Planetary and Space Science 59 (2011) 1559–1600

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Global geological map of Venus

Mikhail A. Ivanov[a,b], James W. Head[b,*]

[a] Vernadsky Institute, Russian Academy of Sciences, 119991 Kosygin St., 19, Moscow, Russia
[b] Department of Geological Sciences, Box 1846, Brown University, Providence, RI 02912, USA

ARTICLE INFO

Article history:
Received 28 April 2011
Received in revised form
13 July 2011
Accepted 27 July 2011
Available online 4 August 2011

Keywords:
Venus
Global geological map
Volcanism
Tectonism

ABSTRACT

The surface area of Venus ($\sim 460 \times 10^6$ km^2) is $\sim$90% of that of the Earth. Using Magellan radar image and altimetry data, supplemented by Venera-15/16 radar images, we compiled a global geologic map of Venus at a scale of 1:10 M. We outline the history of geological mapping of the Earth and planets to illustrate the importance of utilizing the *dual stratigraphic classification* approach to geological mapping. Using this established approach, we identify 13 distinctive units on the surface of Venus and a series of structures and related features. We present the history and evolution of the definition and characterization of these units, explore and assess alternate methods and approaches that have been suggested, and trace the sequence of mapping from small areas to regional and global scales. We outline the specific defining nature and characteristics of these units, map their distribution, and assess their stratigraphic relationships. On the basis of these data, we then compare local and regional stratigraphic columns and compile a global stratigraphic column, defining rock-stratigraphic units, time-stratigraphic units, and geological time units. We use superposed craters, stratigraphic relationships and impact crater parabola degradation to assess the geologic time represented by the global stratigraphic column. Using the characteristics of these units, we interpret the geological processes that were responsible for their formation. On the basis of unit superposition and stratigraphic relationships, we interpret the sequence of events and processes recorded in the global stratigraphic column. The earliest part of the history of Venus (Pre-Fortunian) predates the observed surface geological features and units, although remnants may exist in the form of deformed rocks and minerals. We find that the observable geological history of Venus can be subdivided into three distinctive phases. The earlier phase (Fortunian Period, its lower stratigraphic boundary cannot be determined with the available data sets) involved intense deformation and building of regions of thicker crust (tessera). This was followed by the Guineverian Period. Distributed deformed plains, mountain belts, and regional interconnected groove belts characterize the first part and the vast majority of coronae began to form during this time. The second part of the Guineverian Period involved global emplacement of vast and mildly deformed plains of volcanic origin. A period of global wrinkle ridge formation largely followed the emplacement of these plains. The third phase (Atlian Period) involved the formation of prominent rift zones and fields of lava flows unmodified by wrinkle ridges that are often associated with large shield volcanoes and, in places, with earlier-formed coronae. Atlian volcanism may continue to the present. About 70% of the exposed surface of Venus was resurfaced during the Guineverian Period and only about 16% during the Atlian Period. Estimates of model absolute ages suggest that the Atlian Period was about twice as long as the Guineverian and, thus, characterized by significantly reduced rates of volcanism and tectonism. The three major phases of activity documented in the global stratigraphy and geological map, and their interpreted temporal relations, provide a basis for assessing the geodynamical processes operating earlier in Venus history that led to the preserved record.

1. Introduction: comparative planetology and the principles of geologic mapping

One of the most important developments in the geological sciences in the past 50 years has been the exploration of the planets and the perspective that comparative planetology has brought to the understanding of the history of the Earth. Systematic observations of the surface characteristics of different terrestrial planetary bodies has led to a cataloging and comparison of their features, study of the processes that produce these features, and the mapping and stratigraphic assessment of the geological units that make up their crusts. In concert with the exploration of each successive body, regional to global data sets have led to a synthesis of observations, construction of local and

* Correspondence author. Tel.: +1401 863 2526; fax: +1401 863 3978.
E-mail address: James_Head@brown.edu (J.W. Head).

0032-0633/$ - see front matter
doi:10.1016/j.pss.2011.07.008

regional geological maps, and integration into a global picture of their geologic history. Such analyses of the smaller terrestrial planetary bodies, the Moon (Wilhelms, 1987), Mars (Tanaka et al., 1992), and Mercury (Spudis and Guest, 1988) and their intercomparisons have led to the emergence of some basic themes of planetary evolution (Head and Solomon, 1981). These analyses have also led to many outstanding questions. Among these questions is how these relatively stable one-plate planetary bodies (Solomon, 1978), all less than about one-half the diameter of Earth, compare to Earth? Key to addressing this question is knowledge of the geological history of Venus, the most Earth-like of the terrestrial planets. In what ways is Venus like the Earth and how does its history and evolution compare to the smaller terrestrial planetary bodies? In order to address this question, we have compiled a global geological map of Venus at a scale of 1:10 M, and we report here on our approach, the process of mapping and the results. Important to understanding the mapping of an Earth-sized planet are the principles of geologic mapping and a synthesis of the history of their development into the modern space age.

Steps to understanding the global geological history of a planet include geological definition of stratigraphic units, their mapping and ordering into stratigraphic sequences and columns, correlation of these columns from region to region, and the interpretation of the resulting stratigraphic record in terms of the sequence of geological events and processes that they represent (e.g., Gradstein et al., 2004). The history of geological mapping of Earth provides an important context for applying the lessons learned and rules developed from this effort to the mapping of the moons and planets. Despite 17th century observations about the succession of strata by Nicholas Steno, views on the history of the Earth were dominated well into the 18th century by the biblical account of the flood, and the concept of *catastrophism* in explaining geological observations. The Age of Enlightenment brought renewed interest in basic observations, but one catastrophic explanaton (biblical) was replaced by another (Werner's Neptunism). After decades of debate in the late 18th and early 19th century, James Hutton formulated the principle of uniformitarianism (in contrast to the catastrophism view) in which it was recognized that the conditions that produced the rock record of the past are essentially the same ones that are operating today, and that they operated over millions of years of Earth history in a constant and repetitive manner to build up the geologic record. Hutton developed and applied the principle of superposition and William Smith used lithologic characteristics to show that rock units, although no longer flat lying, could be correlated and traced over significant distances. Smith's efforts produced the first geological map and stratigraphic column of Britain (1813), showing the distribution of 31 major rock units and numerous subdivisions.

In the following decades of the 19th century, these stratigraphic and geological mapping principles, practices and conventions were used in extensive geological mapping in Europe, leading to the definition of the major geological periods. Rock classification developed an additional significance in terms of time classification. Rock systems, often separated by unconformities, began to be viewed as representing episodes in Earth history; the abrupt termination of many faunal elements led to the concept of catastrophism, the idea that rock and time sequences were separated by cataclysmic events in Earth history. Initial success in linking sequences separated by unconformities within Europe, and between Europe and the United States, further solidified the interpretative framework of punctuated global catastrophism: in this view, unconformities were world-wide and represented intermittent global orogenic episodes that uplifted continents, formed mountain ranges and radically changed the biota. Therefore, in the early part of the 20th century, diastrophism, with its time-based episodic formation of near global unconformities, became the interpretive framework for regional and global correlation of stratigraphic sequences.

The detailed mapping of North America, however, began to reveal unconformities where none were expected and no unconformities where some were expected; this led to new organizations and subdivisions in the major stratigraphic classifications schemes. Thus, following the first two centuries of evolution of stratigraphic classification of the rock record of Earth, stratigraphers in the 1930s began to understand that the classical time-based, diastrophism-unconformity paradigm for stratigraphic classification was increasingly discrepant in light of the vast amount of surface and subsurface stratigraphic data that was being accumulated. Emphasis on subsurface exploration, where units were traced on the basis of their definable physical properties, placed significant emphasis on the development of defining stratigraphic units on the basis of simple observable criteria, rather than time considerations. The development of this *dual stratigraphic classification* emphasized two distinctive stratigraphic units: (1) definition and mapping of rock units based on an objective description of their observable characteristics *independent of a broader interpretative paradigm* and (2) groupings of strata distinguished on the basis of their position in geologic time. This basic subdivision and distinction eventually led to modern stratigraphic nomenclature on Earth (see International Commission on Stratigraphy; Gradstein et al., 2004). This system recognizes four basic units (NACSN, 2005):

(1) A *lithostratigraphic unit* is a stratum or body of strata, generally… layered, generally…tabular, that conforms to the Law of Superposition and is distinguished and delimited on the basis of lithic characteristics and stratigraphic position.
(2) A *biostratigraphic unit* is a body of rock defined and characterized by its fossil content.
(3) A *chronostratigraphic unit* is a body of rock established to serve as the material reference for all rocks formed during the same span of time.
(4) A *geochronologic unit* is a division of time distinguished on the basis of the rock record preserved in a chronostratigraphic unit.

This *dual stratigraphic classification scheme* thus successfully separates out *material units* (lithostratigraphic/biostratigraphic) defined on the basis of content and observable, repeatable characteristics, and distinguishes them from *materials of a specific age* (chonostratigraphic), and from a *division of geologic time* (geochronologic; not a material unit but a conceptual unit of time). This major change in approach to stratigraphy, specifically moving away from the heavy influence of an interpretive paradigm in unit definition and interpretation (be it the biblical flood, catastrophism or diastrophism) toward objective, repeatable definition and characterization of units, separated from implications of both geological origin and time, ushered in the modern age of stratigraphy. In the intervening years, lithostratigraphic units have been defined locally, correlated regionally and between continents, and then independently related to chronostratigraphic and geochronologic units globally, leading to a clear picture of the outlines of Earth history and the evolution of geological processes and conditions represented by the independently defined stratigraphic record (e.g., Gradstein et al., 2004).

It is testimony to the usefulness and strength of the dual stratigraphic classification scheme that the advent of the theory of plate tectonics did not alter the basic approach. Instead of *defining* new units in the *context* of this paradigm, independently defined units were used to *test* the new paradigm. Simultaneously, exploration of the solar system caused a parallel revolution in understanding the history of terrestrial planets, revealing major trends in their evolution due to the external flux of projectiles, their internal thermal evolution, and the mechanisms of heat loss. Fortunately, the geologists who turned their attention to determining and deciphering planetary geological history through geological mapping of the Moon and planets were trained in an era when the usefulness of the *dual stratigraphic classification scheme* was well known. Basic stratigraphic principles developed on Earth were applied to the geological mapping of the Moon and other planetary bodies (Shoemaker and Hackman, 1962 and additional articles cited in Wilhelms, 1990).

Of course even with the success of the application of the dual stratigraphic classification scheme to the Moon, some modifications were necessary due to differences in types of data available to define units, scales of mapping, and different geological processes that produced the stratigraphic units. For example, the use of remote sensing data meant that a host of new information was available for stratigraphic unit definition and characterization (see Head et al., 1978, for a discussion of their application). The remote image perspective also placed emphasis on the *use of morphological attributes* of a unit in its definition (e.g., Shoemaker and Hackman, 1962), in addition to its other independently observed characteristics (color, grain size, mineralogy, contact relations, etc.); some even used the term morphostratigraphic unit, in the same manner that lithostratigraphic units are defined on Earth.

Following its successful implementation on the Moon, the *dual stratigraphic classification scheme* was applied to geological mapping and definition of stratigraphic units on Mars, Mercury and the Galilean satellites (e.g., Scott and Tanaka, 1986; Spudis and Guest, 1988; Shoemaker et al., 1982). Each planetary body presented its own unique challenges, but each potential problem was addressed in the context of the dual stratigraphic classification scheme, preserving the independence of observations that defined the units from ad hoc solutions and the pressures of new interpretative paradigms. For example, some regional lithostratigraphic units, such as widespread smooth plains, were characterized by the presence of wrinkle ridges, interpreted to be a tectonic feature superposed on the unit. Global mappers used these features as part of the surface morphology that defined a "ridged plains" unit, and that, together with other characteristics, helped distinguish it from smooth plains (e.g., Greeley and Guest, 1987; Tanaka et al., 2005). Although the tectonic features could have formed at any time, superposition and stratigraphic relationships showed that the ridged plains formed prior to the emplacement of most smooth plains units. Thus, although the most preferable approach would be to use specific primary attributes of the unit itself, rather than superposed structures, the careful application of this modified approach produced important stratigraphic information. Furthermore, some parts of Mars were so highly deformed (the Aureole terrains surrounding Olympus Mons) that the structures themselves became one of the major defining characteristics of the unit (Scott and Tanaka, 1986; Greeley and Guest, 1987); the deformation was so pervasive that it eradicated or subordinated other characteristics. As with ridged plains, stratigraphic relationships permitted the successful interpretation of these units and their stratigraphic position. Similar types of problems were encountered with the Galilean satellites (Shoemaker et al., 1982).

Although these basic principles and guidelines have occasionally been challenged (e.g., Guest and Stofan, 1999; Hansen, 2000), most workers continue to find them the most useful and productive. For example, Shoemaker et al. (1982) used Voyager image data to map the nature of the surface of Ganymede and defined two major geologic units, ancient cratered terrain and grooved terrain. They pointed out that "although these terms derive from the dominant structural features found in the two units, they are lithologic, rather than structural." Collectively, these data resulted in a preliminary geological map (Shoemaker et al., 1982; their plates 2 and 3). In a similar manner, Greeley et al. (2000) used both Voyager and Galileo data to construct a geological map of Europa. Europa contrasted with Ganymede in terms of the lack of a heavily cratered terrain and the even more dense and pervasive surface tectonic fabric. There were almost no craters on the surface of Europa, thus precluding the use of the density of impacts for the distinction of relative unit ages. In terms of the pervasive structure, Greeley et al. (2000) followed basic principles and practices of the dual stratigraphic classification scheme, as modified by precedent on Mars, as follows: "The basic premise of geologic mapping is that units are composed of three-dimensional materials (i.e., they have thicknesses that extend below the surface) which can be placed in a stratigraphic position relative to other units and structures. Units are usually shown by colors or patterns on geological maps. Structures (such as faults and fractures) represent deformation or alteration of the geologic units in response to tectonic or other processes and are typically shown on maps by various symbols. In some cases, structures are so distinctive or characteristic of a terrain that they are used as part of the defining characteristics of the unit, although every effort is made to distinguish between the material properties of a unit and the superposed structure."

Geological mapping of Venus has been undertaken at a wide variety of scales and by a large number of individuals, including broad terrain maps derived from Earth-based radar images (e.g., Campbell et al., 1991), classifications and geologic mapping based on Pioneer-Venus topography (e.g., Masursky et al., 1980) and imaging (e.g., Senske, 1990), comprehensive geological mapping based on the northern area covered by Venera-15/16 radar and altimetry data (e.g., Barsukov et al., 1986), specific thematic areas using all available data sets (e.g., Ivanov and Head, 2010a,b), generalized global terrain maps compiled using Magellan data (e.g., Tanaka et al., 1997), and specific areas (quadrangles) mapped at specific scales. An example of the latter is the currently ongoing NASA program administered by the U.S. Geological Survey that involves many individual geologists and their coworkers. These NASA/USGS mapping efforts have resulted in publication of 27 quadrangles (out of 62) that cover about 35% of the surface of Venus. These maps provide valuable documentation of the local to regional geological settings and processes. Although there are general guidelines and conventions for geological mapping (Tanaka, 1994), the goal of compilation of these individual maps is to study specific geologic problems and processes. Therefore, individual maps often employ different guidelines and conventions in terms of the details of unit definition and mapping. For example, a worker mapping a quadrangle to study the volcanic history of a region might map individual lava flows emanating from different volcanic sources separately (e.g., McGill, 2004), while a worker assessing rift zones and tectonics problems might lump these flows into a larger unit of volcanic origin (e.g., Basilevsky, 2008). Although this approach produces valuable results for individual areas, it often makes it difficult to compare these individual maps in adjacent areas and across the planet in order to assess the general global geological evolution of Venus.

There are several important problems in the geology of Venus, however, that require observations and constraints from the broader, more global geological point of view. What is the character of the evolution of Venus as a whole during the observable portion of its geological record? Did geological processes operate in a regional mode in different places at different times, much as Wilson cycles do on Earth (e.g., Guest and Stofan, 1999)? If so what are these processes and how did their "Wilson cycles" work? Are there any broad themes that emerge in the geological evolution of Venus (e.g., Solomon and Head, 1982), such as those seen on the Earth, Moon, Mars, and Mercury (e.g., Head and Solomon, 1981; Head, 2001)? If so, what are these themes and how did they change with time? What were the rates of specific processes such as impact cratering, tectonism, and volcanism? What is the nature of planetary resurfacing on Venus? Was it local and balanced with the accumulation rate of impact craters (e.g., Phillips et al., 1992) or did it take on a more catastrophic form (e.g., Schaber et al., 1992)? What is the history of the long-wavelength topography and geoid that might reflect processes of mantle dynamics on Venus? Is there evidence suggesting when the large-scale patterns of the topography and the figure of the planet were established? What is the evidence (if any) for the nature and relationship of different global styles of tectonics and volcanism on Venus? What mechanisms of heat loss are most consistent with the observable and extinct regimes of broad-scale tectonics and volcanism (e.g. Turcotte, 1993, 1995)? What can the observable geologic record of Venus, thought to represent about the last 20% of the history of the planet (e.g., McKinnon et al., 1997), tell us about the geology and geodynamics of the first ~80% of the history of Venus?

Addressing all of these major questions and issues requires a broad and self-consistent definition of units in the stratigraphic record of the planet that will show the distribution of the geological events (portrayed as specific stratigraphic units) in space and time. The core of such a framework is the question of the presence or absence of the time correlation of units at the global scale.

In this paper we adopt the *dual stratigraphic classification scheme* described above. This *dual stratigraphic classification scheme* thus separates out *material units* (lithostratigraphic) defined on the basis of content and observable, repeatable characteristics, and distinguishes them from *materials of a specific age* (chonostratigraphic), and from a *division of geologic time* (geochronologic; not a material unit but a conceptual unit of time). This approach to stratigraphy ensures objective, repeatable definition and characterization of units, separated from implications of both geological origin and time. It is specifically independent of any interpretive paradigm, such as catastrophism, diastrophism, or plate tectonics. We first outline how we have defined the geological map units. Then we describe in detail the specific morphologic characteristics of the map units that make up the surface from pole to pole (about 100% of the surface of Venus except for the data gaps) and their stratigraphic relations. We discuss rock-stratigraphic units and structures, time-stratigraphic units, and geological time units. We then trace and discuss their global spatial distribution, their time correlation, and the geological sequence of events and history.

2. Definition of units

The sheer size of Venus, imaged at high resolution, precluded systematic geological mapping in the short term. One approach to this daunting task of defining stratigraphic units and compiling a geologic map for an Earth-sized planet was taken by Basilevsky and Head (1995a,b). They reasoned that the definition of units, and examination of their stratigraphic sequence and relationships, at numerous places spread across the globe, and comparison of the content of these stratigraphic columns, would lead to a first-order test of whether local regions on Venus had elements of a global stratigraphy, or whether the units identified occurred in some more random stratigraphic order. They proceeded to apply the dual stratigraphic classification scheme, and the definition of units by their objective definable characteristics independent of any interpretative paradigm, to the analysis of stratigraphic units on Venus. Knowing from the initial Magellan analyses (Campbell et al., 1992) that the youngest impact craters had surrounding dark halos that apparently disappeared with time (somewhat analogous to the Copernican and Eratosthenian craters on the Moon), Basilevsky and Head (1995a,b) chose 36 different regions on Venus that had dark-haloed craters (and thus were by definition randomly distributed) and defined units and compiled geologic maps of an area around them of about 1000 × 1000 km. They found that: (1) all stratigraphic columns were not the same; some had units that others did not; (2) all stratigraphic columns had at least some of the units that others had despite being greatly separated in space; (3) all stratigraphic columns shared some similar units and these appeared in the same relative stratigraphic sequence in each of the columns; (4) no stratigraphic sequences showed an apparently random distribution of the geologic units identified. These initial results suggested that the correlation of stratigraphic units across at least significance parts of Venus might be possible. Unknown at that time was whether these sequences of units were indeed directly correlative (whether or not you could "walk the contact" to connect them) or whether they might just represent a Wilson cycle-type sequence of events that repeats itself at different times in different parts of the planet, and thus are sequentially similar but not globally correlative.

In parallel with the USGS mapping effort described above, Basilevsky and Head (1997, 1998, 2000, 2002) followed their initial mapping of 36 different stratigraphic columns randomly distributed around Venus (Basilevsky and Head, 1995a,b), and again employed the dual stratigraphic classification approach to analyze stratigraphic units and sequences in intervening areas of Venus, producing additional new stratigraphic columns. These were used (1) to test and modify their initial approach to unit definition, (2) to assess correlations with previously determined stratigraphic columns, and (3) using regional correlations, to interpret the geological history of Venus.

In order to accomplish the task of compiling the global geological map, we have examined and tested the set of material units that was first described in Basilevsky and Head (1995a,b, 1998) and then refined during regional mapping (Ivanov and Head, 2001a, 2004a, 2005a, 2006a, 2008b, 2010a) as the basis for the compilation of the global-scale geological map. Before the compilation of the map, we have tested if the units proposed by Basilevsky and Head (1995a,b, 1998) and their temporal correlations are applicable within large and contiguous regions that include zones within the V-55, V-4, V-13, V-61, and V-3 USGS quadrangles (Ivanov and Head, 2001a, 2004a, 2005a, 2006a, 2008b) and two circum-global zones, the geotraverses, at 30°N (Ivanov and Head, 2001b) and along the equator (Ivanov and Head, 2006b). All these maps (Fig. 1) cover about 60% of the surface of Venus (Table 1). The maps of the quadrangles and geotraverses show the spatial distribution of units that we have defined in the traditional manner of rock-stratigraphic unit definition: If the surface of a terrain has a specific and distinctive morphology which is different from other terrains, this morphology defines a rock unit (e.g., Wilhelms, 1974). We strongly emphasize here that our unit definitions have a pure descriptive character and no a priori hypotheses or models were involved in the definition. Because of this, the units are based fundamentally on their descriptive nature and do not include an interpretative component. The map composed of such units is, thus, a purely descriptive document that provides the base for the further interpretations of the nature of units, their sequences, and age relationships. A purely morphologically defined unit, however, may include materials produced by a variety of processes that may have operated in different areas at different times if the results of these processes have similar morphologic characteristics. For example, two different geological

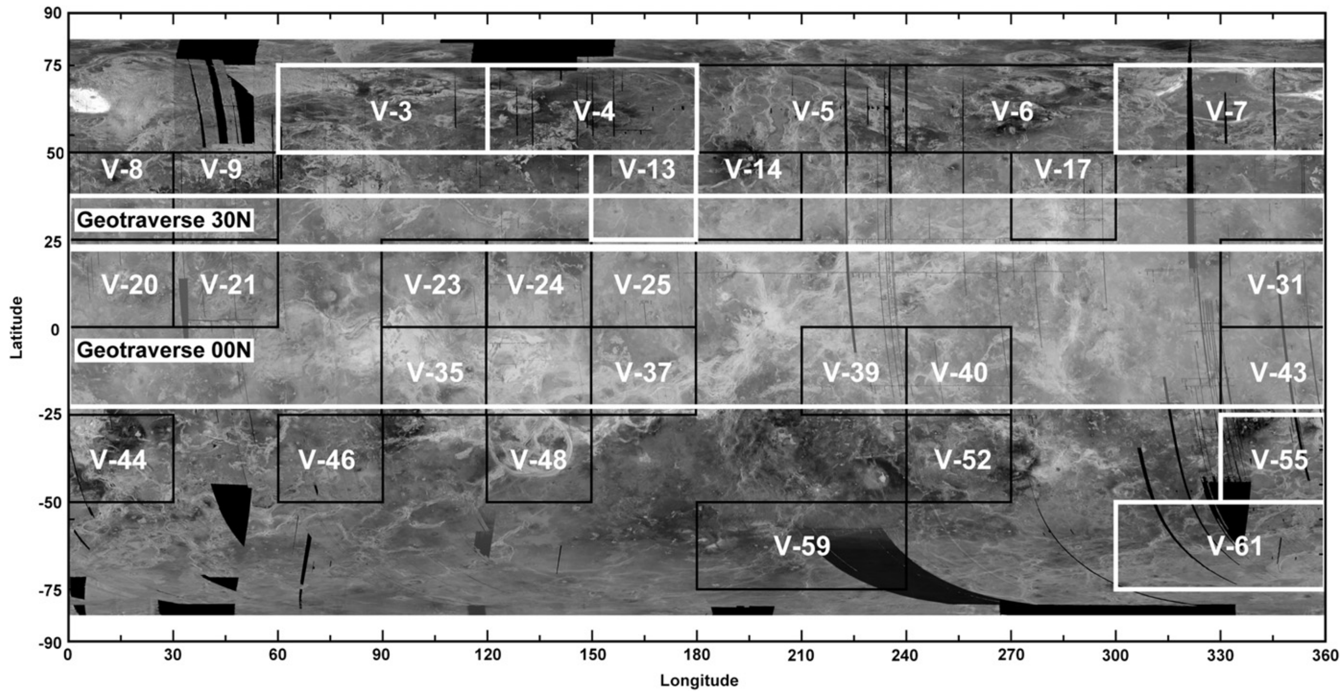

Fig. 1. Position of the published geological maps and the geotraverses at 30°N and 0°N. Areas mapped by Ivanov and Head (2001a,b, 2004a, 2005a, 2006a,b, 2008b, 2010a) are shaded. Simple cylindrical projection.

Table 1
Fraction of the surface of Venus covered by mapping of Ivanov and Head (2001a,b, 2004a, 2005a, 2006a,b, 2008b, 2010a).

Map region	Area, 10^6 km^2	Percent of the surface
Geotraverse 30N	52.8	11.5
Geotraverse 00N	179.0	38.9
V-3	7.7	1.7
V-4	7.7	1.7
V-7	7.7	1.7
V-13	6.6	1.4
V-55	6.6	1.4
V-61	7.7	1.7
Total	275.6	59.9

Table 2
Area of units mapped on the global geological map.

Unit	Area, 10^6 km^2	Percent of the surface
t	33.2	7.3
pdl	7.2	1.6
pr	9.6	2.1
mt	1.3	0.3
gb	37.1	8.1
psh	79.3	17.4
rp1	141.8	31.1
rp2	42.0	9.2
sc	3.3	0.7
rz	22.6	5.0
ps	10.3	2.3
pl	37.8	8.3
c, cf	2.6	0.6
gaps	28.1	6.2
Total	456.3	100.0

Note: Total area is between 82.5°N and 82.5°S.

processes on Venus may have contributed to formation of the material unit of smooth plains that are characterized by morphologically smooth, tectonically undeformed, and usually radar-dark surface. The plains may have either a volcanic nature (for example, if they are found to be associated with volcanic centers), or they may consist of fine-grain fall-out deposits from the ejecta of impact craters (if patches of the plains occur near impact craters).

In the case of Venus where the total number of impact craters is small (Schaber et al., 1992, 1998; Herrick et al., 1997) and erosional processes are inhibited (e.g., Arvidson et al., 1992), the absolute majority of materials that make up the surface have been interpreted to have a volcanic origin (e.g., Head et al., 1992). These units are commonly deformed by tectonic structures to varying degrees (Solomon et al., 1992; Squyres et al., 1992). This situation allows a robust identification of the primary process of formation of the units.

Another issue that is related to the morphological definition of units is the presence of tectonic structures that are secondary features to a material unit. Although we have mapped tectonic structures independently of material units, in several cases the structures are such a pervasive part of morphology that they should be included into the definition of a unit (see the discussion above; Shoemaker et al., 1982; Greeley et al., 2000). For example, our unit of tessera is similar to Aureole member 4 of the Olympus Mons Formation on Mars: "Forms broad…lobes; corrugated, cut by numerous faults that formed scarps and deep troughs and grabens" (Scott and Tanaka, 1986) and ridged plains material is similar to Ridge band material on Europa: "…linear to curvilinear features consisting of alternating ridges and troughs…" (Figueredo and Greeley, 2000). In the definition of these units on Mars and Europa, tectonic structures play a key role. In the published geological maps of Venus, the same approach of using structures in geologic unit definition has been successfully applied in the mapping of several quadrangles that portray geologically diverse provinces (e.g., Rosenberg and McGill, 2001; Bridges and McGill, 2002; Campbell and Campbell, 2002; Hansen and DeShon, 2002). In other cases, where the structures are more discrete and separated, the priority in the definition was given to the material component of the unit. The abundance of tectonic structures and their role in the morphologic characteristics of the surface define three broad categories of units on the global geological map: structural–material, material, and structural units. In the first category, the primary materials are certainly present but they are severely deformed and the priority in the definition of such units is given to the secondary tectonic structures (e.g., tessera). Material units are usually much less deformed and priority in their definition is given to the characteristics of the primary material. The structural units formed by pure tectonic deformation of various older materials and the definition of these units is based on the character and density of tectonic structures.

3. Description of units

The results of our geological mapping in six USGS quadrangles (V-3, V-4, V-7, V-13, V-55, and V-61) and in the geotraverses (Ivanov and Head, 2001b, 2006b) are self-consistent and suggest that a specific set of material, structural–material, and structural units adequately describe the geological situation in these regions. Based on these results, we expanded our mapping to cover Venus globally in order to continue to test the applicability of the proposed stratigraphic reconstructions (e.g., Basilevsky and Head, 1995a,b, 1998; Basilevsky et al., 1997) and to compile a contiguous geological map accompanied by a correlation chart that will represent the geologic history of Venus. In this section we present the morphologic description of units that we mapped in comparison with the units shown in all other geological maps of Venus published recently (Tables 3 and 4). In the description, we follow the general order from the older to younger units.

