Regional and global stratigraphy of Venus: a preliminary assessment and implications for the geological history of Venus

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Received 2 December 1994; revised 3 April 1995; accepted 3 April 1995

Abstract. Photogeologic analysis of Magellan images for 36 widespread sites and several larger areas permits the definition and characterization of a sequence of mappable stratigraphic units and tectonic structures deforming them. Seven rock-stratigraphic units, three related time-stratigraphic units (Systems), and three geologic time subdivisions (Periods) are proposed to describe the vast majority of the areas under study. The first widespread geologic unit preserved on Venus is the highly deformed tessera terrain formed during the Fortunian Period, apparently the result of an event that destroyed the morphology of preexisting terrain and any superposed craters. Global image data reveal no evidence for extensive terrain dating from the pre-Fortunian time, comprising the first 80-90% of the history of Venus, although rocks dating from this period are almost certainly contained within the tessera. Immediately following the Fortunian an extensive period of plains volcanism began, the Guineverian Period, during which the majority of Venus was volcanically resurfaced. During the Guineverian early widespread plains of the Sigrun Group were deformed by extensive and closely-spaced graben systems. Continued widespread plains emplacement occurred and units of the Lavinia Group were deformed, some into extensive ridge belts, recording a change from distributed extensional deformation to often-focused compressional deformation. Plains of the Rusalka Group are the most widespread currently exposed, and are characterized by extensive development of wrinkle ridges of compressional origin. These Guineverian Period plains must have been emplaced and deformed over a relatively short period of time (probably less than about a hundred million years) because the vast majority of impact craters are superposed on the plains, and the crater retention age of this surface is of the order of 300-500 Ma. This extensive plains volcanism then gave way to materials of the Atia Group, local volcanic edifices and flow units with sources associated with coronae and rifts that were emplaced in the late Guineverian and Aurelian Periods. The Aurelian Period, defined by impact craters with dark parabolae, is interpreted to extend from the present back to about 30-50 Ma ago. During this period extensive rifting occurred in several areas of Venus and volcanism has continued at a reduced level relative to the earlier parts of the Guineverian period. Our observations favor a model in which the observed part of the geologic history of Venus (which is the last 20% or less) started with catastrophic tectonic deformation and volcanic resurfacing, followed by the period of declining surface activity of endogenic origin which lasts until now. The lack of surface units representing the first 80-90% of the history of Venus is remarkable from the standpoint of its present low level of activity. This contrast, together with the emerging geologic history of the last 10% of the lifetime of Venus, suggest that catastrophic and/or episodic global processes may have characterized Venus in its earlier history. This factor may also provide an insight into earliest Earth history.

Introduction

The global high-resolution image data set recently acquired by the Magellan mission (Saunders et al., 1992) and complemented by previous Venera orbiter and lander, Pioneer Venus, Earth-based, and related Magellan data, has provided unprecedented global coverage for an Earth-sized planet at an average resolution better than that presently available for the Earth's solid surface. These data provide a basis for establishing the characteristics of the major geologic units and structures, for assessing their
stratigraphic relations, and for interpreting the geologic history of the planet. Such an endeavor will require many years of intensive mapping and analysis of the data before a detailed picture emerges. Here we report on an initial analysis of widely distributed areas on the planet and a preliminary assessment of regional stratigraphic units and implications for the geologic history of Venus. Using the **Magellan C1- and F-MIDRP** mosaics both in hard copy and in digital format (and related altimetry and physical property data) we first studied stratigraphic relations in thirty-six 1000 x 1000 km areas randomly spaced on Venus (Basilevsky and Head, 1993, 1994a,b, 1995). This study was followed by photogeologic analysis of several larger regions including western Ishtar Terra, northern Beta Regio, Bell Regio, Lavinia Planitia, Hildr channel, and the Venera and Vega landing sites region (Fig. 1).

The stratigraphic relations among the terrains, features and structures were determined using the traditional principle of superposition as was successfully done by the U.S. Geological Survey in the case of the Moon and Mars (e.g., Wilhelms, 1972, 1990; Scott and Tanaka, 1986). In our earlier studies we identified 16 terrain units and structures with which we could describe the major characteristics of the geology and stratigraphic relations in any of the widespread areas of our studies (Fig. 2; Table 1). Those 16 terrain units and structure represent a natural mixture of material units and deformation episodes. Following confirmation of their validity and utility in our analyses of the previously mentioned larger areas (western Ishtar Terra, etc.), we split them into two different categories: (1) mappable stratigraphic material units and (2) tectonic structures which also are a part of the age sequence (Basi-

**Table 1. Location of the typical examples of the 16 major types of units and structures (S) (see Fig. 2) encountered in mapping the 36 areas**

<table>
<thead>
<tr>
<th>N</th>
<th>Unit</th>
<th>Symbol</th>
<th>Site number</th>
<th>Area size (km)</th>
<th>Coordinates of the center</th>
<th>Image source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tessera</td>
<td>Tt</td>
<td>8</td>
<td>50 x 50</td>
<td>9.3°S, 62.5°</td>
<td>F-MIDRP.10S065.1</td>
</tr>
<tr>
<td>2</td>
<td>Densely fractured terrain of coronae</td>
<td>Codf</td>
<td>30</td>
<td>50 x 50</td>
<td>68.2°N, 295.4°</td>
<td>F-MIDRP.70N296.1</td>
</tr>
<tr>
<td>3</td>
<td>Densely fractured terrain of the plains</td>
<td>Pdr</td>
<td>1</td>
<td>50 x 50</td>
<td>19.2°N, 3.6°</td>
<td>F-MIDRP.20N003.1</td>
</tr>
<tr>
<td>4</td>
<td>Fractured and ridged plains</td>
<td>Pfr</td>
<td>21</td>
<td>50 x 50</td>
<td>40.7°N, 192.9°</td>
<td>F-MIDRP.40N194.1</td>
</tr>
<tr>
<td>5</td>
<td>Ridge belts</td>
<td>KB</td>
<td>2</td>
<td>50 x 50</td>
<td>39.9°S, 18.7°</td>
<td>F-MIDRP.45S011.1</td>
</tr>
<tr>
<td>6</td>
<td>Plains with wrinkle ridges</td>
<td>Pwr</td>
<td>22</td>
<td>50 x 50</td>
<td>38.8°N, 196.9°</td>
<td>F-MIDRP.40N194.1</td>
</tr>
<tr>
<td>7</td>
<td>Ridges of corona annulus (S)</td>
<td>COr</td>
<td>79</td>
<td>50 x 50</td>
<td>56.1°N, 795.9°</td>
<td>F-MIDRP.55N291.1</td>
</tr>
<tr>
<td>8</td>
<td>Ridges of arachnoid annulus (S)</td>
<td>Aar</td>
<td>3</td>
<td>50 x 50</td>
<td>45.2°N, 19.2°</td>
<td>F-MIDRP.45N019.1</td>
</tr>
<tr>
<td>9</td>
<td>Smooth plains</td>
<td>Ps</td>
<td>2</td>
<td>50 x 50</td>
<td>52.1°S, 14.9°</td>
<td>F-MIDRP.50S013.1</td>
</tr>
<tr>
<td>10</td>
<td>Lobate plains</td>
<td>Pl</td>
<td>36</td>
<td>50 x 50</td>
<td>18.3°N, 34.8°</td>
<td>F-MIDRP.20N351.1</td>
</tr>
<tr>
<td>11</td>
<td>Fractures of corona annulus (S)</td>
<td>Coaf</td>
<td>19</td>
<td>50 x 50</td>
<td>25.1°S, 174.0°</td>
<td>F-MIDRP.25S174.1</td>
</tr>
<tr>
<td>12</td>
<td>Fractures (S)</td>
<td>F</td>
<td>2</td>
<td>50 x 50</td>
<td>18.2°N, 1.6°</td>
<td>F-MIDRP.20N003.1</td>
</tr>
<tr>
<td>13</td>
<td>Rift-associated fractures (S)</td>
<td>Fra</td>
<td>1</td>
<td>50 x 50</td>
<td>50.3°S, 17.5°</td>
<td>F-MIDRP.50S013.1</td>
</tr>
<tr>
<td>14</td>
<td>Craters with dark paraboloids</td>
<td>Cdp</td>
<td>6</td>
<td>50 x 50</td>
<td>15.0°S, 46.5°</td>
<td>C2-MIDRP.30S026.201</td>
</tr>
<tr>
<td>15</td>
<td>Surficial streaks</td>
<td>Ss</td>
<td>29</td>
<td>50 x 50</td>
<td>59.0°N, 279.3</td>
<td>F-MIDRP.60N281.1</td>
</tr>
<tr>
<td>16</td>
<td>Surficial patches</td>
<td>Sp</td>
<td>29</td>
<td>50 x 50</td>
<td>57.8°N, 270.0</td>
<td>F-MIDRP.60N270.1</td>
</tr>
</tbody>
</table>
levsky and Head, 1994a, 1995). Here we present a preliminary definition and classification of these materials, following the U.S. Geological Survey’s *Venus Geologic Mappers’ Handbook* (Tanaka, 1992). In developing the basic stratigraphic sequence and hierarchy, we followed the guidelines used on Earth (outlined in the code of stratigraphic nomenclature; ACSN, 1961) and other planets mapped geologically (see, e.g. Wilhelms, 1972, 1990; Scott and Tanaka, 1986), defining first rock-stratigraphic units, then time-stratigraphic units, and then geological time subdivisions. This is analogous to the periods of time on Earth in which geological exploration was concentrated in newly explored areas, such as the western United States and Central Asia during the nineteenth century, and broad stratigraphic classifications were proposed. Further detailed studies, especially made through the NASA-sponsored Venus Mapping Program, are necessary to verify, subdivide, and more formally define the broad units into formations (Fig. 3). What we propose is a first step in this direction and will be further tested and modified during the Venus Mapping Program.

