Sequence of tectonic deformation in the history of Venus: Evidence from global stratigraphic relationships

James W. Head
Department of Geological Sciences, Brown University, Providence, Rhode Island 02912
Alexander T. Basilevsky
V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow 117975 Russia

ABSTRACT

Analysis of local and regional stratigraphic relationships has permitted the assessment of the nature of tectonic structures and their distribution throughout the observed history of Venus, spanning the past several hundreds of millions of years. We find that shortening characteristic of intensely deformed tessera terrain gave way to widespread distributed fracturing and extension within the tessera and early post-tessera volcanic plains. This phase was followed by distributed deformation of the widespread younger volcanic plains involving compression to form broad ridge belts and closely following—and sometimes simultaneous—extension to form fracture belts. Emplacement of the most areally extensive regional volcanic plains exposed today was followed by widely distributed compression forming wrinkle ridges on the plains' surfaces. Focused extensional deformation (localized, linear rift systems) dominated the latest stages. These major temporal trends appear well established from a stratigraphic point of view and provide guidelines and constraints on models for the geologic history of Venus.

INTRODUCTION

The Venera 15/16 and Magellan missions showed that Venus, Earth-like in many ways, had a surface only a few hundreds of millions of years old that may have been catastrophically globally resurfaced relatively recently in its geologic history (summarized in Solomon, 1993). What was the sequence of events in this apparently unusual history, and why do Venus and Earth, so similar in some ways, differ so much in others?

Global high-resolution imaging data obtained by Magellan permitted the Venus-wide assessment of features and processes related to tectonism (Solomon et al., 1992), volcanism (Head et al., 1992), and impact cratering (Schaber et al., 1992; Phillips et al., 1992), leading to several hypotheses for the geologic history of Venus (e.g., Parmentier and Hess, 1992; Turcotte, 1993; Strom et al., 1994; Phillips and Hansen, 1994). Although local relationships among these features and processes were observed, regional and global geologic mapping was required to determine the nature and relationship of global geologic units. This global picture is now becoming more clear, and the early results (e.g., Senske et al., 1994; Basilevsky and Head, 1995; Tanaka et al., 1997; Basilevsky et al., 1997b) permit an assessment of the nature and sequence of tectonic features.

STRATIGRAPHY

In initial approaches to global geologic mapping, we analyzed 36 random 1000 × 1000 km areas (Basilevsky and Head, 1995) in order to define local stratigraphic units and determine their sequence (Fig. 1). We then tested this sequence regionally and globally by mapping individual 1:5 000 000 scale quadrangles (Basilevsky, 1996a; Head and Ivanov, 1996) and several larger regions (Basilevsky and Head, 1996; Basilevsky et al., 1997a), ultimately successfully extending the stratigraphy over approximately 30% of Venus.

In the defined stratigraphic units and sequence (Figs. 1 and 2), one of the characteristics is the presence (or absence) of deformation that differs from unit to unit in its pattern, abundance, and spacing, often forming unconformities between neighboring stratigraphic units. Although structural fabrics are commonly a factor in the definition of planetary geologic units (Tanaka, 1994), we took care to distinguish between well-defined stratigraphic units and structural deformation occurring both as part of them and separately.

The stratigraphically lowest unit mapped is tessera terrain (Tt, Fortuna Group), characterized by high radar brightness and topography, and at least two sets of intersecting, densely spaced ridges and grooves. Embaying the tessera terrain are densely fractured plains (Pdf, Sigrun Group), deformed by swarms of subparallel and sometimes intersecting fractures. Superposed on the Sigrun Group (Pdf) are fractured and ridged plains (Pfr, Lavinia Group), characterized by rela-

Age	Geologic Time Units	Time-Stratigraphic Units	Rock-Stratigraphic Units and Structures		
	Aurelian Period	Aurelian System	Aurelia Group		Cdp
0.1T					
T	Guineverian Period	Guineverian System	Guinevere Supergroup	Atla Group	Ps, Pl
				Rusalka Group	Pwr, Psh
					FB
				Lavinia Group	Pfr, RB
				Sigrun Group	Pdf
1.47 ±0.46T	Fortunian Period	Fortunian System	Fortuna Group		Tessera, Tt
	Pre-Fortunian Period	Pre-Fortunian System	?		?

