 1997, 1998a,b), and the area north of 35°N covering about 21% of the planet (Basilevsky and Head, 1997). The areas studied by other workers include 11 quadrangles each about 6 million km² in size (Copp and Guest, 1995; DeShon and Hansen, 1998; Dohm and Tanaka, 1999; McGill, 1994; Plaut, 1996; Rosenberg, 1995; Saunders, 1996; Senske, 1996 1999a;b; Stofan and Guest, 1996; Tapper and Guest, 1996). Three works of other researchers cover relatively small areas (G. McGill, in Edmunds, 1995; Solomon et al., 1992; Squyres et al., 1992). The Senske et al. (1992) study covered about 28 million km². Finally, the Price (1995a, b) and Senske et al. (1994) studies were both global in scale. Even considering that some of the listed areas are overlapping, local and regional studies in which the described sequence of geologic units was observed cover about one-half of the surface of Venus (see Fig. 1). The two global-scale studies generally confirm the major points of this sequence.

Consistency of the local and regional stratigraphic columns over one-half of the planet places an important constraint on the choice between the options for interpretation of the geologic evolution of Venus mentioned previously. Let us consider a model situation assuming that there are three areas: A, shown left on Fig. 21, B, in the middle, and C, on the right. In each of the areas the local stratigraphic sequence from younger to older is the same: Pwr → RB → Pdf → Tt. But the times of emplacement of the materials comprising the units and their deformation by the characteristic structures in these three areas were not synchronous. For example, wrinkle ridging deforming the Pwr plains in area A was not synchronous with the wrink ridge in areas B and C. Let us assume that wrinkle ridging in area A was synchronous with tesser-forming deformation in area B and with the RB-forming broad ridging in area C. If these three sites are areally separated the deformation will not result in something anomalous in the surface morphology. But if these three areas are touching each other we would expect to see morphologic evidence of the hypothesized nonsynchronity. In the boundary zone between areas A and B we should see cases where some tesser massif is embayed by Pwr plains on the area B side and is formed at the expense of Pwr plains on the area A side. In the boundary zone between areas B and C, we should see that tesser terrain which is embayed by the Pfr/RB material in area B starts to form at the expense of Pfr/RB material. So in this model situation we expect to see distinctive variations on typical stratigraphic sequences. In this given case, a mapper should see in area A two tesserae: the old one, embayed by the Pdf, Pfr/RB, and Pwr materials, and a young one, formed at the expense of Pwr plains. Similarly in area
C the mapper should see older tesserae, embayed by the Pdf and Pfr/RB materials, and younger tesserae, formed at the expense of Pfr/RB material. But these hypothetical situations have not been observed by us or other mappers.

One can consider hypothetical model situations of this sort with other stratigraphic units and the conclusions are the same: nonsynchrony of unit-forming geologic processes in neighboring areas should inevitably result in a violation, repetition, or reversal of the sequence of units in the observed stratigraphic sequence. When the area covered by stratigraphic studies was relatively small and the study sites were areally separated (as at the time of Basilevsky and Head, 1995a,b,c), the options of (1) nonsynchronous, (2) synchronous and (3) semisynchronous formation of the same geologic units in local/regional stratigraphic columns were all acceptable explanations. At the present time, however, one-half of Venus has been stratigraphically studied, including areally continuous mapping covering about 30% of the surface of Venus (Basilevsky et al., 1997b, 1999b; Ivanov and Head, 1997, 1998a,b). The observed consistency in local/regional stratigraphic columns across this large expanse of the surface appears to be strong evidence in favor of option (2) and makes options (1) and (3) of lower likelihood. Of course, until the surface is totally and continuously mapped, which will take another several years, there is still the possibility that young tesserae or old versions of the undeformed lobate plains may exist on Venus. But the fact that these cases have not yet been observed in mapping shows that even if they exist in unmapped areas, they are not typical of this planet. Therefore, this conclusion provides the basis on which to outline a model of a global stratigraphic sequence for Venus, based on the established local/regional stratigraphic columns, and to examine its predictions and implications.

5. Absolute age estimates

The existing technique of absolute dating of planetary surfaces based on measuring the areal densities of impact craters (BVSP, 1981) is fully applicable to Venus; however, difficulties arise in: (1) having sufficient craters to measure and distinguish units because of the generally young age of the surface of Venus; and (2) the dense atmosphere through which only large crater-forming projectiles reach the surface. The total impact crater population of Venus is close to about 1000 craters (Phillips et al., 1992; Schaber et al., 1995; Schaber et al., 1992; Strom et al., 1994) and this gives an estimate of global average density to be $2.01 \pm 0.14$ craters per million km² (Price and Suppe, 1994). This number of craters is enough for estimates of the average crater retention age of the surface of Venus and geologic units which occupy large areas. But even these estimates are rather different. The average age of the surface of Venus is estimated by Strom et al. (1994) to be $288 \pm 311/98$ m.y.; by Phillips et al. (1992), 400 to 800 m.y., on average about 500 m.y.; and by McKinnon et al. (1997) about 750 m.y with a possible range from 300 m.y. to 1 G.y. The major cause of this diversity in the estimates is the model-dependent transition from the crater densities themselves to absolute ages. This is why we will discuss the age estimates existing in literature not in terms of millions of years, but in terms of fractions of the average age of the surface of Venus (T), returning to conventional time units only when it is necessary. Most of the age estimates discussed below were by workers who used geologic unit names different than the names we used, but the correspondence to our names is straightforward (see Table 1). The following are estimates of average ages of: (1) radar dark parabolas; (2) large volcanoes and prominent lava fields; (3) regional plains; and (4) tesserae. Other units cover areas too small to be reliably dated by the impact crater counting technique.