### Stratigraphic units

In defining stratigraphic units we followed the U.S. Geological Survey’s *Venus Geologic Mappers’ Handbook* according to which “Map units will be defined on the basis of various morphologic, textural, and structural characteristics observable in Magellan images” (Tanaka, 1992). In developing the basic stratigraphic sequence and hierarchy, we followed the guidelines used on Earth (outlined in the code of stratigraphic nomenclature; ACSN, 1961) and other planets mapped geologically (see, e.g. Wilhelms, 1972, 1990; Scott and Tanaka, 1986), defining first rock-stratigraphic units, then time-stratigraphic units, and then geological time subdivisions. This is analogous to the periods of time on Earth in which geological exploration was concentrated in newly explored areas, such as the western United States and Central Asia during the nineteenth century, and broad stratigraphic classifications were proposed. Further detailed studies, especially made through the NASA-sponsored Venus Mapping Program, are necessary to verify, subdivide, and more formally define the broad units into formations (Fig. 3). What we propose is a first step in this direction and will be further tested and modified during the Venus Mapping Program.

There is a consensus among those who study Venus geology that there are two major types of terrains on this planet: (1) highly tectonized tessera terrain (Barsukov et al., 1986; Sukhanov et al., 1989; Bindschadler et al., 1992b; Ivanov and Head, 1995), and (2) various plains which embay and overlie tessera (Guest et al., 1992; Basilevsky and Head, 1994a, 1995). On the basis of the relations observed on Venus we suggest that it is appropriate to subdivide the majority of the surface units seen in Magellan images into two major groupings. The first includes materials of all varieties of tessera terrain (see Barsukov et al., 1986; Sukhanov et al., 1989; Bindschadler et al., 1992b; Ivanov and Head, 1995), and (2) various plains which embay and overlie tessera (Guest et al., 1992; Basilevsky and Head, 1994a, 1995). On the basis of the relations observed on Venus we suggest that it is appropriate to subdivide the majority of the surface units seen in Magellan images into two major groupings. The first includes materials of all varieties of tessera terrain (see Barsukov et al., 1986; Sukhanov et al., 1989; Bindschadler and Head, 1991; Bindschadler et al., 1992b) and is stratigraphically older than the second grouping, which includes all the plains-forming materials. Following the tradition to give stratigraphic names of geographic areas where their typical representatives (stratotypes) occur (ACSN, 1961) we suggest that the first group be named for Fortuna Tessera which is a large tessera massif containing several different varieties of this terrain (Fig. 4). This is also the area where this type of terrain was identified for the first time in the *Venera* 15/16 images (Barsukov et al., 1986). The second grouping consists in
turn of two major subdivisions: (1) a sequence of plains-forming materials with varieties of morphologies composing the Guinevere Supergroup, and (2) overlying radar-dark parabola-shaped mantles associated with some impact craters, and isolated streaks and patches, composing the Aurelia Group. The Guinevere Supergroup is named from Guinevere Planitia which is the largest plain on Venus and contains representatives of all the plains units described below. The Aurelia Group is named after the crater Aurelia, which is a typical representative of craters having associated dark paraboloids. Subdivision of the Fortuna Group into units of lower hierarchy is mostly a task for future studies, although many subdivisions have been suggested (Sukhanov et al., 1989; Bindschadler and Head, 1991; Bindschadler et al., 1992b). It is suggested that the Guinevere Supergroup (Fig. 3) be subdivided into several groups, each of them in turn consisting of the materials of one or more of the units described by Basilevsky and Head (1994a, 1995). These subdivided units too will be more well-defined, and formally proposed where appropriate, in the course of detailed geologic mapping of the planet. The following is a description of the proposed preliminary stratigraphic sequence.

Fortuna Group

Units of this group include tessera terrain (Tt) and its several subdivisions, which together form large and small islands among the venusian plains (Fig. 5). It covers about 8% of the surface of Venus (Ivanov and Head, 1993, 1995). This material is heavily modified by multiple and variously oriented deformation patterns which determine the well-known rough morphology of tesserae. It is formally defined as "sets of ridges and grooves, commonly intersecting each other" (Basilevsky et al., 1986). Following the precedent of Barsukov et al. (1986), we continue to use the term "tessera" as a convenient informal designation for the surface morphological texture of this unit. Fortuna Group material is also at least somewhere deformed by practically all subsequent episodes of tectonic deformation and is emplaced or overlain by all other stratigraphic units. Tesserae typically have about 5-10\(^\circ\) surface RMS slopes indicating a high meter-scale surface roughness (GSDRP, 1993) that agrees well with the highly tectonized nature of tessera materials in the images. Fresnel reflectance and microwave emissivity values for tesserae, as for other terrains, are mostly a complex function not only of the material intrinsic physical properties but surface roughness, and even altitude (Pettengill et al., 1992; Tyler et al., 1992; Klose et al., 1992). This decreases their value in unit definition but is useful in unit characterization (e.g. Head et al., 1978).

The materials of the mountain belts surrounding Lakshmi Planum (Danu, Akna, Freyja, and Maxwell) geographically merge through gradual change of their patterns into adjacent tesserae (Fig. 6). The surface RMS slopes for the mountain belts and tesserae are practically the same. Moreover, a large circum-Lakshmi structure made of Akna, Freyja, Maxwell and Danu Montes is only an inner part of the even larger concentric structure of Western Ishtar including tesserae Atropos, Itzpapalotl, Western Fortuna and Clotho. This structural alignment implies at least partial contemporaneity of the tessera-forming deformation and the mountain range formation. This, in turn, puts the mountain range materials in the lowest part of the global stratigraphic sequence where the tessera material sits. On the basis of these observations, these mountain belts appear to be a subunit or tectonic facies of the Fortuna Group. We propose that this unit be designated the Maxwell Formation because its prominent representative is well displayed in Maxwell Montes. The Maxwell Formation includes the materials of the belts of subparallel ridges of Akna, Freyja, and Danu Montes, and it is defined as a material composing systems of parallel and subparallel, often arcuate, ridges and grooves occupying a linear belt of high topography usually rising in excess of 1 km above the surrounding terrain (Table 2).