Tessera (t, Fortuna Formation, Fig. 2a**)**: Tessera was discovered during the Venera-15/16 mission (e.g., Barsukov et al., 1986; Bindschadler and Head, 1991; Sukhanov, 1992) and represents one of the most tectonically deformed types of terrain on Venus. Both the material and tectonic structures play an important role in the definition of tessera and it represents a classic structural–material unit. The materials that form the bulk of tessera are heavily deformed tectonically (Fig. 2a) and the surface of the unit is characterized by at least two sets of intersecting structures, but usually several sets are visible. Tectonic features of both contractional (ridges) and extensional (graben and fractures) origin occur

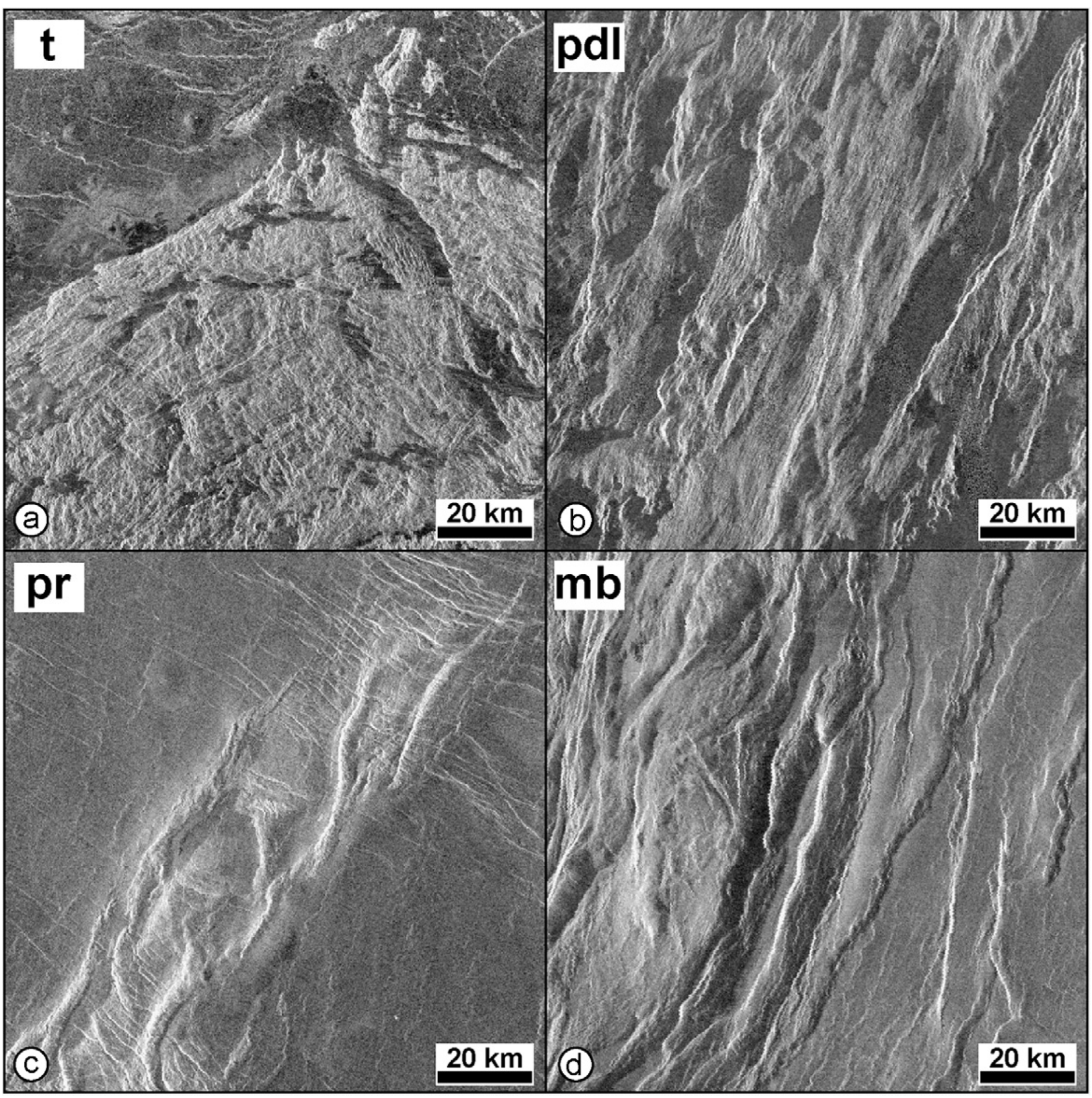

Fig. 2. Examples of the older, heavily tectonized units: (a) tessera (t), fragment of 45n138;1, center of the image is at 51.4°N, 130.2°E; (b) densely lineated plains (pdl), part of C1-75n299;1, center of the image is at 71.2°N, 310.4°E; (c) ridged plains (pr), part of C1-45s350;1, center of the image is at 38.1°S, 348.1°E; (d) mountain belts (mb), part of C1-75n299;1, center of the image is at 67.9°N, 317.5°E. All images are in sinusoidal projection, illumination from the left.

Table 3
Name and location of quadrangles reviewed in this study.

Map	Region	Author(s)
V-3	Meskhent Tessera (50–75°N; 60–120°E)	Ivanov and Head (2008a,b)
V-4	Atalanta Planitia (50–75°N; 120–180°E)	Ivanov and Head (2008a,b)
V-5	Pandrosos Dorsa (50–75°N; 180–240°E)	Rosenberg and McGill (2001)
V-7	Lakshmi Planum (50–75°N; 300–360°E)	Ivanov and Head (2010a,b)
V-8	Bereghinya Planitia (25–50°N; 0–30°E)	McGill (2004)
V-9	Bell Regio (25–50°N; 30–60°E)	Campbell and Campbell (2002)
V-13	Nemesis Tesserae (25–50°N; 150–180°E)	Ivanov and Head (2005a,b)
V-14	Ganiki Planitia (25–50°N; 180–210°E)	Grosfils et al. (2011)
V-17	Beta Regio (25–50°N; 270–300°E)	Basilevsky (2008)
V-20	Sappho Patera (0–25°N; 0–30°E)	McGill (2000)
V-21	Mead (0–25°N; 30–60°E)	Campbell and Clark (2006)
V-23	Niobe Planitia (0–25°N; 90–120°E)	Hansen (2009)
V-24	Greenaway (0–25°N; 120–150°E)	Lang and Hansen (2010)
V-25	Rusalka Planitia (0–25°N; 150–180°E)	Young and Hansen (2004)
V-31	Sif Mons (0–25°N; 330–360°E)	Copp and Guest (2007)
V-35	Ovda Regio (0–25°S; 90–120°E)	Bleamaster and Hansen (2005)
V-37	Diana Chasma (0–25°S; 150–180°E)	Hansen and DeShon (2002)
V-39	Taussig (0–25°S; 210–240°E)	Brian et al. (2005)
V-40	Galindo (0–25°S; 240–270°E)	Chapman (1999)
V-43	Carson (0–25°S; 330–360°E)	Bender et al. (2000)
V-44	Kaiwan Fluctus (25–50°S; 0–30°E)	Bridges and McGill (2002)
V-46	Aino Planitia (25–50°S; 60–90°E)	Stofan and Guest (2003)
V-48	Artemis Chasma (25–50°S; 120–150°E)	Bannister and Hansen (2010)
V-52	Helen Planitia (25–50°S; 240–270°E)	Lopez and Hansen (2008)
V-55	Lavinia Planitia (25–50°S; 330–360°E)	Ivanov and Head (2001)
V-59	Barrymore (50–75°S; 180–210°E)	Johnson et al. (1999)
V-61	Mylitta Fluctus (50–75°S; 300–360°E)	Ivanov and Head (2006a,b)

at different scales, from a few hundred meters up to several tens of kilometers in width and up to several hundreds of kilometers in length. A diagnostic characteristic of tessera is its high radar backscatter cross-section, which is noticeably higher than that of the surroundings (e.g., Bindschadler et al., 1990). The surface is rough at all scales compared to most other units and usually stands topographically higher than the surroundings. Occurrences of tessera are mostly equidimensional or slightly elongated (with a few exceptions, e.g., Nemesis Tessera) and vary in size from a few tens of kilometers up to a few thousands of kilometers (Ivanov and Head, 1996). Owing to its very specific characteristics, tessera is one of the most prominent units on Venus and all geologists who map the surface of Venus show this unit if it exists in the region of the mapping (Fig. 3).

On the basis of the new global map, tessera occupies about 33.2×10^6 km^2 (7.3% of the mapped area, Table 2), which is slightly less than the ~8% reported earlier (Ivanov and Head, 1996). This unit is non-randomly distributed on the surface of Venus (Ivanov and Head, 1996) and tends to occur within several extensive provinces (Fig. 4a): in and around Ishtar Terra (I in Fig. 4a), in a group that includes Thetis, Ovda, and Alpha Tesserae (A-T in Fig. 4a), and in a large area between Nemesis Tessera and Beta-Phoebe Regiones (N-P in Fig. 4a). These major clusters of larger and smaller tessera massifs are shown by dashed lines in Fig. 4a. Smaller tessera massifs preferentially occur within these clusters and generally are not seen outside of them. The high topography of the large tessera regions (Ivanov and Head, 1996) (Fig. 5a) prevents their flooding by successive plains units that were only able to embay the high-standing massifs. Thus, the areal distribution of the larger tesserae may indicate the major sites where they preferentially formed. A very important characteristic of tessera is that the boundaries of its massifs provide compelling evidence for embayment by materials of the other units (e.g., high sinuosity of tessera boundaries due to penetration of younger materials into tessera, Figs. 2a and 3). This stratigraphic relationship by so many units provides evidence that tessera represents one of the stratigraphically oldest units. Due to the extensive deformation of tessera, remnants of preexisting (or precursor) materials are rarely observed within tessera outcrops, and are almost never seen in small tessera fragments. The few materials that have survived tectonic modification in the larger tessera regions appear to have the morphology of lava plains (Ivanov, 2001). Type locations of tessera are at 33.0°N, 98.8°E; 8.5°S, 126.0°E.

Densely lineated plains (pdl, Atropos Formation, Fig. 2b): The surface of this unit is heavily dissected by numerous densely packed lineaments, which are narrow (from a few hundred meters wide and down to the resolution limit), relatively short (a few tens of kilometers long), and parallel or subparallel to each other (Fig. 2b). If the lineaments are wide enough they usually appear as fractures. The characteristic pattern of deformation plays a very important role in the definition of densely lineated plains and thus this unit represents a typical structural–material unit. Densely lineated plains occupy a small area of the global map, about 7.2×10^6 km^2 (1.6% of the mapped area, Table 2) and are observed as slightly elevated and usually small (tens of kilometers across) occurrences. The hypsogram of these plains is almost coincident with the total hypsogram (Fig. 5b). Equidimensional, elongated, and arc-like fragments of these plains have a noticeably high radar backscatter cross-section, which, however, is lower than that of tessera. Arcuate patches of the plains often occur in the rims of coronae and corona-like features. Fragments of the plains are more evenly distributed over the surface of Venus than those of tessera (compare Fig. 4a and b) and do not form distinctive clusters. The characteristically low relief of the occurrences of densely lineated plains (in contrast with the high-standing outcrops of tessera, for example) suggests that they can be relatively easily covered by the later volcanic plains. The wide areal distribution of fragments of pdl may imply relatively thin younger embaying plains that were not able to completely hide the occurrences of densely lineated plains from view. Some large and low-lying plains in the southern hemisphere of Venus (Helen, Aino, Laimdota, Imapinua, and Zhibek Planitiae), however, lack occurrences of pdl (Fig. 4b), which suggests that the thickness of the younger plains in these regions is greater.

Table 4
Comparison of units in the global map with the units mapped in specific quadrangles.

Map	Unit	Unit name	Comment	Lat.	Lon.	Fig.
Tessera (t)						
V-05	t	Tessera	Specific unit	58.6	201.3	3a
V-08	t	Tessera material	Specific unit	40.8	0.8	3b
V-09	t	Tessera material	Specific unit	44.5	48.7	3c
V-14	t	Tessera terrain	Specific unit	41.3	186.9	3d
V-17	t	Tessera material	Specific unit	30.5	286.5	3e
V-20	t	Tessera material	Specific unit	17.9	12.9	3f
V-21	t	Tessera material	Specific unit	20.7	44.6	3g
V-23	rtHG	Haasttse-baad and Gegute ribbon-tessera terrain	Specific unit	7.1	111.8	3h
V-24	rtGH	Tessera terrain of Gegute and Haasttse-baad Tssr.	Specific unit	6.9	131.9	3i
V-25	bU	Basal material of Urutonga Colles	Specific unit	22.9	159.4	3j
V-31	t	Tessera material	Specific unit	20.1	355.7	3k
V-35	tO	Ovda Regio tessera terrain	Specific unit	−10.3	100.3	3l
V-37	tN	Nuahine Tessera material	Specific unit	−6.2	156.2	3m
V-39		NO t IN THIS AREA				3n
V-40	tpr	Tessera material of Phoebe Regio	Specific unit	−8.0	267.5	3o
V-43	t	Tessera material	Specific unit	−22.1	360.6	3p
V-44	t	Tessera material	Specific unit	−29.2	8.6	3q
V-46	t	Tessera material	Specific unit	−25.1	62.3	3r
V-48		NO t IN THIS AREA				3s
V-52	tu	Tessera terrain, undivided	Specific unit	−49.9	262.8	3t
V-59		NO t IN THIS AREA				–
Densely lineated plains (pdl)						
V-05	t	Tessera	Specific unit	64.8	216.9	6a
V-08	pb	Bright plains material	Specific unit	46.5	0.8	6b
V-09	prl	Densely lineated plains material	Specific unit	27.0	53.5	6c
V-14	pl	Lineated plains material	Specific unit	39.4	201.5	6d
V-17	pdf	Densely fractured plains material	Specific unit	44.6	290.1	6e
V-20	pl	Lineated plains material	Specific unit	19.3	3.5	6f
V-21	ld	Densely lineated material	Specific unit	0.0	48.8	6g
V-23	frN	Niobe Planitia fracture terrain	Specific unit			6h
V-24	lL	Llorona Planitia lineated terrain	Specific unit			6i
V-25	fu	Flow material, undifferentiated	Not mapped	18.0	159.7	6j
V-31	t	Tessera material	Specific unit	10.5	338.4	6k
V-35	tO	Ovda Regio tessera terrain	Specific unit	−16.3	91.8	6l
V-37		NO pdl IN THIS AREA				6m
V-39	pdf	Densely fractured plains material	Specific unit	−7.7	232.5	6n
V-40	tpr	Tessera material of Phoebe Regio	Specific unit	−10.8	241.9	6o
V-43	t	Tessera material	Specific unit	−12.8	350.7	6p
V-44	t	Tessera material	Specific unit	−26.4	12.8	6q
V-46	pdAb	Aino deformed plains material, unit b	Specific unit	−25.6	63.1	6r
V-48		NO pdl IN THIS AREA				6s
V-52	tu	Tessera terrain, undivided	Specific unit			6t
V-59	t	Tessera material	Specific unit	−65.7	204.3	–
Ridged plains (pr)						
V-05	blb	Linear belt material b	Specific unit	63.7	213.9	8a
V-08	pr	Regional plains material	Ridges as lines	47.5	22.5	8b
V-09	prrd	Densely ridged plains material	Ridges as lines	26.2	35.7	8c
V-14	bl	Deformation belt material	Specific unit	40.3	195.7	8d
V-17	pfr	Fractured and ridged plains material	Specific unit	26.2	297.7	8e
V-20	pt	Textured plains material	Specific unit	18.4	21.0	8f
V-21	pr	Regional plains material	Ridges as lines	19.3	31.6	8g
V-23	rtO	Ovda Regio ribbon-tessera terrain	Specific unit	5.0	105.1	8h
V-24		NO pr IN THIS AREA				8i
V-25	bU	Basal material of Urutonga Colles	Specific unit	22.1	157.4	8j
V-31		NO pr IN THIS AREA				8k
V-35	fR	Rosmerta Corona flow material	Ridges as lines	−2.9	119.9	8l
V-37	cSi	Sith Corona flow material	Ridges as lines	−9.2	177.7	8m
V-39		NO pr IN THIS AREA				8n
V-40		NO pr IN THIS AREA				8o
V-43	pc	Plains material, unit c	Specific unit	−6.1	342.8	8p
V-44	b	Belt material	Specific unit	−47.9	27.4	8q
V-46		NO pr IN THIS AREA				8r
V-48	fcAa	Composite flow material b of Artemis	Ridges as lines	−32.1	120.8	8s
V-52		NO pr IN THIS AREA				8t
V-59	pr	Regional plains material	Ridges as lines	−54.1	209.1	–
Groove belts (gb)						
V-05	cob	Corona material b	Grooves as lines	66.4	219.9	10a
V-08	pb	Bright plains material	Specific unit	42.6	7.3	10b
V-09	prr	Ridged plains material	Grooves as lines	38.5	59.9	10c
V-14	fe	Volcanic edifice flow material	Grooves as lines	26.6	205.2	10d
V-17	fb	Fracture belts	Specific unit	37.0	271.9	10e
V-20	prb	Regional plains material, member b	Grooves as lines	13.3	22.6	10f

Table 4 (*continued*)

Map	Unit	Unit name	Comment	Lat.	Lon.	Fig.
V-21	ld	Densely lineated material	Specific unit	10.8	37.0	10g
V-23	frN	Niobe Planitia fracture terrain	Grooves as lines	18.1	98.8	10h
V-24	lL	Llorona Planitia lineated terrain		18.1	140.4	10i
V-25	sU	Shield field material of Urutonga Colles	Grooves as lines	3.0	151.9	10j
V-31	fB2	Benten Corona flow material 2	grooves as lines	14.5	340.2	10k
V-35	fchu	Chasmata flow material, undifferentiated	Grooves as lines	−18.5	98.2	10l
V-37	cSe	Sela Corona flow material	Grooves as lines	−1.4	152.9	10m
V-39	fLe1	Lengdin Corona flow material, member 1	Grooves as lines	−1.4	220.8	10n
V-40	f2	Flow materials, unit 2	Grooves as lines	−8.4	251.5	10o
V-43	fd	Digitate flows	Grooves as lines	−20.7	352.2	10p
V-44	prl	Lineated regional plains material	Specific unit	−34.0	25.9	10q
V-46	pfA	Aino fractured plains material	Specific unit	−34.0	74.4	10r
V-48	fu	Flows, undivided	Grooves as lines	−47.9	137.0	10s
V-52	hu	Heterogeneous material, undivided	Grooves as lines	−38.6	246.0	10t
V-59		NO gb IN THIS AREA				–
Shield plains (psh)						
V-05	pm	Mottled local plains material	Specific unit	57.9	200.5	12a
V-08	pr	Regional plains material	Specific unit	30.3	18.8	12b
V-09	prrd	Densely ridged plains material	Specific unit	43.1	57.1	12c
V-14	ps	Shield plains material	Specific unit	27.9	204.9	12d
V-17	psh	Shield plains material	Specific unit	37.6	276.2	12e
V-20	fs	Shield field flow material	Specific unit	8.4	6.9	12f
V-21	phO	Homogenous plains material of Ovda Regio	Specific unit	5.7	53.9	12g
V-23	s	Shield terrain	Specific unit	15.7	101.7	12h
V-24	st	Shield terrain	Specific unit	21.5	137.5	12i
V-25	bU	Basal material of Urutonga Colles	Specific unit	15.2	158.0	12j
V-31	plmG	Guinevere Planitia lineated and mottled pl. Mat.	Specific unit	12.1	333.3	12k
V-35	fb2	Basal flow material, member 2	Specific unit	−21.1	94.0	12l
V-37	itb	Intratessera basin material	Specific unit	−9.0	159.2	12m
V-39	ef	Edifice field material	Specific unit	−12.8	231.1	12n
V-40	pt	Tessera-embaying plains material	Specific unit	−8.5	265.3	12o
V-43	pml	Mottled, lineated plains material	Specific unit	−11.4	337.5	12p
V-44	prt	Textured regional plains material	Specific unit	−34.9	9.9	12q
V-46	e	Edifice field material	Specific unit	−27.6	79.7	12r
V-48	fcAb	Composite flow material b of Artemis	Specific unit	−32.1	139.6	12s
V-52	hu	Heterogeneous material, undivided	Specific unit	−44.8	250.3	12t
V-59	df	Dome fields	Specific unit	−66.4	185.0	–
Regional plains, lower unit (rp_1)						
V-05	prc	Radar-dark regional plains material	Specific unit	56.4	180.9	13a
V-08	pr	Regional plains material	Specific unit	38.5	4.9	13b
V-09	prr	Ridged plains material	Specific unit	40.1	51.3	13c
V-14	pr_2	Regional plains material, 2	Specific unit	31.5	197.3	13d
V-17	pwr1	Wrinkle ridged plains material, member 1	Specific unit	47.4	277.8	13e
V-20	prb	Regional plains material, member b	Specific unit	18.9	11.7	13f
V-21	pr	Regional plains material	Specific unit	4.8	35.4	13g
V-23	s	Shield terrain	Specific unit	17.4	91.8	13h
V-24	st	Shield terrain	Specific unit	18.4	145.6	13i
V-25	fu	Flow material, undifferentiated	Specific unit	17.4	166.8	13j
V-31	prG	Guinevere Planitia regional plains material	Specific unit	17.3	333.8	13k
V-35	fb2	Basal flow material, member 2	Specific unit	−22.8	93.0	13l
V-37	cES	Eigin and Saunau Coronae flow mat., undiff.	Specific unit	−3.7	161.4	13m
V-39	prT	Taussig regional plains material	Specific unit	−20.8	226.1	13n
V-40	pd	Radar-dark plains material	Specific unit	−9.8	259.0	13o
V-43	pr	Regional plains material	Specific unit	−16.4	358.1	13p
V-44	prl	Lineated regional plains material	Specific unit	−25.1	24.4	13q
V-46	pcA	Aino composite plains material	Specific unit	−27.8	70.4	13r
V-48	fu	Flows, undivided	Specific unit	−45.0	128.6	13s
V-52	hu	Heterogeneous material, undivided	Specific unit	−48.6	263.3	13t
V-59	pr	Regional plains material	Specific unit	−55.5	217.2	–
Regional plains, upper unit (rp_2)						
V-05	pra	Radar-bright regional plains material	Specific unit	55.4	182.3	14a
V-08	fcu	Corona flow material, undifferentiated	Specific unit	39.7	16.5	14b
V-09	prr	Ridged plains material	Specific unit	40.7	55.8	14c
V-14	pr_1	Regional plains material, 1	Specific unit	39.4	189.3	14d
V-17	pwr2	Wrinkle ridged plains material, member 2	Specific unit	49.2	280.8	14e
V-20	f	Flow material, undifferentiated	Specific unit	21.8	9.2	14f
V-21	fc	Flow material of coronae	Specific unit	22.3	42.0	14g
V-23	cob	Crater outflow material, unit b	Specific unit	17.6	95.0	14h
V-24	fcI	Ituana Corona flow material	Specific unit	19.1	148.4	14i
V-25	fcIt	Flow material of Ituana Corona	Specific unit	16.7	151.1	14j
V-31	fB1	Benten Corona flow material 1	Specific unit	8.9	339.9	14k
V-35	fLS	Lo Shen Valles flow material	Specific unit	−19.7	90.9	14l
V-37	cES	Eigin and Saunau Coronae flow mat., undiff.	Specific unit	0.8	174.9	14m
V-39	pli	Lineated plains material	Specific unit	−10.7	216.5	14n

Table 4 (*continued*)

Map	Unit	Unit name	Comment	Lat.	Lon.	Fig.
V-40	mb	Mons materials, unit b	Specific unit	−9.2	255.7	14o
V-43	fd	Digitate flows	Specific unit	−11.3	354.8	14p
V-44	fd	Digitate and lobate flow material	Specific unit	−24.8	22.9	14q
V-46	fCpa	Copia Corona flow material, unit a	Specific unit	−37.0	61.4	14r
V-48	fu	Flows, undivided	Specific unit	−46.4	146.9	14s
V-52	fcOA	Flows from Oanuava Coronae and Achall Corona	Specific unit	−34.1	250.6	14t
V-59	prm	Mottled ridged plains material	Specific unit	−49.8	223.2	–
Shield clusters (sc)						
V-05	fd	Digitate flow material	Specific unit	56.3	218.0	17a
V-08		NO sc IN THIS AREA				17b
V-09		NO sc IN THIS AREA				17c
V-14		NO sc IN THIS AREA				17d
V-17						17e
V-20	fl	Irnini Mons flow material	Specific unit	16.7	18.5	17f
V-21		NO sc IN THIS AREA				17g
V-23		NO sc IN THIS AREA				17h
V-24		NO sc IN THIS AREA				17i
V-25	mZa	Zaltu Mons sourced flow material	Specific unit	17.7	163.4	17j
V-31	ef	Edifice field material	Specific unit	18.0	352.8	17k
V-35	fl1b	Inari Corona flow material, member 1b	Specific unit	−18.0	113.0	17l
V-37	sf	Shield field flow material	Specific unit	−0.6	164.7	17m
V-39		NO sc IN THIS AREA				17n
V-40	cok	Corona materials, unit k	Specific unit	−17.1	245.5	17o
V-43	fm	Mottled flows	Specific unit	−4.9	345.4	17p
V-44	fUA	Ubastst Fluctus and Astkhik Planum flow mat.	Specific unit	−48.5	22.8	17q
V-46	sK2	Kunapipi summit material, unit 2	Specific unit	−33.9	86.1	17r
V-48		NO sc IN THIS AREA				17s
V-52	fsZ	Flows and shield-related materials around Zerine	Specific unit	−29.0	253.2	17t
V-59		NO sc IN THIS AREA				–
Smooth plains (ps)						
V-05	prc	Radar-dark regional plains material	Specific unit	57.2	224.8	18a
V-08	pr	Regional plains material	Specific unit	47.9	29.3	18b
V-09	fN2	Middle lobate material of Nyx Mons	Specific unit	33.5	47.1	18c
V-14	pr_1	Regional plains material, 1	Specific unit	27.5	191.9	18d
V-17		NO ps IN THIS AREA				18e
V-20	prb	Regional plains material, member b	Specific unit	20.7	4.5	18f
V-21	fc	Flow material of coronae	Specific unit	18.0	49.7	18g
V-23	fsu	Smooth flows, undivided	Specific unit	8.4	98.0	18h
V-24	fcR	Rosmerta Corona flow material	Specific unit	5.4	125.5	18i
V-25		NO ps IN THIS AREA				18j
V-31		NO ps IN THIS AREA				18k
V-35	fTh	Tahmina Planitia flow material	Specific unit	−24.9	99.7	18l
V-37	cCBM	Ceres, Bona, and Miralaidji Cor. flow mat., undiff.	Specific unit	−24.8	150.4	18m
V-39		NO ps IN THIS AREA				18n
V-40	coo	Corona materials, unit o	Specific unit	−15.8	263.4	18o
V-43	cpC	Crater parabolic egjecta material, Carson	Specific unit	−22.3	345.0	18p
V-44	prh	Homogenous regional plains material	Specific unit	−34.9	12.4	18q
V-46		NO ps IN THIS AREA				18r
V-48	fcCBM	Ceres, Bona, and Miralaidji Coronae flow material.	Specific unit	−26.9	148.6	18s
V-52	hu	Heterogeneous material, undivided	Specific unit	−37.3	257.3	18t
V-59		NO ps IN THIS AREA				–
Lobate plains (pl)						
V-05	fd	Digitate Flow Material		57.1	219.0	19a
V-08	fcO1	Onatah Corona flow material, member 1	Specific unit	49.5	8.8	19b
V-09	fN3	Upper lobate material of Nyx Mons	Specific unit	25.6	49.0	19c
V-14	fe	Volcanic edifice flow material	Specific unit	39.9	205.5	19d
V-17	pl	Lobate plains material	Specific unit	27.6	280.8	19e
V-20	fA	Anala Mons flow material	Specific unit	12.1	12.3	19f
V-21	fc	Flow material of coronae	Specific unit	15.7	36.7	19g
V-23	fsu	Smooth flows, undivided	Specific unit	9.9	96.8	19h
V-24	fcR	Rosmerta Corona flow material	Specific unit	1.5	127.7	19i
V-25	fcZy	Zaryanitsa Dorsa regional flow material	Specific unit	5.9	160.5	19j
V-31	eS	Sif Mons material	Specific unit	22.4	352.6	19k
V-35	fl2	Inari Corona flow material, member 2	Specific unit	−20.0	115.1	19l
V-37	cMa	Miralaidji Corona flow material, unit a	Specific unit	−11.1	164.0	19m
V-39	fMb	Mbokomu Mons flow material	Specific unit	−15.4	217.2	19n
V-40	mf	Mons materials, unit f	Specific unit	−14.3	262.2	19o
V-43	fcTM	Corona flows, Takus Mana	Specific unit	−18.8	345.0	19p
V-44	fUA	Ubastst Fluctus and Astkhik Planum flow mat.	Specific unit	−49.2	24.3	19q
V-46	fK2	Kunapipi flow material, unit 2	Specific unit	−37.2	88.3	19r
V-48	fcAa	Composite flow material b of Artemis	Specific unit	−31.6	125.3	19s
V-52	fchP	Flows from fractures and coronae of Parga Chasmata	Specific unit	−31.6	264.6	19t
V-59		NO pl IN THIS AREA				–

Table 4 (*continued*)

Map	Unit	Unit name	Comment	Lat.	Lon.	Fig.
Rift zones (rz)						
V-05		NO rz IN THIS AREA				20a
V-08		NO rz IN THIS AREA				20b
V-09		NO rz IN THIS AREA				20c
V-14	pr_1	Regional plains material, 1	Grooves as lines	29.8	200.9	20d
V-17	r	Rifted terrain	Specific unit	28.3	283.3	20e
V-20	prb	Regional plains material, member b	Grooves as lines	17.6	2.5	20f
V-21		NO rz IN THIS AREA				20g
V-23		NO rz IN THIS AREA				20h
V-24	fcR	Rosmerta Corona flow material	Grooves as lines	4.7	123.9	20i
V-25		NO rz IN THIS AREA				20j
V-31		NO rz IN THIS AREA				20k
V-35	fl1a	Inari Corona flow material, member 1a	Grooves as lines	−17.2	111.4	20l
V-37	cK	Khabuchi Corona flow material	Grooves as lines	−12.2	170.6	20m
V-39	fC2	Chantico Corona flow material, member 2	Grooves as lines	−3.0	217.2	20n
V-40	mf	Mons materials, unit f	Grooves as lines	−11.3	263.1	20o
V-43		NO rz IN THIS AREA				20p
V-44	prl	Lineated regional plains material	Grooves as lines	151.6	13.1	20q
V-46		NO rz IN THIS AREA				20r
V-48	fu	Flows, undivided	Grooves as lines	−26.2	139.2	20s
V-52	fchP	Flows from fractures and coronae of Parga Chasmata	Grooves as lines	−30.5	266.5	20t
V-59		NO rz IN THIS AREA				–

Except for the V-37 quadrangle (Hansen and DeShon, 2002), densely lineated plains are seen in all published geological maps of Venus (Fig. 6) where they have almost identical morphologic characteristics, but have been mapped under different names; "Densely lineated material" (Rosenberg and McGill, 2001; Campbell and Campbell, 2002; Campbell and Clark, 2006), "Basal material of Urotonga Colles" (Young and Hansen, 2004), "Aino deformed plains material" (Stofan and Guest, 2003), etc.

In places where tessera and densely lineated plains are in contact there is evidence for embayment of tessera by pdl material. It is not typical of pdl, however, to occur preferentially at tessera margins (Fig. 4b). Such relationships suggest an older age for tessera but the majority of the occurrences of densely lineated plains are away from the contact with tessera and thus, partially contemporaneous formation of these units cannot be ruled out. Moreover, some large massifs of pdl (e.g., Atropos Tessera, Fig. 4b) are additionally deformed and their surface demonstrates a tessera-like structural pattern (Ivanov and Head, 2001b, 2008a, 2010a). The existence of this type of morphology, which has characteristics of both tessera and densely lineated plains, the tessera transitional terrain (ttt) (Ivanov and Head, 2001b), suggests that times of formation of these units may overlap each other in some cases. Vast and mildly deformed plains units (shield plains and regional plains) embay all occurrences of the unit pdl and, thus represent the upper stratigraphic limit for densely lineated plains.

In the majority of occurrences of pdl the lineaments are packed so densely that they completely obscure the morphology of the precursor materials. In some patches of the plains, however, remnants of preexisting material are visible between the lineaments and show the smooth morphology of lava plains. The materials of pdl are interpreted to be volcanic plains, heavily deformed by extensional and/or shear structures. Type locations of densely lineated plains are at 67.2°N, 309.0°E; 43.8°N, 298.9°E.