Figure 1. Venus stratigraphic units and global correlations (Basilevsky and Head, 1995). ***T*** **= average age of surface.**

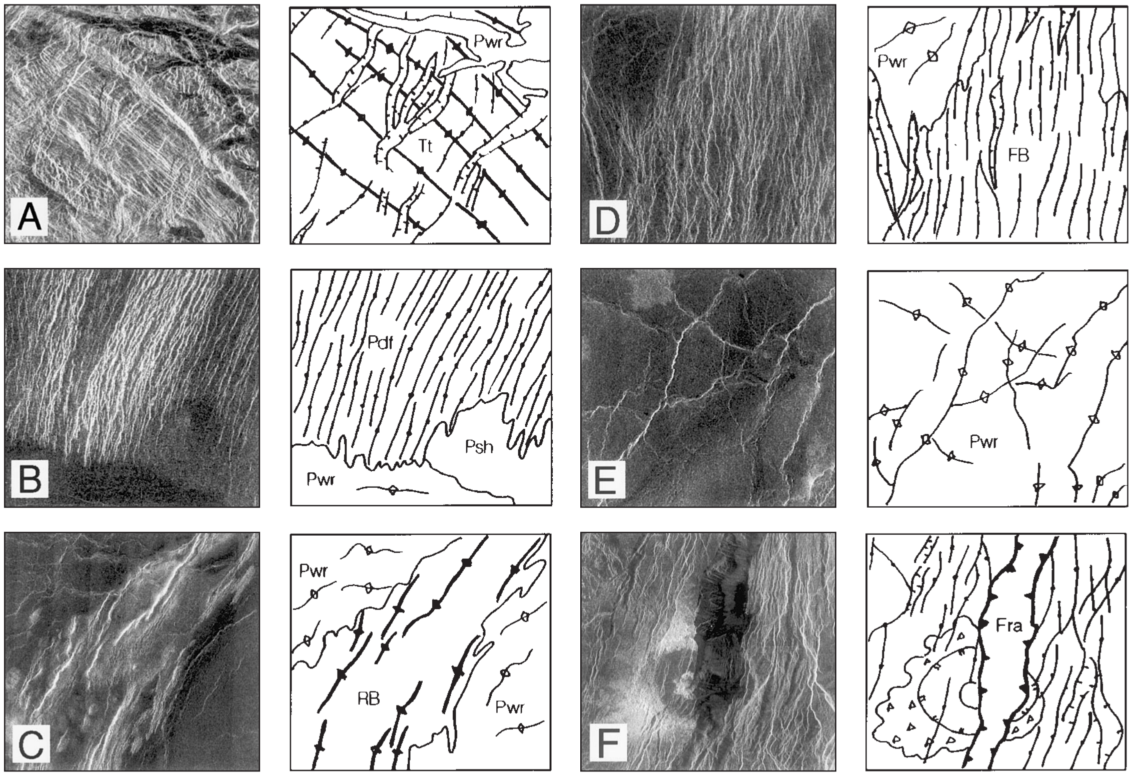

Figure 2. Typical tectonic features observed and their interpretation. Left, Magellan image of features; right, sketch map with units keyed to Figure 1 and text. North is at top. Symbols on maps: solid, continuous lines—contacts; thick solid lines with black diamonds—crests of broad highs and ridges; paired lines with internally oriented hachures—grabens; thin lines with black dots—faults; sinuous lines with open diamonds—wrinkle ridges; bold lines with inward-facing black teeth—rift valleys; continuous line with double hachures toward interior—crater-rim crest; triangle pattern—crater ejecta. A: Tessera terrain (Tt) of Fortuna Group embayed by plains with wrinkle ridges (Pwr) (43.0°N, 75.0°; part of C1MIDR-45N074;1; width is 85 km). B: Densely fractured plains (Pdf) of Sigrun Group embayed by shield plains (Psh) and then by plains with wrinkle ridges (Pwr) (19.1°N, 3.73°; part of FMIDR-20N003;1; width is 35 km). C: Ridge belts (RB) of Lavinia Group embayed by plains with wrinkle ridges (Pwr) (40.5°N, 155.1°; part of C1MIDR-45N159;1; width is 85 km). D: Fracture belt (FB) of Lavinia Group embayed by plains with wrinkle ridges (Pwr) (37.2°N, 271.4°; part of FMIDR-35N270;1; width is 38 km). E: Wrinkle ridges on plains with wrinkle ridges (Pwr) of Rusalka Group (50.65°N, 164.3°; part of FMIDR-50N163;1; width is 80 km). F: Rift-associated fracturing (Fra) of Atla and Aurelia Groups (30.15°N, 283.0°; part of FMIDR-30N281;1; width is 38 km).