The Maxwell Formation was involved in some of the deformation occurring during the time of emplacement and deformation of the Guinevere Supergroup. For example, some 250-300 km west and northwest of crater Cleopatra the ridged material of Maxwell Montes is upthrust and sinistrally shifted (Fig. 7a). To the south this complex deformation merges into the ridge belt deforming the plains of eastern Lakshmi Planum and northern Sedna Planitia. The northern continuation of this deformation merges into the Semi Dorsa ridge belt which deforms Sengurochka Planitia plains and the adjacent areas of Fortuna Tessera. This deformation of Maxwell Montes is topographically and structurally distinct from the parallel linear patterns of ridges and troughs making up the basic fabric of the mountain range and strikes at high angles to it (Fig. 7b). Thus, the relations of this distinctive fault feature provide further evidence that much of the deformation of Maxwell Montes predates the major period of plains formation and deformation.

The compositional nature of the material making up the Fortuna Group is unknown. The topographically high position of tesserae and the mountain belts compared to the lower basaltic plains may be due to a lower bulk density of the materials of the units or may be an effect of thickening of the crust of the same density or both, as is the case for terrestrial continents (see discussions on this theme in Basilevsky (1990) and Head (1990). So one may hypothesize that tessera material is compositionally different from basalts and enriched in feldspars (Nikolaeva et al., 1988, 1992) or that it is mostly basaltic too, being formed of older pre-tessera basaltic plains units. None of the Venus/Vega landers made surface geochemical measurements on Fortuna Group materials (Surkov, 1983; Surkov et al., 1984, 1986). Some of the measurements made on the plains, however, showed the presence of materials which may be more geochemically evolved than basalts (Vinogradov et al., 1973; Surkov, 1983; Nikolaeva, 1990, Basilevsky et al., 1992). Magellan radar observations discovered steep-sided volcanic domes which may be formed by eruption of viscous lavas that are considered as a possible indication of a nonbasaltic composition (Pavr et al., 1992; McKenzie et al., 1992; Basilevsky et al., 1992; Weitz and Basilevsky, 1993). These
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Fig. 2. Examples of the 16 different terrain units and structures distinguished by Basilevsky and Head (1994a, 1995). The width of each example is 50 km, with the exception of Cdp (number 14), which is 1000 km. (1) Tessera (unit Tt), (2) densely fractured terrains associated with coronae (unit COdf), and (3) densely fractured terrains in the form of remnants among plains and not associated with coronae (unit Pdf); (4) fractured and ridged plains (unit Pfr); (5) ridge belts (RB structure); (6) plains with wrinkle ridges (unit Pwr); (7) ridges associated with coronae annulæ (COar structure); (8) ridges of arachnoid annulæ (Aar structure); (9) smooth plains (unit Ps); (10) lobate plains (unit Pl); (11) fractures of coronae annulæ (COaf structure); (12) fractures (F structure); (13) rift-associated fractures (Fra structure); (14) craters with associated dark paraboloids (unit Cdp); (15) surficial streaks (unit Ss); (16) surficial patches (unit Sp). The locations of each of these typical areas are listed in Table 1.
Fig. 4. Part of Fortuna Tessera east of Maxwell Montes imaged by Venera 15/16 (fragment of B-5 Photomap; *Atlas of Venus Surface*, 1989). Area is 600 × 1000 km. This area was a stratotype for the identification of the "parquet" terrain (Barsukov et al., 1986) later renamed as "tessera". Other varieties of tessera terrain with structural patterns different from this one are common in many areas of Venus (Sukhanov et al., 1989; Sukhanov, 1992).

Fig. 5. Island of tessera in Rusalka Planitia north of Diana Chasma. Area is 160 × 230 km. Tessera terrain is embayed by plains with wrinkle ridges, a situation very typical for the surface of Venus. Fragment of P-MIDRP.05S155;1
Fig. 6. Eastern part of Maxwell Montes and the adjacent part of Fortuna Tessera. Area is 500 × 750 km. N–S trending subparallel ridges of Maxwell Montes merge eastward gradually into the diagonal pattern of this part of Fortuna Tessera. The surface of Maxwell is covered by the high-reflectivity low-emissivity material which is considered to be an altitude-dependent weathering effect (Pettengill et al., 1992; Klose et al., 1992). The surface of Fortuna Tessera, which is lower in elevation, lacks this anomalous high reflectivity and low emissivity. Fragment of C1-MIDRP.60N014:1.

Fig. 7. (a) Stereo pair of images (Plaut, 1993) of Maxwell Montes and the adjacent areas of Lakshmi Planum and Sedna Planitia. Imaged area is 600 × 850 km. An upthrust with sinistral shift is seen in the Maxwell massif 250–300 km west and northwest of the crater Cleopatra. It merges to the south into the low-relief ridge belt deforming the plains of Lakshmi and Sedna. Fragments of F-MIDRPs 60N014:1 (right) and 60N014:301 (left). (b) Simplified geologic map of Maxwell Montes and adjacent areas showing the continuation of the thrust fault (teeth on overthrust side) with sinistral shift mentioned above, into ridge belts deforming plains of Lakshmi and Sedna to the south, and SNEGurochka and the adjacent part of Fortuna Tessera to the north. Thrusting and strike slip faulting in this area were previously described by a number of authors (sec, e.g. Pronin, 1986, 1992; Vorder Bruegge et al., 1990; Amsan et al., 1994). The identification and stratigraphic significance of the indicated thrust fault, however, have become evidence only with the availability of Magellan radar stereo imaging.
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Rusalka and Lavinia Groups

undivided Slgrun Group

Fortuna Group

Maxwell Formation

Ridge

Wrinkle ridges

Upthrust fault

Faults

Scarp of Lakshmi Plateau

Crater
Fig. 8. Southwestern part of Sigrun Fossae, a belt of densely fractured terrain representing the stratotype of the Sigrun Group. (a) *Magellan* image. (b) Sketch map. Area is 750 × 1050 km. It shows a belt of the terrain with subparallel tectonic pattern (Pdf) extending from lower left to upper right in the middle of the image. Locally the pattern changes into a concentric one (COdf) thus forming corona-like features. About 300 km SE of Sigrun Fossae (the lower right portion of photo) is a part of Ausra Dorsa, a ridge belt representing the stratigraphically overlying Lavinia Group. Fragment of C1-MIDRP:45N011:1
Fig. 9. Pair of stereo images of densely fractured terrain (Pdf) of Northern Sedna and adjacent part of Clotho Tessera. Area is 225 × 350 km. Pdf embays tessera and in turn is locally flooded here by smooth plains (Ps) and plains with wrinkle ridges (Pwr). Swarms of mostly WNW-trending fractures enter from Pdf into tessera. Fragments of F-MIDRPs 55N337;1 (right) and 55N337.201 (left).
Fig. 10. Ridge belts of Lavinia Planitia, a stratotype of the Lavinia Group. (a) Magellan image. (b) Sketch map. Area is 450 × 650 km. Ridge belts of the imaged area are mostly N–S trending. They are formed of a system of rather wide (3–6 km) ridges a few tens km long arranged en echelon. The ridges deform mostly smooth locally fractured plains of intermediate radar brightness. Here these topographically elevated belts of widely ridged plains are classified as Ridge Belts (RB). In other areas of Venus where the spacing of the ridges is significantly wider this material is classified as Fractured and ridged plains (Pfr). The ridge belts here are embayed by darker plains with wrinkle ridges (Pwr) which, in turn, are cut by long and narrow NW-trending fractures. In the lower right of the image is seen an area of densely fractured terrain (Pfd) which is partly deformed by the previously noted wide ridges and embayed by Pwr. Both Pfr and RB are locally crossed by anastomosing mostly NW-trending fractures which do not extend into Pwr and evidently predate it. These anastomosing fractures are similar to younger rift-associated fractures and may be evidence for older rifting. Fragment of C1-MIDRP.45S350.1
Fig. 11. Stereo image pair of Vedma Dorsa ridge belt in Vellamo Planitia. Area is 400 × 500 km. Plains of intermediate radar brightness are deformed by rather broad en echelon ridges thus forming Ridge belts (RB) which rise above and are embayed by darker plains with wrinkle ridges (Pwr). Fragments of F-MIDRPs 40N159;1 (left) and 40N159;301 (right).