Ridged plains (pr, Lavinia Formation, Fig. 2c**):** Materials of ridged plains have the morphology of lava plains that are often deformed by broad (5–10 km wide) and long (several tens of kilometers) linear and curvilinear ridges (Fig. 2c). Where pr is not prominantly ridged, it has a gently rolling and morphologically smooth surface that is slightly elevated above the surroundings. The ridges typically have a smooth surface and a rounded and slightly undulating crest area, and they appear to be symmetrical in cross-section. Very often the ridges are collected into prominent belts (ridge belts; Frank and Head, 1990; Kryuchkov, 1992). The radar backscatter cross-section of ridged plains (both the plains and ridged facies) is noticeably higher than that of the surrounding regional plains (McGill and Campbell, 2006) but typically lower than that of tessera and densely lineated plains. Clear differences in the radar albedo, together with embayment relations, help to establish the older ages of ridged plains/ridge belts relative to regional plains (e.g., McGill and Campbell, 2006). Ridged plains and ridge belts occupy about 9.6×10^6 km^2 (2.1% of the mapped area, Table 2) and usually form elongated occurrences hundreds of kilometers long and many tens (to a few hundred) kilometers wide (Fig. 7a). Fragments of ridged plains and, especially, ridge belts, have higher relief than patches of densely lineated plains and the hypsogram of ridged plains is slightly shifted toward higher elevations relative to the total hypsogram (Fig. 5c). The topographic configuration of fragments of the plains suggests that they are less sensitive to later embayment and flooding. Thus, the actual distribution of ridged plains/ridge belts is likely to mark the regions where these features formed. The most prominent occurrence of ridge belts is located within a broad fan-shaped area that includes parts of Vinmara, Atalanta, Ganiki, and Vellamo Planitiae. centered at ~200°E (Fig. 7a), which has been known since the Venera-15/16 mission (Barsukov et al., 1986; Frank and Head, 1990; Kryuchkov, 1990, 1992). The other major occurrences of ridge belts/ridged plains are between Ovda and Thetis Regiones and in the southern hemisphere within Lavinia Planitia (Squyres et al., 1992; Ivanov and Head, 2001a).

In places where ridged plains occur in contact either with tessera or densely lineated plains, material of the ridged plains embays these units, which suggests that both emplacement and deformation of ridged plains took place after formation of the units t and pdl. Many of the fragments of ridged plains, however, are away from massifs of tessera and densely lineated plains (Fig. 7a) and it is impossible to establish directly the age relationships between and among these units in these cases. In some places at the contact with tessera (W edge of Alpha Tessera, SW edge of Tellus Tessera, tesserae in Beta Regio, northern edge of Ovda Tessera; Gilmore and Head, 2000; Ivanov and Head, 2001b; Basilevsky, 2008) ridge belts are additionally deformed by tectonic structures and have a tessera-like pattern of deformation

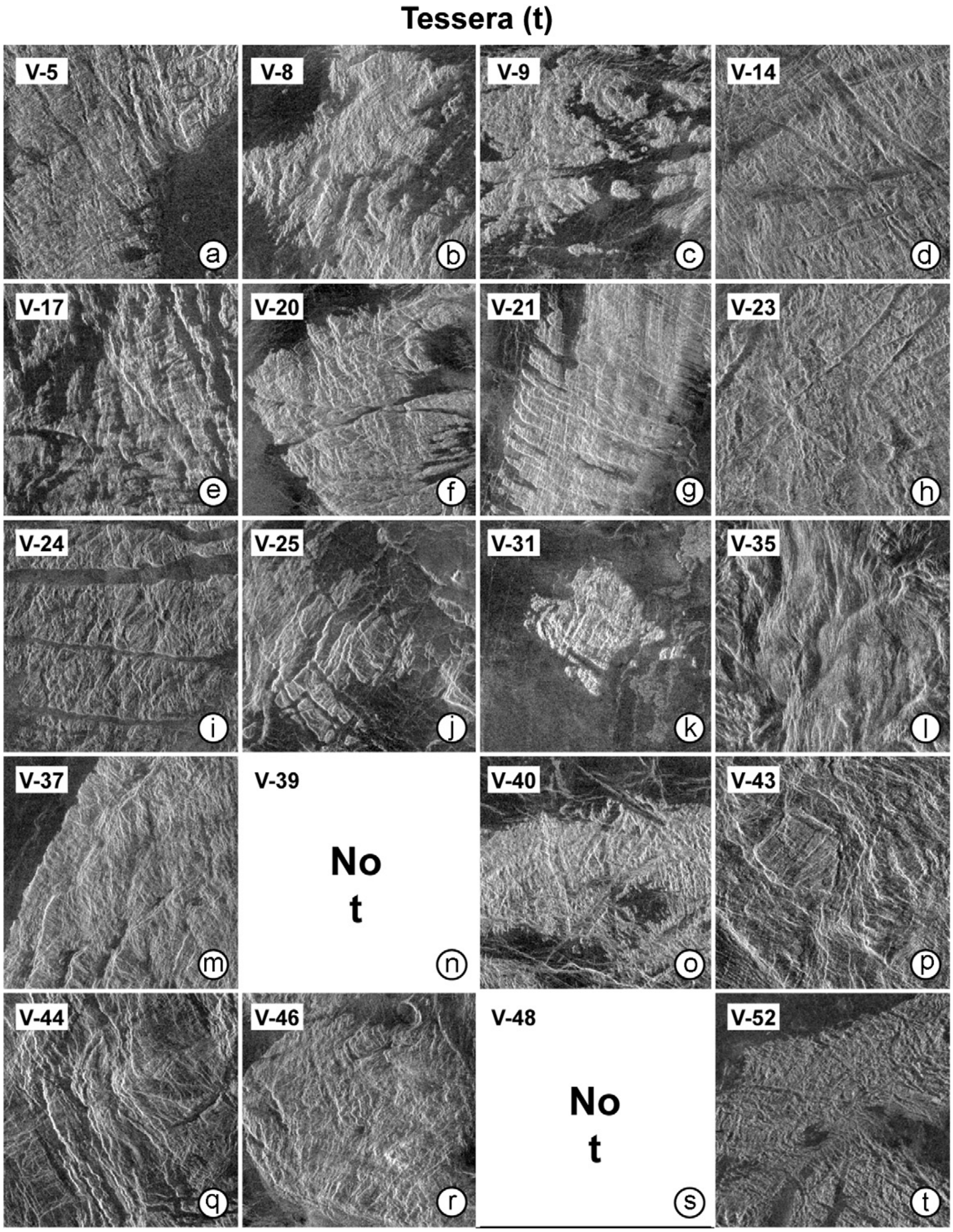

Fig. 3. A mosaic of images of tessera (unit t, Fig. 2a) taken from the published USGS geological maps. See Table 4 for the coordinates of the centers of the images and the original name of the units in each quadrangle. Each image is 57.6 × 57.6 km.

(the ttt-terrain), which suggests (as in the case of densely lineated plains) that formation of tessera and ridged plains may have partly overlapped in time. Mildly deformed vast plains (e.g., shield plains, regional plains) embay occurrences of ridged plains and represent the upper stratigraphic limit for this unit.

Quadrangles V-31 (Copp and Guest, 2007), V-39 (Brian et al., 2005), V-40 (Chapman, 1999), and V-46 (Stofan and Guest, 2003) lack ridged plains/belts (Fig. 8). In all other mapped areas the ridged plains/belts occur and show almost identical morphology. Some researchers, however, have chosen to map ridges of ridged plains as structures and not as a specific unit (Johnson et al., 1999; Campbell and Campbell, 2002; Hansen and DeShon, 2002; McGill, 2004; Campbell and Clark, 2006). Materials of ridged plains are interpreted to be volcanic plains deformed by contractional tectonic structures. Type locations are at 64.8°N, 190.2°E; 39.3°N, 157.3°E.

Mountain belts (mb, Akna Formation, Fig. 2**d):** This unit comprises a tiny portion of the global mapped area (1.3×10^6 km^2 or 0.3% of the mapped surface, Table 2) and occurs only in the area surrounding Lakshmi Planum (Fig. 7a). It is important, however, because it represents the only real mountain ranges on Venus

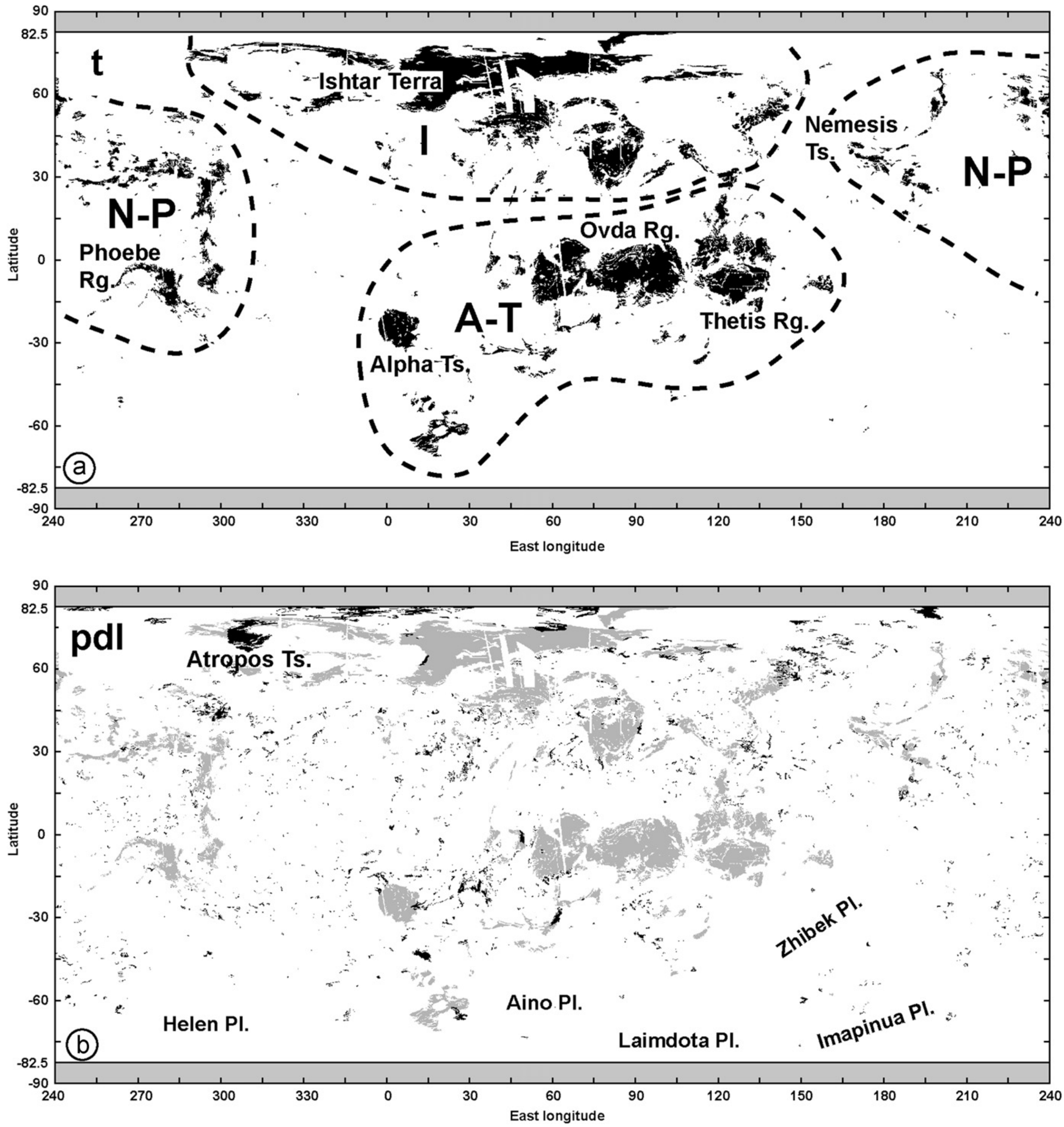

Fig. 4. (a) Areal distribution of tessera (t) on Venus. Dashed lines outline major clusters: I—Ishtar cluster, A-T—Alpha-Thetis cluster, N-P—Nemesis-Phoebe cluster. (b) Areal distribution of densely lineated plains (pdl, black) on Venus. For reference, the tessera distribution is shown in light gray. Simple cylindrical projection.

(Pettengill et al., 1980; Masursky et al., 1980; Barsukov et al., 1986; Head, 1990; Pronin, 1992). Densely packed ridges that are 5–15 km wide and tens to a few hundreds of kilometers long characterize all mountain belts. Morphologically, the belts resemble ridge belts but strongly differ from them in their topographic characteristics (Fig. 5d). Mountain belts represent a structural unit and various materials may have been involved in their formation. There are four mountain belts. The belt of Danu Montes, which is about 100 km wide and reaches an elevation about 1 km above the surface of the plateau of Lakshmi Planum, extends for about 1000–1200 km along the southern margin of Lakshmi (DM in Fig. 7a). Akna Montes represent a shorter (about 800–900 km), wider (about 200 km), and higher (about 3 km above the surface of the plateau) mountain range, which is slightly convex toward the plateau of Lakshmi (AM in Fig. 7a). The mountain belt of Freyja Montes (FM in Fig. 7a) forms the northern and northeastern boundary of Lakshmi Planum. This belt is wide (about 300 km) and high (about 3 km above the surface of Lakshmi) and characterized by complicated structure consisting of several domains with their own pattern of deformation. The mountain range of Maxwell Montes is at the eastern edge of Lakshmi Planum (MM in Fig. 7a) and is the highest mountain construct on Venus (about 12 km above mean planetary radius, about 8 km above the surface of Lakshmi).

Broad ridges similar to those seen within the mountain belts additionally deform densely lineated plains within Atropos

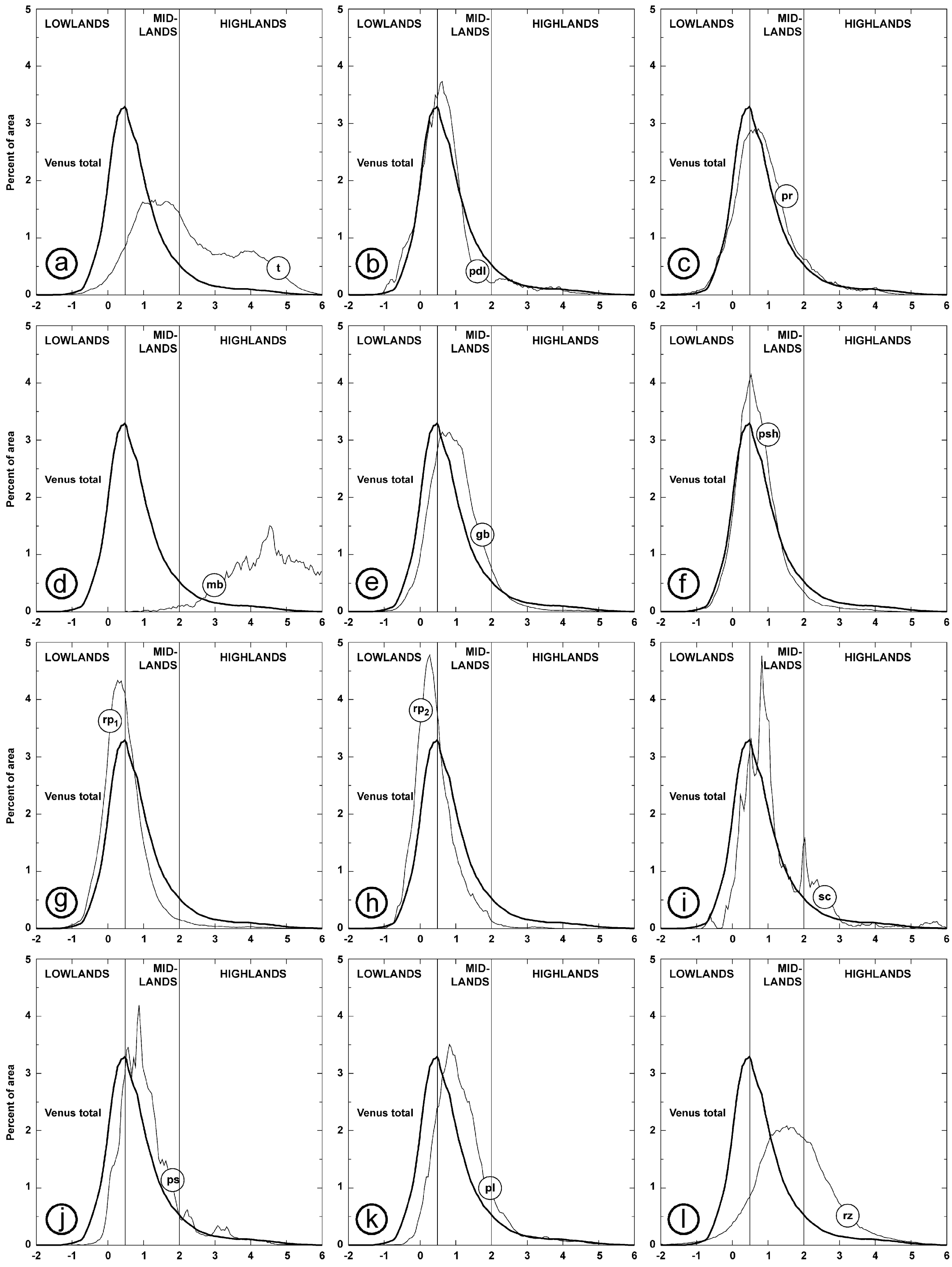

Fig. 5. Series of hypsograms for the units that compose the global geological map. Each hypsogram is shown in comparison with the total hypsogram. In order to emphasize the general topographic configuration of the units, each hypsogram (including the total one) was normalized to the area of the corresponding unit. Thus, the area below each curve (except the curve for mountain belt) is almost 100%.

Tessera (west of Akna Montes) and Itzpapalotl Tessera (north of Freyja Montes). Thus, the belts apparently postdate formation of these units at Lakshmi Planum (Ivanov and Head, 2008a). Ridges at the inner side of the belts (with respect to Lakshmi Planum) are embayed by material of regional plains that covers the surface of the plateau. The surface of the plains, however, is tilted toward the mountain belts and deformed by wrinkle-type ridges that are parallel to the trend of the belt. These relationships suggest that formation of the morphologically distinctive, short-wavelength structures of the belts (an orogenic phase) took place mostly before emplacement of regional plains material (Ivanov and Head, 2008a) and the long-wavelength component of the deformation

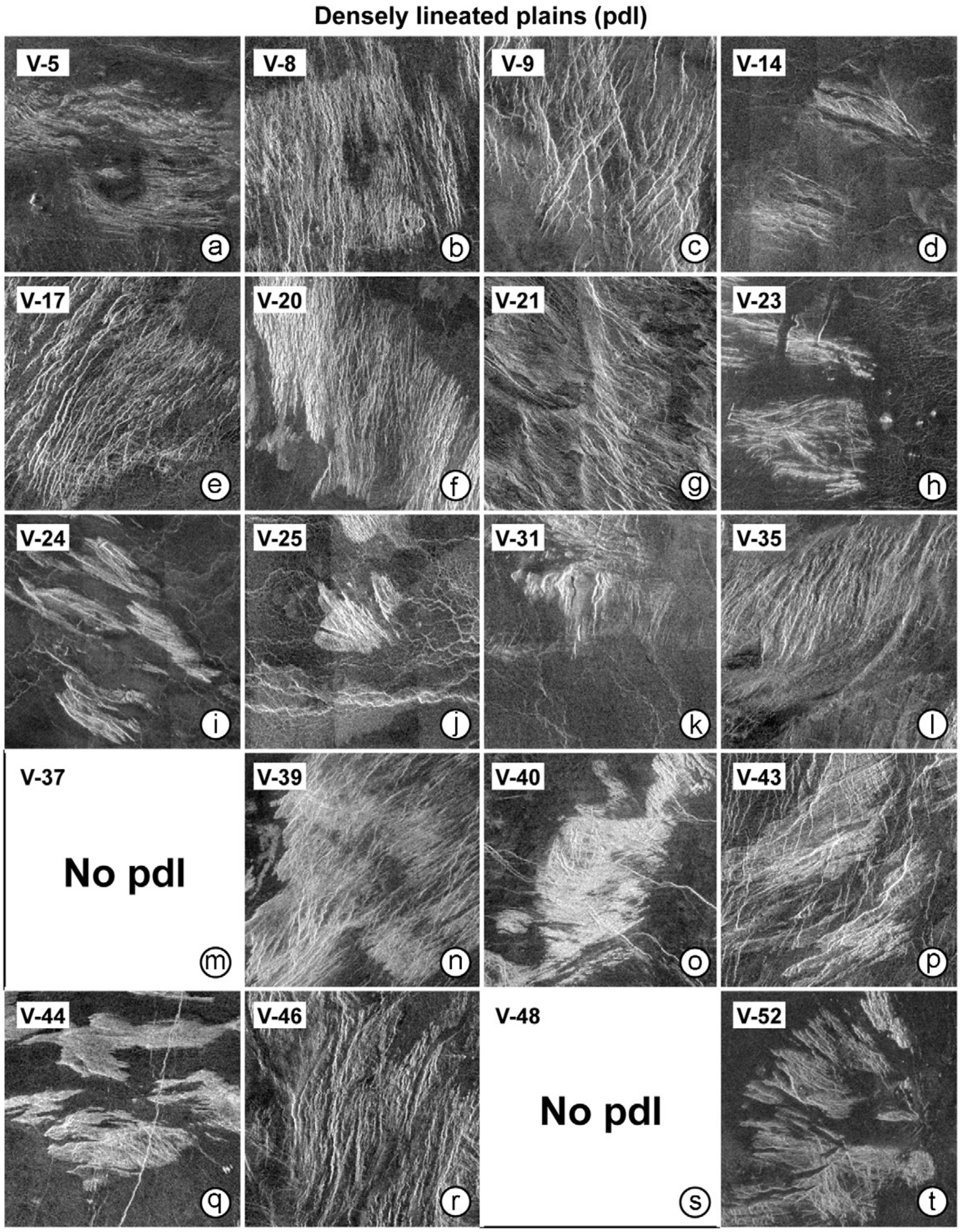

Fig. 6. A mosaic of images of densely lineated plains (unit pdl) taken from the published USGS geological maps. See Table 4 for the coordinates of the centers of the images and the original name of the units in each quadrangle. Each image is 57.6 × 57.6 km.

(the broad tilting of plains at the contact with the mountain ranges) is probably related to the later evolution of the belts. This broad warping is similar to the situation at large tessera regions where materials of plains units are tilted away from the tesserae (Head and Ivanov, 1996; Ivanov and Head, 1996), which is interpreted to be the consequence of late epeirogeny of regions of thickened crust. Type locations for mountain belts are at 68.6°N, 317.3°E (Akna Montes); 74.0°N, 329.4°E (Freyja Montes).

Groove belts (gb, Agrona Formation, Fig. 9a**):** Groove belts represent another structural unit, which is formed by densely packed extensional structures. Usually, graben and fractures are mapped as individual features independently of the material units on which they are superposed. In some places, however, the density of fractures is so great that they almost completely obscure the characteristics of underlying materials at the scale of the mapping. When this occurs, we follow the guidelines of Wilhelms (1990): "when the deformed rock units are not recognizable … it is better to map such structural units as 'fractured plains material'…than to ignore the presence of the structures in order to adhere strictly to the Code" (Wilhelms, 1990, pp. 227–2283). Swarms of numerous linear and curvilinear

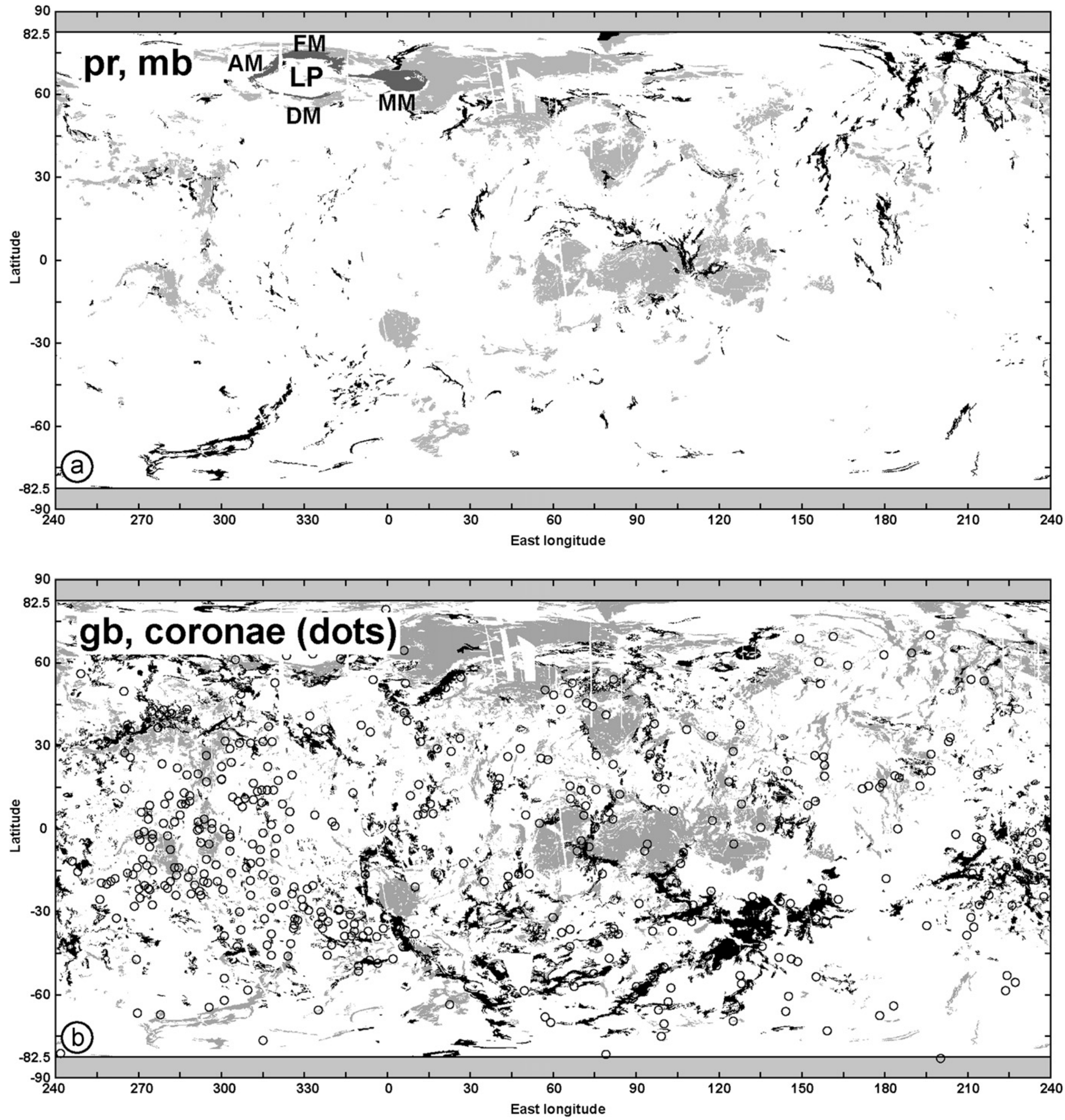

Fig. 7. (a) Areal distribution of ridged plains (pr, black) and mountain belts (mb, dark gray) on Venus. (b) Areal distribution of groove belts (gb, black) and coronae (dots, Stofan et al., 1992) on Venus. For reference, in both images the tessera distribution is shown in light gray. Simple cylindrical projection.

subparallel lineaments, which are usually wide enough to be resolved as fractures or graben, characterize the unit of groove belts (Fig. 9a). The typical widths of these features are about several hundred meters and up to 1–2 km (Mastrapa, 1997; Guseva, 2008), and individual fractures can reach several tens of kilometers in length. The main morphologic differences between groove belts and densely lineated plains are the shape and dimensions of occurrences (a more belt-like form for gb and more patch-like occurrences for pdl), as well as the larger spacing, width, and length of structures in fracture belts. Between the structures of groove belts, small fragments of preexisting units are often seen but usually the fractures/graben of gb are so dense at the scale of our map that they completely override the morphological signatures of the preexisting materials.

Groove belts occupy about 37.1×10^6 km^2 (8.1% of the mapped area, Table 2) and occur as zones of hundreds (up to thousands) of kilometers long and a few hundred kilometers wide (Fig. 7b). These zones are typically elevated above the surrounding plains. This is illustrated by the hypsogram of groove belts that is clearly shifted to higher elevations relative to the total hypsometric curve (Fig. 5e). Inside the belts the swarms of fractures are often anastomosing and form elliptical and circular features. In many places, the swarms of graben/fractures comprise either rims of coronae or the star-like pattern of novae. A high radar backscatter

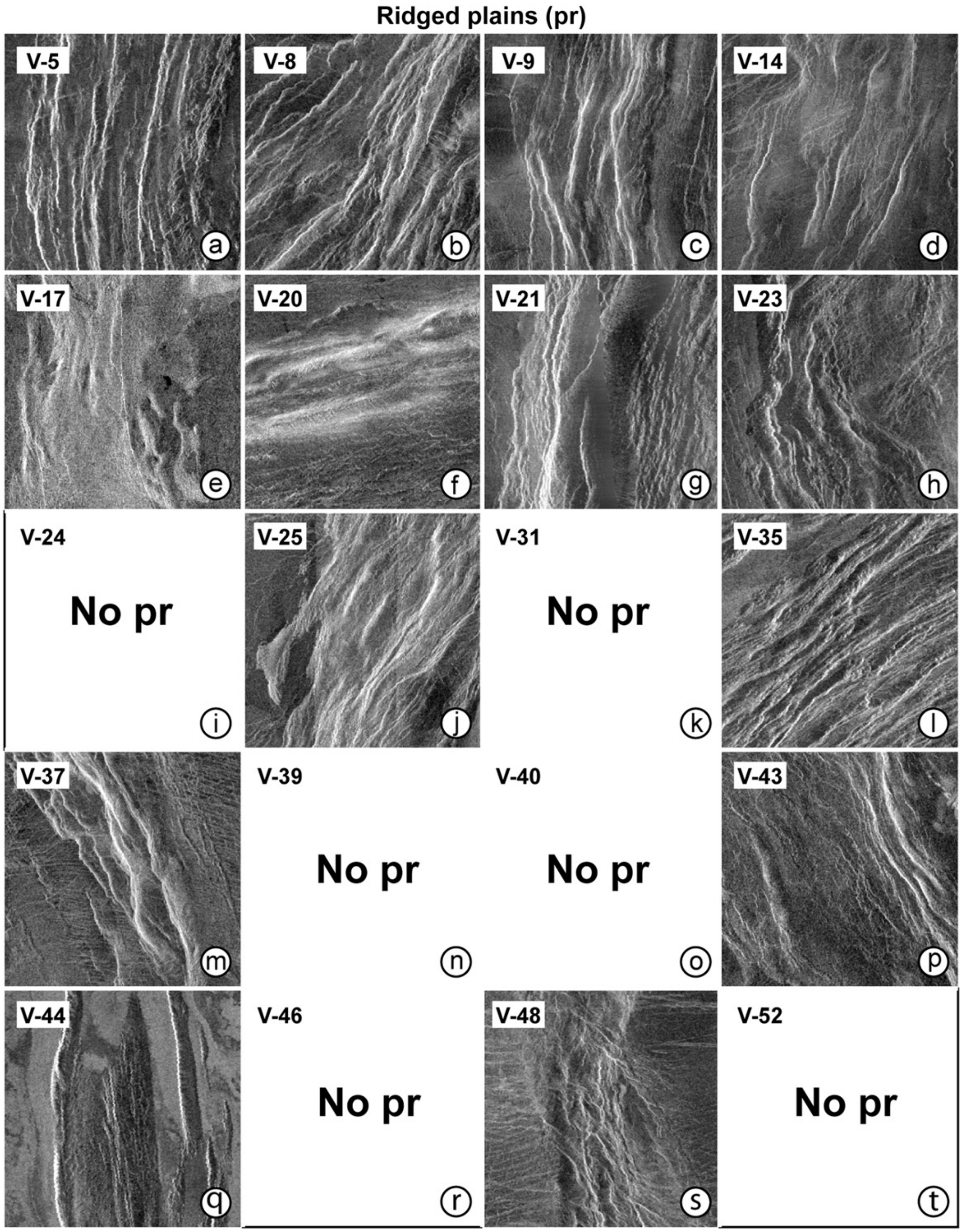

Fig. 8. A mosaic of images of ridged plains (unit pr) taken from the published USGS geological maps. See Table 4 for the coordinates of the centers of the images and the original name of the units in each quadrangle. Each image is 57.6 × 57.6 km.

cross-section, which locally can be as high as that of tessera, characterizes the belts.