tively broad 5–10-km-wide ridges tens of kilometers long and associated fractures. Relatively radar-dark plains peppered with small shields of apparent volcanic origin (Psh, Rusalka Group) embay fractured and ridged plains and older units. The most abundant unit exposed on the surface is a regional plains unit that shows variations in radar backscatter and that has been deformed by wrinkle ridges subsequent to its emplacement (Pwr, Rusalka Group). Undeformed, smooth, flow like units commonly with lobate margins (Ps, smooth plains; Pl, lobate plains; Atla Group) are superposed on plains with wrinkle ridges and older units. Finally, craters of impact origin characterized by dark parabolas (Cdp; Aurelia Group) are superposed on virtually all older units.

ORIGIN AND DISTRIBUTION OF STRUCTURES

By using this stratigraphic sequence (Fig. 1) as a basis, we can now examine the origin of the observed structures (Fig. 2) and assess whether the deformation is local, regional, or global. Tessera terrain is interpreted to involve an early phase of compression and crustal shortening, followed by a later phase of crustal extension (Fig. 2A), the latter related to gravitational relaxation of the initially thickened crust (Solomon et al., 1992; Ivanov and Head, 1996). The alternative interpretation of Hansen and Willis (1996) suggests that tessera deformation changed from extension to compression. Tessera terrain, embayed by all other units, is currently exposed over 8% of the surface, primarily in large contiguous highlands and widespread smaller patches (Ivanov and Head, 1996). Tessera deformation is thought to involve high strain rates (Grimm, 1994) and to have occurred over a relatively short period of time (Ivanov and Basilevsky, 1993; Gilmore et al., 1997).

The volcanic plains that first embayed the tessera terrain (Pdf, densely fractured plains) are characterized by deformation interpreted to be due to extension and possible shear (Fig. 2B). The broad distribution of the outcrops of this unit, in the form of relatively small kipukas, suggests that this deformation phase was near-global. The increasingly large areas of much less deformed and undeformed plains of volcanic origin comprising succeeding units suggest that the intensity of tectonic deformation decreased over time. Fractured and ridged plains (Pfr), stratigraphically above densely fractured plains (Pdf), show evidence for both extension (fractures) and compression (ridges), but much of the plains' surface is relatively undeformed.

An important class of geologic structure in this part of the stratigraphic sequence (within the Lavinia Group, Fig. 1) is broad ridge belts (RB) consisting of clusters of densely spaced en echelon ridges 5–10 km wide and tens to hundreds of kilometers long. Although occurring in numerous places, these structures are concentrated in certain regions (e.g., Atalanta and Lavinia Planitiae) and have patterns that are interpreted to represent broad-scale shortening and folding (Fig. 2C). These features are very similar to ridges and arches observed in the lunar maria and interpreted to be due to folding, and faulting, with some shear (Watters, 1992).

In some areas of Venus, there are clusters and belts of fractures and narrow grabens that cut Lavinian fractured and ridged plains (Pfr) and ridge belts (RB) and are in turn embayed by plains with shields (Psh) and plains with wrinkle ridges (Pwr) (Fig. 1). These fracture belts (FB) are interpreted to be of extensional origin because of the large number of closely spaced grabens and fractures (Fig. 2D). In some places, a few structures of the fracture belts appear to cut plains with shields (Psh) and plains with wrinkle ridges (Pwr), suggesting that waning stages of the deformation typical of that which produced the fracture belts continued into the time of formation of the oldest part of the Rusalkan Group. The occurrence of fracture belts within units of the Lavinia Group and partly extending into units of the Rusalka Group is evidence of the presence of local to regional extensional deformation during this compression-dominated time.