5.1. Radar-dark parabolas

These were distinguished in early stage of the Magellan data analysis as features associated with the youngest part of the crater population (Campbell et al., 1992). There are about 55 craters larger than 12–13 km in diameter which have associated parabolas. This is 5.5% of the crater population. However, well-developed parabolas are observed only in association with craters larger than 20 km in diameter. This agrees with the estimates which show that smaller craters do not produce ejecta plumes capable of breaching the atmosphere (Vervack and Melosh, 1992). Keeping this in mind, 55 craters with associated parabolas compose about 10% of crater subpopulation which is expected to be able to produce the parabolas. So the dark-parabola craters should have an age not more than about 10% of the time of the production of the crater population of the planet, that is 0.1 T (Basilevsky, 1993; Strom, 1993).

5.2. Large volcanoes and prominent lava flows

These estimates are related mostly to our lobate plains (Pl) with minor admixture of wrinkle ridged flows which we consider as unit Pwr2. Namiki and Solomon (1994) estimated the crater density on 175 volcanoes each at least 50 km in diameter. This population of volcanoes is obviously dominated by large rift-associated volcanoes such as Ozza Mons or Maat...
Mons. Older wrinkle ridged edifices, such as one seen in the supposed beginning of Baltis Vallis channel (Baker et al., 1992), are also present in the population but their percentage is small. The crater density on this volcano population was found to be $0.9 \pm 0.2$ craters per million km$^2$, which is about half of the global average, so the age estimate is about 0.5 T.

Price and Suppe (1994) found that the crater density on 128 large volcanoes to be $0.51 \pm 0.32$ craters per million km$^2$. The difference compared to the results of Namiki and Solomon is probably due to slightly different volcano populations studied by these two groups and to the different attributions of craters which are on the boundaries of two different geologic units. For geologic units from many individual localities the latter problem may be a reason for noticeable differences. Price and Suppe (1994) also estimated the crater density on 48 flood-type lava flow fields. Among these flow fields our lobate plains unit (Pl) dominates, but some localities of our Pwr2 unit are also present. The average crater density on these lava fields is found to be $0.92 \pm 0.65$ craters per million km$^2$, that is, about one-half of the global average.

Combining the results of Namiki and Solomon (1994) and Price and Suppe (1994) and ignoring the admixture of the Pwr component to the populations studied by them, the average age of our lobate plains (Pl) may be estimated to be about 0.5 T.

5.3. Regional plains

Because $T$ is an average crater retention age of the surface of Venus, it should be close to the average age of the most widespread unit on the planet, which is regional plains consisting mostly of our plains with wrinkle ridges (Pwr) with a significant admixture of shield plains (Psh), which are stratigraphically close to them. Combined together these units cover about 70–80% of the surface of Venus (Basilevsky et al., 1997b; Ivanov and Head, 1997a,b; 1998a,b).

Price (1995a,b), based on synoptic 1:30 M geologic mapping, subdivided the Venus plains into four stratigraphic units (Pl1, Pl2, Pl3, and Ps). She determined the surface age of each of them through crater density measurements. Crater densities increase from Pl1 to Ps, yielding age estimates of $0.7 \pm 0.25$ T for Pl1; $0.8 \pm 0.13$ T for Pl2; $1.09 \pm 0.15$ T for Pl3; and $1.23 \pm 0.15$ T for Ps. As we discussed in a previous section, her plains units are mixtures of our plains units with the increasing participation of our older plains units in her older plains units and vice versa. Taking this in mind, in particular the fact that her Pl1 unit is essentially our lobate plains (Pl), her estimates agree well with our estimate of average age of the regional plains as about T.

5.4. Tessera

The average surface age of the observed blocks of tessera was estimated to be $(1.47 \pm 0.46)$T by Ivanov and Basilevsky (1993). Later work by Gilmore et al. (1997), which concluded that the average surface age of tessera was about 1.4 T, confirmed this estimate. The difficult part of the tessera age estimate, besides the fact that the morphologically rough and radar bright surface of this terrain camouflages smaller craters from identification (see Basilevsky et al., 1997a; Gilmore et al., 1997 for details), is the large error bars and the problem of boundary craters. The first is due to the relatively small number of on-tessera craters which, in turn, is a result of the relatively small percentage of the surface of Venus occupied by tessera, about 8% according to Ivanov and Head (1996), and the previously mentioned rather small total number of impact craters on the planet. The latter problem is due to the fact that a significant part of tessera material is present in the form of relatively small kipukas among the plains. As a result, about one-third of the craters superposed on tessera are superposed on the adjacent plains too, and this leads to additional uncertainties in the age estimates (for details see Ivanov and Basilevsky, 1993).

In summary, consideration of existing estimates of the average age of several geologic units of our stratigraphic model show that the unit which is uppermost in our model (Cdp) has the youngest average absolute age (about 0.1 T). Next in the sequence, unit (Pl) has a noticeably older, but still rather small, average age (about 0.5 T). The combination of units which have an intermediate position in our stratigraphic sequence (Pwr+Psh) shows an intermediate average absolute age (about T). And finally, the lowermost unit of our sequence (Tt) shows the largest average absolute age (about 1.4 T).

Although these estimates are average values and thus do not put constraints on the age of individual outcrops of any of the considered units they nevertheless provide meaningful information on the internal age structure of the units. For example, the mentioned estimates, showing that unit Pl is on average about twice younger than the Pwr+Psh regional plains, do not preclude the possibility that in some area(s) unit Pl may be older than units Pwr in other(s). However these estimates do show that in the majority of its outcrops the unit Pl has to be younger than the unit Pwr in the majority of its outcrops. Otherwise the observed difference in the average values would not be the case. This agrees well with the observed consistency of the local stratigraphic columns across a significant part of the planet, thus supporting the synchronous option of the model of the geologic history of Venus.

This model was first suggested in Basilevsky and Head (1995a,b,c) and, on the basis of discussion and critical comments from our colleagues, was further discussed and developed in Basilevsky et al. (1997) and Basilevsky and Head (1998). This stratigraphy (Fig. 22) consists of six major units which we rank as groups. The following is their description given in order from younger to older.