Where groove belts are in contact with other units, there is evidence for crosscutting of units t, pdl, and pr by fractures of the belts, which suggests that groove belts formed later than these units. The abundance of the occurrences of the belts on the surface of Venus (Fig. 7b) allows tracing these relationships in many areas and everywhere they can be established, the belts appear to be younger. Vast plains units such as shield plains and regional plains embay groove belts. A few fractures of gb, however, sometimes cut materials of the plains. This suggests that the main episode of groove belt formation occurred before emplacement of the vast plains, but the waning stages of tectonic activity at the belts were contemporaneous with formation of some of the broad plains units.

In all published geological maps of Venus where groove belts occur they look almost identical morphologically (Fig. 10). The structures of the belts heavily deform the underlying material and largely obscure its morphologic characteristics. Remnants of the precursor terrains within groove belts are typically small and

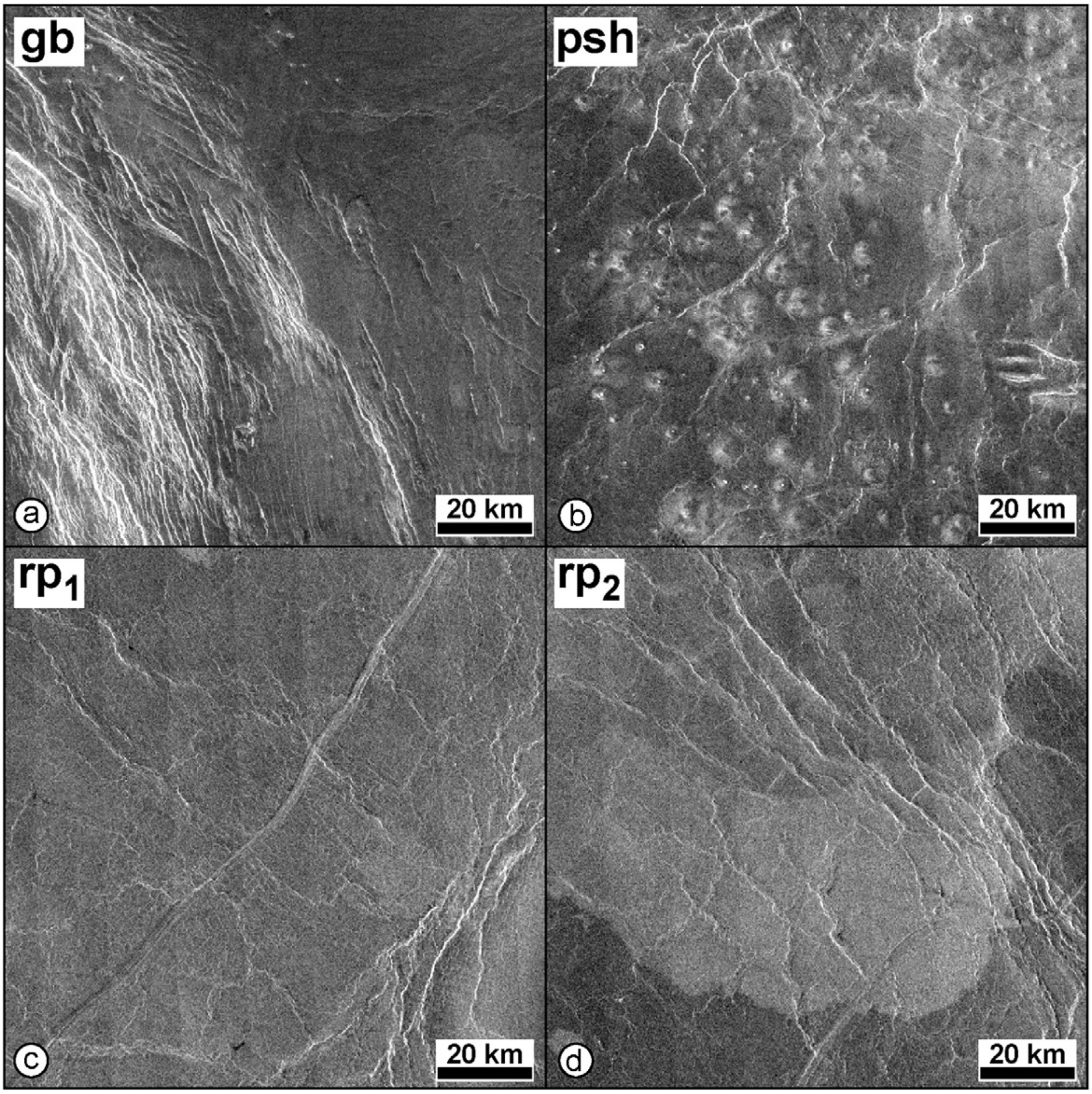

Fig. 9. Examples of units that occupy the middle portions of the observable stratigraphic sequence: (a) groove belts (gb), part of C1-15n095;1, center of the image is at 10.3°N, 91.5°E; (b) shield plains (psh), part of C1-60n153;1, center of the image is at 58.3°N, 152.4°E; (c) the lower unit of regional plains (rp_1), part of C1-45n159;1, center of the image is at 47.6°N, 161.0°E; (d) the upper unit of regional plains (rp_2), part of C1-45n159;1, center of the image is at 48.6°N, 161.6°E. All images are in sinusoidal projection, illumination from the left.

cannot be mapped at the scale of the global map. In quadrangle V-5 (Rosenberg and McGill, 2001), groove belts were mapped as a specific unit of 'densely lineated material' and in quadrangle V-17 (Basilevsky, 2008) the belts were mapped as a structural unit of 'fracture belts'. The authors of quadrangles V-35 (Bleamaster and Hansen, 2005) and V-39 (Brian et al., 2005) have mapped the belts as either 'Chasmata flow material, undivided' (V-35) or 'Lengdin Corona flow material, member 1' (V-39). The majority of researchers, despite the unclear characteristics of the underlying material (Fig. 10), prefer to map the belts as structural lines and not as a specific structural unit; quadrangles V-8 (McGill, 2004), V-9 (Campbell and Campbell, 2002), V-20 (McGill, 2000), V-21 (Campbell and Clark, 2006), V-25 (Young and Hansen, 2004), V-31 (Copp and Guest, 2007) V-37 (Hansen and DeShon, 2002), V-40 (Chapman, 1999), V-43 (Bender et al., 2000), V-44 (Bridges and McGill, 2002), and V-46 (Stofan and Guest, 2003). In the global map we have chosen to map them as a distinctive structural unit and interpret the unit as various volcanic materials heavily deformed by extensional (and perhaps shear) tectonic features. Type locations are at 36.2°N, 271.7°E; 40.2°S, 353.2°E.

Shield plains (psh, Accruva Formation, Fig. 9b**):** The presence of abundant small (from a few kilometers up to ~10 km across) shield-like features that are interpreted as volcanic edifices (Aubele and Slyuta, 1990; Head et al., 1992; Guest et al., 1992) characterizes the surface of shield plains (Fig. 9b). In many cases the shields occur close to each other and form groups of structures. The surface of both the shields and the plains between them is morphologically smooth and sometimes is deformed by wrinkle ridges. Shield plains represent the first unit in the stratigraphic scheme that display no pervasive deformation; psh is only mildly deformed by tectonic structures (wrinkle ridges and sparse fractures/graben). Because of this, the priority in the definition of shield plains was given to the morphologic characteristics of the surface material that comprises them and this unit thus represents a true material unit. The radar backscatter cross-section of the plains appears to be slightly higher than that of the surrounding overlying regional plains and obviously lower than that of the tectonized structural–material units such as t, pdl, pr, and gb. The overall relief of the unit appears to be hilly due to the abundant shield features, and

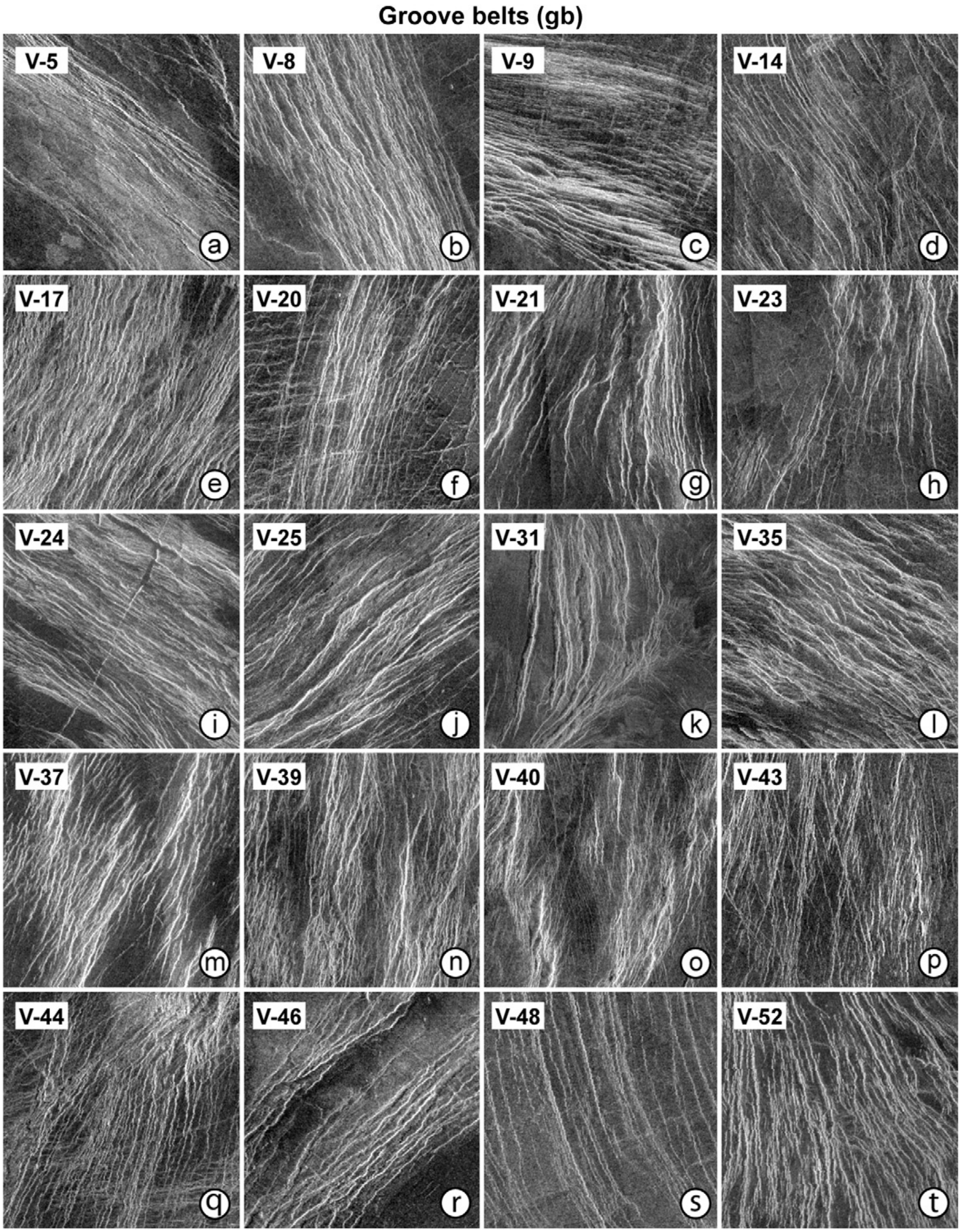

Fig. 10. A mosaic of images of groove belts (unit gb) taken from the published USGS geological maps. See Table 4 for the coordinates of the centers of the images and the original name of the units in each quadrangle. Each image is 57.6 × 57.6 km.

occurrences of shield plains tend to be slightly higher than the surrounding regional plains. Shield plains cover a significant portion of the surface of Venus, about 79.3×10^6 km^2 or 17.4% of the mapped area (Table 2) and typically occur as more or less equidimensional patches several tens to hundreds of kilometers across (Fig. 11a). The hypsogram of shield plains coincides almost exactly with the total hypsogram (Fig. 5f) suggesting that the plains represent a "typical" topographic level on Venus.

In general, the areal distribution of shield plains is broad and homogenous, but there are several large areas where the occurrences of the plains are less abundant or absent (Fig. 11a). These regions correspond to the largest tesserae (e.g., Fortuna, Ovda, Thetis Regions), Lakshmi Planum, the largest chasmata (e.g., Parga Chasma and canyons in Eastern Aphrodite), and some wide lowlands covered by regional plains (e.g., Sedna, Atalanta, Hellen Planitiae). Material of shield plains embays the older heavily tectonized units such as tessera, densely lineated plains, etc., everywhere where these units are in contact, which means that shield plains are younger at regional to global scales. Thus, the absence of the plains within the large tessera and in Lakshmi

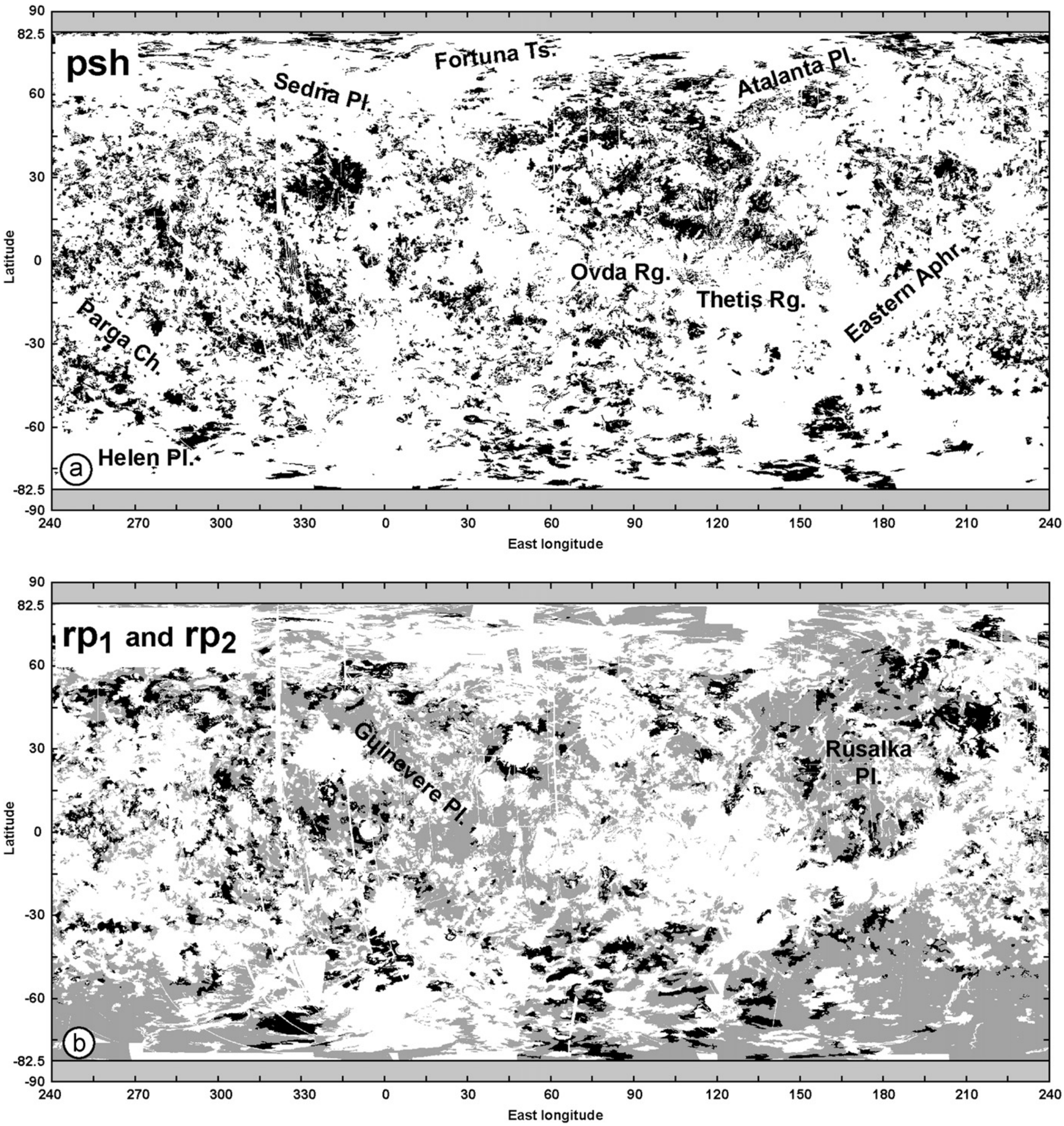

Fig. 11. (a) Areal distribution of shield plains (psh) on Venus. (b) Areal distribution of the lower unit of regional plains (rp_1, gray) and the upper unit of regional plains (rp_2, black) on Venus. Simple cylindrical projection.

Planum is consistent with the presence of thickened crust in these regions (Grimm, 1994) that may have served as a rheological barrier inhibiting formation of the plains (Ivanov and Head, 2008a). Morphologic (Grosfils and Head, 1995) and morphometric analysis (Kreslavsky and Head, 1999) at the contacts of shield plains with regional plains shows that regional plains embay and postdate shield plains; planet-wide stratigraphic analyses of the relationships of these units suggests that the same relationship holds true for the vast majority of shield plains (Ivanov and Head, 2004b). These age relationships may explain the scarcity or absence of shield plains within some lowlands, the surface of which is covered by material of the younger regional plains. Chasmata represent major zones of young extensional structures postdating both shield plains and regional plains; chasmata have probably destroyed the older occurrences of shield plains.

The small shields and related plains materials are not completely confined to the stratigraphic interval between the heavily tectonized units and regional plains (e.g., Basilevsky and Head, 1998, 2000; Addington, 2001). Some groups of small shields postdate regional plains and are associated, spatially and temporarily, with the youngest plains units (Ivanov and Head, 2004b, 2005b). The number of occurrences of this type of shield, however, is small (see description of the unit sc, shield clusters) and can be readily distinguished on morphologic and stratigraphic

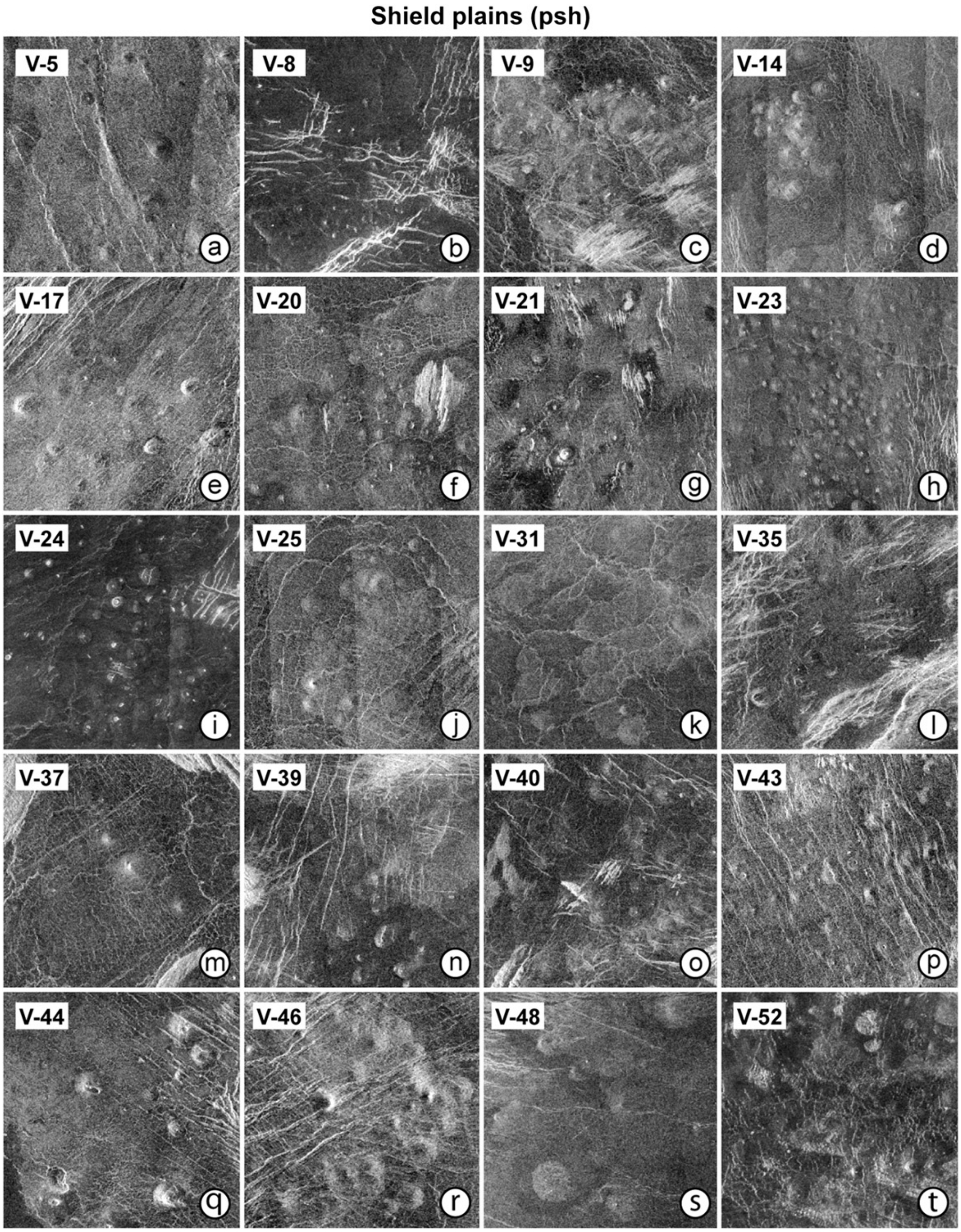

Fig. 12. A mosaic of images of shield plains (unit psh) taken from the published USGS geological maps. See Table 4 for the coordinates of the centers of the images and the original name of the units in each quadrangle. Each image is 57.6 × 57.6 km.

grounds (Ivanov and Head, 2004b). Shield plains (psh) have a very similar morphology everywhere on Venus and occur in all published geological maps of this planet (Fig. 12). In three maps, V-9 (Campbell and Campbell, 2002), V-21 (Campbell and Clark, 2006), and V-46 (Stofan and Guest, 2003), shield plains were not mapped as a specific unit but considered as a part of the broader units of regional plains. In summary, we interpret shield plains (psh) as volcanic plains with numerous small sources; the plains are mildly tectonically deformed. Type locations are at 29.4°N, 131.0°E; 11.9°S, 335.8°E.

Regional Plains (rp): Regional plains represent the most widespread material unit on Venus, occupy about 182.8 × 10^6 km^2 or 40.3 % of the map area (Table 2), and are composed of morphologically smooth, homogeneous plains materials of intermediate-dark to intermediate-bright radar backscatter. Materials of the plains are deformed by narrow, linear to anastomosing, wrinkle ridges (a structural element) in subparallel to parallel lines or intersecting networks (Bilotti and Suppe, 1999). Regional plains are defined by the characteristic morphology of their materials and, thus, belong to the class of true

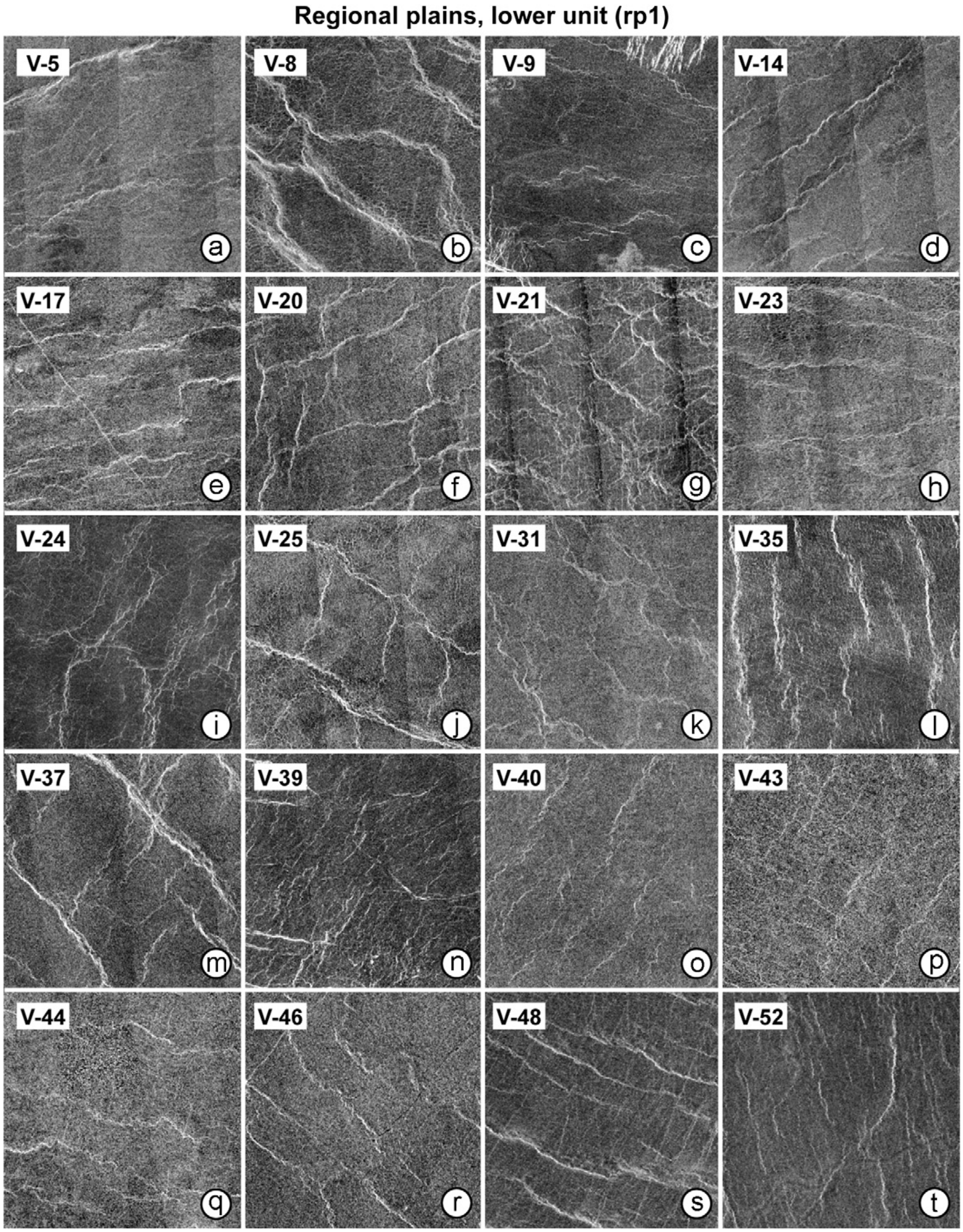

Fig. 13. A mosaic of images of the lower unit of regional plains (unit rp_1) taken from the published USGS geological maps. See Table 4 for the coordinates of the centers of the images and the original name of the units in each quadrangle. Each image is 57.6×57.6 km.

material units. This unit resembles the ridged unit of the plateau sequence on Mars (Scott and Tanaka, 1986), which is a plains unit defined by "long, linear to sinuous mare-type (wrinkle) ridges." The unit is interpreted to be regional plains of volcanic origin that were subsequently deformed by wrinkle ridges. Volcanic edifices and sources of the plains are commonly not obvious at the resolution of Magellan data.

Regional plains are subdivided into two units on the basis of the typical characteristics of their radar backscatter. **The lower unit of regional plains (rp_1, Rusalka Formation,** Fig. 9c**)** generally has a morphologically smooth surface with a homogeneous and relatively low radar backscatter that can appear locally mottled. Long and narrow, sinuous channel-like features (e.g., Baker et al., 1997) are often associated with the lower unit of regional plains (Fig. 9c). This unit is the most abundant unit on Venus (about 141.8×10^6 km^2 or 31.1% of the mapped area, Table 2) and can be traced almost continuously around the globe. The lower unit of regional plains preferentially makes up the floor of the lowlands surrounding the major tessera-bearing uplands and occurs between elevated regions composed of the heavily tectonized units and shield plains (Fig. 11b). The lower unit of regional plains preferentially occurs in the vast low-lying plains

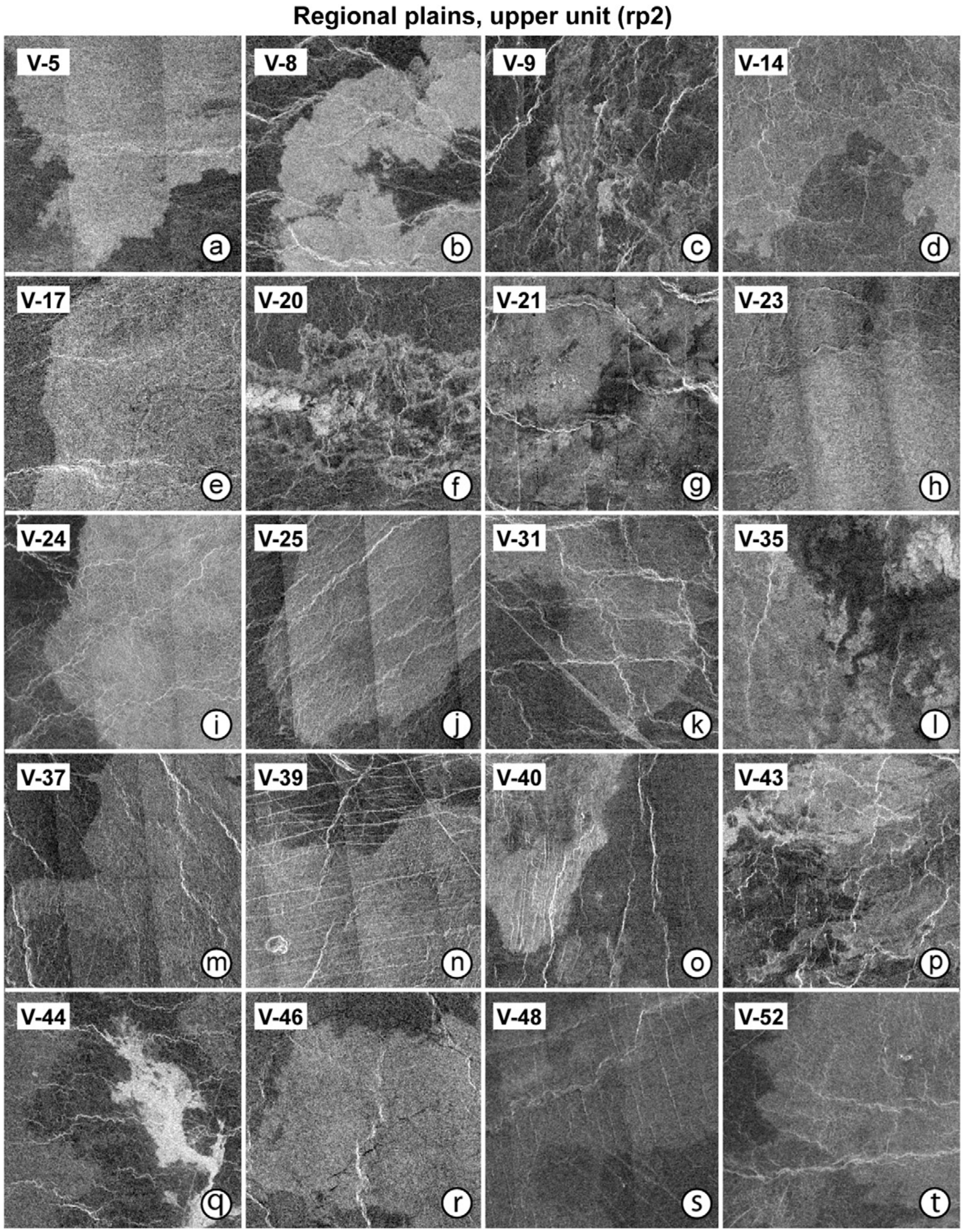

Fig. 14. A mosaic of images of the upper unit of regional plains (unit rp_2) taken from the published USGS geological maps. See Table 4 for the coordinates of the centers of the images and the original name of the units in each quadrangle. Each image is 57.6 × 57.6 km.

lacking occurrences of tessera and the other heavily tectonized units. This unit also makes up the majority of Guinevere, Rusalka, and Atalanta Planitiae in the northern hemisphere of Venus (Fig. 11). The hypsogram of the lower unit of regional plains (Fig. 5g) is clearly shifted toward lower elevations because of the preferential association of this unit with the regional lowlands. Due to this, the areal distribution of the plains mimics the general pattern of long-wavelength topography (the X-pattern of lowlands) known since the Pioneer-Venus mission (Pettengill et al., 1980; Masursky et al., 1980).