Widespread volcanic flooding and embayment of preexisting units occurred subsequent to the formation of broad ridge belts, creating the Rusalka Group plains (Fig. 1), the most areally significant unit present on Venus today. The initial units were Psh (shield plains), followed by extremely widespread smooth plains. Following their emplacement, the smooth plains units were deformed by wrinkle ridges to create Pwr (plains with wrinkle ridges). Wrinkle ridges are typically about 1 km wide and a few tens of kilometers long; they form a network of parallel and commonly orthogonal ridges (McGill, 1993). Consistent with earlier analyses of similar wrinkle ridges on the Moon, we interpret these to represent the surface manifestation of regional shortening, through flexure, buckling, and near-surface faulting (Fig. 2E). Orientations of these ridges are related to local topography (McGill, 1993) and to regional and global trends (Basilevsky, 1996b; Bilotti, 1992). The distribution of these features strongly suggests that they represent a distinctive global phase in the tectonic history of Venus.

Subsequent deformation is represented by structures interpreted to be normal faults that commonly occur in groups forming regional rift zones (Fig. 2F). These structures (fractures and rifts; Fra) are overprinted on practically all stratigraphic units and formed predominantly in the late part of the Guineverian Period (Fig. 1), but in a few cases, there is evidence that they are very young. Some even postdate certain Aurelian-aged impact craters (Basilevsky, 1993), which suggests that they may be forming today. Their distribution is global, but individual linear zones several hundred kilometers wide form concentrated networks that converge at rises such as Atla and Beta Regiones. These features are interpreted to be due to extensional tectonism.

TECTONIC TRENDS IN THE HISTORY OF VENUS

The duration of the morphologically distinguishable part of the geologic history of Venus is estimated from the density of impact craters and is the subject of continuing debate. The average age of the surface of Venus has been estimated to be 288 +311/–98 Ma by Strom et al. (1994); 400 to 800 Ma by Phillips et al. (1992); and even 800 +800/–400 Ma by Zahnle and McKinnon (1996). The wide range in estimates is due to the model-dependent conversion from crater densities to absolute ages. Because of this, we discuss the geologic history not in terms of millions of years but in fractions of the average age of the surface (*T*) (Basilevsky et al., 1997b). Deformation of material of unknown age and origin that led to formation of tessera occurred about 1.47*T* ago, with possible variations of this estimate from 1.01*T* to 1.93*T*. The combined duration of the subsequent formation of the Sigrun, Lavinia, and Rusalka Groups is estimated to be about 0.1*T* to 0.2*T*. The Rusalka Group emplacement duration is estimated to have been between 0.01*T* and 0.06*T*. The end of Rusalka Group formation is interpreted to have happened at about 1*T*. The time interval between the emplacement of the Rusalka Group plains and their deformation by wrinkle ridges was as short as 0.01*T* to 0.13*T*. The formation of the Atla Group apparently lasted from about 0.9*T*–1.0*T* to about 0.1*T*, the longest duration among the stratigraphic units considered. The modern Aurelian Period dates from about 0.1*T* to the present.

What, then, are the major tectonic trends in this observable final 10%–20% of the total geologic history of Venus? The stratigraphic order of the deformational episodes (Fig. 3) allows us to interpret the dominant deformational environments as a function of time. The earliest and most intense was the deformation that determined the observed highly deformed morphology of tessera terrain (Fortuna Group), which is the result of complex patterns of synchronous deformation and/or intensive multiple deformation patterns. This deformation was so intense that it destroyed the morphologic characteristics (e.g., craters, plains) of the preexisting terrain that represented the prior history of Venus. The full duration of tessera-forming deformation is unknown, but the compressional stage of deformation is estimated to have ceased in a very short period of time (within a few million years or less; Gilmore et al., 1997). The subsequent extensional stage of tessera-forming deformation is estimated to have lasted for a few tens of million years (Ivanov and Basilevsky, 1993; Gilmore et al., 1997).