The Aurelia Group is composed of materials of parabolic radar-dark mantles typical of the youngest 10% or so of impact craters (Cdp) and other crater materials of this crater subpopulation (Basilevsky, 1993; Campbell et al., 1992; Strom, 1993). Also included in this group are some debris accumulations in the form of radar patches (Sp) in local topographic lows against or behind positive topographic obstacles, as well as some radar-dark wind streaks (Ss) (Greeley et al., 1992). The dark-parabola crater Aurelia (20.27°N, 331.80°E; D = 31 km) was designated as the type area on the basis of the excellent development of these properties there. Aurelia Group materials overlay all other stratigraphic units except for the rare cases where volcanic materials belonging to the youngest part of Atla Group postdate dark paraboloid craters (Basilevsky, 1993).

The Guinevere Supergroup consists of four major groups of regional plains interpreted to be of volcanic origin. The youngest, the Atla Group, consists of materials of lobate (Pl) and smooth (Ps) plains undeformed by wrinkle ridges. The tectonic unit of the Rift terrain material (RT) also belongs to the Atla Group. The name Atla was suggested because lobate and smooth plains are very common in Atla Regio. Atla Group materials tend to be concentrated in association with large-scale rift zones forming either areas of essentially flat plains such as Mylitta Fluctus (Magee Roberts et al., 1992) or mountains with gently sloping flanks, such as Sif, Gula, or Theia Montes (Senske et al., 1992). Atla Regio is the junction of several rifts and contains the rift-associated Maat and Ozza shield volcanoes. Atla Group materials are often observed in association with coronae, forming the stratigraphically youngest apron of flows surrounding them. Regional mapping (e.g., Basilevsky et al., 1997b, 1999b) has shown that Atlal lobate plains associated with neither rifts nor coronae are present in noticeable amounts. The younger ameoboid-type shield fields superposed on wrinkle ridges of Pwr plains are also considered as a component of the Atla Group.

The Rusalka Group consists of the materials of plains with wrinkle ridges (Pwr) and of the majority of shield plains (Psh). The name Rusalka was assigned because Rusalka Planitia is mostly made of plains with wrinkle ridges and because geochemical measurements by Vega 1 and 2 provided direct data on the chemical composition (basalts) of these materials (Barsukov, 1992; Surkov, 1986, 1990). Pwr plains, and the majority of Psh plains, are deformed by the network of wrinkle ridges which forms a discontinuity separating materials of the Rusalka Group from those belonging to younger Atla Group. In some rare cases (e.g. at 74.5°N, 275°E) two wrinkle ridge networks are observed and their formation appears to be separated by emplacement of plains material. Subsequent emplacement of two wrinkle ridge sets was also described by McGill (1993). Generally, however, the wrinkle ridge network forms a continuous pattern over very large regions of the planet (Billotti, 1992;
Bilotti and Suppe, 1999; Sandwell et al., 1997), thus providing a practical tool for separation of Rusalkian from Atlian materials.

The Lavinia Group is composed of the materials of fractured and ridged plains (Pfr) and ridge belts (RB). The name Lavinia was given because these materials are common in Lavinia Planitia, forming kipukas among the Rusalkian plains with wrinkle ridges. Broad ridges forming a discontinuity separating materials of the Lavinia Group from the overlying materials of the Rusalkian and younger ages, is typical for this group. As described in section 2, fracture belt materials (FB) mostly occur near the boundary between the Rusalka and Lavinia Groups.

The Sigrun Group consists of materials of densely fractured plains (Pdf). The name Sigrun was chosen because of the well-developed examples in the Sigrun Fossae belt of densely fractured terrain. At the time we initially named this Group, we did not distinguish densely fractured plains (Pdf) from fracture belts (FB) (Basilevsky and Head, 1995a,b,c). Subsequent mapping has shown that the Sigrun Fossae belt contains not only Pdf material but an FB component too. The dense, typically subparallel fracturing characteristic of Pdf plains forms a discontinuity separating Sigrun Group material from the materials of Lavinian and younger ages. Kipukas of Sigrunian Pdf plains are very widespread around the planet, giving the impression that Pdf-type fracturing did affect all the plains formed at Sigrunian time. If not, some of the plains presently classified as Lavinian may actually represent a mixture of Lavinian and Sigrunian materials or Sigrunian materials only.

The Fortuna Group includes materials of tessera terrain (Ti) and mountain belts (M). The name Fortuna was derived from Fortuna Tessera, which is a large tessera massif containing several different varieties of this terrain, and is also the place where this type of the terrain was first identified in the analysis of the Venera 15/16 SAR images (Barsukov et al., 1986). The complex of tessera-forming deformation forms a discontinuity separating Fortuna Group materials from the materials of younger groups. Beside the prominent structural signature which determines its characteristic appearance, tessera terrain, being the oldest terrain on the planet, also commonly accumulated structural signatures of later episodes of tectonic activity on Venus. This later deformation sometimes crosses the boundaries of tessera and the surrounding plains.

This, however, does not mean that the basic processes that caused tessera formation extended significantly into times younger than Fortunian, as suggested by Senske (1998). Tessera is typically embayed by stratigraphically much younger regional Rusalkian plains, while localities where it is in contact with older, Lavinian and Sigrunian plains units, are more rare. However, although small in areal extent, these contacts with older plains do exist in many places widely distributed across the planet (e.g., Basilevsky and Head, 1998; Ivanov and Head, 1996, 1998a,b) and show embayment of tessera by the materials of these plains (see Figs. 13 and 14 in this paper, and Figs. 3 and 4 in Senske, 1998). As described in our previous discussions, despite the many well-documented local embayment relations of tessera by post-tessera units (Pdf, Pfr, etc.), and their global occurrence in association with the ~8% of the surface mapped as tessera, we should keep in mind that a significant portion of these earlier units are hidden below younger units. Thus, the detailed nature of units underlying these large expanses of younger regional deposits (e.g., Pwr) is not known, and some of these underlying units could be partly laterally continuous facies of the tessera massifs, perhaps representing different and complementary styles of formation and modification (e.g., see Ivanov and Head, 1996). It is also evident that stratigraphic relations within the tessera massifs are not studied yet in the necessary detail. Some observations show that what is synoptically mapped as tessera massifs may contain intimate admixtures of Pdf and Pfr materials crossed by rather late (but pre-Pwr) deformation (Basilevsky, 1996a; Ivanov, 1998). So some tessera massifs may contain not only Fortunian Group material but Sigrunian and Lavinian materials as well. Work is underway to assess these questions.