The lower unit of regional plains occurs and was mapped in all published geological maps of Venus (Fig. 13). In all maps (except the map V-25, Young and Hansen, 2004) the unit with the characteristic morphology of regional plains occupies the middle stratigraphic position and is shown as superposed on heavily tectonized units (such as tessera) and embayed by undeformed lava plains and flows. The areal abundance, similar morphologic characteristics almost everywhere, and its position in the local to regional stratigraphic columns, combine to make the lower unit of regional plains of extreme importance in deciphering the geologic

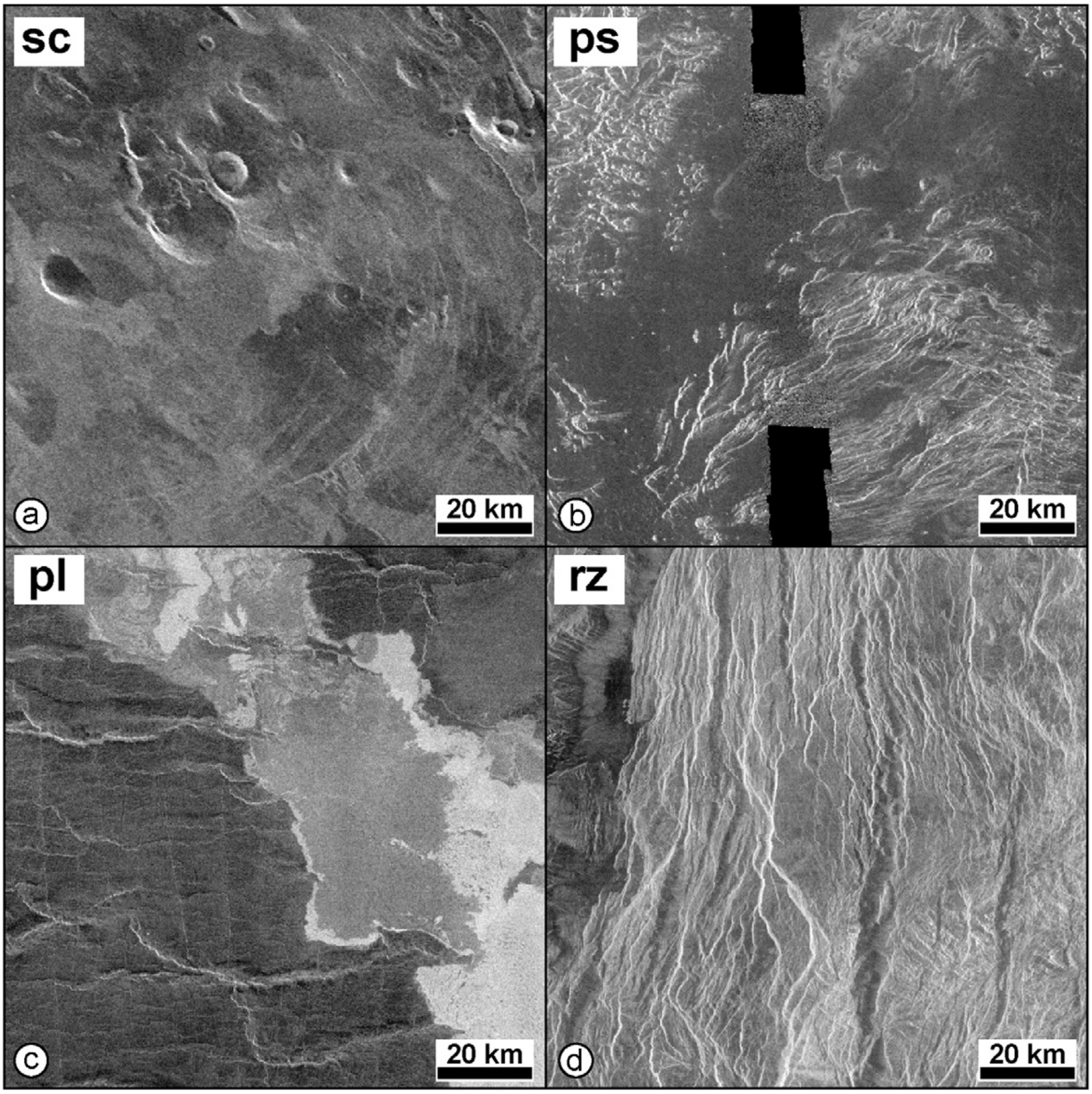

Fig. 15. Examples of units that form the upper portions of the stratigraphic sequence: (a) shield clusters (sc), part of C1-75s023;1, center of the image is at 70.0°S, 2.2°E; (b) smooth plains (ps), part of C1-60n125;1, center of the image is at 63.8°N, 128.6°E; (c) lobate plains (pl), part of C1-30n045;201, center of the image is at 25.1°N, 42.4°E; (d) rift zones (rz), part of C1-30n279;1, center of the image is at 30.0°N, 283.7°E. All images are in sinusoidal projection, illumination from the left.

history of Venus. We will discuss this question in the later sections of the paper. Type locations are at 45.1°N, 143.6°E; 42.9°S, 162.3°E.

The upper unit of regional plains (rp_2, Ituana Formation, Fig. 9d**)** is characterized by a morphologically smooth surface that is moderately deformed by numerous low, narrow, and sinuous wrinkle ridges. The ridges appear to belong to the same family of structures that deform the lower member of the plains (Fig. 9d). The key difference between the upper and lower units of regional plains is radar albedo variation. In contrast to the uniform and relatively low albedo of rp_1, the upper member of the plains has a more uniform, and noticeably higher albedo (Fig. 9d). Less frequently, this unit displays a non-uniform radar albedo that consists of brighter and darker flow-like features. The upper member of regional plains covers about 42.0×10^6 km^2 or 9% of the mapped area (Table 2) and occurs usually as equidimensional or slightly elongated patches of flow-like shape from tens of kilometers to several hundred kilometers across (Fig. 11b). Boundaries between the two members of the regional plains vary from sharp to diffuse. In many cases there is evidence for the embayment of the lower member (rp_1) by material of the upper unit (rp_2) (Fig. 9d). This suggests that rp_2 is younger, but both units predate formation of wrinkle ridges. Fields of the upper member of regional plains (rp_2) are relatively evenly distributed over the surface of Venus but do not occur within the large tessera regions and in the vast plains, the surface of which is made up solely by the lower unit (rp_1) of regional plains (Fig. 11b). The overall topographic distribution of the upper unit of regional plains is almost identical to that of the lower unit (Fig. 5h). Occurrences of rp_2 surround some of large volcanic centers, such as coronae and large volcanoes, and form distal aprons of volcanic materials around them. The younger lavas usually cover the central portions of these volcanic centers.

The upper unit of regional plains (rp_2) occurs within the areas of all published geological maps of Venus (Fig. 14). In two maps, V-9 (Campbell and Campbell, 2002) and V-21 (Campbell and Clark, 2006), this unit was considered as part of broader regional plains. In the map V-17 (Basilevsky, 2008), this unit is shown as the upper unit of plains with wrinkle ridges. In all other maps, the upper unit of regional plains was mapped as various flow

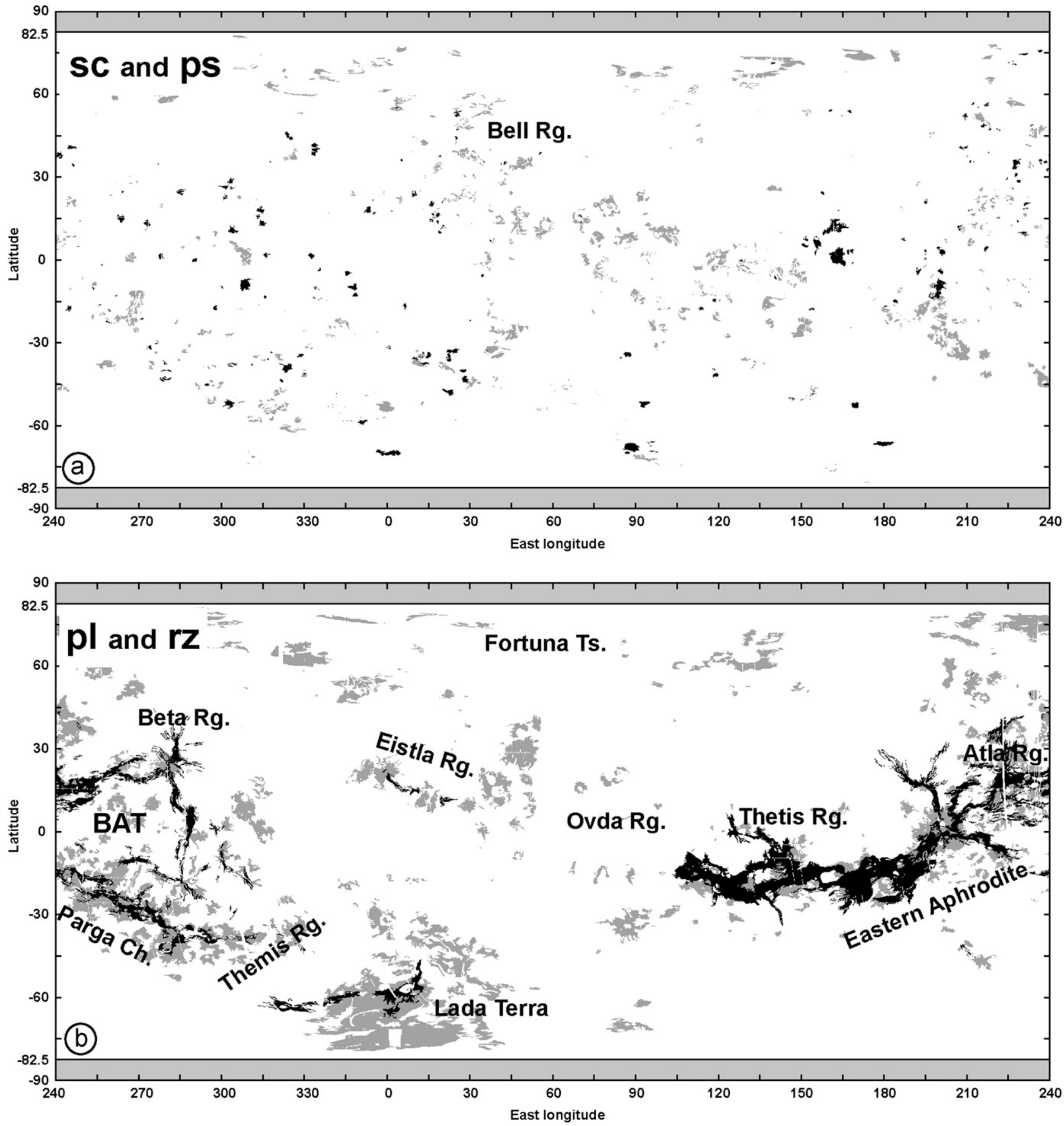

Fig. 16. (a) Areal distribution of shield clusters (sc, black) and smooth plains (ps, gray) on Venus. (b) Areal distribution of lobate plains (pl, gray) and rift zones (rz, black) on Venus. Simple cylindrical projection.

units: 'Vallis flow material' in the V-8 quadrangle (McGill, 2004) or 'Flow material, unit 3' in the V-40 quadrangle (Chapman, 1999), etc. Type locations are at 49.1°N, 161.3°E; 36.3°S, 163.4°E.

Shield clusters (sc, Boala Formation, Fig. 15a**):** The surface of this unit appears to be morphologically similar to that of shield plains (psh, Fig. 9b). In contrast to psh, this unit is tectonically undeformed and its materials superpose structures of regional plains if shield clusters and regional plains are in contact. Small shields on the surface of unit sc often appear as sources of small but distinct lava flows superimposed on the surrounding plains, in contrast to the typical characteristics of unit psh (Ivanov and Head, 2004b). For an assessment of the differences between shield plains and shield clusters, and detailed criteria for distinguishing their stratigraphic relationships and ages, the reader is referred to Ivanov and Head (2004b). The unit of shield clusters represents a true material unit because it is defined primarily by the specific morphology of its material. Analysis of the stratigraphic relationships of shield fields cataloged by Crumpler and Aubele (2000) reveals that about 10% of the population of the fields appears to be younger than regional plains (both the lower and upper units) (Ivanov and Head, 2004b). These shield fields were mapped in the global map as a specific material unit of

Table 5
Units that are equivalent to shield plains (psh) and shield clusters in different geological maps of Venus.

Map	Units equivalent to psh	Units equivalent to sc
V-5	Mottled local plains material	Part of digitate flow material
V-8	Shield flow material	No
V-9	Mapped as part of vast plains units (prr and prrd)	No
V-14		No
V-17	Shield plains	No
V-20	Shield field flow material	Low-relief shield plains material
V-21	Mapped as part of regional plains material (pr)	No
V-23	Shield terrain	No
V-24	Shield terrain	No
V-25	Shield field material of Urutonga Colles	Shield field and flow material of llorona corona
V-31	Guinevere Planitia lineated and mottled plains material	Edifice field material
V-35	Shield-emplaced flow material, member c	Inani Corona flow material, member 1b
V-37	Intratessera basin material	Shield field flow material
V-39	Edifice field material, undulating plains material	No
V-40	Tessera-embaying plains material	Corona materials, unit k
V-43	Mottled, lineated plains material	Mottled flows
V-44	Textured regional plains material	No
V-46	Not mapped	Kunapipi summit material, unit 2
V-48	Composite flow material b of artemis	No
V-52	Heterogeneous material, undivided	Flows and shield-related materials around Zerine
V-59	Corrugated ridged plains material	No

clusters of shields (sc). Although this unit covers a very small fraction of Venus, about 3.3×10^6 km^2 or 0.7% of the map area (Table 2, Fig. 16a), it is distinctive, mappable, and plays an important role in the understanding of the history of volcanism on Venus. The topographic distribution of shield clusters shows two peaks (Fig. 5i). The first is near the mode of the total hypsogram and close to the mode of shield plains (psh) and the second peak occurs near 2 km elevation. The higher peak is partly related to shield clusters that occur at the summits of some large volcanoes (Stofan and Guest, 2003; Young and Hansen, 2004).

Owing to its scarcity, the unit of shield clusters does not occur in many published geological maps (V-8, -9, -17, -21, -39, -59, Fig. 17). Within the other quadrangles, shield clusters were mapped as a specific unit that is different from more widespread shield fields (Table 5). Small shields that form shield clusters and material that immediately surrounds them appear to be superposed on the adjacent regional plains (both the lower rp_1, and upper rp_2, units) and in some cases volcanic flows from the clusters clearly embay regional plains (Fig. 17). These relationships suggest that most of the clusters postdate emplacement of regional plains. In some areas (for example, within quadrangle V-43; Fig. 17) material of shield clusters is superposed on the lower unit of regional plains and deformed by wrinkle ridges. This indicates that a few clusters were emplaced later than the lower unit of regional plains but before formation of the ridges. Type locations for this unit (sc) are at 56.1°N, 217.0°E; 69.3°S, 357.2°E.

Smooth plains (ps, Gunda Formation, Fig. 15b**):** The material unit of smooth plains has a morphologically smooth, tectonically undisturbed, and featureless surface (Fig. 15b). In rare cases, low domes are visible within the plains, and these may be the sources for a portion of the plains material. Areas of smooth plains are usually characterized by a low radar backscatter cross-section and appear dark. Smooth plains make up a small portion of the surface, about 10.3×10^6 km^2 or 2.3% of the mapped area (Table 2). The unit usually occurs as small equidimensional and elongated fields a few tens of kilometers across. Some patches of the plains, however, may reach dimensions of hundreds of kilometers (Fig. 16a). These occurrences are usually spatially associated with impact craters. The surface of smooth plains is tectonically undeformed (Fig. 15b), and there is evidence that some smooth plains embay wrinkle ridges. There are three types of geological settings for smooth plains: (1) Abundant fields of smooth plains occur near and within regions of abundant young volcanism (for example, Bell Regio) where the plains are closely associated with fields of lobate plains. In these regions, occurrences of smooth plains are typically smaller and superposed on adjacent regional plains (both rp_1 and rp_2 units). The relationships of smooth plains and lobate plains are mostly unclear due to the small area covered by ps, and there is no convincing evidence to establish the relative ages of these two units. In some cases these plains may represent different facies of the same volcanic plains. (2) Some groups of smooth plains units are spatially associated with impact craters and occur as patches of dark deposits around the craters. Such dark plains, thus, may represent remnants of dark parabolas formed due to impact events (e.g. Campbell et al., 1992; Izenberg et al., 1994). (3) Small patches of smooth plains occur inside some large tessera regions (e.g., Ovda Regio). In these areas, smooth plains are likely to have a volcanic origin. The hypsogram of smooth plains is clearly shifted toward higher elevations (Fig. 5j). This suggests that the plains more often represent young volcanic materials that tend to occur at higher topographic levels (Fig. 5k). If the fine-grained impact-related materials were the main component of the plains, the topographic distribution of the unit would be expected to mimic the total hypsogram, reflecting the more random distribution of impact craters.

In those published geological maps where smooth plains occur (Fig. 18), their materials were interpreted either as a portion of vast regional plains (V-5, Rosenberg and McGill, 2001; V-9, Campbell and Campbell, 2002), or as independent plains-forming materials (V-8, McGill, 2004; V-20, McGill, 2000; V-44, Bridges and McGill, 2002), or as volcanic flow material (V-21, Campbell and Clark, 2006; V-35, Bleamaster and Hansen, 2005; V-40, Chapman, 1999), or as impact-related materials (V-43, Bender et al., 2000). Because of the characteristic associations of smooth plains with either volcanic centers or impact craters we interpret this unit to have both a volcanic and impact ejecta origin. On the basis of local stratigraphic relationships this unit formed after emplacement of material of regional plains and its deformation by wrinkle ridges. Type locations are at 73.6°N, 171.4°E; 12.3°S, 268.0°E.

Lobate plains (pl, Bell Formation, Fig. 15c**):** Occurrences of the material unit of lobate plains usually have morphologically smooth surfaces that are occasionally disturbed by a few extensional features related to rift zones. The most characteristic

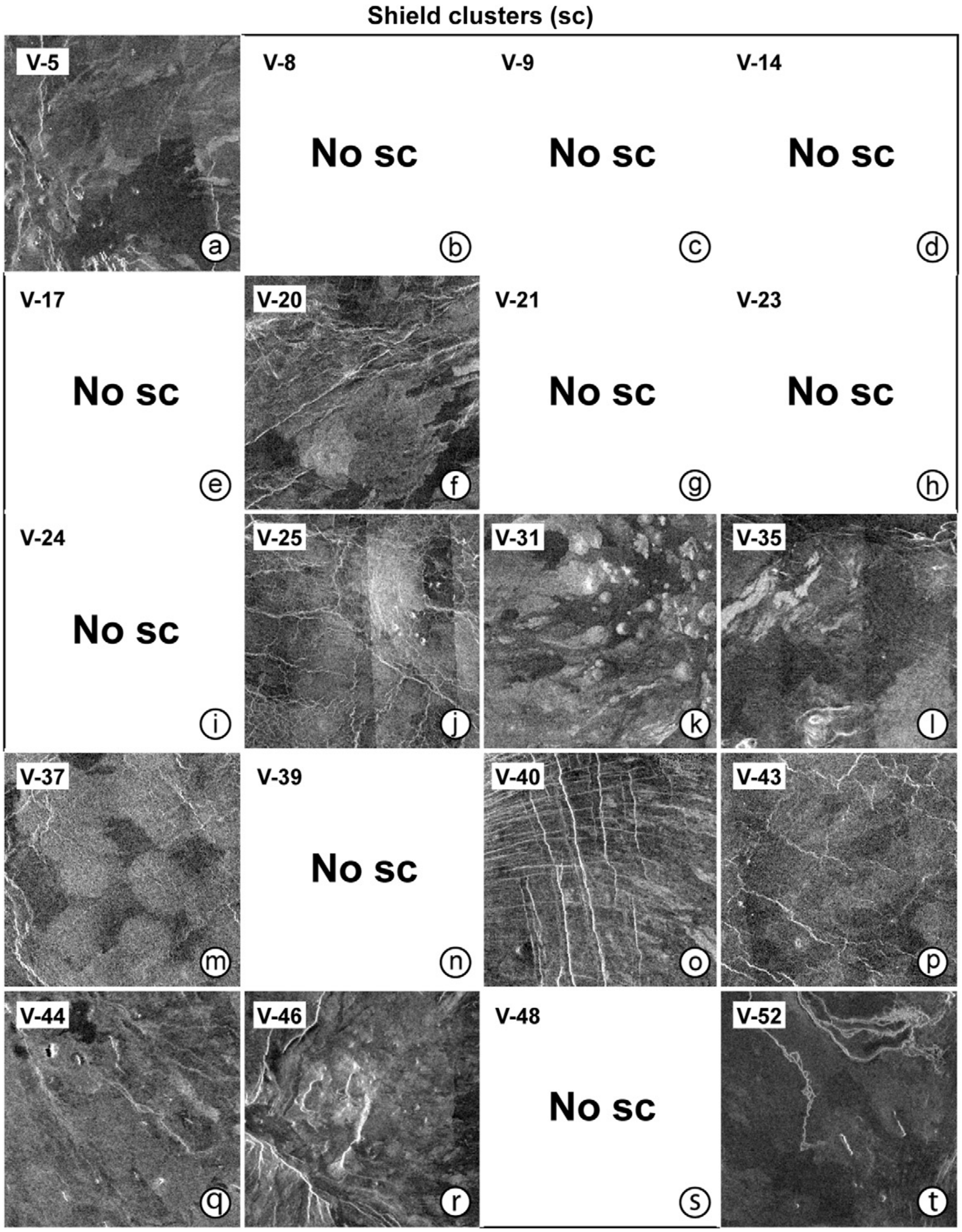

Fig. 17. A mosaic of images of shield clusters (unit sc) taken from the published USGS geological maps. See Table 4 for the coordinates of the centers of the images and the original name of the units in each quadrangle. Each image is 57.6 × 57.6 km.

feature of lobate plains is their non-uniform albedo pattern consisting of numerous bright and dark flow-like features. The flows can be as long as several hundred kilometers and tens of kilometers wide (Fig. 15c). Lobate plains make up a significant portion of the surface of Venus, about 37.8×10^6 km^2 or 8.3% of the map area (Table 2). Occurrences of the plains form distinct equidimensional fields from tens of kilometers up to 1000 km across (Fig. 16b). The presence of lobate plains is often a characteristic feature of many large volcanic centers on Venus. The plains are usually associated with the large dome-shaped rises (for example, Beta, Eistla, Atla Regions, and Lada Terra, Fig. 16b). This type of association leads to the clear shift of the hypsogram of lobate plains toward higher elevations (Fig. 5k). Large, high-standing, and plateau-shaped tessera regions (e.g., Fortuna, Ovda, etc.) lack significant occurrences of lobate plains. Within the BAT (Beta-Atla-Themis) region, especially along Parga Chasma (Fig. 16b), lobate plains are spatially associated with rift zones.

In places where lobate plains occur in contact with the units of regional plains, material of lobate plains embays wrinkle ridges (Fig. 15c). This implies that lobate plains are younger. Some occurrences of the upper unit of regional plains (usually varieties

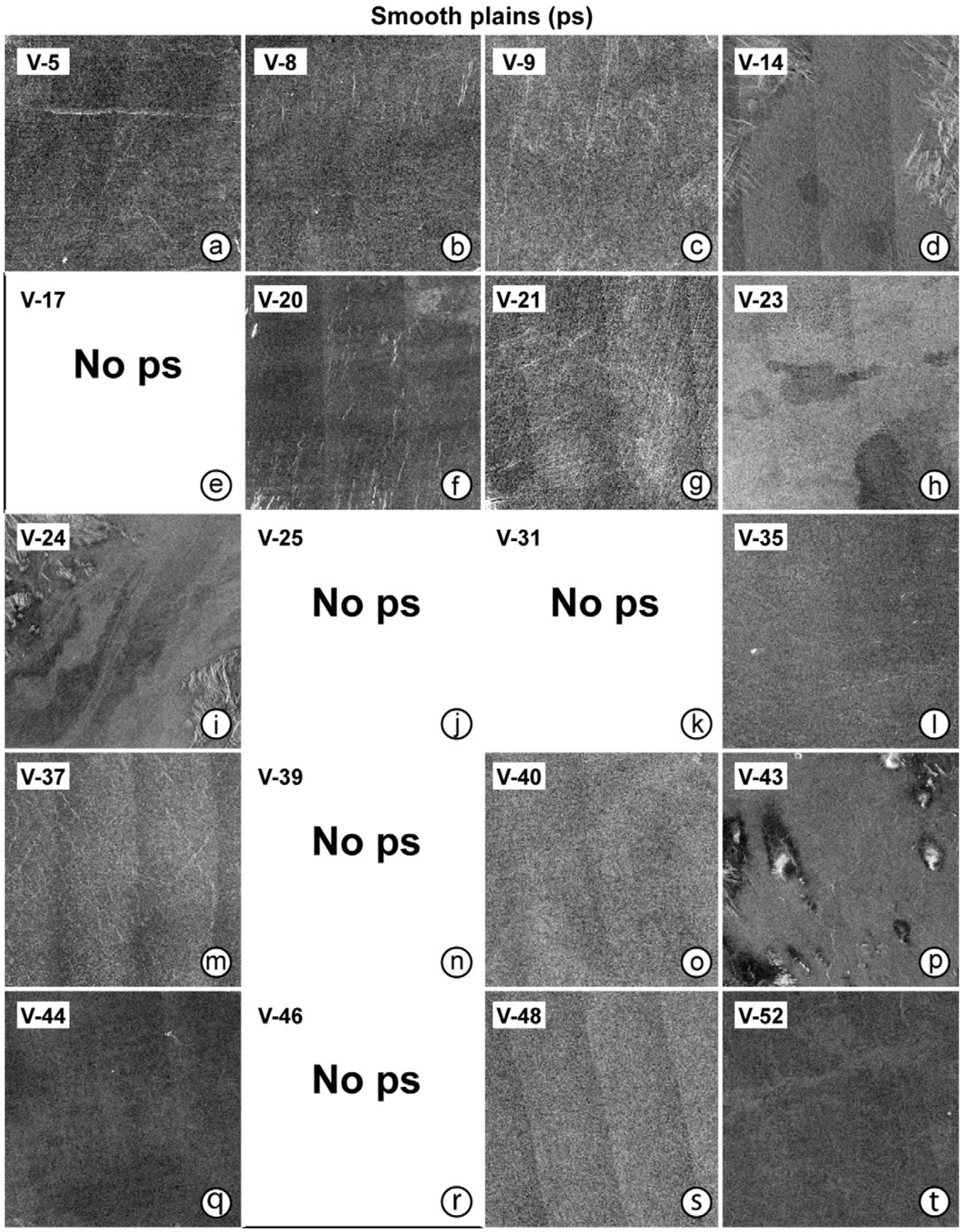

Fig. 18. A mosaic of images of smooth plains (unit ps) taken from the published USGS geological maps. See Table 4 for the coordinates of the centers of the images and the original name of the units in each quadrangle. Each image is 57.6 × 57.6 km.

of the unit with a non-uniform albedo) are associated with the same volcanic centers as the lobate plains and occur at larger distances from them. Stratigraphic relationships between lobate plains, shield clusters, smooth plains, and rift zones are often hard to directly establish, due to their commonly small outcrop occurrences, although lobate plains and rift zones are commonly seen together.

Lobate plains occur in all published geological maps of Venus, except V-59 (Fig. 19). Because of its characteristic albedo pattern and usually sharp and well-defined boundaries between neighboring lobes, the possibility exists to undertake very detailed subdivisions of materials that form lobate plains. In some geological maps there are a large number of units that make up the tops of the regional stratigraphic columns and correspond to different distinctive volcanic centers and/or different phases of volcanism. For example, in the V-39 map (Brian et al., 2005) there are 46 units that have been mapped to define different stages of volcanic activity at different centers. This approach is appropriate during mapping of some specific regions on Venus because it may describe important details of volcanism in these regions. For the global geological mapping, however, it is impractical because this style of mapping would create many hundreds (if not thousands)

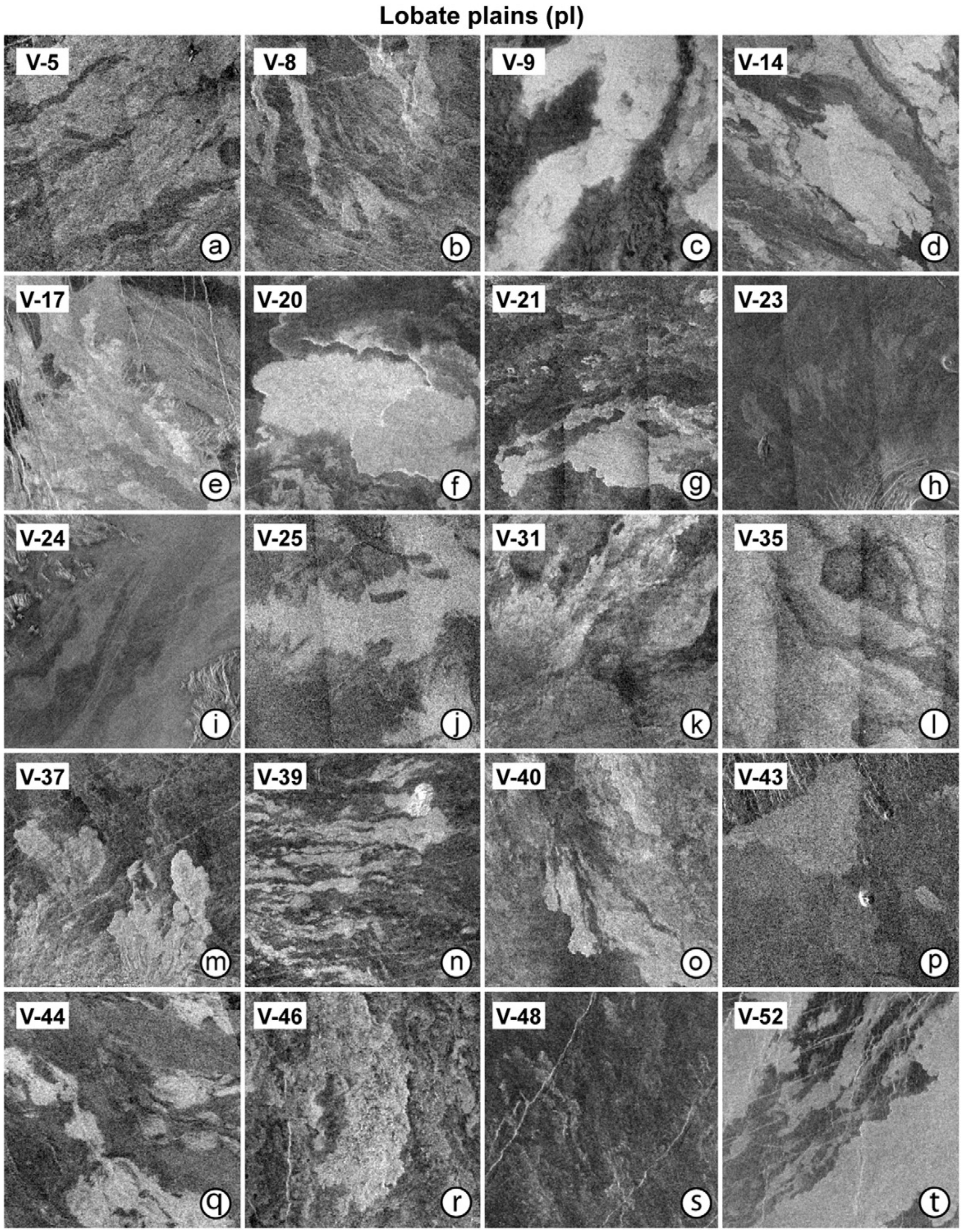

Fig. 19. A mosaic of images of lobate plains (unit pl) taken from the published USGS geological maps. See Table 4 for the coordinates of the centers of the images and the original name of the units in each quadrangle. Each image is 57.6 × 57.6 km.

of units, the main difference among which is their geographic location and local overlap. In contrast, in our mapping we lumped all morphologically similar and tectonically undeformed lobe-like units into one composite unit of lobate plains (Figs. 15c and 19). In summary, we interpret the unit of lobate plains to be volcanic materials emplaced during massive and multiple eruptions at large and localized centers and sometimes slightly deformed by extensional tectonic features. Type locations are at 25.5°N, 48.0°E; 36.4°S, 88.6°E.