Following and at least partly contemporaneous with the terminal stages of tessera deformation was extensional faulting now visible as remnants of the densely fractured Sigrun Group; together, these units are widespread over Venus. A transition from the dominance of extension to an environment characterized mostly by global-scale compression, local and regional extension, and some associated strike-slip movement is seen following the emplacement of the fractured and ridged plains (Pfr) and during formation of the ridge belts (RB) and fracture belts (FB) of the Lavinia Group. Compressional deformation formed broad ridges, fragments of which are now seen in many places on Venus. More broadly distributed compressional deformation continued following the emplacement of the very widespread Rusalka Group plains with wrinkle ridges (Pwr).

Finally, the youngest deformation is observed primarily in the form of long and relatively narrow rift zones and fracture belts (Senske et al., 1992; Solomon et al., 1992) formed contemporaneously with the Atla and Aurelia Groups (Fig. 1). The broad distribution of rift zones implies a new change in deformational environment from moderate compression to moderate extension, often accompanied by volcanism, which has lasted for several hundred million years.

SUMMARY AND CONCLUSIONS

The global distribution of the observed tectonic deformation is a striking feature of the geologic record of Venus. Localized deformation is seen either in the form of relatively young (late Guineverian–Aurelian) rift zones, whose formation postdates wrinkle-ridge formation, or in the form of several hundred coronae (Stofan et al., 1992), many of which were developed on background terrain during the early Guineverian Period (Basilevsky and Head, 1995), first in the form of concentric and radial deformation, and later (predominantly

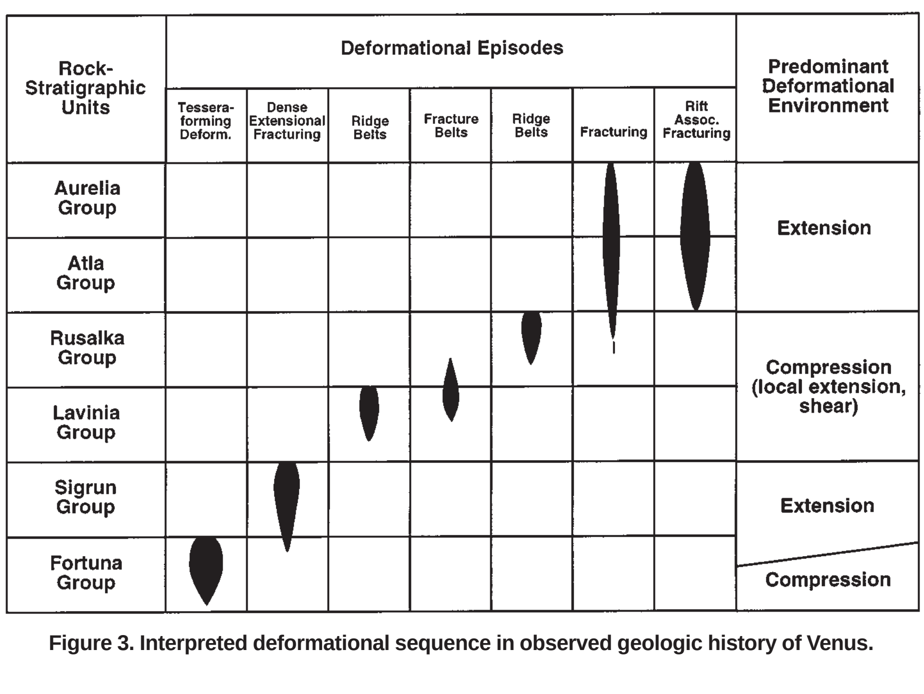

Figure 3. Interpreted deformational sequence in observed geologic history of Venus.

during the time of emplacement of the Atla Group) in the form of localized volcanism.

An important characteristic of these global tectonic episodes is that each given episode appears to have occurred at different places on Venus almost simultaneously. This situation, where Venus apparently had episodes of near-global dominence of compression or extension, is not typical of Phanerozoic Earth where plate-tectonics–related mechanisms have provided an approximate balance between extension and compression on a global scale. The quasi-synchroneity of these alternating global-scale compression and extension episodes is supported by the consistent stratigraphic relationships seen in the 30% of Venus that we have analyzed.