7. Durations of time-stratigraphic units

If the described units appear generally synchronous over the surface of Venus, what evidence exists for their mode of formation and the duration of their emplacement, and is this information generally consistent with the interpreted synchronous stratigraphy? This discussion is mostly based on estimates of the average absolute ages of areally dominant geologic units, as described in part 4 of this paper and some additional estimates of the time duration of the emplacement of some material units and structures.

As it was shown, dark-parabola craters which compose the areally predominant part of the Aurelia Group should not be older than about 0.1 T. So one can conclude that the Aureliac period started about 0.1 T and lasts until now (Fig. 22). It was also shown that the average age of our lobate plains (Pl), which are a significant component of the Atla Group, is estimated to be about 0.5 T. The apparent upper boundary of Atlian time is the beginning of the Aureliac time, that is ~0.1 T, although in some rare cases lobate plains (Pl) may postdate the Aureliac dark parabolas, so some time overlap between the Atlian and Aureliac materials does exist. The lower boundary of the Atlian
time is the upper boundary of the Rusalkian time, which is equivalent to the time when the wrinkle ridge network (deforming Pwr and the dominant part of the Psh plains) was emplaced.

The average age of the Rusalkian plains (e.g., the average time of their exposure to impact cratering) was found to be about 1 T. The duration of emplacement of these plains can also be estimated through analysis of the impact crater population. Such an analysis was recently completed (Collins et al., 1996, 1999) for plains with wrinkle ridges (Pwr), which are the dominant component of the Rusalkian plains. Collins et al. (1996, 1999) compiled three data sets: (1) the percentage of impact craters on Pwr plains which were emplaced by these plains materials (~1%); (2) estimates of the thickness of Pwr plains-forming material (63% of the plains are thinner than 500 m); and (3) knowledge of impact crater relief (Sharpton, 1994).

On the basis of this information, the time duration of emplacement of the Rusalkian plains that was required to maintain the observed number of emplaced impact craters, was estimated through Monte Carlo modelling. This estimate showed that this time period should be very short: between 0.01 T and 0.06 T.

Another time estimate relevant to the absolute age boundaries of the Rusalkian time period is an analysis of the duration of the time period between the emplacement of the plains materials and their deformation by the wrinkle ridge network. This time period has to be very short because among about 650 impact craters superposed on the Rusalkian plains only seven craters have been found to be deformed by wrinkle ridges (Basilevsky, 1996b; Schaber et al., 1995). At first glance, this means that the time interval between the emplacement of Pwr plains and their wrinkle ridging should be about 0.01 T (7/650 = ~0.01). But if we consider the possibility that some craters emplaced before the wrinkle ridging episode might not be ridged because their sizes were smaller than the wrinkle ridge network spacing, then the time interval between the emplacement of Pwr plains and their wrinkle ridging may be increased up to 0.13 T (Basilevsky, 1996b).

In summary, considering that the average absolute surface age of the Rusalkian plains is about 1 T, the duration of the Pwr plains emplacement is apparently (0.01-0.06)T, and the time period between the emplacement of the Rusalkian plains and their wrinkle ridging was probably as long as 0.01–0.13 T, we conclude that the upper boundary of Rusalkian time is about 1 T and the lower boundary, about 1.1 T.

Crater densities and the absolute age estimates for the Lavinia and Sigrun Groups have not yet been determined. When this is accomplished in the future, the dating results are, unfortunately, expected to be rather uncertain because these units cover relatively small percentages of the surface of Venus, so the numbers of craters superposed on them will be small. In addition, these units are present in the form of numerous small inliers, so the problem of boundary craters will be even more severe than it was for tessera terrain (Ivanov and Basilevsky, 1993). So one substantial way to place some constraints on the time boundaries of the Lavinia and Sigrun Groups is to address the age estimates of the underlying tessera terrain.

The average surface age of tessera, which comprises the predominant part of Fortuna Group, was found to be about 1.4 T (Gilmore et al., 1997) with a possible range from 1.01 to 1.93 T (Ivanov and Basilevsky, 1993). The large error bars are due to the small number of craters superposed on tessera terrain. In total there are 80 on-tessera craters, of which only craters larger than 16 km in diameter are meaningful for tessera age estimates (see Ivanov and Basilevsky, 1993, for details). So there is no known approach at present to narrow this interval of uncertainty. Because this is the average surface age of tesserae, one may suspect that different tessera massifs may differ in surface age from one to the other. For the same reason (the small total number of craters), this suspicion can be neither confirmed nor rejected to a high degree of certainty.

We can only say that the differences in age between individual tessera massifs, if they exist, can not be too large because the crater densities on the eight largest tessera massifs vary from 1.5 to 3.3 craters per million km², while the average crater density for tessera is 2.29 craters per million km² (Gilmore et al., 1997). The estimated value of about 1.4 T is the average age of tessera as a terrain, not the age of the tessera terrain material. The latter may be either close to the age of the terrain, or significantly older, or both.

Although tessera formed through very significant deformation of the precursor terrain, we do not see a single heavily deformed crater on tessera terrain. This means that although tessera formation could have involved long-term accumulation of deformation, at least close to the end of its formation the deformation was strong enough to destroy all earlier-formed craters (if they did exist) and fast enough not to have even one new crater formed in competition with this deformational stage. We observe superposed on tessera only seven craters moderately deformed by later extensional structures typical of the waning stages of tessera-formation (Gilmore et al., 1997; Ivanov and Head, 1996). These characteristics of the on-tessera crater population can be interpreted in the following way: The estimate of about 1.4 T is the average age of tessera terrain marking the end of the heavy deformation stage. The duration of that stage was less than 1/80 of the tessera terrain age that is about 0.02 T. The duration of the waning stage of tessera formation, when seven of 80 on-tessera craters formed, was 7/80 of the...
tessera age, that is, about (0.1–0.2)T (Gilmore et al., 1997).