Fig. 12. Plains with wrinkle ridges (Pwr) in Rusalka Planitia, a stratotype of Rusalka Group. Area is 500 × 500 km. Rusalka Planitia is a region were Vega 1 and 2 landers made geochemical measurements and found a tholeiitic composition of the surface material (Surkov et al., 1986). Nominal landing point of the Vega 1 spacecraft is in the lower left of the image. Ridge belts (RB) are seen in the upper and lower right of the image. Fragment of F-MIDRP.10N177;1
Fig. 13. Double-ringed crater Barrymore (52.3 S, 195.6 E; D = 50 km), superposed on plains about 900 km SW of Imdr Regio. Wrinkle ridges deform both the plains and the crater. The extreme rarity of impact craters deformed by wrinkle ridges implies that the time period between the emplacement of plains and formation of ridges was very short. The faint morphology of Barrymore ejecta is consistent with its old age. Mosaics of fragments of C1-MIDRPs 45S202:1 and 60S208:1: made by USGS Flagstaff, courtesy of G. G. Schaber.

Fig. 14. The 38 km diameter crater Caccini (17.4 N, 170.4 E) superposed on Rusalka Planitia plains with wrinkle ridges. Area is 135 x 190 km. Outflow emplacement NW of the crater rim was partly controlled by the wrinkle ridges. Crater floor looks smooth with no wrinkle ridges on it. Fragment of C1-MIDRP.15N163:1.
Fig. 15. Lobate plains (Pl) of the Atla area, a stratotype of the Atla Group. (a) *Magellan* image. (b) Sketch map. Area is 500 x 600 km. Lava flows from rift-associated Ozza Mons (upper right) and Maat Mons volcanoes (lower part of the image) overlay plains with wrinkle ridges of the Rusalka Group. South of this area Maat Mons lavas flood the rift-associated fractures which cross dark-paraboloid crater Uvaysi so they belong to the youngest part of Atla Group volcanics which were thus formed during Aurelian Period time (see also Robinson and Wood, 1993). The 23 km crater Melba in the image center looks superposed on the plains with wrinkle ridges. Its radar-bright outflows are partly controlled by wrinkle ridges. F-MIDRP.05N194;1
Fig. 16. Lobate lava flows (Pl), part of the Atla Group materials, in association with corona-like feature about 1000 km west of the crater Boleyn, site 25 of Basilevsky and Head (1994a, 1995). (a) Magellan image. (b) Sketch map. Area is 400 x 600 km. Corona-like feature is mostly made of remnants of densely fractured terrain (COdf). Rusalka Group plains with wrinkle ridges (Pwr) are seen in the lower left corner of the image. Fragment of C1-MIDR 30N207;1
Fig. 17. (a) Crater Aurelia (20.27°N, 331.80°E, D = 31 km) and (b) the associated dark paraboloid, a stratotype of the Aurelia Group. Areas are (a) 150 x 150 km, and (b) 900 x 1200 km. The crater Aurelia is central-peaked and is characterized by butterfly-type asymmetric ejecta, implying oblique impact from NW to SE, and SE extending outflows, whose emplacement is partially controlled by the wrinkle ridges. Dark paraboloid associated with Aurelia looks well preserved in its front part and disturbed in the rear part probably by the oblique impact from S to N which formed 65 km crater Seymour (Schultz, 1992). Fragments of F-MIDRP.20N334 and C2-MIDRP.30N355;2
Fig. 19. Rift-associated fractures (Rfa) on top of the Beta Regio rise. (a) Magellan image. (b) Sketch map. Area is 180 km × 270 km. The image illustrates the typical characteristics of rift-associated fractures; they are anastomosing with very variable fracture widths and fracture to fracture spacing. At the center of the image is the 37 km diameter crater Somerville split by Rfa and stretched in an E-W direction. By restoring the circularity of the crater this part of the rift is estimated to have as much as 20-30% extension. Fragment of F MIDRP.30N281;1
Fig. 20. A cluster of fractures (F) crossing plains with wrinkle ridges (right) 400 km east of a 150 km diameter volcano which seems to be the source of the 6800 km long Hildr (recently renamed Baltis) channel (left) (Baker et al., 1992). (a) Magellan image. (b) Sketch map. Area is 500 km x 600 km. Fracturing is related to a local activity center (45°N, 191°E) and is associated with radar-bright lava flows. Fractures may be related to subsurface dike emplacement around a magmatic center (e.g. Grosfils and Head, 1994). The volcano to the west is deformed by wrinkle ridges and shows no evidence of post-ridging volcanic activity. Long N-S flow-like fracture in the upper left merges northward into the beginning of Hildr channel (see Fig. 23). F-MIDRP.45N1881
Fig. 21. Demeter Corona (55.0° N, 295.0° E; 330 × 670 km). (a) Magellan image. (b) Sketch map. Area is 550 × 800 km. The eastern segment of the annulus of Demeter and part of its core are made of densely fractured terrain (COdf) which is embayed by plains. The northern and southern segments of the annulus are made of arcuate ridges (COar) deforming the plains which are part of the plains with wrinkle ridges (Pwr). The wrinkle ridges of the regional network near the coronae are in alignment with the ridges of the corona annulus. Several radar bright lobate lava flows (PI) are seen in association with this corona. Fragment of C1-MIDRP 60N291.
Fig. 22. Hildr channel (recently renamed Baltis Vallis). Images centered at (a) 48°N162 E, and (b) 49°N184 E. Areas are 150 × 150 km each. The channel is incised in the plains of intermediate radar brightness which are postdated by a brighter flow-like plains unit. This brighter material fills in segments of Hildr (see center of photo (a) and upper left of (b)). Both plains units of this area are deformed by wrinkle ridges which cross the channel and deform the channel floor. Fragments of F-MIDRPs 50N163;1 (a), and 50N180;1 (b)
geochemical and morphological observations, indicating the possible presence of nonbasaltic material on Venus, favor the idea of nonbasaltic composition of at least part of Fortuna Group materials but, of course, only direct geochemical measurements may resolve this problem.

One can also expect a compositional diversity of Fortuna Group materials on the basis of other evidence. For example, within the Maxwell Montes massif there are patches and bands of radar-brighter and -darker materials involved in upthrusting and sinistral shift, as previously mentioned. Stereo images of this area (Fig. 7a) show clearly that this difference in surface brightness is not a simple altitude effect, so the possibility of inherent compositional differences (lower iron content in areas with radar dark regions?) seems plausible.

The crater retention age of tessera terrain seems to be higher than the crater retention age of the total Venus surface (1.01-1.93 T, where T is the average age of the Venusian surface: Ivanov and Basilevsky (1993)). Only a minor part of the craters on tessera have noticeable tectonic deformation. This means that the deformation that formed the presently visible highly tectonized morphology of the tessera was not long-lasting, but occurred over a rather short period of time (Ivanov and Basilevsky, 1993).

Radiometric ages of the Fortuna Group materials may significantly extend the crater retention age since the deformation that formed their distinctive surface texture is unlikely to have reset the radiometric ages of the rocks.

**Guinevere Supergroup**

These units include all plains-forming materials of the surface of Venus except the parabolic-shaped mantles and associated materials of the Aurelia Group. Based on results of stratigraphic analyses in 36 areas, about 1000 x 1000 km each (Basilevsky and Head, 1994a, 1995) and subsequent analyses of a number of larger areas which confirmed the usefulness and validity of the proposed stratigraphic sequence, we suggest the Guinevere Supergroup be subdivided into four groups (Fig. 3).