In summary, in the relatively recent, preserved part of its history, Venus appears to have undergone two alternating periods in which compression and then extension dominated regional and global tectonics. The intensity of deformation appears to have decreased globally with time. These observations and conclusions provide a basis for the assessment of models of the geophysical evolution of Venus and can be used to help determine whether such deformational trends might be due to (1) changes in the net state of stress in the lithosphere during global thermal evolution (as in the case of the Moon; e.g., Solomon and Head, 1980), (2) differences in mantle convective processes and rates (e.g., Solomon 1993), (3) catastrophic heat loss (e.g., Parmentier and Hess, 1992), or (4) some combination of these mechanisms.

ACKNOWLEDGMENTS

We gratefully acknowledge financial support from National Aeronautics and Space Administration PG&G Grant NAGW-1873, and fruitful discussions with M. A. Ivanov, V. P. Kryuchkov, A. A. Pronin, and G. McGill.

REFERENCES CITED

Basilevsky, A. T., 1993, Age of rifting and associated volcanism in Atla Regio, Venus: Geophysical Research Letters, v. 20, p. 883–886.

Basilevsky, A. T., 1996a, Geologic mapping of V17 Beta Regio quadrangle: Preliminary results: Porceedings, Lunar and Planetary Science Conference, 27th, p. 65–66.

Basilevsky, A. T., 1996b, On the stratigraphic significance of wrinkle ridges on Venus: Proceedings, Lunar and Planetary Science Conference, 27th, p. 67–68.

Basilevsky, A. T., and Head, J. W., 1995, Regional and global stratigraphy of Venus: A preliminary assessment and implications for the geologic history of Venus: Planetary and Space Science, v. 43, p. 1523–1553.

Basilevsky, A. T., and Head, J. W., 1996, Evidence for rapid and widespread emplacement of volcanic plains on Venus: Stratigraphic studies in the Baltis Vallis region: Geophysical Research Letters, v. 23, p. 1497–1500.

Basilevsky, A. T., Burba, G. A., Ivanov, M. A., Kryuchkov, V. P., Pronin, A. A., Bobina, N. N., Shashkina, V. P., and Head, J. W., 1997a, The photogeologic mapping of northern Venus: Proceedings, Lunar and Planetary Science Conference, 28th, p. 75–76.

Basilevsky, A. T., Head, J. W., Schaber, G. G., and Strom, R. G., 1997b, The resurfacing history of Venus, *in* Bougher, S. W., Hunten, D. M., and Phillips, R. J., eds., Venus II—Geology, geophysics, atmosphere, and solar wind environment: Tucson, University of Arizona Press, p. 1047–1086.

Bilotti, F., 1992, Global organization of tectonic deformation on Venus: Proceedings, Lunar and Planetary Science Conference, 24th, p. 107–108.

Gilmore, M. S., Ivanov, M. A., Head, J. W., and Basilevsky, A. T., 1997, Duration of tessera deformation on Venus: Journal of Geophysical Research, v. 102, p. 13357–13368.

Grimm, R. E., 1994, Recent deformation rates on Venus: Journal of Geophysical Research, v. 99, p. 23163–23171.

Hansen, V. L., and Willis, J. J., 1996, Structural analysis of a sampling of tesserae: Implications for Venus geodynamics: Icarus, v. 123, p. 296–312.

Head, J. W., and Ivanov, M. A., 1996, Evidence for regional basin formation in early post-tessera Venus history: Geology of the Lavinia Planitia Area (V55): Proceedings, Lunar and Planetary Science Conference, 27th, p. 515–516.

Head, J. W., Crumpler, L., Aubele, J., Guest, J., and Saunders, R. S., 1992, Venus volcanism: Classification of volcanic features and structures, associations, and global distribution from Magellan data: Journal of Geophysical Research, v. 97, p. 13153–13197.