Structures of this (0.1–0.2)T-long waning stage of the tessera-forming deformation are embayed by the plains surrounding tesserae. These plains are mostly plains with wrinkle ridges so we can definitely say that these structures predate Pwr plains. There are good examples of embayment of tessera and all its structures by the Pfr/RB and Pfd materials (see Figs. 13 and 14). However, extensional structures typical of units Pfd and FB appear similar to structures which deformed the seven on-tessera craters, so one may suggest that the latter structures overlapped in time with the emplacement of Pfr/RB and Pfd materials. In summary, we conclude that the end of Fortunian time was at about 1.4 T, and that Sigrun and Lavinia Groups formed between about 1.4 and 1.1 T.

This estimate is supported by the recent study of Basilevsky et al. (1999a) in the area north of 35°N. Within this area, comprising about 21% of the surface of Venus, 200 impact craters were observed and the geologic units on which they were superposed were determined. Among them 51–63 craters were superposed on the relatively old units (Tt, Pfd, Pfr, FB) predating Pwr + Psh regional plains. The majority of these craters show obvious evidence that they postdated not only these old units but Pwr + Psh plains too, and only two to eight of these craters were found to be formed before the emplacement of the Pwr + Psh regional plains. This was interpreted to mean that the time interval between the formation of these older units and emplacement of the regional plains should be geologically short: from a few percent to about 20% of T.

In conclusion, we suggest the following estimated ages for the time-stratigraphic units: Aurelian Period — from the present to 0.1 T; Atlitian Period — 0.1 T to 1 T; Rusalkian Period — 1–1.1 T; Lavinian and Sigrunian periods together — 1.1–1.4 T; and Fortunian Period — 1.4 T to some undetermined earlier time.

8. The thickness of post-Fortunian plains units and rates of volcanism

What are the thicknesses of these units and does this stratigraphic sequence produce reasonable and consistent estimates for the volumes and rates of volcanism? The general characteristics and stratigraphic relations of the geologic units identified and described above, considered together with the hypsometry of the units, provide a basis on which to estimate the vertical structure and lateral dimensions of parts of the upper crust of Venus (Head and Basilevsky, 1999). The lowest stratigraphic level observed on the surface is material of tessera terrain. In this analysis we consider what is above tessera as materials of the Aurelian Group, and the Guinevere Supergroup, consisting of a suite of Atlitian, Rusalkian, Lavinian and Sigrunian materials most of which are apparently volcanic. First we will estimate their total thickness, then the thicknesses of each of these units, and finally, using the estimates of the areas, volumes, and time boundaries of the units we will try to estimate the corresponding rates of volcanism.

The total thickness of the post-Fortunian materials may be estimated from the range of relief of the tessera terrain assuming that tessera underlies a significant part, if not all, of the subsequent plains (Ivanov and Head, 1996). To bury the tessera over the majority of Venus, the thickness of the material emplaced has to be greater than the typical relief of tessera terrain. Within now existing continent-sized tessera outcrops, such as Fortuna or Ovda, the range of the relief on the hundred-km horizontal base is typically of 1–3 km. Assuming that at the areas buried by the post-tessera materials the tessera relief was the same, one may conclude that the thickness of those materials should not be less than 1 to 3 km (Ivanov and Head, 1996). Considering that small outcrops of tessera material are present in practically all regions of Venus the thickness estimated on this basis should be not significantly greater than 1–3 km and probably close to this estimate (Ivanov and Head, 1996). If we assume that this thickness estimate is relevant to 92% of the surface where tessera is not exposed, then the total volume of the post-Fortunian materials is 4 to 12 × 10^8 km^3 (e.g., Head et al., 1996).

The uppermost member of the suite of post-Fortunian materials is Aurelian materials which are mostly materials of the dark parabolas occupying a total of about 8% of Venus. They are evidently thin because their total volume is only a fraction of the volume of ejecta of those ~55 dark-parabola craters. Campbell et al. (1992) estimated the parabola material thickness to be from a few centimeters to 1 or 2 m, based on their ability to obscure other features. If we assume that the thickness is ~1 m, the total volume of the dark parabola material on Venus is about 4 × 10^4 km^3. This is probably the upper possible estimate because it is comparable to the total volume of the ejecta of these 55 craters. The volumes of other Aurelian materials are evidently also of that order of magnitude or smaller. So it is obvious that the role of Aurelian materials in the total budget of post-Fortunian materials is negligible.

Atlitian materials, the vast majority of which are volcanic, typically overlie Rusalkian plains (plains with wrinkle ridges and shield plains). Atlitian volcanics are represented by lava fields and volcanic edifices. According to Crumpler et al. (1997), 212 lava fields larger than approximately 50,000 km^2 occupy about
9% of the surface, which is about $4 \times 10^7$ km$^2$. The lava fields often follow lows in the undulations of the pre-Atlian topography of the Rusalkian plains. The topographic range of these undulations is usually no more than a few hundred meters (Baker et al., 1997). Kipukas of small shields of the Psh type typically less than a few hundred meters high are relatively common among these extensive lava fields. If we assume on the basis of these observations that the average thickness of Atlian lava fields is about 200 m, this leads to an estimate of their volume as $8 \times 10^6$ km$^3$. Atlian volcanic edifices are mostly characterized by large ($> 100$ km in diameter) and intermediate (20–100 km) sizes. According to Crumpler et al. (1997), the 167 large volcanoes (the vast majority of which are Atlian) have a total volume $\approx 8.7 \times 10^9$ km$^3$. The 289 intermediate-size volcanoes (a significant part of which are also Atlian) add less than $0.1 \times 10^9$ km$^3$. In summary, the total volume of Atlian volcanic edifices is estimated to be about $9 \times 10^6$ km$^3$, and the total volume of all Atlian volcanics is estimated to be about $17 \times 10^6$ km$^3$.