Rift zones (rz, Devana Formation, Fig. 15d**):** Rift zones (in a manner similar to groove belts) define a structural unit consisting of numerous and densely packed extensional structures. This unit is characterized by numerous fissures and flat-floored troughs (interpreted to be fractures and graben, respectively) that can reach hundreds of kilometers in length and tens of kilometers in width (Fig. 15d). On average, structures of rift zones are broader, longer and somewhat less densely packed than structures of groove belts. Although the features of rift zones are usually very dense, small fragments of preexisting units are often seen between fractures and graben. As in the case of fracture belts, however, these fragments are typically far too small to be properly outlined at the scale of our mapping. Within rift zones the fractures and

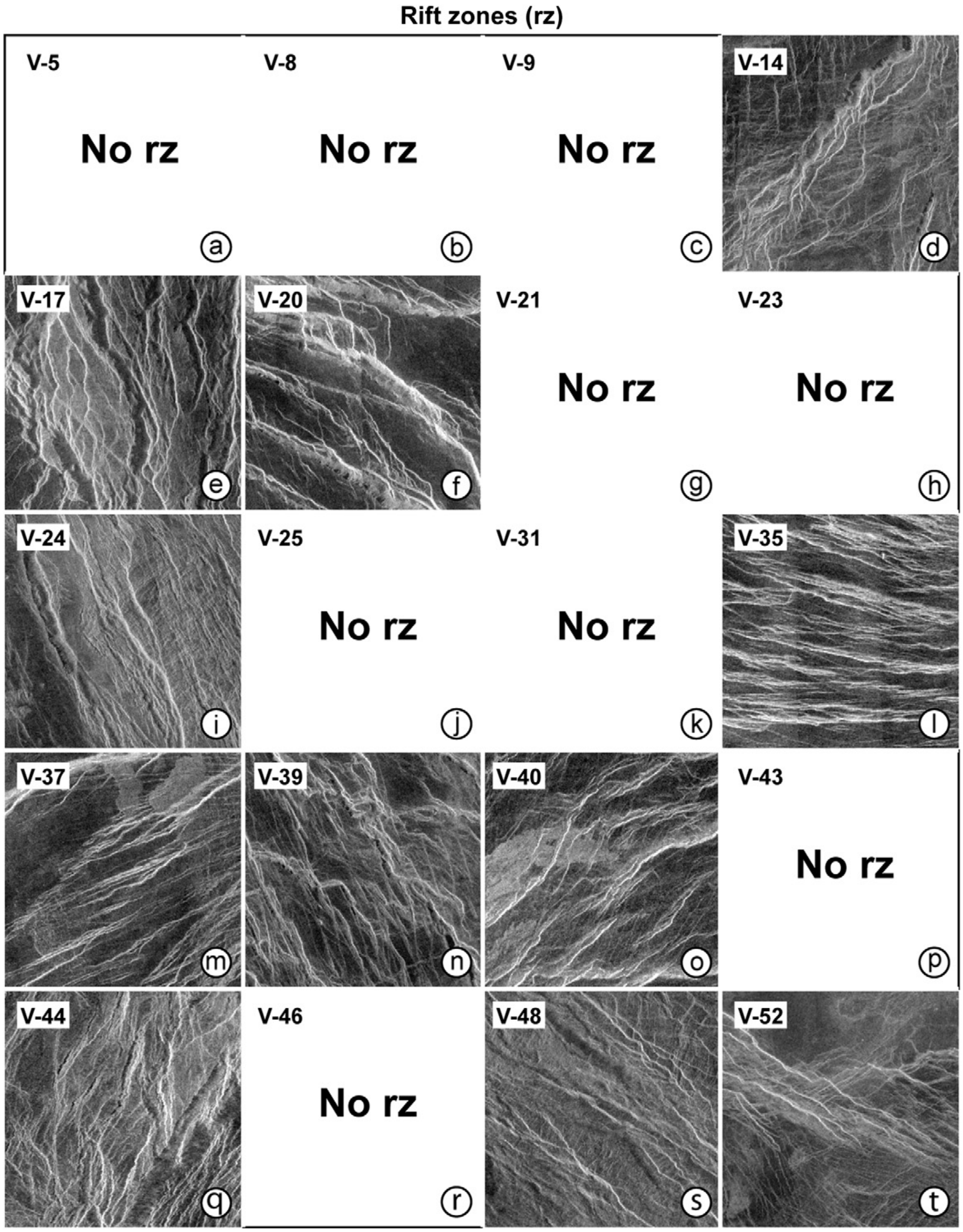

Fig. 20. A mosaic of images of rift zones (unit pl) taken from the published USGS geological maps. See Table 4 for the coordinates of the centers of the images and the original name of the units in each quadrangle. Each image is 57.6 × 57.6 km.

graben are often anastomosing and have a zigzag planform. Rift zones are characterized by a high radar backscatter cross-section which can be locally as high as that of tessera. This unit (rz) occupies about 22.6×10^6 km^2 or 5.0% of the mapped area (Table 2) and occurs as prominent belts that are up to a few hundred kilometers wide and can be several thousands of kilometers long (Fig. 16b). Rift zones occur in close spatial association with lobate plains (Fig. 16b), and there is evidence for partly contemporaneous formation of the rifts and these young volcanic plains. Rift zones as well as lobate plains preferentially occur within regional highs in the equatorial zone of Venus (eastern Aphrodite) and major branches of rift zones outline the BAT region (Fig. 16b). Due to this, the hypsogram of rift zones is strongly shifted toward higher elevations (Fig. 5l). By themselves, however, rift zones form deep elongated depressions.

The characteristic morphology of rift zones is prominent in any geological map areas where they occur (Fig. 20). In three maps, V-20 (McGill, 2000), V-40 (Chapman, 1999), and V-44 (Bridges and McGill, 2002), rifts were mapped as structures. In the V-17 quadrangle (Basilevsky, 2008), rifts are shown as a structural unit. In three more maps, V-35 (Bleamaster and Hansen, 2005), V-37 (Hansen and DeShon, 2002), and V-39 (Brian et al., 2005), areas of rifts were mapped as material units related to volcanic flows from coronae. We do not consider rifts zones (as well as groove belts) as a purely material unit because these zones of intense deformation are formed by dense swarms of tectonic structures. Thus, we have mapped rifts as a specific structural unit because they are very prominent and usually completely erase the morphologic characteristics of all underlying units. We interpret the unit of rift zones to be different materials heavily deformed by extensional tectonic structures. Type locations are as at 11.1°N, 198.7°E; 1.1°N, 287.7°E.

Units of impact craters and crater outflows (c and cf) include materials of the central peak, floor, walls, rim, continuous ejecta deposits, and materials forming outflows from impact craters. Impact craters must have been formed throughout the entire geologic history of Venus. The currently observed impact craters, however, appear to have a mostly pristine morphology (Schaber et al., 1992), which coincides with our observations during the global mapping. Only a small proportion of craters are clearly embayed from the exterior by volcanic plains (about 6%, e.g., Heloise, 40.0°N, 51.9°E, 38 km; Alcott, 59.5°S, 354.4°E, 66 km) and about 11% of craters are deformed by tectonic structures (e.g. Balch, 29.9°N, 282.9°E, 40 km; Rosa Bonheur, 9.7°N, 288.8°E, 104 km). Type locations for different types of craters are 51.9°N, 143.4°E, Cochran; 55.6°S, 321.6°E, Meitner (pristine structure); 26.3°N, 42.8°E, Gautier; 59.5°S, 354.4°E, Alcott (embayed crater); and 15.2°N, 217.4°E, Batten; 9.7°N, 288.8°E, Rosa Bonheur (tectonized crater).

4. Discussion

4.1. Correlation of units

Several authors have applied different techniques (e.g., craters on specific units, dike swarms) in an attempt to correlate units/structures on Venus (Namiki and Solomon, 1994; Price and Suppe, 1994; McGill, 1994; Basilevsky and Head, 2000; Ernst et al., 2003). These attempts show general agreement with our results (e.g., tessera is old, regional plains are at the mid stratigraphic position, lobate plains are at the top of the global stratigraphic column). The findings by these authors, however, were restricted to either specific features (e.g., large volcanoes, coronae) or specific regions (e.g., Guinevere Planitia, or individual published geological maps) or generalized units such as tessera, rifts, and regional plains (Grosfils and Head, 1996).

The resulting global geological map compiled in this study (Fig. 21a–f) portrays the spatial distribution of the morphologically distinctive units described in detail in the previous section, but it does not show whether or not these units are temporally correlative. The visible differences in morphology do not in of themselves, suggest differences in the time of emplacement of the units and, of course, units with the same or similar morphology do not necessarily form at the same time. As described throughout the unit definitions section, however, embayment, superposition and crosscutting relationships are the key factors in

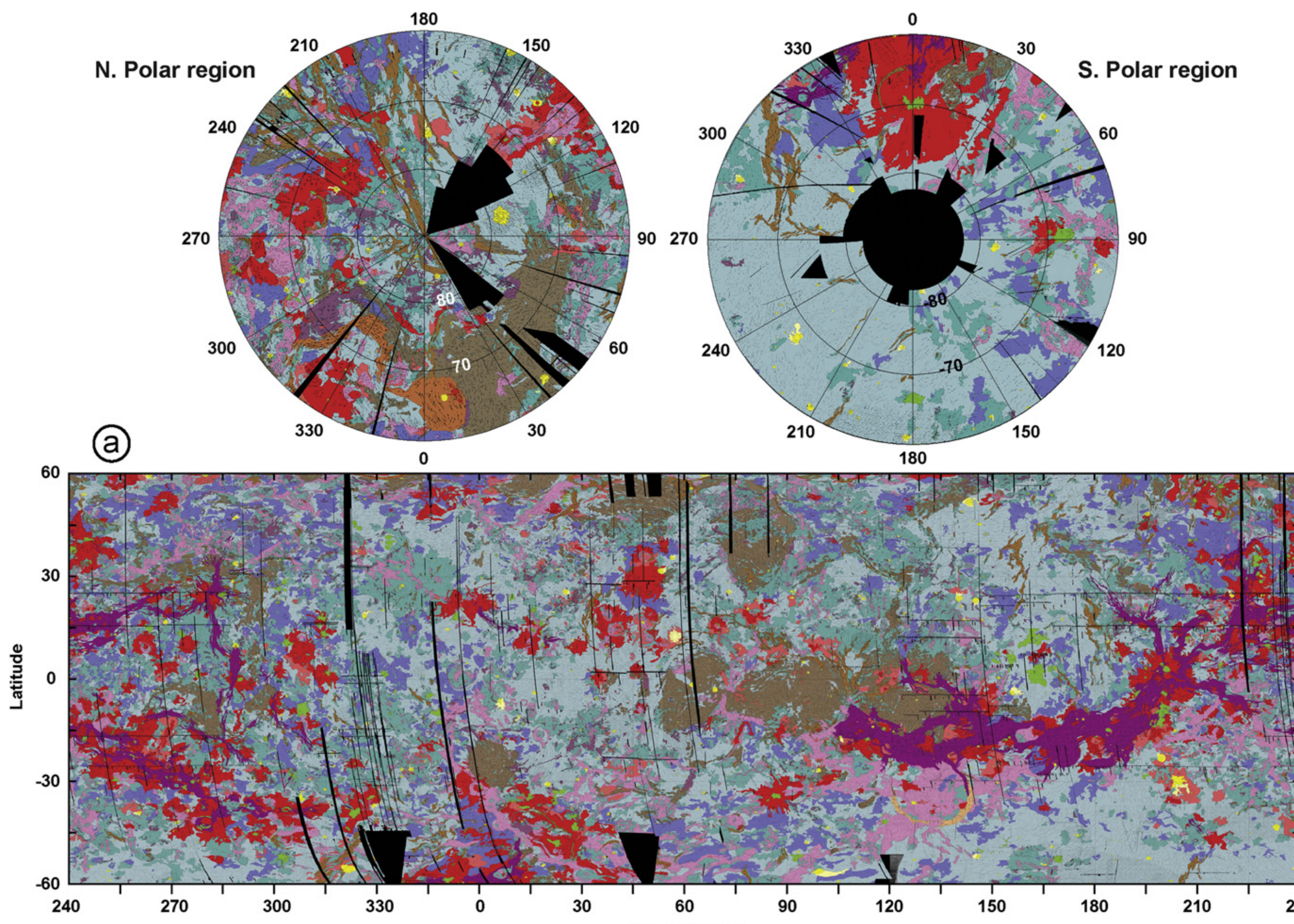

Fig. 21. The global geological map of Venus showing the spatial distribution of the morphologically defined units. (a) Equatorial region: simple cylindrical projection; polar regions: polar stereographic projection; (b) orthographic projection, central meridian: 0°E; (c) orthographic projection, central meridian: 90°E; (d) orthographic projection, central meridian: 180°E; (e) orthographic projection, central meridian: 270°E; (f) key showing names and letter designations for units.

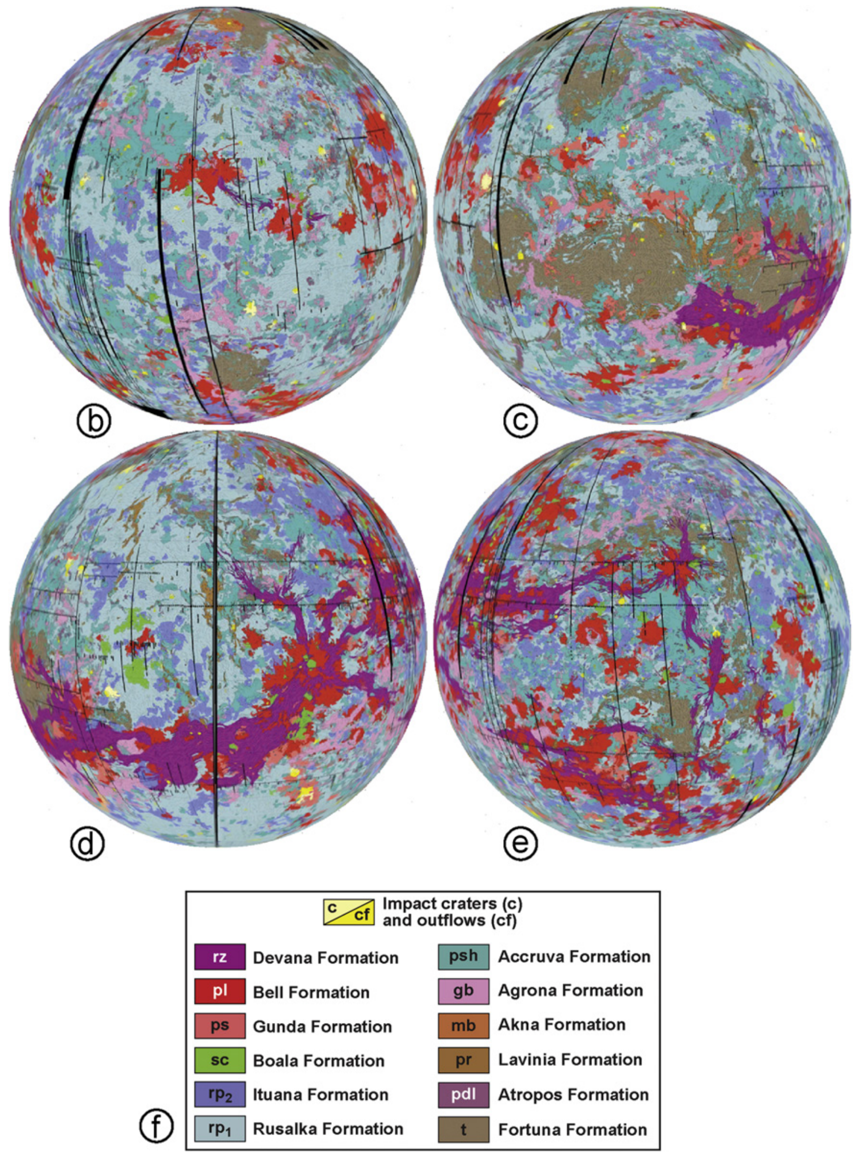

Fig. 21. (*continued*)

establishing the relative ages among the units and constructing the stratigraphic column.

Basilevsky and Head (1995a,b) analyzed the geological characteristics and relationships (the sets of specific units and their relative age relationships) in a stratigraphic sample consisting of 36 randomly selected areas about 1000×1000 km each. They found that the sequences of these units are themselves repeated from site to site (Basilevsky and Head, 1995a,b). The consistent relative age relationships among the units strongly suggest that the same sequence of events characterized each sub-region within a random stratigraphic sample that comprises ~8% of the surface of Venus (Basilevsky and Head, 1995a,b).

These findings were extended to different and larger areas (Basilevsky and Head, 1998, 2000) and were found to be consistent there as well. Using the dual stratigraphic classification scheme of units and regional stratigraphic correlations described above, as well as estimates of the model absolute time of emplacement of these units, Basilevsky and Head (1998, 2000) and Basilevsky et al. (1997), proposed that the major units are generally globally time-correlative over the entire planet. Guest and Stofan (1999) examined seven areas as examples of geological relationships on Venus, and presented an alternative interpretative paradigm for the geological evolution of Venus in which geological units are diachronous and not time-correlative, forming locally as a series of units representing a sort of "Wilson Cycle" of activity that occurred at different times in different places around the globe. These two approaches correspond to two principally different scenarios for the geologic history of Venus. Guest and Stofan (1999) characterized the approach of Basilevsky and Head as "directional", because the interpreted geologic history based on the extensive geological mapping implied changes in volcanic and tectonic style as a function of time. Guest and Stofan (1999) characterized their approach as "non-directional", implying that the geologic history followed a more steady-state manner of successive local "Wilson cycles" with no major changes in tectonic style or rate of resurfacing as a function of time. Both approaches make specific and testable predictions about the global stratigraphy and geology. For example, the "non-directional interpretation" of Guest and Stofan (1999) predicts a patchwork-like distribution of regions with their own local sequences of events, occurring at different times. The so-called "directional" interpretation of Basilevsky and Head (1998) is based on a documented similar sequence of units at over 36 different places on Venus, and the regional correlation of these units over a number of different areas. For the entire globe, the dual-classification approach of Basilevsky and Head suggests that the basic sequence of units established in the 36 local areas may be traceable between regions, and that if they are indeed correlative, the units should remain in the same sequence as that observed in the 36 local areas, and that the different local occurrences can be contiguously linked to establish a global correlation. These key predictions of the two approaches were one of the main subjects for testing during the compilation of the global geological map.

After the work by Basilevsky and Head (1995a,b), the survey of morphological units and their age relationships was expanded when the USGS program of geological mapping of Venus started and different groups of geologists began to compile their geological maps. The sets of units defined and mapped by these groups appear to be different in many details (Chapman, 1999; Johnson et al., 1999; McGill, 2000, 2004; Bender et al., 2000; Rosenberg and McGill, 2001; Campbell and Campbell, 2002; Hansen and DeShon, 2002; Bridges and McGill, 2002; Stofan and Guest, 2003; Young and Hansen, 2004; Bleamaster and Hansen, 2005; Brian et al., 2005; Campbell and Clark, 2006; Copp and Guest, 2007; Basilevsky, 2008). If one compares the published geological maps and correlation charts (Basilevsky and Head, 2000) two important things become evident. First, the morphologic similarity of units (including those that make up the majority of the surface) mapped in different regions by different authors is obvious (Figs. 3,6,8,10,12–14, 17–20)). Second, the generalized sequence of units appears similar in each published map. The heavily deformed units such as tessera, densely lineated plains (and analogous units), etc., form the base of the stratigraphic columns. Vast and mildly deformed plains (such as regional and/or shield plains) occupy the middle portions of the columns while the undeformed plains/flows (lobate plains, smooth plains) and rift zones, form the upper levels in places where they occur.

The results of the mapping of the individual quadrangles could be consistent with both approaches. In the framework of the "directional" approach of Basilevsky and Head (1998), the individual quadrangles simply represent samples from the general, planet-wide, stratigraphic sequence. For the "non-directional" interpretation (Guest and Stofan, 1999), these results suggest that the quadrangles sample regions with the same general sequence of events, but are not necessarily time correlative. According to the Guest and Stofan (1999) hypothesis, the sequences in these regions can be shifted in time relative to each other and thus the global correlation of units would not be observed at the global scale and the planetary geologic record would not demonstrate specific evolutionary trends. The morphologically similar units and their similar general sequence, however, strongly restrict the applicability of the Guest and Stofan (1999) "non-directional" interpretation.

Geological mapping in the relatively small ($\sim$3000 km across) and individual areas such as the USGS quadrangles does not provide the possibility to address the major problem of the more regional to global stratigraphic correlation of the units: at the global scale are the units non-correlative or time-transgressive (the prediction of the "non-directional" interpretation (Guest and Stofan, 1999)) or are they generally correlative and broadly synchronous (the prediction of the "directional" interpretation; Basilevsky and Head, 1998)? Geological mapping in the large and contiguous zones is important to constrain this problem. Mapping in such zones connects different quadrangles and permits correlation of units mapped there by continuous tracing of the most extensive units. This attempt at a regional correlation of units was one of the goals of mapping within a geotraverse that was centered at 30°N (from 22.3° to 37.6°N) and extended around the entire globe of Venus (Ivanov and Head, 2001b). The geotraverse connects 11 quadrangles (Fig. 1): V-8 (McGill, 2004), V-9 (Campbell and Campbell, 2002), V-13 (Ivanov and Head, 2005a), V-14 (Grosfils et al., 2011), V-17 (Basilevsky, 2008), V-20 (McGill, 2000), V-21 (Campbell and Clark, 2006), V-23 (Hansen, 2009), V-24 (Lang and Hansen, 2010), V-25 (Young and Hansen, 2004), and V-31 (Copp and Guest, 2007). The most abundant and ubiquitous unit within the geotraverse is the lower unit of wrinkle ridged plains (corresponding exactly to the lower unit of regional plains (rp_1) in the global map, Figs. 9c and 13). This unit occupies the middle stratigraphic position, is everywhere embaying or superposed on the heavily tectonized units (e.g., tessera) and is covered by plains units that are practically undeformed by tectonic structures (e.g., lobate plains; Fig. 22). Within all maps that are connected by the geotraverse, the most abundant units are those that are morphologically similar to the lower unit of regional plains (Figs. 9c and 13) and occur at the middle levels of the regional stratigraphic columns (Fig. 22).

The same results were found in the much larger geotraverse along the equator (from 22.5°S to 22.5°N, Fig. 1) (Ivanov and Head, 2006b). This zone connects also 11 quadrangles: V-20 (McGill, 2000), V-21 (Campbell and Clark, 2006), V-23 (Hansen, 2009), V-24 (Lang and Hansen, 2010), V-25 (Young and Hansen, 2004), V-31 (Copp and Guest, 2007), V-35 (Bleamaster and Hansen, 2005), V-37 (Hansen and DeShon, 2002), V-39 (Brian et al., 2005), V-40 (Chapman, 1999), and V-43 (Bender et al., 2000). In this equatorial global geotraverse, the most abundant units occur at the middle stratigraphic levels and are morphologically identical to the lower unit of regional plains (Figs. 9c and 13). Thus, the lower unit of regional plains has three characteristics of key importance: (1) It is almost invariant morphologically (broad, thousands of kilometers across, regions of uniform radar backscatter, lack of visible sources, morphologically smooth and mildly deformed by tectonic structures, associated with narrow channels, etc.). (2) Material of this unit always embays heavily tectonized structural–material units (e.g., tessera, ridge belts, etc.) and is embayed by tectonically undeformed plains and lava flows. (3) This unit occurs virtually everywhere on Venus. These characteristics of the lower unit of regional plains suggest that this unit can be used as a reference unit in the reconstruction of local to regional sequences of events.

What are the modes of formation and timing of emplacement of this global unit? The similarity of morphology of regional plains in different and sometimes very distant locations implies that whatever specific style of volcanism was responsible for formation of the plains, its results are fairly similar everywhere. This suggests that the range of possible processes that could have formed regional plains is rather narrow; a broad, regional volcanic flooding, successfully accounts for the important characteristics of regional plains (Head et al., 1992). The problem of the timing of formation of this unit has great importance and, at first glance, appears to be much less constrained. The total number of impact craters on the surface of Venus is small (Schaber et al., 1992, 1998; Herrick and Phillips, 1994; Herrick et al., 1997), which means that the surface of the planet is relatively young. The model estimates of the age vary from $\sim$750 to $\sim$240 Ma (Schaber et al., 1992; Phillips et al., 1992; Strom et al., 1994; McKinnon et al., 1997; Le Feuvre and Wieczorek, 2011). Several tests conducted by different authors that used different statistical techniques have shown that the total population of impact craters on Venus is randomly spatially distributed (Phillips et al., 1992; Strom et al., 1994; Hauck et al., 1998). Subpopulations of embayed craters are preferentially associated with the occurrences of lobate plains (Ivanov, 2009) and tectonized craters are deformed by structures of rift zones. These two units (pl and rz) are not randomly spatially distributed on the surface of Venus (Fig. 16b). We interpret this to mean that resurfacing processes after emplacement of regional plains were not sufficient to create

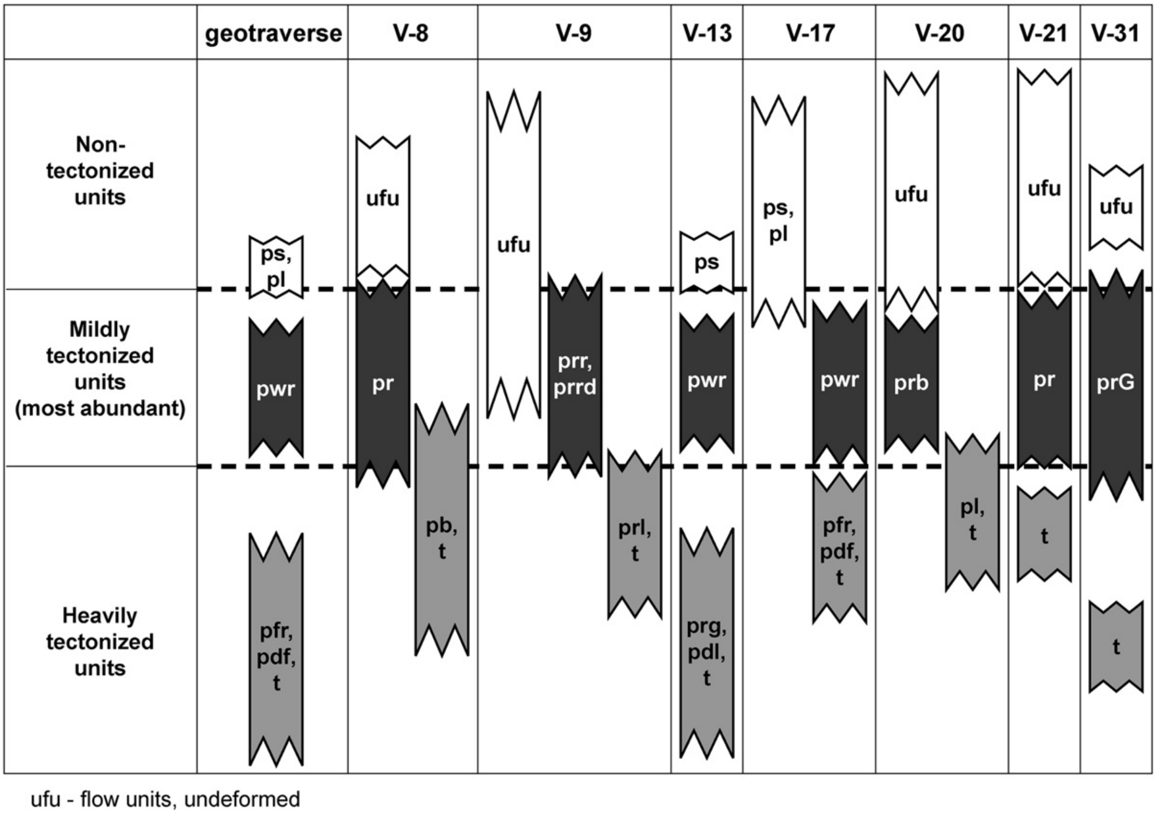

Fig. 22. Correlation of units mapped within the geotraverse along 30°N and in individual quadrangles that are crossed by the geotraverse (see text for details).

a noticeable non-randomness of the areal distribution of the entire population of impact craters. In any case, the small number of the craters and their random spatial distribution complicate the use of standard size-frequency distribution techniques to date units (Campbell, 1999; Kreslavsky et al., 2009).

Therefore, attention must be focused on the definition of geologic units and structures, and analysis of crosscutting, embayment, and superposition relations among structures and units to establish their relative ages. The stratigraphic approach to the problem of the timing of the unit emplacement may not be able to establish the exact time or duration of emplacement of the unit. For example, regional plains may have a time-transgressive nature and then in different locations the morphologically same unit could form at different times (Fig. 23a). Because the "non-directional" interpretation states that "… the plains have been built up by lavas erupted in a number of different styles, each occurring throughout the history…" (Guest and Stofan, 1999), the time-transgressive emplacement of the plains-forming units (and their interleaving with other different types of units) is one of the most important requirements of the interpretation. If the "non-directional" model is the case, the observable constant stratigraphic relationships of regional plains with other units (Fig. 22) dictate that at least the units that overlie regional plains (e.g., lobate plains) must also be time-transgressive and or repetitive (Fig. 23b). This inevitably leads to the situation when regional plains in one locality (C in Fig. 23b) will be younger than lobate plains in other locality (A in Fig. 23b) and a situation where a "flow" of regional plains superposes a suite of flows of lobate plains may occur in some places (Fig. 24a). If the units underlying regional plains (e.g., tessera) also have a time-transgressive or repetitive character then a situation when tessera-forming structures deform and incorporate regional or/and lobate plains may also emerge (Fig. 24b).