**Sigrun Group.** The densely fractured terrains of plains (Pdf) and coronae (COdf) are the units that form this group (Basilevsky and Head, 1994a, 1995) (Fig. 7). The name Sigrun is suggested because Sigrun Fossae contains representatives of these two units (Fig. 8). Sigrun Group materials are deformed by dense swarms of faults but if one ignores the faults the terrains composed of this material seem to be plains. Where they are in contact with tessera representing the Fortuna Group the Sigrun Group materials appear to be embaying tessera, while many

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**Table 2. Descriptions and type localities of units described in the paper**

<table>
<thead>
<tr>
<th>Map units</th>
<th>Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aurelia Group</td>
<td>Cdp</td>
<td>Craters with dark paraboloids: craters residing in apical parts of eastward facing radar-dark parabolic features hundreds of kilometers in extent.</td>
</tr>
<tr>
<td>Guinevere Atla Group</td>
<td>Ps. Pl</td>
<td>Smooth plains: plains of homogeneous radar brightness not deformed by Pdf type fractures, broad linear, or wrinkle ridges.</td>
</tr>
<tr>
<td>Rusalka Group</td>
<td>Pwr</td>
<td>Plains with wrinkle ridges: plains of various radar brightness deformed by wrinkle ridges.</td>
</tr>
<tr>
<td>Lavinia Group</td>
<td>Pfr. RB</td>
<td>Fractured and ridged plains: plains of various (usually intermediate) radar brightness sparsely deformed by broad (typical 3-5 km) linear ridges, often with islands of Pdf type.</td>
</tr>
<tr>
<td>Sigrun Group</td>
<td>Pdf. COdf</td>
<td>Densely fractured terrain of coronae: densely fractured arcuate bands and irregular patches composing annuli and cores of coronae, usually with radial and/or concentric pattern.</td>
</tr>
<tr>
<td>Fortuna Group</td>
<td>Maxwell Fm</td>
<td>Tesserae: terrain consisting of at least two sets of intersecting ridges and grooves, typical spacing 3-10 km.</td>
</tr>
</tbody>
</table>

**Location of stratotype**

- 20.27 N, 331.80 E
- 3.5 N, 198.27 E (Ps)
- 5.5 N, 196.0 E (Pl)
- 8.0 N, 177.0 E
- 37.7 S, 396.6 E (Pfr)
- 45.0 S, 352.5 E (RB)
- 48.5 N, 15.0 E (Pdf)
- 67.5 N, 20.0 E (Tt)
- 46.0 N, 4.0 E (M)
faults forming typical swarms within the Sigrun Group extend into tessa material (Fig. 9). The Sigrun Group materials are observed on the surface as islands or kipukas embayed by different varieties of ridged and smooth or lobate plains. Their average abundance at the 36 sites is no more than 3–5% of the surface analyzed and on the basis of preliminary global analyses this number appears to be representative of the planet as a whole. Patches of densely fractured Sigrun Group materials are involved in formation of belts of broad ridges on plains, ridges of coronae annulæ, and are dissected by varieties of younger faults. The plains-forming character of Sigrun Group materials suggest that they are mostly made of mafic volcanics.

**Lavinia Group.** This group is composed of units of smooth areas of fractured and ridged plains (Pfr), and ridge belts (RB) (Basilevsky and Head, 1990a, 1995) (Fig. 2), and together they cover about 1–3% of the surface of the sites analyzed. The name Lavinia is suggested because these terrains are a typical and well-developed characteristic of Lavinia Planitia. These units contain and embryo remnants of the Sigrun Group and are embayed, in turn, by plains with wrinkle ridges and smooth and lobate plains (Figs 10 and 11). The materials making up the Lavinia Group are deformed by belts of broad ridges and locally wrinkle ridges and younger faults. Pfr and RB are structural facies of the Lavinia Group materials which we distinguish based on the degree of their involvement in broad ridging. If the broad ridging is distributed over quite a large area this unit is classified as Pfr. If the broad ridges are clustered and observed as a chain of islands or one long island among the plains with wrinkle ridges or smooth and lobate plains it is classified as RB. In the undeformed state the Lavinia Group materials look quite similar to the materials of younger plains with wrinkle ridges as well as smooth and lobate plains, evidence that they are mostly made of basaltic lavas.

**Rusalka Group.** Units of this group are the variety of subunits comprising the plains with wrinkle ridges (Pwr) representing about 70% of the surface of Venus (Basilevsky and Head, 1994a, 1995) (Fig. 2). The name Rusalka is given because Rusalka Planitia is mostly made of plains with wrinkle ridges and because geochemical measurements made in Rusalka Planitia by *Vega* 1 and 2 landers with high reliability characterize the materials of those plains as tholeiitic basalts (Surkov et al., 1986) (Fig. 12). Rusalka Group materials embay materials of Fortuna Group as well as Sigrun and Lavinia Groups and are embayed by materials of smooth and lobate plains. Rusalka Group materials are deformed by wrinkle ridges forming regional to global networks (McGill, 1993), and by younger faults. Because of their predominance on the surface of Venus, these materials bear the majority of impact craters on Venus so the average crater retention age of the surface of Venus (approximately 500 m.y., Schaber et al., 1992; or approximately 300 m.y., Strom et al., 1994)) is mostly the crater retention age of the Rusalka Group. Among about 1000 impact craters on Venus, only a few are deformed by the wrinkle ridges (Fig. 13) which form the regional to global network on the Rusalka Group, and most are superposed on the wrinkle-ridged plains (Fig. 14).

This is in contrast to the results of Price et al. (1994) who reported that about 80% of the craters on Venus predate the emplacement of wrinkle ridges (Bilotti, 1992). On the basis of examination of the craters and personal discussions we find that the discrepancy arises from the cases where wrinkle ridges intersect the crater ejecta. Price et al. (1994) interpreted most of these cases as evidence that the ridges deform the ejecta. When wrinkle ridges enter into the ejecta deposits they can either predate (be covered by) or postdate the cratering event (cut the ejecta). The most convincing evidence that wrinkle ridges postdate the crater is the presence of a ridge on the crater floor where the floor is flat and wrinkle ridges are easily visible. Slightly more ambiguous are the cases where ejecta outflow patterns are controlled by the presence of wrinkle ridges in the adjacent plains. Our qualitative estimate for the approximately 20% of the surface that we have examined is that the majority of impact craters postdate the emplacement of plains with wrinkle ridges and the wrinkle ridges themselves. Our estimates agree with those of Schaber et al. (1992) who found that only one of the 842 craters that they studied (Barrymore, 52.3 S, 195.6 E, \( D = 50 \) km) had obvious deformation of its floor by wrinkle ridges of the regional network. This means that the time period between the emplacement of the Rusalka Group materials and their deformation with wrinkle ridges was very short. The Rusalka Group materials, if we ignore the wrinkle ridges, form smooth plains of intermediate radarg-brightness with small and large radar-bright and radar-dark flows. The surface morphology of these materials and geochemical measurements made by *Venera* / *Vega* landers show that the Rusalkan materials are mostly made of basaltic lavas (Surkov et al., 1986; Basilevsky et al., 1992; Weitz and Basilevsky, 1993).