Rusalkian materials, which are evidently mostly lavas, occupy about 70% of the surface. Of these Rusalkian materials, 50–60% are Pwr plains and 10–15% are Psh plains. Rusalkian lavas are certainly also present in most of the areas now covered by the younger Atlian volcanics. We may thus estimate that the total area on which Rusalkian lavas were emplaced is about 80% of the planet, which is about $3.7 \times 10^8$ km$^2$, of which $2.8 \times 10^8$ km$^2$ are Pwr materials and $0.9 \times 10^8$ km$^2$ are Psh materials. The total thickness of Pwr materials was estimated to be about 0.5 km on the basis of results of geologic mapping and on the assumption that the slope of their basal contact is less than about 1°, on the basis of outcrops of stratigraphically older Pfr/RB, Pfd, and Tt materials exposed as kipukas among them (Collins et al., 1996, 1999). This estimate agrees well with the fact that kipukas of Pfr/RB and Pfd materials are present in practically all areas of 1000–10000 km size, or even less, although the surface relief of Pfr and Pfd plains in the areas where they are not covered by the younger materials is less than a few hundred meters (e.g., Kreslavsky and Head, 1999). An excellent example of such areas is Lahesis Tessera (42–46°N, 296–302°), which is actually not tessera terrain but instead is an assemblage of patches of Pfr and Pfd. Fields of older Psh plains typically stand above the surrounding Pwr plains by about 200 m (Ivanov and Head, 1998), so the average thickness of the Psh materials is evidently about 700 m. This leads to an estimate of total volume of Pwr materials to be $\approx 1.4 \times 10^9$ km$^3$, Psh materials, $\approx 0.6 \times 10^8$ km$^3$, and Rusalkian volcanics altogether (Pwr and Psh), $\approx 2 \times 10^8$ km$^3$.

Lavinian and Sigrunian materials are also believed to be mostly volcanic. Taken together they should comprise the lower part of the post-Fortunian material complex, the total thickness of which was estimated to be $\approx 1$–3 km. Subtracting the estimated contribution of the Atlian and Rusalkian materials from the total, the combined thickness of Lavinian and Sigrunian materials should be about 0.5–2.5 km, most probably 1–2 km. Lavinian materials are not thick enough where they are exposed today to prevent outcropping of the underlying Pfd materials, although the observed relief of Pfd plains is less than a few hundred meters (Ivanov and Head, 1998a,b). This means that the thickness of the Lavinian materials should be comparable to this value and the major component of the combined Lavinian and Sigrunian sequence should therefore be Sigrunian materials. If we assume that Lavinian+Sigrunian materials occur everywhere on Venus except the areas where tessera outcrops, then their total volume is estimated to be $\lesssim 2$ to $10 \times 10^8$ km$^3$, most likely $\approx 4$ to $8 \times 10^8$ km$^3$.

These volume estimates, combined with estimates of the length of time of emplacement of the several time-stratigraphic units, provide a basis on which to estimate average volcanic effusion rates. In order to accomplish this we need to express the time durations not in fractions of the average surface age, $T$, of the planet, but in conventional time units. For this purpose, we assume that $T$ is 500 million years, clearly understandable that it may be a factor of 2 higher or lower (see discussion in section 5 of this paper). On this basis, the average post-Fortunian rate of volcanism is estimated to be about 1–3 km$^3$ y$^{-1}$. The average rate of Atlian volcanism is about $4 \times 10^{-2}$ km$^3$ y$^{-1}$. The average rate of Rusalkian volcanism is about $4$ km$^3$ y$^{-1}$. The average rate of Lavinian+Sigrunian volcanism is estimated to be about 3–6 km$^3$ y$^{-1}$. The average rate of Rusalkian+Lavinian+Sigrunian volcanism is estimated to be 2.5 to 7.5 km$^3$ y$^{-1}$. In relation to pre-Atlian volcanism, these estimates agree well with those made by us previously (Basilevsky et al., 1997; Head et al., 1996) because we use very similar figures for volumes and time. In relation to Atlian volcanism our new estimates are lower than our previous estimates by a factor of 2.5–5 because we now use more accurate estimates of the volumes of Atlian volcanics made by Crumpler et al. (1997). Comparing the estimates obtained with the volcanic rates of modern Earth (Crisp, 1984; Head et al., 1992) one can see that the major pre-Atlian plains-forming volcanism is comparable in its average rate with terrestrial mid-ocean ridge extrusive (not intrusive) volcanism (about $3$ km$^3$ y$^{-1}$) although it was emplaced in an entirely different style. The average rate of Atlian volcanism is significantly lower than that. It seems to be an order of magnitude lower than that of terrestrial intra-plate volcanism (e.g., $\approx 0.5$ km$^3$ y$^{-1}$), more comparable
to average rates typical of the average lunar flux during the period of mare volcanism ($\sim 10^{-2}$ km$^3$ y$^{-1}$) and those presently typical of individual eruptions on Earth (e.g., Kilauea and Etna) (Head and Wilson, 1992). Due to assumptions and uncertainties in estimates of both the unit thicknesses and absolute ages these values of volcanic rates are very preliminary. For example if we adopt a duration of $T$ as 1 G.y. and thickness of post-Fortunian materials as only 1 km, the post-Fortunian rate of volcanism would change from 1–3 km$^3$ y$^{-1}$ to 0.5 km$^3$ y$^{-1}$. Nevertheless we believe that the estimates given above are useful because they provide the possibility for comparisons. Moreover because the procedure of how they are obtained is very straightforward, this will hopefully allow workers to improve their accuracy in future studies.

9. A scenario for the geologic history of Venus

Definition of the sequence of geologic units observed on Magellan images, and interpretation of their mode and time of emplacement, provides the basis for an outline of the interpreted geologic history of Venus (Fig. 22). The morphologically recognizable part of the history comprises only the last 10–20% of the total time of the evolution of Venus. This period of preservation of the record started at an as yet poorly constrained time between about 300 and 1300 m.y. ago, that is, about 1.4 times longer than that time we called $T$.