None of these situations (Fig. 24a,b) have ever been documented in any of the published geological maps of Venus. As we compiled the global map, we paid special attention to detecting possible examples of these situations. Instead, we consistently observed that lobate/smooth plains always superpose regional plains and the opposite relationships were never observed by us or in other quadrangles independently mapped by other investigators. In some minor regions there is evidence suggesting expansion of the tessera structural pattern by additional deformation of densely lineated plains and ridged plains (tessera transitional terrain, ttt) (Ivanov and Head, 2001b, 2008a; Basilevsky, 2008). But the vast and mildly deformed plains units (shield plains and both units of regional plains) always embay these features and are not deformed by the tessera-forming structures. Thus, in no region on Venus is the general sequence of units (from the highly tectonized through shield and regional plains to lobate and smooth plains) violated.

Two alternative hypotheses could potentially explain this firmly established absence of any regions where the general stratigraphic sequence is not observed: (1) First, the surface of Venus may have a domain-like structure. Units within the domains may have been emplaced quasi-synchronously and in the same sequence at local to regional scale but a time shift between and among the domains could produce a diachronous character of the units at the global scale. In this case, the general stratigraphic sequence from tessera to regional plains to lobate plains (Fig. 22) may characterize the interiors of the domains (Fig. 25). At their boundaries, however, the general sequence of units may be disturbed and the reverse stratigraphic relationships may be observed there (Fig. 24). (2) Secondly, the units may not have a time-transgressive nature and instead be broadly synchronous at the global scale.

There are two end members within the first hypothesis. The domains may either (1) have relatively narrow (less than

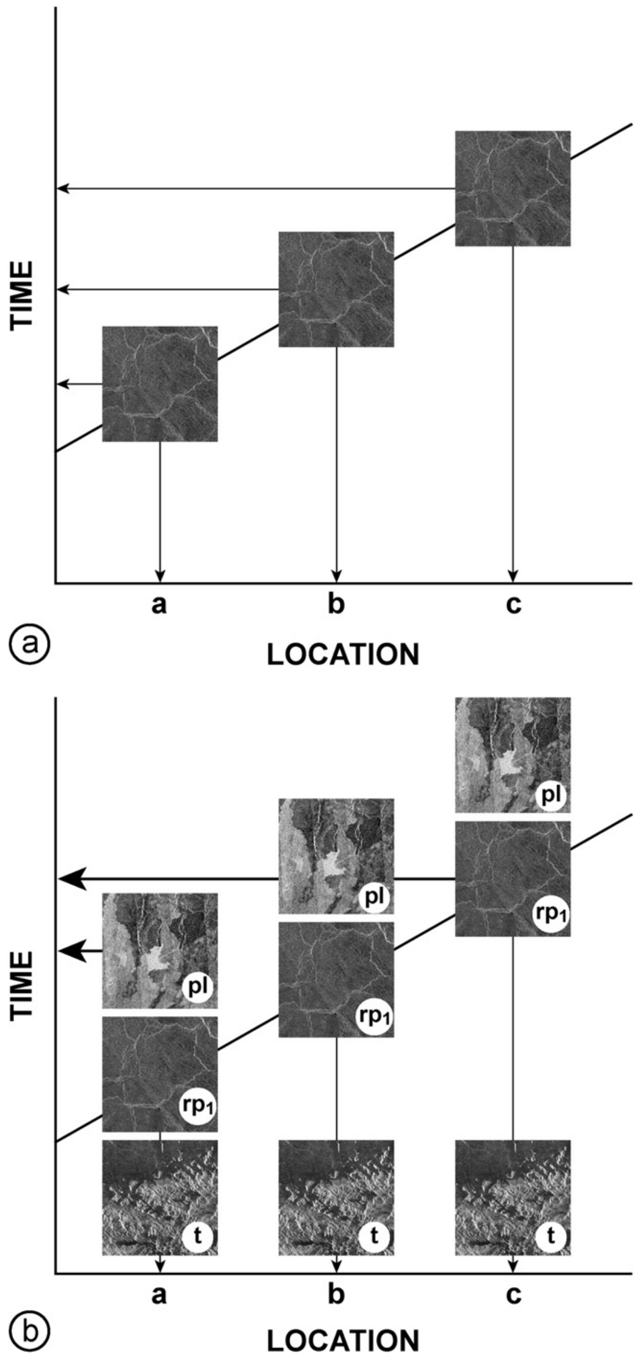

Fig. 23. A time-transgressive model for emplacement of regional plains (see text for details). (a) Diachronous formation of the lower unit of regional plains would cause its emplacement in various locations at different times. (b) In the case of time-transgressive emplacement of the lower unit of regional plains, the units that superpose it will also form diachronously.

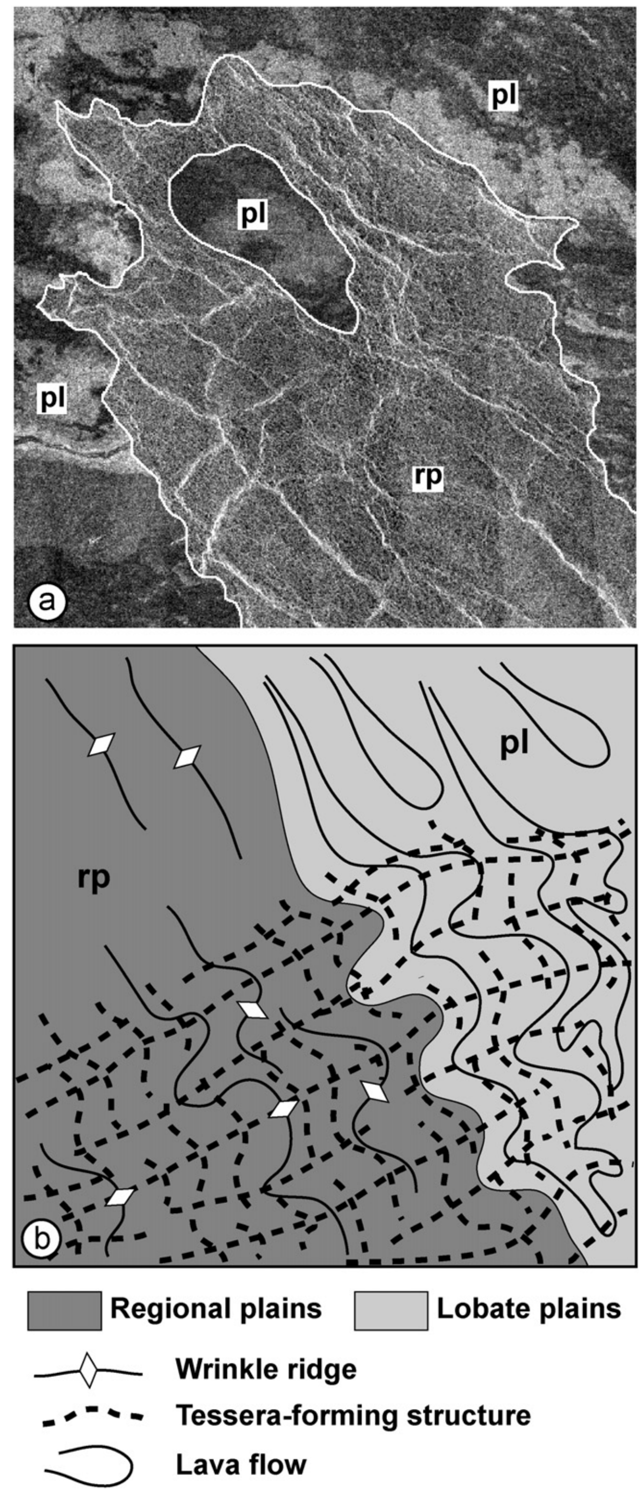

Fig. 24. Expected consequences of the time-transgressive emplacement of units on Venus. (a) If regional plains (rp) formed non-synchronously at the global scale, the superposition of these units on lobate plains is expected to occur somewhere on Venus. The figure is made artificially by cutting a random piece of regional plains and superposing it on the area of lobate plains; in no place on Venus are such relationships observed. (b) If the older, heavily tectonized units (for example, tessera) are also formed in a time-transgressive manner then a situation where tessera consumes the plains units (for example, regional plains and/or lobate plains) is expected. In no place on Venus are such relationships observed.

the dimensions of a USGS quadrangle) and well-defined edges or (2) the boundary zones between the neighboring domains are broad and poorly defined. The first end member appears to be highly implausible. Due to the absence of the situations shown in Fig. 24, this hypothesis requires that all published geological maps correspond to the interiors of the domains and none of the individual maps cover the transition from one domain to the other. In order to satisfy these requirements the domains (the natural geologic objects) must be as perfectly arranged in space as the USGS map sheets, which is highly unlikely. Another objection to the hypothesis of the domain structure comes from the results of mapping within the geotraverses (Ivanov and Head, 2001b, 2006b). The geotraverses are contiguous zones that together cover an area from about 23°S to 37.5°N (about 50% of

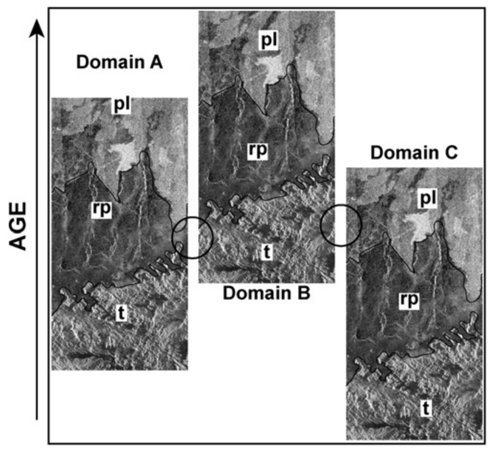

Fig. 25. The model of the domain structure of the surface of Venus. The observable general sequence of units from tessera to regional plains to lobate plains occurs within the individual domains (local synchroneity). The time shift between the domains would indicate the global diachroneity of the units. At the borders of the domains (circles) the reverse stratigraphic sequences should appear (e.g., tessera in Domain B is younger than regional plains in Domain C).

the surface of Venus) and very likely would cross several domains if indeed such domains existed. Violations of the general stratigraphic sequence (Fig. 24) were not found in any region within the area of the geotraverses and, thus, the existence of the domains is not consistent with the observations.

The second end member may explain the situation if the transitional zones from one domain to the other are very broad, indistinct, and much larger than the characteristic dimensions of the USGS quadrangles. If these zones where the possible transgressive relationships occur are much larger than the size of the individual maps then evidence for the disturbance of the common stratigraphic sequence (Fig. 24) may not be seen within either one map or even a group of maps (Fig. 26a). The length of the zones, however, cannot exceed the size of the planet and then at least one major zone of the reverse sequence of units must appear (Fig. 26b). Neither the results of the mapping in the geotraverses nor the global geological map support the existence of such a zone. The whole spectrum of situations between these end-members faces the same problems and does not have observational support.

Thus, we conclude that the surface of Venus likely represents a single domain where the typical stratigraphic sequence can be documented virtually everywhere. Our detailed mapping and correlation thus support the conclusion that at least several of the key units mapped are generally globally synchronous. The key position in the globally observed sequence is that of the lower unit of regional plains (rp_1) that divides the entire sequence into older (t, pdl, pr, gb, psh) and the younger (rp_2, sc/ps/pl/rz) parts. This indicates that the lower unit of regional plains (Figs. 9c and 13) may indeed be a planet-wide stratigraphic reference unit that can be used to help construct the global stratigraphic column of Venus (Figs. 27 and 28).

4.2. The global stratigraphy of Venus

Our assessment of the geological history of Venus is based on two major findings that were made as we compiled the global-scale geological map of this planet:

(1) Evidence for the global areal distribution, continuity of exposure, stratigraphic position and near-synchronous formation of the most abundant and pervasive unit (the lower unit of regional plains, rp_1, the Rusalka Formation).
(2) The established, documented, and globally consistent individual and stratigraphic sequence relationships of the other units with rp_1 and each other.

We first analyzed and tested the Venus stratigraphic units proposed earlier by Basilevsky and Head (1998, their Figure 1). These units and this sequence, even if based on analysis of limited regions relative to the entire globe (Basilevsky and Head, 1995a,b, 1998), provide a testable stratigraphic sequence, which allows further assessment and refinement and modification for the adequate description and interpretation of the geologic history of Venus from a global standpoint. In our interpretation of the observed and documented (Fig. 21) relationships of the units, we have modified and updated the stratigraphic units, their subdivisions and groupings, and divided the history of the planet into four periods.

The geological records of the earlier and the longest period of evolution of Venus (Pre-Fortunian Period, adopted from Basilevsky and Head, 1998, Fig. 28) are hidden. Only remnants of these records may exist as deformed rocks and minerals and they are not recognized yet with the resolution of available data sets. The other possible trace of Pre-Fortunian is the high D/H ratio detected in the atmosphere of Venus (Donahue et al., 1982; de Berg et al., 1991). One possible interpretation of this ratio, which is about 100 times higher than on Earth, suggests the existence of a primordial ocean on Venus (Donahue and Hodges, 1992; Donahue, 1999) during the Pre-Fortunian Period. If this interpretation is correct then specific (e.g., water-rich) environments and petrogenesis (e.g., formation of K-granite-like and/or Na-TTG-like series of rocks) may have characterized the Pre-Fortunian or some portion of it (Taylor and McLennan, 2009).

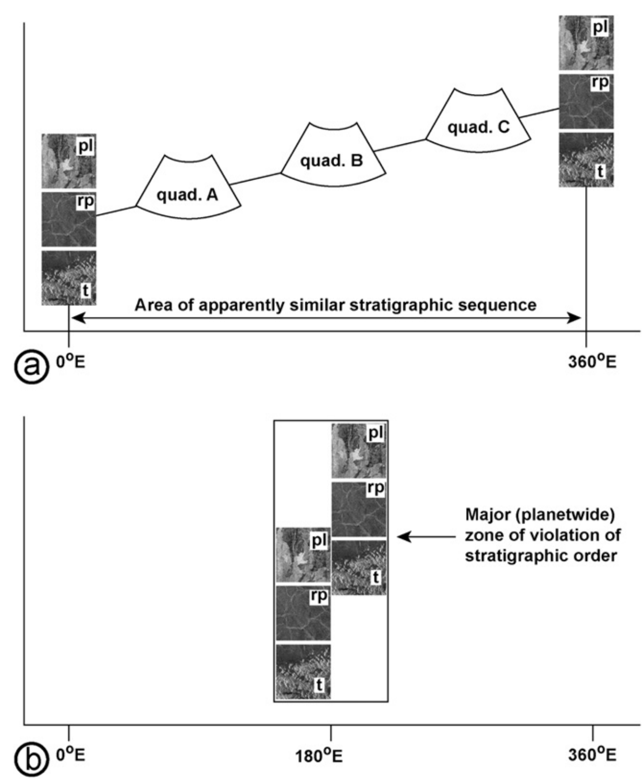

Fig. 26. The model of domain structure with very wide transitional zones between the domains. (a) Units that formed in the time-transgressive manner may show similar stratigraphic sequences within the areas that are much smaller than the dimensions of the transitional zones. (b) Because the dimensions of transitional zones are limited by the size of the planet, a major zone where the common stratigraphic sequence is violated should appear. No such zones were documented.

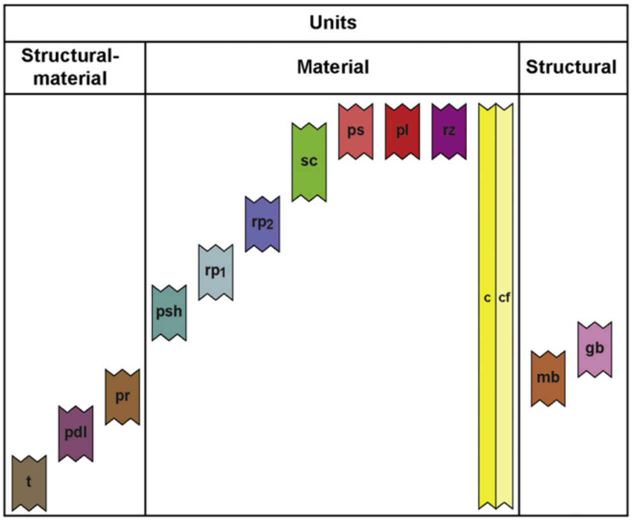

Fig. 27. Global correlation chart of the units that shows their relationships (see also Fig. 21).

Alternatively, the high D/H ratio is interpreted as the result of massive outgassing due to a catastrophic resurfacing event about 0.5 – 1 Gyr ago (Grinspoon, 1993). In this case, the unusual D/H ratio is a signature of the Guineverian period of the geologic history of Venus.

The observable geological record starts with the Fortunian Period (adopted from Basilevsky and Head, 1998; Fig. 28), during which intense deformation of crustal materials and building of locally to regionally important areas of thicker crust dominated. The Fortuna Formation (Basilevsky and Head, 1998) represents the tessera structural–material unit that was defined by its unique pattern of deformation (Figs. 2a and 3) (Barsukov et al., 1986; Sukhanov, 1992; Bindschadler and Head, 1989). In places where tessera is in contact with the other units, these units embay/cut tessera materials, which suggests that tessera is older. The most important features of the Fortunian are large tessera-bearing crustal plateaus (e.g., Fortuna, Ovda, etc.) that form a specific class of first-order (a few thousands of kilometers across) highs on Venus (Sjogren et al., 1983; Smrekar and Phillips, 1991). The exposed area of Fortuna Formation, for example, is about 7.3% of the surface of Venus (Table 2). The lowest stratigraphic position of tessera (Figs. 27 and 28) and its relative abundance show that this unit is of extreme importance as a probable 'window' into the geological past of Venus. The nature of the Fortuna Formation (heavily tectonized materials of tessera) strongly suggests that tectonics dominated the Fortunian Period. The lower boundary of Fortunian is not determined stratigraphically and the duration of this period cannot be estimated.

Broadly distributed and typically small occurrences of the Atropos Formation (densely lineated plains, pdl; Figs. 2b and 6) occur at the beginning of the Guineverian Period (Basilevsky and Head, 1998) (Fig. 28). The Atropos Formation is named for the largest occurrence of unit pdl northwest of Lakshmi Planum (Fig. 4b) (Ivanov and Head, 2008a, 2010a). The Lavinia Group (Basilevsky and Head, 1998 (Fig. 28) includes the Lavinia Formation (ridged plains, pr, Figs. 2c and 8) and the Akna Formation (mountain belts, mb, Fig. 2d). The name Akna Formation is for the Akna Montes, which is one of the largest mountain ranges on Venus, at the western edge of Lakshmi Planum (Barsukov et al., 1986; Pronin, 1992) (Fig. 7a). All these units are either structural–material (pdl, pr) or structural (mb) and they often display heavily tectonized crustal materials.

Among these, mountain belts appear to be the most deformed by contractional structures (Fig. 2d). Materials of the Atropos

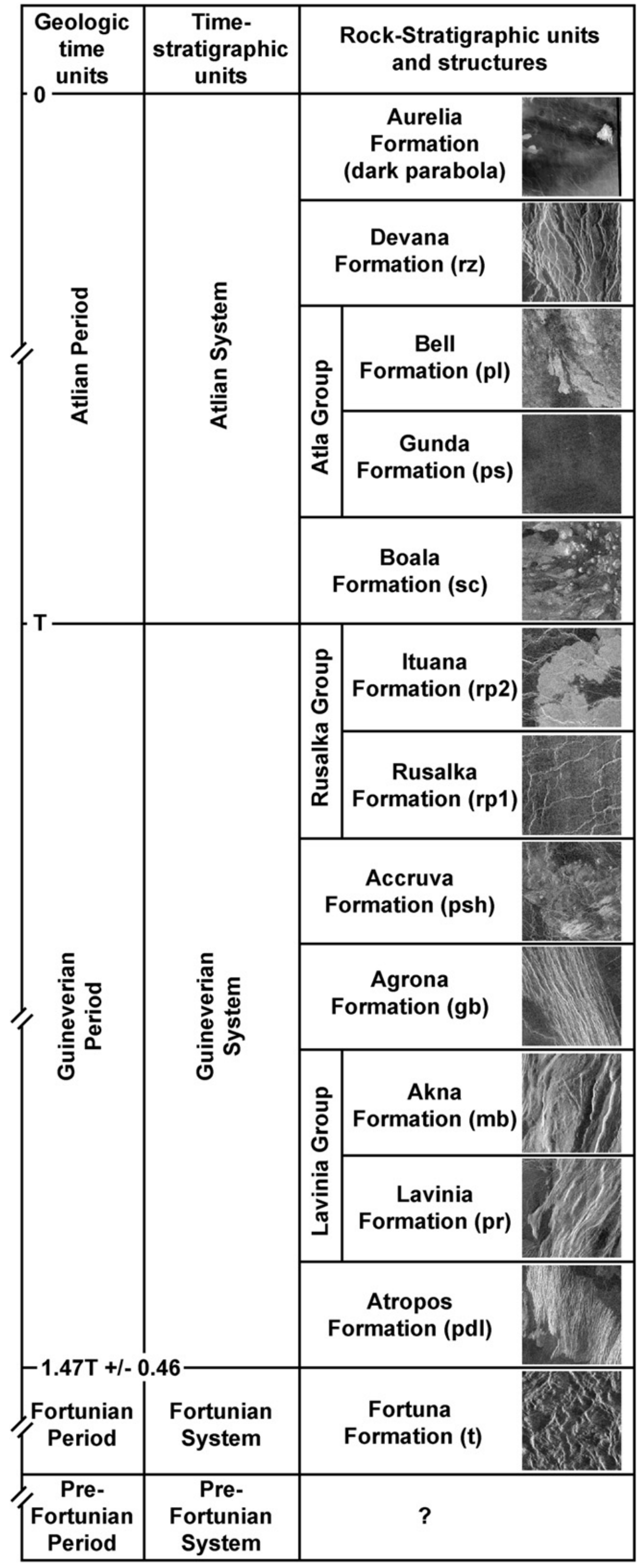

Fig. 28. Stratigraphy of defined and mapped geologic units on Venus. The visible geologic history of Venus consists of the Fortunian, Guineverian, and Atlian Periods. The major portion of the surface of Venus (about 70%) was resurfaced during the Guineverian Period. See text for discussion. T is the mean model absolute age of the surface (Price and Suppe, 1995; Schaber et al., 1992; Phillips et al., 1992; Strom et al., 1994; McKinnon et al., 1997).

Formation are deformed by dense sets of extensional structures (fractures, Fig. 2b) and the primary structures of the Lavinia Formation are ridges of contractional origin (Fig. 2c). Materials of both formations usually embay tessera when these units are in contact. In a few places, however, sets of additional structures (either extensional or contractional) deform the surface of densely lineated and ridges plains and these units then somewhat resemble tessera (tessera transitional terrain, ttt). The existence of these transitional morphologies suggests that the Fortuna (t), Atropos (pdl), and Lavinia (pr) Formations may be partly contemporaneous in some places and may characterize the very beginning of the assessable geologic history of Venus. The orogenic phase of formation of mountain belts (Akna Formation, mb) surrounding Lakshmi Planum also occurred near the beginning of the visible geologic history of this region (Ivanov and Head, 2008a). Relationships of the belts with the other units (Ivanov and Head, 2008a, 2010a) suggest that the belts postdate tessera and may be contemporaneous with deformation of ridged plains.

Abundant (Table 2) and widely distributed (Fig. 7b) zones of groove belts (Agrona Formation, gb, Figs. 9a and 10; the name stands for a very prominent swarm of graben and fractures that outlines Beta Regio from the North, Basilevsky, 2008) appear at the middle of the Guineverian Period (Fig. 28). The global-scale system of zones of extensional structures (groove belts) is closely associated spatially with the distribution of coronae (Fig. 7b). Evolution of coronae represents a two-stage process that starts from updoming of the surface and formation of a tectonically deformed annulus and is followed by volcanic activity (e.g., Smrekar and Stofan, 1997). Stratigraphic studies of about 15% of the total population of coronae (Basilevsky and Head, 1997; Ivanov and Head, 2001b) have shown that: (1) the first, tectonic, phase of coronae evolution was largely completed prior to the emplacement of regional plains, (2) the tectonic annulus of coronae in many cases either coincides with or is closely associated (both spatially and temporarily) with individual branches of groove belts (Figs. 7b and 3) the second, volcanic, phase (if present) occurred predominantly subsequent to the emplacement of regional plains. Thus, the middle of Guineverian Period was characterized by formation of globally distributed belts of extensional structures and the tectonic annulae of most of the coronae.

Vast, mildly deformed, volcanic plains broadly embay structures of groove belts and corona annulae. These relationships, which are observed at the global scale, imply a significant decline of tectonic activity and the dominant role of volcanism during the late Guineverian (Fig. 28). This volcanic activity appeared in initial phases in the form of small-scale eruptions from widely distributed sources across the globe that formed shield plains (Accruva Group, psh, Figs. 9b and 12; this name stands for Accruva Planitia in the northern hemisphere of Venus where shield plains are very abundant and make a distinctive material unit, Aubele and Slyuta, 1990; Aubele, 1994, 1995). The volcanic style of small shields changed to voluminous eruptions, volcanic flooding, and formation of the most abundant and morphologically homogenous material unit, the lower unit of regional plains, that shows evidence for the global scale, generally synchronous emplacement (Rusalka Formation, rp_1, lower part of Rusalka Group, Figs. 9c and 13; Basilevsky and Head, 1998, Fig. 28). Emplacement of unit rp_1 changed (Fig. 28) to more localized eruptions of the upper unit of regional plains (Ituana Formation, rp_2, Figs. 9d and 14; the name stands for Ituana Corona that shows large and very well developed lava flows deformed by a regional network of wrinkle ridges, Young and Hansen, 2004) that often are associated with distinctive large volcanic sources. A period of global wrinkle ridge formation largely followed the emplacement of regional plains.

The total area of the Guineverian System units comprises about 70% of the surface of Venus (Table 2). Younger materials and structures cover and/or deform the Guineverian System units and, thus, the exposed area represents a minimum estimate of the abundance of Guineverian materials. The degree of their deformation (from heavily tectonized units to mildly deformed units) and abundances and apparent duration of Guineverian (about 0.5T, where T is the mean age of the surface, see discussion in Basilevsky et al. (1997) and Basilevsky and Head, 1998) suggest the following: (1) Tectonic resurfacing, which continued the trend of Fortunian Period, dominated during about the first half of Guineverian, but changed to predominantly volcanic resurfacing during the second half of this period. Thus, Guineverian corresponds to a major decline of tectonic activity on Venus during its visible geologic history. (2) The Guineverian volcanic plains (Accruva, Rusalka, and Ituana Formations) are very extensive and responsible for resurfacing of about 60% of the surface of Venus. (3) Owing to the apparently short duration of the Guineverian (Fig. 28) and the large fraction of the surface of Venus occupied by Guineverian units (Table 2), the tectonic and especially volcanic resurfacing during this time must have operated at a high rate.

The Atlian Period of the geologic history of Venus includes one structural and four material units. The name Atlian is for Atla Regio, where young volcanic and tectonic features are very prominent and abundant. Two major features characterize the Atlian Period (Fig. 28): (1) formation of large and prominent rift zones (Devana Formation, rz, Figs. 15d, 20; the name is for Devana Chasma that extends from Phoebe Regio to Beta Regio (Campbell and Burns, 1980; Stofan et al., 1989; Basilevsly, 2008) and (2) extensive lava flows and their fields (Bell Formation, pl, Figs. 15c and 19; the name is for Bell Regio, which is characterized by abundant young lava flows but show no evidence for rifting (Ivanov and Head, 2001b; Campbell and Campbell, 2002)).

Structures of rift zones cut, and lava flows of lobate plains embay, all structures and units of the Fortunian and Guineverian periods. This unequivocally indicates that the Atlian units formed during the stratigraphically youngest activity on Venus. Between themselves, rift zones and lobate plains do not display consistent relationships of relative age and parts of these units can both predate and postdate each other. We interpret these relationships as evidence for the broadly contemporaneous formation of rift zones and lobate plains. Recent interpretations of the Venus Express data on the atmospheric radio-noises (Russell et al., 2007) and emissivity (Helbert et al., 2008; Smrekar et al., 2010) as well as the interpretation of the radiophysical properties of surficial materials (Bondarenko et al., 2010) provide evidence for recent volcanic activity on Venus. This suggests that the type of geological activity characterizing the Atlian Period continues to the present day.

The most extensive fields (many hundreds of kilometers across) of lobate plains are almost exclusively associated with large shield volcanoes and dome-shaped rises (Atla Regio and Beta Regio, Lada Terra, etc., Fig. 16b). This type of association suggests that Atlian volcanic activity is related to a smaller number but larger volcanic sources than during the Guineverian Period. In places, Atlian volcanism continued to form flows associated with coronae, and relatively small occurrences of smooth plains (ps) and shield clusters (sc). Smooth plains are mapped as the Gunda Formation (Figs. 15b and 18); the name is for Gunda Planitia, the largest fraction of which is covered by featureless, dark, and morphologically smooth plains (Chapman, 1999). Clusters of small volcanoes form the Boala Formation (Figs. 15a and 17); the name is for Boala Corona, the floor of which displays a cluster of small shields that formed simultaneously with the surrounding lobate plains (Ivanov and Head, 2010b). Rift zones cut the central parts of the rises, interconnect some of them (e.g., in the BAT region), and form a global system of very prominent but concentrated zones of extensional structures (Fig. 16b) contrasting to the broadly distributed and more pervasive groove belts (Fig. 7b). Craters with dark parabolas

(Aurelia Formation; adopted from Basilevsky and Head, 1998) are among the youngest features on Venus (Campbell et al., 1992), forming in approximately the last 0.1T years. Basilevsky and Head (2002) showed that the dark halo and dark parabola deposits of impact craters are interleaved with structures of rift zones and flows of lobate plains.

The total area of each of the major units of the Atlian Period, rift zones and lobate plains, are close to each other (Table 2), which suggests that both tectonics and volcanism were almost equally important factors in the geologic history at this time. Although the Atlian Period lasted apparently twice as long as the Guineverian Period (Fig. 28), only about 16% of the surface of Venus was resurfaced during this time (Table 2). This means that the Atlian is characterized as a period of relative geologic quiescence when the rate of volcanic and tectonic processes was significantly lower than during Fortunian and Guineverian periods.

5. Conclusions

(1) The global geological map ($\sim$1:10 M scale, Fig. 21) shows the spatial distribution of morphologically distinctive units over the entire surface of Venus. The units were defined according to the dual stratigraphic classification scheme. They are thus based on their characteristic descriptive nature and morphology, and are not based on an interpretative or time component.

(2) The global map consists of a specific set of rock-stratigraphic units, as follows: tessera (t), densely lineated plains (pdl), ridged plains (pr), mountain belts (mb), groove belts (gb), shield plains (psh), regional plains, rp (lower, rp_1, an upper, rp_2, units), shield clusters (sc), smooth plains (ps), lobate plains (pl), and rift zones (rz). Each of these stratigraphic units has morphological characteristics that are similar across the surface of Venus and each specific unit can be readily distinguished from the others.

(3) On the basis of superposition and stratigraphic relationships of these units, we interpret the sequence of events and processes recorded in the global stratigraphic column. The earliest part of the history of Venus (Pre-Fortunian) predates the observed geological features and units. The observable geologic history of Venus is subdivided into three distinctive phases (Fig. 28). The earliest phase (Fortunian Period, composed of the Fortuna Formation, t) involved intense deformation and building of regions of thicker crust (tessera). This was followed by the Guineverian Period. Tectonized materials of Atropos (pdl), Lavinia (pr), Akna (mb), and Agrona (gb) Formations characterize the first part of the Guineverian. The second part of the Guineverian involved global emplacement of vast plains of the Accruva (psh), Rusalka (rp1), and Ituana (rp2) Formations. A period of global wrinkle ridge formation largely followed emplacement of these plains. The third phase (Atlian Period) involved formation of prominent rift zones (Devana Formation, rz) and fields of lava flows (Bell Formation, pl) unmodified by wrinkle ridges. In places, the Atlian volcanic activity, which may continue to the present, formed small occurrences of smooth plains (Gunda Formation, ps) and clusters of small volcanoes (Boala Formation, sc).