Ivanov, M. A., and Basilevsky, A. T., 1993, Density and morphology of impact craters on tessera terrain, Venus: Geophysical Research Letters, v. 20, p. 2579–2582.

Ivanov, M. A., and Head, J. W., 1996, Tessera terrain on Venus: A survey of the global distribution, characteristics, and relation to surrounding units from Magellan data: Journal of Geophysical Research, v. 101, p. 14861–14908.

McGill, G. E., 1993, Wrinkle ridges, stress domains, and kinematics of Venusian plains: Geophysical Research Letters, v. 20, p. 2407–2410.

Parmentier, E. M., and Hess, P. C., 1992, Chemical differentiation of a convecting planetary interior: Consequences for a one plate planet such as Venus: Geophysical Research Letters, v. 19, p. 2015–2018.

Phillips, R. J., and Hansen, V. L., 1994, Tectonic and magmatic evolution of Venus: Annual Reviews of Earth and Planetary Sciences, v. 22, p. 597–654.

Phillips, R. J., Raubertas, R. F., Arvidson, R. E., Sarkar, I. C., Herrick, R. R., Izenberg, N., and Grimm, R. E., 1992, Impact craters and Venus resurfacing history: Journal of Geophysical Research, v. 97, p. 15923–15948.

Schaber, G. G., Strom, R. G., Moore, J. J., Soderblom, L. A., Kirk, R. L., Chadwick, D. J., Dawson, D. D., Gaddis, L. R., Boyce, J. M., and Russell, J., 1992, Geology and distribution of impact craters on Venus: What are they telling us?: Journal of Geophysical Research, v. 97, p. 13257–13301.

Senske, D. A., Schaber, G. G., and Stofan, E. R., 1992, Regional topographic rises on Venus: Geology of Western Eistla Regio and comparison to Beta Regio and Atla Regio: Journal of Geophysical Research, v. 97, p. 13395–13420.

Senske, D. A., Saunders, R. S., Stofan, E. R., and Members of the Magellan Science Team, 1994, The global geology of Venus: Classification of landforms and geologic history: Proceedings, Lunar and Planetary Science Conference, 25th, p. 1245–1246.

Solomon, S. C., 1993, The geophysics of Venus: Physics Today, v. 46, p. 48–55.

Solomon, S. C., and Head, J. W., 1980, Lunar mascon basins: Lava filling, tectonics, and evolution of the lithosphere: Reviews of Geophysics and Space Physics, v. 18, p. 107–141.

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., and Stofan, E. R., 1992, Venus tectonics: An overview of Magellan observations: Journal of Geophysical Research, v. 97, p. 13199–13256.

Stofan, E. R., Sharpton, V. L., Schubert, G., Baer, G., Bindschadler, D. L., Janes, D. M., and Squyres, S. W., 1992, Global distribution and characteristics of coronae and related features of Venus: Implications for origin and relation to mantle processes: Journal of Geophysical Research, v. 97, p. 13347–13378.

Strom, R. G., Schaber, G. G., and Dawson, D. D., 1994, The global resurfacing of Venus: Journal of Geophysical Research, v. 99, p. 12899–12926.

Tanaka, K. L., compiler, 1994, Venus geologic mappers' handbook (second edition): U.S. Geological Survey Open-File Report 94-438.

Tanaka, K. L., Senske, D. A., Price, M., and Kirk, R. L., 1997, Physiography geomorphic/geologic mapping and stratigraphy of Venus, *in* Bougher, S. W., Hunten, D. M., and Phillips, R. J., eds., Venus II—Geology, geophysics, atmosphere, and solar wind environment: Tucson, University of Arizona Press, p. 667–696.

Turcotte, D. L., 1993, An episodic hypothesis for venusian tectonics: Journal of Geophysical Research, v. 98, p. 17061–17068.

Watters, T. R., 1992, System of tectonic features common to Earth, Mars, and Venus: Geology, v. 20, p. 609–612.

Zahnle, K. J., and McKinnon, W. B., 1996, Age of the surface of Venus [abs.]: American Astronomical Society Bulletin, v. 28, p. 1119.

Manuscript received July 31, 1997
Revised manuscript received October 8, 1997
Manuscript accepted October 16, 1997