This beginning was marked by intensive global or almost global tectonic deformation which formed the tessera terrain. Many workers interpret the early stages of that deformation to be largely contractional and later extensional (Bindschadler and Head, 1991; Solomon et al., Ivanov and Head, 1996), but differences of opinion exist about the sequence in different places (Hansen and Willis, 1996), and whether the large presently preserved tessera blocks might represent downwelling (Bindschadler and Head, 1991; Bindschadler and Parmentier, 1990; Bindschadler et al., 1992a,b; Ivanov and Head, 1996) or upwelling (Herrick and Phillips, 1990; Ghent and Hansen, 1997). Termination of the contractional stage is estimated to have occurred about 1.4 T ago, while the extensional stage lasted for another 0.1–0.2 T, partly overlapping with the emplacement of the lower part of the regional plains materials.

A number of hypotheses have been proposed to account for the tessera-forming deformation (see summary in Ivanov and Head, 1996). Among these are gravitational instabilities causing mantle overturn (Head et al., 1994; Parmentier and Hess, 1992), an oscillatory convective regime of the mantle (Arkani-Hamed and Toksoz, 1984; Arkani-Hamed et al., 1993), episodic plate tectonics (Turcotte, 1993), a ‘catastrophic’ convective episode caused by a phase transition in the mantle (Herrick and Parmentier, 1994; Steinbach and Yuen, 1992; Weinstein, 1993), a different convective regime (Phillips and Hansen, 1994; Solomatov and Moresi, 1996), thermal evolution during stagnant lid convection (Reese et al., 1999), or something else. This intensive tectonism was accompanied by volcanic activity (Ivanov and Head, 1996). Thus, emplacement of tessera-forming material and its deformation into tessera terrain are the major geologic events of what we call Fortunian time. We can state this for the areas where the tessera terrain is now observed. For the areas covered by later plains, depending on hypotheses for the cause of tessera-forming deformation, the dominant processes might be both the same or different. For example, if we consider the hypothesis of mantle overturn, the now observed tesserae evidently correspond to areas of downwelling while regions in between them correspond areas of upwelling. The latter should obviously be loci of extension and extensive volcanism (Head et al., 1994).

After tessera formation, several stages of areally extensive volcanism occurred (Fig. 19). On the basis of geochemical measurements at the Venera/Vega landing sites (Barsukov, 1992; Surkov, 1990), and on the morphologies of lava flows and volcanic constructs, this volcanism was evidently mafic in nature. These extrusive volcanic events buried vast areas of tessera and formed what we see now as the regional plains of Sigrunian, Lavinian, and Rusalkian age. The average global rate of volcanism was about a few km$^3$ y$^{-1}$, which is comparable to the present rate of terrestrial mid-ocean ridge extrusive volcanism (e.g., Head et al., 1992, Fig. 16; Basilevsky and Head, 1996b; Head et al., 1996).

Plains-forming materials of the Sigrunian, Lavinian, and Rusalkian Groups are separated from each other, from the underlying Fortunian Group, and from the overlying Atlian and Aurelian Groups, by discontinuities formed by tessera-forming deformation, Pdf-type dense fracturing, Pfr/RB-type broad ridging, and finally wrinkle-ridging (Figs. 19 and 20). These tectonic episodes had to be broadly synchronous in different areas of Venus because otherwise, multiple variations of the observed sequence of stratigraphic units would be observed (Fig. 21), and this is not the case. This also means that in the part of the geologic history of Venus presently exposed, there were episodes characterized by the dominance of contraction, then extension, then again contraction, and finally extension (Head and Basilevsky, 1998a) (Fig. 22).

It is not clear if there were distinct Sigrunian, then Lavinian, then Rusalkian volcanic pulses, separated by tectonic episodes. Alternatively, on the global scale,
the emplacement of the Sigrunian, Lavinian and Rusalkian plains-forming materials may have been more or less continuous, but global-wide tectonic episodes characterized by changing style separated the volcanic accumulation into portions of morphologically distinct materials: e.g., densely-fractured, broadly-ridged, or wrinkle-ridged. These tectonically imprinted morphologic signatures, together with independent unit characteristics and primary formational signatures (such as the dominance of small volcanic shields in unit Psh, or lobate flow-like features in unit Pl), were the basis for the initial identification of the proposed stratigraphic units. The presence of tectonically determined discontinuities among the majority of the proposed units is similar to the types that are commonly observed in stratigraphic analyses in terrestrial geology. Of course, this distinction was possible on Venus not only because of the visible change in the style of tectonic deformation with time, but also because of the significant decrease of intensity of tectonic deformation with time, so that in most cases the later deformation did not overwrite the earlier stratigraphic record and structural imprints.

The last distributed global-scale tectonic episode, the formation of an extensive network of wrinkle-ridges, happened at about 0.1 T ago, which was very close in time to the emplacement of the Late-Rusalkian plains. This episode marked the transition to the present stage of the history of Venus, which is characterized by a predominance of regional rifting and localized rift-associated volcanism in the form of shield volcanic constructions and lobate volcanic plains-forming units. In some cases we may suspect that this transition started before the emplacement of the wrinkle ridge network. For example, lobate flows of Sif and Gula volcanoes cover the surrounding plains with wrinkle ridges. But the latter are concentrically aligned around this twin volcano construct implying that at the moment of the ridge emplacement some rise was already there (Basilevsky, 1994). The majority of this latest stage is represented by the Atlian Period, which appears to have lasted from about 0.1 T to 0.0 T before the present. This makes this period the longest time duration among the stratigraphic units considered, although the resulting tectonic and volcanic features and deposits cover only 10–20% of the surface of Venus. This observation means that the general intensity of tectonics and the flux of volcanism in the Atlian period were much lower than those in pre-Atlian time. According to the estimates derived previously, the average rate of this latest volcanism was a few hundredths of a km$^3$ y$^{-1}$, which is less than the average present rate of intraplate volcanism on Earth (Crisp, 1984; Head et al., 1992).