**Atla Group.** Units of this group are the smooth (Ps) and lobate (PI) plains with no wrinkle ridges, representing about 10% of the surface (Basilevsky and Head, 1994a, 1995) (Fig. 2). The name Atla is suggested because smooth and lobate plains are very common and well displayed in Atla Regio (Fig. 15). Atla Group materials embay all the units discussed previously and are covered in some places by materials of dark-paraboloid features (Campbell et al., 1992) associated with some impact craters. In a few cases Atla Group materials postdate materials of dark-paraboloid features and are crossed by the youngest faults which formed during the period of formation of the dark-paraboloid craters (Basilevsky, 1993). Atla Group materials tend to be concentrated within and in the vicinity of the large-scale rift zones (Solomon et al., 1992; Senske et al., 1992) forming either areas of practically horizontal plains (Magee Roberts et al., 1992) or gentle-sloping mountains such as Sif, Gula or Ozza montes (Senske et al., 1992). They are also often observed, typically in the form of lobate plains, in association with coronae (Fig. 16) (Magee Roberts and Head, 1993). Surface morphology and surface geochemical measurements (*Venera* 14; Surkov et al., 1984)) show that these materials are mostly basalts. As mentioned above, the emplacement of wrinkle ridges deforming Rusalka Group plains occurred shortly after the emplacement of the Rusalka Group materials themselves (≈ 300 or 500 m.y. ago). Emplacement of craters which now have associated dark par-
aboloids (Cdp) records the beginning of a new epoch, starting about 30–50 m.y. ago (Basilevsky, 1993; Strom, 1993). According to Price and Suppe (1994) the mean age of the large volcanoes belonging to the Atla Group is 69 ± 44 m.y., large lava flows 123 ± 87 m.y., and rift-forming faults, 81 ± 117 m.y. This indicates that the period of time in which the Atla Group materials were emplaced may represent a very long segment of geologic history on Venus (several hundred million years; see also Namiki and Solomon (1994)).

Aurelia Group. Units of this group are distinguished from the subdivision of the Guinevere Supergroup and are composed of the variety of parabolic radar-dark mantles typical of the youngest about 10% of impact craters (Cdp) and other crater materials of this crater subpopulation (Basilevsky and Head, 1994a, 1995) (Fig. 2). Some debris accumulations forming radar-dark patches (Sp) in local topographic lows and against or behind positive topographic obstacles, as well as some of the radar-dark wind streaks (Ss) ( Greeley et al., 1992) are included in this group and are evidently contemporaneous with Cdp. The name Aurelia is given because the crater Aurelia displays many of the characteristics of dark-paraboloid craters (Fig. 17). The use of dark-paraboloid craters as a stratigraphic unit and marker is analogous to the use of rayed craters on the Moon. Bright rays form part of the definition of a lunar rock-stratigraphic unit, are included in the Copernican System (time-stratigraphic unit) and formed during the Copernican Period (geologic time unit). Yet these rays degrade with time so that some crater rock-stratigraphic units are defined as not having rays, and formed during the Eratosthenian Period geologic time unit (Wilhelms, 1987).

Some of the Aurelia Group materials are cut by rift-associated fractures (Basilevsky, 1993). In addition, some lavas of Maat Mons volcano postdate dark-paraboloid craters and are considered to be some of the youngest lavas of Venus. The very young age of Maat lavas is consistent with the very high elevation of this volcano and with the fact that its summit lacks radar-reflective low-emissivity surface material (Klose et al., 1992; Robinson and Wood, 1993). Thus, materials of the Atla Group overlap in time with materials of the Aurelia Group (Fig. 3). As mentioned above the emplacement of the Aurelia Group materials started about 30–50 m.y. ago and continues to the present. The surface morphology and radiophysical properties of Aurelia Group units show that they are represented by relatively fine debris (radar-dark paraboloids, patches and streaks), crater-related breccias and impact melts.

In summary, the regional and global stratigraphy of Venus can be summarized by a series of rock-stratigraphic units ranging in hierarchy from formations (informally and formally defined) to supergroups (Fig. 3; Table 2). We propose that the rock-stratigraphic units are distinctive enough to represent three major time-stratigraphic units (Systems), and three corresponding geologic time units, in order of decreasing age, the Fortunian Period, the Guineverian Period, and the Aurelian Period. Estimates of the duration and absolute ages of these geologic time periods are shown in Fig. 3. The vast majority of the geologic history of Venus (the first 85–90%) is apparently not represented in the surface geologic units (pre-Fortunian Period), although rocks representing this earlier history are likely to reside in parts of the tessera terrain.

Interpretation of structural deformation and relationship to units

In the defined stratigraphic units and proposed stratigraphic sequence (Basilevsky and Head, 1994a, 1995) one of the characteristics of the stratigraphic units if the presence (or absence) of deformation which differs from unit to unit in its pattern, abundance and spacing. Although structural fabrics are commonly a factor in the definition of planetary geologic units (see Tanaka, 1994), care must be taken to distinguish between the well-defined stratigraphic units and structural deformation occurring both as part of them and separately. Of course, deformation of certain types can be overprinted both on newly-formed material and on the material formed during the previous geological epoch(s) and now sitting aside or beneath this new-formed material. This fact indicates that caution should be used when structural elements make up a portion of the definition of a unit (e.g., Tanaka, 1994). Fortunately, in the case of Venus only the oldest of the suggested stratigraphic units, representing the Fortuna Group, have such intensive characteristic tectonic overprinting. Indeed, it is difficult, if not impossible to see the nature of the tessera precursor terrain. However, it is also clear that most of the deformation responsible for the observed morphology of the Fortuna Group units was concentrated in time since few of the impacts superposed on the tessera (Ivanov and Basilevsky, 1993) show evidence of significant deformation.

For the Sigrun Group, next in sequence, in spite of its very heavy faulting it is definitely possible to conclude that its precursor terrain is plains, not tessera. Indeed, we see this dense faulting characteristic of the Sigrun Group on tessera too but in this case we are able to see that it is superposed on, or forms part of, the characteristic tessera structural pattern.

For younger stratigraphic units, the typical tectonic overprint is much less dense so one can easily distinguish when the broad ridge belts (characteristic of the Lavinia Group) affect primarily undeformed plains, and when they deform densely fractured terrains, which are often included as islands in the fractured and ridged plains or ridge belts. Depending on the scale, these units (with inclusions) might be mapped as Lavinia Group (ridge belts), or at much larger local scale, the islands might be subdivided from the ridge belt and mapped as members of the Sigrun Group plains.

Wrinkle ridging which is typical for the Rusalka Group is also not dense and the precursor terrain can easily be seen. The wrinkle ridges may be clearly superposed on primarily undeformed plains and we classify the latter as Rusalkan ones, or wrinkle ridges can be superposed on plains already affected by broad ridges and in this case we classify the plains as part of the Lavinia Group even though wrinkle ridges are present. We have never
observed wrinkle ridges superposed on Fortuna Group tessera and only in very rare and unclear cases did we see them superposed on Sigrun Group densely fractured terrains. Obviously, highly fractured materials of the Fortuna Group are likely to consist of large-scale rubble mechanically analogous to the breccias of the lunar highlands, and like these may have physical properties not as favorable for warping into wrinkle ridges as the adjacent volcanic plains, as appears to be the case on the Moon (Muehlberger, 1974).

Younger deformation represented by faults both associated and not associated with rifts are overprinted on practically all stratigraphic units. In most cases it is possible to see through them what unit(s) they deform (e.g. Senske et al., 1992) in Beta Regio. But in some areas of rift zones the faulting is so dense that it is difficult to decide what type of terrain is deformed there. In this case introducing additional highly tectonized unit(s) in the future may be advisable.

**Tectonic deformation and correlation with stratigraphic units**

Several distinctive structural features and groups of features were distinguished in the areas under study and these could be subdivided stratigraphically into several episodes of deformation (Fig. 18). The earliest and most intense is the deformation which determined the observed rough morphology of tessera terrain (Fortuna Group). Indeed, what we see now as tessera is a result of complex patterns of synchronous deformation and intensive multiple deformation patterns; the predominant sense of deformation probably changed with time from compression to extension (Bindschadler and Head, 1991; Bindschadler et al., 1992b; Ivanov and Head, 1993, 1995; Head and Ivanov, 1993). Subparallel ridging in the circum-Lakshmi mountain belts is evidently a representative of the compressional stage almost not affected in this place by the subsequent extensional deformation.

Following and evidently contemporaneous with the terminal stages of tessera deformation was extensional faulting now visible in the remnants of Sigrun Group densely fractured material widespread over all of Venus.

Next in time was the formation of broad ridges, fragments of which are now seen in many places on Venus as islands of Lavinia Group material. This marks a transition from the dominance of extension to an environment characterized mostly by compression. The superposed wrinkle ridges now mostly visible on the Rusalkan plains practically everywhere were also formed in the compressional environment.