(4) About 70% of the exposed surface of Venus was resurfaced during the Guineverian Period and only about 16% during the Atlian Period. Estimates of model absolute ages suggest that the Atlian Period was about twice as long as the Guineverian (Basilevsky et al., 1997; Basilevsky and Head, 1998) and, thus, characterized by significantly reduced rates of volcanism and tectonism.

(5) Comparison of rock-stratigraphic units from the global map with those that have been mapped by different authors in different regions shows that the units from the global map are morphologically similar or identical to the units that were mapped regionally (Figs. 3,6,8,10,12–14, 17–20). At the local to regional scales, the morphologically distinctive units show the same stratigraphic sequence from the older and heavily tectonized units (e.g., tessera) through vast expanses of mildly tectonized plains (e.g., regional plains), to tectonically undeformed plains (e.g., lobate plains). This generalized sequence of units/events is repeated in virtually any region of Venus selected at random. This observation is consistent with the global predictions and "directional" interpretation of the geologic history of Venus (Basilevsky et al., 1997; Basilevsky and Head, 1998; Ivanov and Head, 2001b). Although these observations could be consistent with parts of the "non-directional" interpretation of Guest and Stofan (1999), they introduce important constraints on this interpretation. Specifically, for the "non-directional" model to be correct, Venus should possess a domain structure with the same sequence of units/events within the domains (local synchroneity). Global-scale diachronism, which is a requirement of the non-directional interpretation, may then be provided by a time shift between the domains. As an inevitable consequence of this, the typical stratigraphic order of units should be violated in the transition zones from one domain to another.

(6) Careful documentation of the relative age relationships among the units within the smaller geological maps (the USGS quadrangles), the large and contiguous regions (e.g. geotraverses), and during the compilation of the global map does not reveal regions characterized by violations of the common stratigraphic sequences. On the basis of our analysis, we do not find support for the "non-directional" (Guest and Stofan, 1999) interpretation of the geologic history of Venus.

(7) The most pervasive and ubiquitous unit in all of the published maps and in the global map as well is the lower unit of regional plains. This unit (Fig. 9c) occurs in each region (Fig. 11b), everywhere displays the same morphologic characteristics, and always embays the heavily tectonized units and underlies the tectonically undeformed plains. This unit has a distinctive character of a broad (planet-wide) stratigraphic unit that divides the observable sequence of events into older and younger parts. Thus, the lower unit of regional plains (together with the global mapping and correlation of other units) provides the possibility to correlate stratigraphic sequences that occur in remote regions and to construct a planet-wide correlation chart (Figs. 27 and 28).

(8) The dual stratigraphic classification approach to the global stratigraphy has extremely important implications in terms of the geological history of Venus. It supports the hypothesis that there was a major (global) episode of resurfacing (it may have consisted of several phases) near the beginning of the observable geological record of Venus (e.g., Schaber et al., 1992; Strom et al., 1994). It also suggests the existence of major trends in evolution of long-wavelength topography, volcanism, and tectonics and implies time-dependent mechanisms of heat lost from the Venus interior.

Acknowledgements

Thanks are extended to Alexander Basilevsky for his initial recognition and insight into the stratigraphy of Venus following acquisition of the Venera-15/16 and Magellan mission data and to Jayne Aubele for her detailed discussions about regional and global units and relations. We particularly appreciate helpful discussions with George McGill, Steve Saunders, Jim Zimbelman, Nathan Bridges, Rebecca Ghent, and Les Bleamaster. We gratefully acknowledge very helpful reviews from Robert Strom and Eric Grofils. The work was partly supported by NASA Grant NNX08AL476 from the NASA Planetary Geology and Geophysics Program.

References

Addington, E.A., 2001. A stratigraphic study of small volcano clusters on Venus. Icarus 149, 16–36.
Arvidson, R.E., Greeley, R., Malin, M.C., Saunders, R.S., Izenberg, N., Plaut, J.J., Stofan, E.R., Shepard, M.K., 1992. Surface modification of Venus as inferred from Magellan observation of plains. J. Geophys. Res. 97, 13303–13317.
Aubele, J.C. 1994. Stratigraphy of small volcanoes and plains terrain in Vellamo Planitia, Venus. In: Proceedings of the Lunar and Planetary Science Conference, 25th, pp. 45–46.
Aubele, J.C. 1995. Stratigraphy of small volcanoes and plains terrain in Vellamo Planitia–Shimti tessera region, Venus. In: Proceedings of the Lunar and Planetary Science Conference, 26th, pp. 59–60.
Aubele, J.C., Slyuta, E.N., 1990. Small domes on Venus: characteristics and origin. Earth Moon Planets 50/51, 493–532.
Baker, V.R., Komatsu, G., Gulick, V.C., Parker, T.J., 1997. Channels and valleys. In: Bougher, S.W., Hunten, D.M., Phillips, R.J. (Eds.), Venus II Geology, Geophysics, Atmosphere, and Solar Wind Environment. University of Arizona Press, Tucson, pp. 757–793.
Bannister, R.A., Hansen, V.L., 2010. Geologic map of the Artemis Chasma Quadrangle (V-48), Venus. USGS Geol. Inv. Ser., Map 3099.
Barsukov, V.L., Basilevsky, A.T., Burba, G.A., et al. (24 others), 1986. The geology and geomorphology of the Venus surface as revealed by the radar images obtained by Venera 15 and 16. J. Geophys. Res. 91, D399–D411.
Basilevsky, A.T., 2008. Geologic map of the Beta Regio quadrangle (V-17), Venus. U.S. Geological Survey Sci. Inv. Map 3023.
Basilevsky, A.T., Head, J.W., 1995a. Global stratigraphy of Venus: analysis of a random sample of thirty-six test areas. Earth Moon Planets 66, 285–336.
Basilevsky, A.T., Head, J.W., 1995b. Regional and global stratigraphy of Venus: a preliminary assessment and implications for the geological history of Venus. Planet. Space Sci. 43, 1523–1553.
Basilevsky, A.T., Head, J.W., 1997. Sequence of geologic events in formation of coronae: Venus. In: Proceedings of the Lunar and Planetary Science Conference, 29th, abstract 1185.
Basilevsky, A.T., Head, J.W., Schaber, G.G., Strom, R.G., 1997. The resurfacing history of Venus. In: Bougher, S.W., Hunten, D.M., Phillips, R.J. (Eds.), Venus II Geology, Geophysics, Atmosphere, and Solar Wind Environment. University of Arizona Press, Tucson, pp. 1047–1086.
Basilevsky, A.T., Head, J.W., 1998. The geologic history of Venus: a stratigraphic view. J. Geophys. Res. 103, 8531–8544.
Basilevsky, A.T., Head, J.W., 2000. Geologic units on Venus: evidence for their global correlation. Planet. Space Sci. 48, 75–111.
Basilevsky, A.T., Head, J.W., 2002. On rates and styles of late volcanism and rifting on Venus. J. Geophys. Res. 107, 10.1029/2000JE001471, 8-1–8-17.
Bender, K.C., Senske, D.A., Greeley, R., 2000. Geologic map of the Carson Quadrangle (V-43), Venus. U.S. Geological Survey Sci. Inv. Map I-2620.
Bilotti, F., Suppe, J., 1999. The global distribution of wrinkle ridges on Venus. Icarus 139, 137–157.
Bindschadler, D.L., Kreslavsky, M.A., Ivanov, M.A., Head, J.W., Basilevsky, A.T., Shkuratov, Yu.G., 1990. Distribution of tessera terrain on Venus: prediction for Magellan. Geophys. Res. Lett. 17, 171–174.
Bindschadler, D.L., Head, J.W., 1989. Characterization of Venera 15/16 geologic units from Pioneer Venus reflectivity and roughness data. Icarus 77, 3–20.
Bindschadler, D.L., Head, J.W., 1991. Tessera terrain, Venus: characterization and models for origin and evolution. J. Geophys. Res. 96, 5889–5907.
Bleamaster, L.F., Hansen, V.L., 2005. Geologic map of the Ovda Regio quadrangle (V-35), Venus. U.S. Geological Survey Sci. Inv. Map I-2808.
Bondarenko, N.V., Head, J.W., Ivanov, M.A., 2010. Present-day volcanism on Venus: evidence from microwave radiometry. Geophys. Res. Lett. 37, L23202. doi:10.1029/2010GL045233.
Brian, A.W., Stofan, E.R., Guest, J.E., 2005. Geologic map of the Taussig Quadrangle (V-39), Venus. U.S. Geological Survey Sci. Inv. Map 2813.
Bridges, N.T., McGill, G.E., 2002. Geologic map of the Kaiwan Fluctus Quadrangle (V-44), Venus. U.S. Geological Survey Sci. Inv. Map I-2747.
Campbell, B.A., 1999. Surface formation rates and impact crater densities on Venus. J. Geophys. Res. 104, 21951–21955.
Campbell, B.A., Campbell, P.G., 2002. Geologic map of the Bell Regio Quadrangle (V-9), Venus. U.S. Geological Survey Sci. Inv. Map I-2743.
Campbell, B.A., Clark, D.A., 2006. Geologic map of the Mead Quadrangle (V-21), Venus. U.S. Geological Survey Sci. Inv. Map 2897.
Campbell, D.B., Burns, B.A., 1980. Earth-based radar imagery of Venus. J. Geophys. Res. 85, 8271–8281.
Campbell, D.B., Senske, D.A., Head, J.W., Hine, A.A., Fisher, P.C., 1991. Venus southern hemisphere: geologic characteristics and ages of major terrains in the Themis-Alpha-Lada region. Science 251, 180–183.
Campbell, D.B., Stacy, N.J.S., Newman, W.I., Arvidson, R.E., Jones, E.M., Musser, G.S., Roper, A.Y., Schaller, C., 1992. Magellan observations of extended impact crater related features on the surface of Venus. J. Geophys. Res. 97, 16249–16278.
Chapman, M.G., 1999. Geologic/geomorphic map of the Galindo quadrangle (V–40), Venus. U I-2613.
Copp, D.L., Guest J.E., 2007. Geologic map of the Sif Mons quadrangle (V-31), Venus. U.S. Geological Survey Sci. Inv. Map 2898.
Crumpler, L.S., Aubele, J., 2000. Volcanismon Venus. In: Sigurdson, H., Houghton, B., Rymer, H., Stix, J., McNutt, S. (Eds.), Encyclopedia of Volcanoes. Academic Press, San Diego, San Francisco, New York, Boston, London, Sydney, Toronto, pp. 727–770.
de Berg, C., Bezard, B., Owen, T., Crisp, D., Maillard, J.-P., Lutz, B.L., 1991. Deuterium on Venus: observations from Earth. Science 251, 547–549.
Donahue, T.M., Hoffman, J.H., Hodges, R.R., Watson, A.J., 1982. Venus was wet: a measurement of the ratio of deuterium to hydrogen. Science 216, 630–633.
Donahue, T.M., Hodges, R.R., 1992. Past and present water budget of Venus. J. Geophys. Res. 97, 6083–6091.
Donahue, T.M., 1999. New analysis of hydrogen and deuterium escape from Venus. Icarus 141, 226–235.
Ernst, R.E., Desnoyers, D., Head, J.W., Grosfils, E.B., 2003. Graben–fissure systems in Guinevere Planitia and Beta Regio (264–312E, 24–60N), Venus, and implications for regional stratigraphy and mantle plumes. Icarus 164, 282–316.
Figueredo, P.H., Greeley, R., 2000. Geologic mapping of the northern leading hemisphere of Europa from Galileo solid-state imaging data. J. Geophys. Res. 105, 22629–22646.
Frank, S.L., Head, J.W., 1990. Ridge belts on Venus: morphology and origin. Earth Moon Planets 50/51, 421–470.
Gilmore, M.S., Head, J.W., 2000. Sequential deformation of plains at the margins of Alpha Regio, Venus: implications for tessera formation. Meteoritics Planet. Sci. 35, 667–687.
Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), 2004. A Geologic Time Scale 2004. Cambridge University Press, Cambridge, UK.
Greeley, R., Guest, J.E., 1987. Geologic map of the eastern equatorial region of Mars, 1:15,000,000 scale. U.S. Geological Survey Sci. Inv. Map I-1802-B.
Greeley, R., Figueredo, P.H., Williams, D.A., et al. (15 others), 2000. Geologic mapping of Europa. J. Geophys. Res. 105, 22559–22578.
Grimm, R.E., 1994. The deep structure of Venusian plateau highlands. Icarus 112 (N1), 89–103.
Grinspoon, D.H., 1993. Implications of the high D/H ratio for the sources of water in Venus' atmosphere. Nature 363, 428–430.
Grosfils, E.B., Head, J.W., 1995. Radiating dike swarms on Venus: evidence for emplacement at zones of neutral buoyancy. Planet. Space Sci. 43, 1555–1560.
Grosfils, E.B., Head, J.W., 1996. The timing of giant radiating dike swarm emplacement on Venus: implications for resurfacing of the planet and its subsequent evolution. J. Geophys. Res 101, 4645–4656.
Grosfils, E.B., Long, S.M., Venechuk, E.M., Hurwitz, D.M., Richards, J.W., Kastl, B., Drury, D.E., Hardin, J., 2011. Geologic map of the Ganiki Planitia Quadrangle (V-14), Venus. USGS Geol. Inv. Ser., Map 3121.
Guest, J.E., Stofan, E.R., 1999. A new view of the stratigraphic history of Venus. Icarus 139, 56–66.
Guest, J.E., Bulmer, M.H., Aubele, J., Beratan, K., Greeley, R., Head, J.W., Michaels, G., Weitz, C., Wiles, C., 1992. Small volcanic edifices and volcanism in the plains of Venus. J. Geophys. Res. 97, 15949–15966.
Guseva, E.N., 2008. Comparative analysis of topography of the Venusian rifts and terrestrial continental rifts in Africa. In: Proceedings of the Lunar and Planetary Science Conference, 39th, abstract 1063.
Hansen, V.L., 2000. Geologic mapping of tectonic planets. Earth and Planetary Science Letters 176, 527–542.
Hansen, V.L., 2009. Geologic map of the Niobe Planitia Quadrangle (V-23), Venus. USGS Geol. Inv. Ser., Map 3025.
Hansen, V.L., DeShon, H.R., 2002. Geologic map of the Diana Chasma Quadrangle (V-37), Venus. U.S. Geological Survey Sci. Inv. Map I-2752.
Hauck, S.A., Phillips, R.J., Price, M.H., 1998. Venus: crater distribution and plains resurfacing models. J. Geophys. Res. 103, 13635–13642.
Head, J.W., 1990. Formation of mountain belts on Venus: evidence for large-scale convergence, underthrusting, and crustal imbrication in Freya Montes, Ishtar Terra. Geology 18, 99–102.
Head, J.W., 2001. Lunar and planetary perspectives on the geological history of the Earth. Earth Moon Planets 85–86, 153–177.
Head, J.W., Pieters, C., McCord, T., Adams, J., Zisk, S., 1978. Definition and detailed characterization of Lunar surface units using remote observations. Icarus 33, 145–172.
Head, J.W., Solomon, S.C., 1981. Tectonic evolution of the terrestrial planets. Science 213, 62–76.
Head, J.W., Crumpler, L.S., Aubele, J.C., Guest, J.E., Saunders, R.S., 1992. Venus volcanism: classification of volcanic features and structures, associations, and global distribution from Magellan data. J. Geophys. Res. 97, 13153–13197.
Head, J.W., Ivanov, M.A., 1996. Tessera terrain formation and evolution on Venus: evidence for phase III epeirogenic uplift in Ovda Regio. In: Proceedings of the Lunar and Planetary Science Conference, 27th, pp. 517–518.
Helbert, J., Muller, N., Kostama, P., Marinangeli, L., Piccioni, G., Drossart, P., 2008. Surface brightness variations seen by VIRTIS on Venus Express and implications for the evolution of the Lada Terra region, Venus. Geophys. Res. Lett. 35, L11201. doi:10.1029/2008GL033609.
Herrick, R.R., Phillips, R.J., 1994. Implications of a global survey of Venusian impact craters. Icarus 111, 387–416.
Herrick, R.R., Sharpton, V.L., Malin, M.C., Lyons, S.N., Feely, K., 1997. Morphology and morphometry of impact craters. In: Bougher, S.W., Hunten, D.M., Phillips, R.J.

(Eds.), Venus II Geology, Geophysics, Atmosphere, and Solar Wind Environment. University of Arizona Press, Tucson, pp. 1015–1046.
Ivanov, M.A., 2001. Morphology of the tessera terrain on Venus: implications for the composition of tessera material. Sol. Syst. Res. 35, 1–17.
Ivanov, M.A., 2009. Embayed craters on Venus: How do they correspond to the catastrophic and equilibrium resurfacing models? In: Proceedings of the Lunar and Planetary Science Conference, 40th, abstract 1150.
Ivanov, M.A., Head, J.W., 1996. Tessera terrain on Venus: a survey of the global distribution, characteristics, and relation to surrounding units from Magellan data. J. Geophys. Res. 101, 14861–14908.
Ivanov, M.A., Head, J.W., 2001a. Geologic map of the Lavinia Planitia Quadrangle (V-55), Venus. U.S. Geological Survey Sci. Inv. Map I-2684.
Ivanov, M.A., Head, J.W., 2001b. Geology of Venus: mapping of a global geotraverse at 30N latitude. J. Geophys. Res. 106, 17515–17566.
Ivanov, M.A., Head, J.W., 2004a. Geologic map of the Atalanta Planitia quadrangle (V-4), Venus. U.S. Geological Survey Sci. Inv. Map I-2792.
Ivanov, M.A., Head, J.W., 2004b. Stratigraphy of small shield volcanoes on Venus: criteria for determining stratigraphic relationships and assessment of relative age and temporal abundance. J. Geophys. Res. 109, NE10001. doi:10.1029/2004JE002252.
Ivanov, M.A., Head, J.W., 2005a. Geologic map of the Nemesis Tesserae quadrangle (V-13), Venus. U.S. Geological Survey Sci. Inv. Map 2870.
Ivanov, M.A., Head, J.W., 2005b. Abundance, geological settings, and areal distribution of young small shield volcanoes on Venus. In: Proceedings of the Lunar and Planetary Science Conference, 34th, abstract 1046.
Ivanov, M.A., Head, J.W., 2006a. Geologic map of the Mylitta Fluctus (V61) quadrangle. U.S. Geological Survey Sci. Inv. Map 2920.
Ivanov, M.A., Head, J.W., 2006b. Testing directional (evolutionary) and non-directional models of the geologic history of Venus: results of mapping in a geotraverse along the equator of Venus. In: Proceedings of the Lunar and Planetary Science Conference, 37th, abstract 1366.
Ivanov, M.A., Head, J.W., 2008a. Formation and evolution of Lakshmi Planum, Venus: assessment of models using observations from geological mapping. Planet. Space Sci. 56, 1949–1966.
Ivanov, M.A., Head, J.W., 2008b. Geologic map of the Meskhent Tessera quadrangle (V-3), Venus. U.S. Geological Survey Sci. Inv. Map 3018.
Ivanov, M.A., Head, J.W., 2010a. Geologic map of the Lakshmi Planum quadrangle (V-7), Venus. U.S. Geological Survey Sci. Inv. Map 3116.
Ivanov, M.A., Head, J.W., 2010b. The Lada Terra rise and Quetzalpetlatl Corona: a region of long-lived mantle upwelling and recent volcanic activity on Venus. Planet. Space Sci. 58, 1880–1894.
Izenberg, N.R., Arvidson, R.E., Phillips, R.J., 1994. Impact crater degradation on Venusian plains. Geophys. Res. Lett. 21, 289–292.
Johnson, J.R., Komatsu, G., Baker, V.R., 1999. Geologic map of the Barrymore Quadrangle (V-59), Venus. U.S. Geological Survey Sci. Inv. Map I-2610.
Kreslavsky, M.A., Head, J.W., 1999. Morphometry of small shield volcanoes on Venus: implications for the thickness of regional plains. J. Geophys. Res. 104, 18925–18932.
Kreslavsky, M.A., Ivanov, M.A., Head, J.W., 2009. History of Venus: constraints from buffered crater densities. In: Proceedings of the Lunar and Planetary Science Conference, 40th, abstract 1096.
Kryuchkov, V.P., 1990. Ridge belts: are they compressional or extensional structures? Earth Moon Planets 50/51, 471–491.
Kryuchkov, V.P., 1992. Ridge belts on plains. In: Barsukov, V.L., Basilevsky, A.T., Volkov, V.P., Zharkov, V.N. (Eds.), Venus Geology, Geochemistry, and Geophysics (Research Results from the USSR). University Arizona Press, Tucson, London, pp. 96–112.
Lang, N.P., Hansen, V.L., 2010. Geologic map of the Greenaway Quadrangle (V-24), Venus. USGS Geol. Inv. Ser., Map 3089.
Le Feuvre, M., Wieczorek, M.A., 2011. Nonuniform cratering of the Moon and a revised crater chronology of the inner Solar System. Icarus 214, 1–20.
Lopez, I., Hansen, V.L., 2008. Geologic map of the Helen Planitia Quadrangle (V-52), Venus. USGS Geol. Inv. Ser., Map 3026.
Mastrapa, R., 1997. Thermal evolution of Venus: a preliminary study based on tectonic feature spacing. In: Proceedings of the Lunar and Planetary Science Conference, 34th, abstract 28th, abstract 1756.
Masursky, H., Eliason, E., Ford, P.G., McGill, G.E., Pettengill, G.H., Schaber, G.G., Schubert, G., 1980. Pioneer-Venus radar results: geology from the images and altimetry. J. Geophys. Res. 85, 8232–8260.
McGill, G.E., 1994. Hotspot evolution and Venusian tectonic style. J. Geophys. Res. 99, 23149–23161.
McGill, G.E., 2000. Geologic map of the Sappho Patera Quadrangle (V-20), Venus. U.S. Geological Survey Sci. Inv. Map I-2637.
McGill, G.E., 2004. Geologic map of the Bereghinya Planitia Quadrangle (V-8), Venus. U.S. Geological Survey Sci. Inv. Map I-2794.
McGill, G.E., Campbell, B.A., 2006. Radar properties as clues to relative ages of ridge belts and plains on Venus. J. Geophys. Res. 111, E12006. doi:10.1029/2006JE002705.
McKinnon, W.B., Zahnle, K.J., Ivanov, B.A., Melosh, H.J., 1997. Cratering on Venus: models and observations. In: Bougher, S.W., Hunten, D.M., Phillips, R.J. (Eds.), Venus II Geology, Geophysics, Atmosphere, and Solar Wind Environment. University of Arizona Press, Tucson, pp. 969–1014.
Namiki, N., Solomon, S.C., 1994. Impact crater densities on volcanoes and coronae on Venus: implications for volcanic resurfacing. Science 265, 929–933.
North American Commision on Stratigraphic Nomenclature, 2005. Code of stratigraphic nomenclature. AAPG Bull. 89, 1547–1591.
Pettengill, G.H., Eliason, E., Ford, P.G., Loriot, G.B., Masursky, H., McGill, G.E., 1980. Pioneer Venus radar results: altimetry and surface properties. J. Geophys. Res. 85, 8261–8270.
Phillips, R.J., Raubertas, R.F., Arvidson, R.E., Sarkar, I.C., Herrick, R.R., Izenberg, N., Grimm, R.E., 1992. Impact craters and Venus resurfacing history. J. Geophys. Res. 97, 15923–15948.
Price, M., Suppe, J., 1994. Mean age of rifting and volcanism on Venus deduced from impact crater densities. Nature 372, 756–759.
Price, M., Suppe, J., 1995. Constraints on the resurfacing history of Venus from the hypsometry and distribution of volcanism, tectonism, and impact craters. Earth Moon Planets 71, 99–145.
Pronin, A.A., 1992. The Lakshmi phenomenon. In: Barsukov, V.L., Basilevsky, A.T., Volkov, V.P., Zharkov, V.N. (Eds.), Venus Geology, Geochemistry, and Geophysics (Research Results from the USSR). University Arizona Press, Tucson, London, pp. 68–81.
Rosenberg, E., McGill, G.E., 2001. Geologic map of the Pandrosos Dorsa Quadrangle (V-5), Venus. U.S. Geological Survey Sci. Inv. Map I-2721.
Russell, C.T., Zhang, L., Delva, M., Magnes, W., Strangeway, R.J., Wei1, H.Y., 2007. Lightning on Venus inferred from whistler-mode waves in the ionosphere. Nature 450, 661–662.
Schaber, G.G., Strom, R.G., Moore, H.J., Soderblom, L.A., Kirk, R.L., Chadwick, D.J., Dawson, D.D., Gaddis, L.R., Boyce, J.M., Russel, J., 1992. Geology and distribution of impact craters on Venus: What are they telling us? J. Geophys. Res. 97 (N.E8), 13257–13301.
Schaber, G.G., Kirk, R.L., Strom, R.G., 1998. Data base of impact craters on Venus based on analysis of Magellan radar images and altimetry data. U.S. Geological Survey Open file report 98–104.
Scott, D.H., Tanaka, K.L., 1986. Geologic map of the western equatorial region of Mars, 1:15,000,000 scale. U.S. Geological Survey Sci. Inv. Map I-1802-A.
Senske, D.A., 1990. Geology of the Venus equatorial region from Pioneer Venus radar imaging. Earth Moon Planets 50/51, 305–327.
Shoemaker, E.M., Hackman, R.J., 1962. Stratigraphic basis for a lunar time scale. In: Kopal, Z., Mikhailov, Z.K. (Eds.), The Moon, Proceedings of the International Astronomical Union Symposium 14, Leningrad, 1960. Academic Press, New York, pp. 289–300.
Shoemaker, E.M., Lucchita, B.K., Plescia, J.B., Squyres, S.W., Wilhelms, D.E., 1982. The geology of Ganymede. In: Morrison, D. (Ed.), Satellites of Jupiter. University of Arizona Press, Tucson, pp. 435–520.
Sjogren, W.L., Bills, B.G., Birkeland, P.W., Esposito, P.B., Konopliv, A.S., Mottinger, N.A., Ritke, S.J., Phillips, R.J., 1983. Venus gravity anomalies and their correlations with topography. J. Geophys. Res. 88, 1119–1128.
Smrekar, S.E., Phillips, R.J., 1991. Venusian highlands: geoid to topography ratios and their implications. Earth Planet. Sci. Lett. 107, 582–597.
Smrekar, S.E., Stofan, E.R., 1997. Corona formation and heat loss on Venus by coupled upwelling and delamination. Science 277, 1289–1294.
Smrekar, S.E., Stofan, E.R., Mueller, N., Treiman, A., Elkins-Tanton, L., Helbert, J., Piccioni, G., Drossart, P., 2010. Recent hot-spot volcanism on Venus from VIRTIS emissivity data. Science 328, 605–608.
Solomon, S.C., 1978. On volcanism and thermal tectonics on one-plate planets. Geophys. Res. Lett. 5, 461–464.
Solomon, S.C., Head, J.W., 1982. Mechanisms for lithospheric heat transport on Venus: implications for tectonic style and volcanism. J. Geophys. Res. 87, 9236–9246.
Solomon, S.C., Smrekar, S.E., Bindschadler, D.L., Grimm, R.E., Kaula, W.M., McGill, G.E., Phillips, R.J., Saunders, R.S., Schubert, G., Squyres, S.W., Stofan, E.R., 1992. Venus tectonics: an overview of Magellan observations. J. Geophys. Res. 97, 13199–13255.
Spudis, P.D., Guest, J.E., 1988. Stratigraphy and geologic history of Mercury. In: Vilas, F., Chapman, C.R., Matthews, M.S. (Eds.), Mercury. University of Arizona Press, pp. 118–164.
Squyres, S.W., Jankowski, D.G., Simons, M., Solomon, S.C., Hager, B.H., McGill, G.E., 1992. Plains tectonism on Venus: the deformation belts of Lavinia Planitia. J. Geophys. Res. 97, 13579–13599.
Stofan, E.R., Head, J.W., Campbell, D.B., Zisk, S.H., Bogomolov, A.F., Rzhiga, O.N., Basilevsky, A.T., Armand, N., 1989. Geology of a rift zone on Venus: Beta Regio and Devana Chasma. Geol. Soc. Am. Bull. 101, 143–156.
Stofan, E.R., Sharpton, V.L., Schubert, G., Baer, G., Bindschadler, D.L., Janes, D.M., Squyres, S.W., 1992. Global distribution and characteristics of coronae and related features on Venus: implications for origin and relation to mantle processes. J. Geophys. Res. 97, 13347–13378.
Stofan, E.R., Guest, J., 2003. Geologic Map of the Aino Planitia Quadrangle (V-46), Venus. U.S. Geological Survey Sci. Inv. Map I-2779.
Strom, R.G., Schaber, G.G., Dawson, D.D., 1994. The global resurfacing of Venus. J. Geophys. Res. 99, 10899–10926.
Sukhanov, A.L., 1992. Tesserae. In: Barsukov, V.L., Basilevsky, A.T., Volkov, V.P., Zharkov, V.N. (Eds.), Venus Geology, Geochemistry, and Geophysics (Research Results from the USSR). University of Arizona Press, Tucson, London, pp. 82–95.
Taylor, S.R., McLennan, S.M., 2009. Planetary Crusts: their Composition, Origin, and Evolution. Cambridge University Press, p. 378.
Tanaka, K.L., 1994. Venus Geologic Mappers' Handbook, second edition. U.S. Geological Survey Open File Report 94-438, 50.
Tanaka, K.L., Scott, D.H., Greeley, R., 1992. Global stratigraphy. In: Kiefer, H.H., Jakosky, B.M., Snyder, C.W., Matthews, M.S. (Eds.), Mars. University of Arizona Press, Tucson and London, pp. 345–382.

Tanaka, K.L., Senske, D.A., Price, M., Kirk, R.L., 1997. Physiography, geologic/geomorphic mapping, and stratigraphy of Venus. In: Bougher, S.W., Hunten, D.M., Phillips, R.J. (Eds.), Venus II Geology, Geophysics, Atmosphere, and Solar Wind Environment. University of Arizona Press, Tucson, pp. 667–694.
Tanaka, K.L., Skinner, J.A., Hare, T.M., 2005. Geologic map of the Northern Plains of Mars. U.S. Geological Survey Sci. Inv. Map 2888.
Turcotte, D.L., 1993. An episodic hypothesis for Venusian tectonics. J. Geophys. Res. 98, 17061–17068.
Turcotte, D.L., 1995. How does Venus lose heat? J. Geophys. Res. 100, 16931–16940.
Wilhelms, D.E., 1974. Geologic mapping of the second planet, Pt 1: Rationale and general methods of Lunar geologic mapping. In: Greeley, R., Schultz, P. (Eds.), A Primer in Lunar Geology. Ames Research Center NASA, pp. 199–215.
Wilhelms, D.E., 1987. The geologic history of the Moon. U.S. Geological Survey Special Paper 1348, 302 pp.
Wilhelms, D.E., 1990. Geologic mapping. In: Greeley, R., Batson, R.M. (Eds.), Planetary Mapping. Cambridge University Press, pp. 208–260.
Young, D.A., Hansen, V.L., 2004. Geologic Map of the Rusalka Planitia Quadrangle (V-25), Venus. U.S. Geological Survey Sci. Inv. Map 2783.