The upper part of this most recent stage of the history of Venus (Fig. 19) is the Aurelian Period, which started about 0.1 T ago and continues up until the present. Its defining characteristics, a preservation of crater-associated radar-dark parabolas, simply reflects a certain level of reworking of the surface by eolian processes (Greeley et al., 1992). In reference to tectonic and volcanic processes, the Aurelian Period is apparently just a continuation of the Atlian Period. The documented cases of rifting and volcanism postdating the dark parabolas (Basilevsky, 1993) show that Venus may be endogenically active, at the low level characteristic of the Atlian Period, even today.

10. Conclusions

The above considerations demonstrate that the morphologically observable part of the geologic history of Venus (Figs. 19, 20 and 22) was characterized by several key characteristics that stand in contrast to the comparable period of geologic history of Earth. Depending on the magnitude of the true value of the mean surface age of Venus ($T$), the corresponding part of the geologic history of Earth may comprise the post-Paleozoic, the Phanerozoic, or even extend into the late Proterozoic. In any of these cases, during that time period observed, the global geodynamic processes of Earth were certainly dominated by plate tectonics, characterized by its general global balance of extension (at divergent plate boundaries) and compression (at convergent plate boundaries), and a variable, but relatively narrow range of rates of plate movement. In the comparable time period, Venus shows no certain signature of plate tectonics, particularly in post-tessera time, and the density of deformational structures and probably the strain rate (Grimm, 1994) were definitely declining with time. In the observed part of the geologic history of Venus, its global tectonic environment passed from an initial dominance of contraction, through extension, then again contraction, and finally extension thus showing a directional style of evolution of Venus, in contrast to a non-directional style (e.g., Guest and Stofan, 1999).

During the observed time period the predominant component of volcanism on Earth was extrusive volcanism at mid-oceanic ridges, characterized by a somewhat variable, but generally stable production rate on a global scale. Subduction zone volcanism and intraplate volcanism played a subordinate role. For some short periods of time the formation of large igneous provinces dominated intraplate volcanism and the global production rate (Coffin and Eldholm, 1994; Head and Coffin, 1997; Larson, 1991). In the beginning of that same period of time, Venus was characterized by the emplacement of plains-forming volcanism at an average rate comparable to terrestrial extrusive volcanism at mid-ocean ridges, although the eruption style
on Venus was very different from that at mid-ocean ridges on Earth. As on the Moon (Head and Wilson, 1992) individual eruptive episodes may have exceeded the average rate by many orders of magnitude (e.g., the emplacement of Baltis Vallis and its deposits; Baker et al., 1997). For the last few hundred million years, Venus has been dominated primarily by rift-associated volcanism emplaced at a production rate even lower than that of present intra-plate volcanism on Earth.

This shows that within the part of the geological history of Venus considered here, geological processes operated largely in a directional fashion. In the sense of tectonics, it was a directional change from intensive tessera-forming tectonics to less intensive but still essentially global-scale Pdf, Pfr/Rb and FB structures and then to still global wrinkle ridge contractional deformation, and then to locally to regionally intensive rifting on the background of the tectonically quiescent majority of the planet. In the sense of volcanism, it was a directional change from a rather high-rate (although in a net sense not essentially higher than the recent mid-ocean ridge basaltic volcanism of Earth) plains-forming floods forming units of global lateral extent to more localized floods and formation of large volcanoes with a significantly lower net rate. It is necessary to emphasize that on the background of this large-scale directionalism there are smaller-scale fluctuations which locally may give the impression of a non-directional fashion of operation of geologic processes (e.g., Guest and Stofan, 1999). For example, the Magellan images show not only young post-Pwr rift zones (our unit RT) but some pre-Pwr rifts too (our unit FB, sometimes part of Pdf). But it is evident from the descriptons above that only since some relatively recent stage of the visible part of the geologic history of Venus has rifting become essentially the only manifestation of tectonism on this planet. Another example is a formation of wrinkle ridges which can be observed sometimes as occuring in a few episodes separated by emplacement of plains-forming material. But again, as we show above, this suite of wrinkle-ridged plains occupies a very definite place in the stratigraphic column clearly postdating Ti, Pdf and Pfr units and pre-dating formation of lobate flows on the slopes of most large rift-associated volcanoes. A final example is the distribution of small volcanic shields. Examples of small shields can be found individually throughout the stratigraphic column, but nonetheless, there is a stratigraphic interval (pre-Pwr) in which these small shields dominate the volcanic plains. Thus, although these types of variations are observed, they do not violate the general stratigraphic definitions and correlations we show here.

This interpreted geologic history of Venus, reconstructed on the basis of the stratigraphic record revealed from mapping at least one-half the surface of the planet, shows the sequence of important events that must be explained by models of the geodynamic evolution and thermal history. The interpreted pulses of global-scale contraction and extension seem unusual if we rely completely on the analogies with Earth geology driven by the generally global net balance characterized by plate-tectonics. However, geological observations and geophysical modelling show that stages of global-scale extensional and contractional tectonism did exist in the geologic history and thermal evolution of the Moon, Mercury, and Mars (Head and Solomon, 1981). In the case of Venus, the global-scale tectonic phases might be responses to the general thermal evolution, specific internal events (such as mantle overturn), or responses to catastrophic changes in the surface temperature of this planet (Bullock and Grinspoon, 1998; Phillips and Bullock, 1999; Solomon et al., 1998). The stratigraphic record also illustrates the distinctive difference between the recent history of Venus and that of the Earth, and will hopefully serve as a basis for the further investigation of the reasons for the differences between two planets that are so similar in other ways.

Acknowledgements

We greatly acknowledge the fruitful exchange of opinions with B. Campbell, G. Collins, M. Gilmore, V. L. Hansen, M. A. Ivanov, V. P. Kryuchkov, G. McGill, and A. A. Pronin. Figures were prepared by Anne C. Cote and photographic work was done by Peter Neivert. This work was supported in part by grants from the NASA Planetary Geology and Geophysics Program to JWH; this support is gratefully acknowledged.

References


Wilhelms, D., 1997. Geologic Map of the Osiris (Jg-12) and Apsu Sulci (Jg-13) quadrangles of Ganymede 1:5,000,000. USGS Miscellaneous Investigation Series Map I-2442.