Younger deformation is mostly observed either in the form of long and relatively narrow rift zones (Senske et al., 1992; Solomon et al., 1992) formed in the late Guineverian or Aurelian periods of time (Fig. 19), or in the form of rare, but widely distributed open fractures (Fig. 20). The broad distribution of rift zones implies a new change in deformational environment from moderate compression to moderate extension, often accompanied by volcanism (Magee Roberts and Head, 1993; Magee and Head, 1995).

An important characteristic of most of the observed deformation is its global distribution. Indeed, in practically any moderate-sized region of Venus (say 1000 x 1000 km) one can see large or small islands of
Synchronous vs nonsynchronous options

The proposed stratigraphic sequence of material units and structures is valid with minor variations for all the areas we studied. The major question which arises then is whether: (1) the same stratigraphic units/structures and corresponding geologic events were practically synchronous in all the sites, or (2) this sequence is just a sequence of events which occurred in different places at different times. The first option means that the proposed stratigraphic sequence describes the corresponding global geologic history of Venus. The second option means that multiple repetition of the same scenario in different places at different times was typical for the geologic history of Venus, a kind of locally realized cycle of tectonism and magmatism.

The resolution of this dilemma will hopefully be reached as a result of the Venus Geological Mapping Program (VMAP) now underway. But some progress in its resolution, we believe, may be reached on the basis of data currently available. This dilemma is actually just another variation of the current discussion on the character of the geologic history of Venus. The extreme options in this discussion are represented by the papers of Schaber et al. (1992) and Phillips et al. (1992). Both of them try to explain the basic observation that, first, most of the observed impact craters on Venus have a pristine appearance and do not look embayed by the surrounding volcanic plains but rather are superposed on them, and second, that the crater area distribution around the planet is not distinguishable from a random one.

Schaber et al. (1992) believe that the observed crater population is a production one which accumulated for the last ~ 300 or 500 m.y. This means that in the beginning of this time period the surface of Venus was catastrophically flooded by volcanic eruptions which destroyed the preexisting crater population. Following this event, volcanic and tectonic activity were minor and bombardment formed the observed crater population. Parmentier and Hess (1992) and Head et al. (1994) suggested that this catastrophic flooding might be caused by gravitational instability in the Venus upper mantle originating from the extraction of basalts, continued vertical crustal accretion, and subsequent compositional and thermal evolution. The eventual net negative buoyancy of the depleted mantle should lead to major overturn in the mantle with sinking of the cooler and denser upper material and rising, and thus decompression melting, of hot and fertile material from lower in the mantle. This, in turn, should lead to widespread deformation of the preexisting crust, thus forming the tessera terrain and eradicating evidence of preexisting craters, and massive melting out and eruption of basaltic magmas to resurface most of the lowlands of Venus (Head et al., 1994). This scenario is compatible with our first option (sequence of almost synchronous geologic events all around the planet).

Phillips et al. (1992) based their model on the same basic facts: pristine appearance of most of the impact craters and the fact that their distribution cannot be distinguished from a random distribution over the Venus globe. But opposite to Schaber et al. (1992), Phillips et al. (1992) considered the crater population not as a production population, but as an equilibrium one. They believe that the observed situation might be the result of permanent endogenic activity which occurred in zones of limited size in different places at different times. They estimated that the observed characteristics of the crater population could be realized if these active zones were about 400 km across. This model is analogous to our option two, the multiple repetition of a typical sequence of events in different places at different times.

Our analyses of the stratigraphic relation of material units and structures in the areas studied helps to make a choice between these options. A key parameter for that is the size of the zones of endogenic activity estimated by Phillips et al. (1992). Indeed the activity cycle certainly might form the observed stratigraphic sequence within any of these zones. But on the boundary of this given activity zone where it neighbors with another zone in which activity occurred at a different time we should observe a superposition of one regional stratigraphic sequence onto another one. As a result the stratigraphically lower units of the younger cycle should be superposed on the upper units of the older cycle. Each of our study areas (from 1000 x 1000 km to 4500 x 4500 km size) should contain at least several neighboring examples of these consecutively active 400 km zones. So if the model of Phillips et al. (1992) is correct we certainly should observe the superposition of local stratigraphic sequences, but we did not.

As a further test of this, we thoroughly analyzed the stratigraphic relations of units and structures along Hildr channel, the longest channel on Venus (Baker et al., 1992) (Figs 22 and 23) (recently renamed Baltis Vallis). It is an excellent stratigraphic marker because its formation may be considered as geologically instantaneous, and it is extremely long (about 7000 km long or about 1/6 of the equatorial dimension of Venus!). Our observations showed that along all of its length, and for great distances from its margins, there are no cases of violation of the stratigraphic sequence (Fig. 23). Over the whole region, Hildr channel is incised into Rusalka Group plains units, which overlie earlier units of the Lavinia, Sigrun, and Fortuna Groups. Several late members of the Rusalka Group (bright flows) were emplaced (and partially flood...
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Fig. 23. Schematic geologic map of Hildr channel region. Area is 4500 x 4500 km. The stratigraphic units used in this map are described in the text and Table 2. The entire region (almost 1/20 of the total surface of Venus) shows very consistent stratigraphic relations between units from place to place. No evidence could be found for superposition of any locally anomalous units or sequences.

Baltis; Fig. 22) prior to the deformation of the plains into the characteristic wrinkle ridges (Komatsu and Baker, 1994). All this leads us to conclude that our first option is closer to reality and this suggests that we may outline a scenario of the geologic history of Venus based on the option that almost global synchronous major events formed the observed stratigraphic sequence.

A preliminary interpretation of the geological history of Venus

About 80-90% of the history of Venus, from planetary formation until several hundreds of millions of years ago, is not preserved in the surface geomorphological record (Fig. 24). We favor a model of gravitational instability causing mantle overturn which is evidently responsible for the catastrophic piling up of preexisting planetary crust, thus forming tessera and mountain belts which compose the Fortuna Group, and for massive eruptions of basaltic lavas, thus forming most of the venusian plains. In the terminal stages of tessera formation, extensive subparallel fault swarms were formed which we now see on the remnants of densely fractured terrains (Sigrun Group) and partly on tessera. As mentioned above, the small percentage of tectonically deformed craters among the population of craters superposed on the tessera implies that the deformation forming the presently observed highly tectonized tessera pattern was not long-lasting (Ivanov and Basilevsky, 1993). The change in the style of deformation from shortening to extension, perhaps is due to a change in the net state of stress in the lithosphere possibly linked to near-global upwelling and pressure-release melting of mantle material (Parmentier and Hess, 1992; Head et al., 1994).

Subsequent to this the emplacement of volcanic plains continued but the nature of the deformation that took place changed from extensional to compressional, perhaps due to the overall cooling and general thickening of the lithosphere. This led to formation of fractured and ridged plains (Lavinia Group) and plains with wrinkle ridges (Rusalka Group). The extreme rarity of craters embayed by plains of the Guinevere Supergroup and craters deformed by wrinkle ridges, implies a relatively short period of time (tens of millions of years?) during which the Sigrun, Lavinia and Rusalka Group materials were emplaced and fractured or ridged. The previously described overthrust with sinistral displacement in the Maxwell Montes massif, which was the last significant deformation in that area, apparently occurred at the same relatively ancient time in the past (middle Guineverian time) as the episode of widespread compressional ridge formation on Venus. This observation puts strong constraints on the effective viscosity of crustal rocks in the Venus environment. In particular, examining the tectonic deformation of mountains in Ishtar Terra and a range
of conditions, Smrekar and Solomon (1992) favored the hypothesis that many of the areas of greatest relief and steepest slopes have been recently tectonically active (tens of millions of years). The great relief and steep (up to 30°) kilometer-scale slopes on the southwest face of Maxwell Montes (Ford and Pettengill, 1992), however, appear to have been stable for a long period of time, perhaps several hundred million years (Figs 3 and 18). This appears to be consistent with new data on the rheology of a very dry diabase (Mackwell et al., 1993) which suggests that the crust is very strong.

During the subsequent hundred million years of history the local emplacement of basaltic lavas along rift zones (Senske et al., 1992) and in association with some coronae (Magee Roberts and Head, 1993) led to formation of Atla Group smooth and lobate plains. The fact that some rift-associated volcanics and fractures postdate the Aurelia Group dark-paraboloid craters, which as mentioned above were formed less than 30–50 m.y. ago, shows that in the most recent Aurelian Period, rifting and associated volcanism continued and probably occur even now. Rifting, which is typical for Late Guineverian and Aurelian times, requires an extensional stress environment. The circum-planet distribution of rift zones (Senske et al., 1992; Crumpler et al., 1993) suggests the possibility of a regional or possibly planet-wide state of extension. This may be a delayed consequence of the proposed catastrophic overturn (Parmentier and Hess, 1992) which has been hypothesized as the source of the deformation of Fortuna Group tessera and mountain belts, and to massive eruptions of basaltic lavas which form the plains of the Sigrun, Lavinia, and Rusalka Groups. Relatively cold and dense upper mantle material, after sinking into deeper horizons, should eventually heat up and thus could potentially cause widespread thermal expansion and global extensional stress.

All volcanics of the Atla Group cover about 10% of Venus and their volume is evidently only a minor part of the volcanics whose geomorphologic record we see. In combination with the long duration of their emplacement...
time previously discussed, it means that the average volcanic flux in post-Rusalkan part of the Guineverian Period (including the Aurelian Period) was very low. A significantly higher volcanic flux is indicated earlier by the broad distribution of Rusalka Group wrinkle-ridged plains and, exposed through them, remnants of Lavinia and Sigrun Group plains. This high flux is further emphasized by the time-compressed character of their emplacement indicated by the very low number of embayed craters. The highest flux occurred probably during the emplacement of Sigrun Group materials because this unit flooded very effectively the vast areas of tessera with kilometer-scale relief (Head and Ivanov, 1993) while the remnants of Sigrun materials themselves, whose proper relief is an order of magnitude less, stick through the Lavinia and Rusalka Group materials practically everywhere.

**Conclusions**

Photogeologic studies of *Magellan* images for thirty six 1000 x 1000 km sites and several larger areas have led to the definition and characterization of a sequence of mappable stratigraphic units (Fig. 3) and the structures deforming them (Fig. 18). Based on this stratigraphic sequence a scenario for the last 300–500 m.y. of the history of Venus is proposed. *Magellan* global image data reveal no evidence for extensive terrain dating from the pre-Fortunian Period, comprising approximately the first 80–90% of the history of Venus. The first widespread geologic unit preserved on Venus is the highly deformed tessera terrain of the Fortuna Group. This and related terrain apparently formed as a result of a global event that caused extensive deformation that destroyed the morphology of preexisting terrain and any superposed craters. Igneous and metamorphic rocks dating from the earlier pre-Fortunian history of Venus are very likely part of this terrain, which formed in the Fortunian Period. The duration of the Fortunian Period is unknown, but is thought to be relatively short, less than about 100 million years.

Immediately following this began an extensive period of plains volcanism, the Guineverian Period, during which the majority of Venus was volcanically resurfaced. Early widespread plains of the Sigrun Group were deformed by extensive and closely-spaced graben systems. Continued widespread plains emplacement occurred and units of the Lavinia Group were deformed, some into extensive ridge belts, recording a change from distributed extensional deformation to often-focused compressional deformation. Plains of the Rusalka Group are the most widespread currently exposed, and are characterized by extensive development of wrinkle ridges of compressional origin. The Rusalka, Lavinia, and Sigrun Group materials must have been emplaced and deformed over a relatively short period of time (probably less than about a hundred million years) because the vast majority of impact craters are superposed on the plains, and the crater retention age of this surface is of the order of 300–500 Ma (Schaber et al., 1992; Strom et al., 1994).

This extensive plains volcanism then gave way to materials of the Atla Group, local volcanic edifices and flow units with sources associated with coronae and rifts (Senske et al., 1992; Magee Roberts and Head, 1993) that were emplaced in the late Guineverian and Aurelian Periods. The Aurelian Period, defined by impact craters with dark parabola, is interpreted to extend from the present back to about 30–50 Ma ago. During this period extensive rifting occurred in several areas of Venus and volcanism has continued at a reduced level relative to the earlier parts of the Guineverian period.

Our observations favor a model in which the observed part of the geologic history of Venus started with catastrophic deformation and resurfacing, followed by a period of declining surface activity of endogenic origin which lasts until now. The lack of surface units representing the first 80–90% of the history of Venus is remarkable from the standpoint of its present low level of activity. The contrast between the present level of activity and that typical of the Fortunian and Guineverian period of intense deformation and flooding suggest that catastrophic (Parentier and Hess, 1992) and/or episodic (Turcotte, 1993) global processes may have characterized Venus in its earlier history. This factor may also provide insight into earliest Earth history, where distinctive changes in volcanic, petrogenetic, and geological style appear to have taken place from time to time (Nisbet, 1987; Head, 1994).

The Venus geologic history scenario described above should be tested and compared to specific geophysical models. Some important questions include: (1) If the formation of the Fortuna Group tessera terrain as well as the emplacement and deformation of the Sigrun, Lavinia, and Rusalka Group materials indeed occurred over a very short period of time, then changes in the regional and global stress regime from compressional (Fortunian time) to extensional (late Fortunian–Sigrunian) and back to compressional (Lavinian–Rusalkan) may put some constraints on heat generation and loss rates and styles during this part of the thermal evolution of Venus. What geophysical models are consistent with these observations? (2) If the observed part of the geologic history of Venus indeed started with global catastrophic deformation and resurfacing, this should inevitably disturb the upper mantle in Fortunian time, thus changing patterns of mantle circulation, including modifying the penetration of hot spot plumes from the deeper interior of the planet. However, in the subsequent (Sigrunian) period we see evidence of corona-forming probable hot spot activity (CODf unit); this could be interpreted to mean that hot spot activity began or was restored immediately following this significant mantle disturbance, or perhaps even associated with it. What mantle convection models are consistent with the spatial and temporal distribution of these features? (3) If the Atla Group volcanic activity closely related to the rift zones is indeed the result of heating up of previously cold and dense upper mantle then it puts constraints on the time which is necessary to heat the material enough to produce rift-forming extensional stresses and to generate the Atla Group magmatic melts. What time duration is consistent with these observations?

The proposed preliminary stratigraphic sequence highlights many important details of the geologic evolution of Venus and should be tested through the Venus Mapping Program. Our observations of the 36 areas, several
detailed regional analyses, and a preliminary review of the majority of the planet at the C-1 MIDR scale, also show that from place to place the geology of the planet is strikingly uniform. In most regions we see practically the same terrains and features representing the same rock-stratigraphic units and the same age sequence. In general, uniformity dominates over variability, and only occasionally do we observe unusual landforms such as channels or steep-sided volcanic domes. In this respect, Venus is more similar to the Moon and Mercury, where impact cratering and volcanism form the major surface units, and differs significantly from Mars and especially the Earth (Head, 1994), where atmospheric and hydrospheric processes add considerable diversity and complexity to the geological record.

Acknowledgements. This paper is dedicated to the memory of Harold Masursky whose vision, inexhaustible energy, and perseverance contributed to making the Magellan mission to Venus a reality, and this work possible. Thanks are extended to many participants in the Venus Geologic Mapping Program for fruitful discussions, and to the National Aeronautics and Space Administration for financial support to ATB (NAGW-3803) and JWH (NAGW-713 and NAGW-1873). Two detailed formal reviews improved the manuscript, as did informal reviews from colleagues. Thanks are extended to Peter Neivert for photographic assistance and to Amy Johnson and Karen Plouff for drafting.

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