DIVERGENT PLATE BOUNDARY CHARACTERISTICS AND CRUSTAL SPREADING IN APHRODITE TERRA, VENUS: A TEST OF SOME PREDICTIONS

JAMES W. HEAD and L. S. CRUMPLER

Department of Geological Sciences, Brown University, Providence, Rhode Island, U.S.A.

(Received 14 December, 1988)

Abstract. It has been proposed that divergence and crustal spreading occur in Western Aphrodite Terra and some adjacent equatorial regions of Venus at rates in the range of a few centimeters per year. If equatorial spreading is common and widespread, then a consequence of this should be: (1) a young average age of the surface of the planet, (2) a trend in age from older terrain in the polar regions to younger terrain toward the equator, and (3) a latitudinal distribution of extensional features in equatorial regions and compressional deformation features in middle to high latitudes. These predictions are tested using published results from Arecibo, VENERA 15/16, and Pioneer Venus data, and it is found that: (1) the northern mid-to-high latitudes are characterized by a young average age, (2) there is a trend in the total number of craters per unit area from high values in the north polar regions to low values toward the equator, and (3) there is evidence for a latitudinal distribution of tectonic features of different types, with extensional features common in equatorial regions and compressional deformation features common in the northern middle to high latitudes. Further tests of these and other predictions can be made using data from the upcoming Magellan mission.

1. Introduction

Exploration of the planets in the last several decades has revealed that the smaller terrestrial planetary bodies (Moon, Mercury, and Mars) have surfaces that formed and stabilized very early in their histories and have remained essentially intact and unsegmented over the course of solar system history (Head and Solomon, 1981). These 'one-plate' planets (Solomon, 1978) are characterized predominantly by vertical tectonic deformation, and lie in contrast to the segmented, laterally moving and subducting crust and lithosphere characteristic of the plate tectonic system on Earth. Venus, the most Earth-like of the terrestrial planets in terms of its size, density, and position in the solar system, might be expected to be characterized by a global tectonic system similar to that of the Earth. Several factors have been cited, however, that suggest that Venus may have a positively buoyant lithosphere (Anderson, 1981) and that the process of plate recycling might not be operating there. The question of the possible presence on Venus of features linked to the processes of crustal spreading and plate tectonics has been debated for several years (Phillips *et al.*, 1981; Phillips and Malin, 1982; Morgan and Phillips, 1983; Kaula and Phillips, 1981; Head *et al.*, 1981; 1987; Arvidson and Davies, 1981; Solomon and Head, 1982; Sotin *et al.*, 1988a, b). In a series of recent studies, evidence has been presented for the existence of features and structures in Western Aphrodite Terra which appear to

Earth, Moon, and Planets **44**: 219–231, 1989.

be very similar morphologically to those characterizing terrestrial oceanic spreading centers (Crumpler *et al.*, 1987; Crumpler and Head, 1988; Head and Crumpler, 1987). On the basis of these features and their distribution and characteristics, Head and Crumpler (1987) concluded that divergence and crustal spreading are occuring in Western Aphrodite Terra, Venus.

If divergence and crustal spreading occur in Western Aphrodite Terra and the adjacent equatorial regions of Venus (Crumpler and Head, 1988), then there are a number of predictions that can be made, and a number of tests of this hypothesis can be proposed based on these predictions. The purpose of this paper is to identify and test some of these predictions.

2. Proposed Divergent Boundary and Spreading Center Processes in Western Aphrodite

Aphrodite Terra is a broad topographic rise that extends about 14 000 km along the equatorial region of Venus (Figures 1 and 2). Detailed examination of the topography and morphology of Western Aphrodite Terra reveals the presence of numerous features which have characteristics similar to those found in terrestrial oceanic divergent plate boundary and spreading center environments (Head and Crumpler, 1987). In addition to the broad linear topographic rise, Western Aphrodite Terra is characterized by a series of parallel linear topographic and structural discontinuities 2000–4000 km in length and 100–200 km wide (Figure 2), which strike at high angles to the general topographic trend of the Aphrodite highlands (Crumpler *et al.*, 1987). The broad characteristics of these cross-strike discontinuities (CSD's) are similar to both (1) strike-slip fault zones and (2) terrestrial oceanic fracture zones.

In an effort to distinguish between these two hypotheses, topographic profiles were taken across Aphrodite Terra in order to test for bilateral symmetry of the type associated with thermal boundary layer topography at spreading centers on Earth (Crumpler and Head, 1988). In addition to a broad bilateral symmetry at a range of angles across the strike of Aphrodite Terra, detailed bilateral symmetry is observed within domains between linear discontinuities in directions generally parallel to the strike of the discontinuities (Figure 3). Also, within a domain, the centers of symmetry of several profiles define a linear rise crest that is oriented normal to the bounding CSD's and that terminates against them (Figure 2). Furthermore, linear rise crests within each domain are offset 200 to 1200 km in a right-lateral sense across the CSD's. If the discontinuities represent strike-slip movement, then retrodeformation of the axes of symmetry by translation of domains parallel to the CSD's to form a straight line should produce a broadly symmetrical topographic high. Instead, when the topography is retrodeformed along the CSD's, the edges of the highlands are characterized by distinctive misfits of topography at the edge of the rise where it intersects the CSD's (Crumpler and Head, 1988). The nature and configuration of the CSD's, the

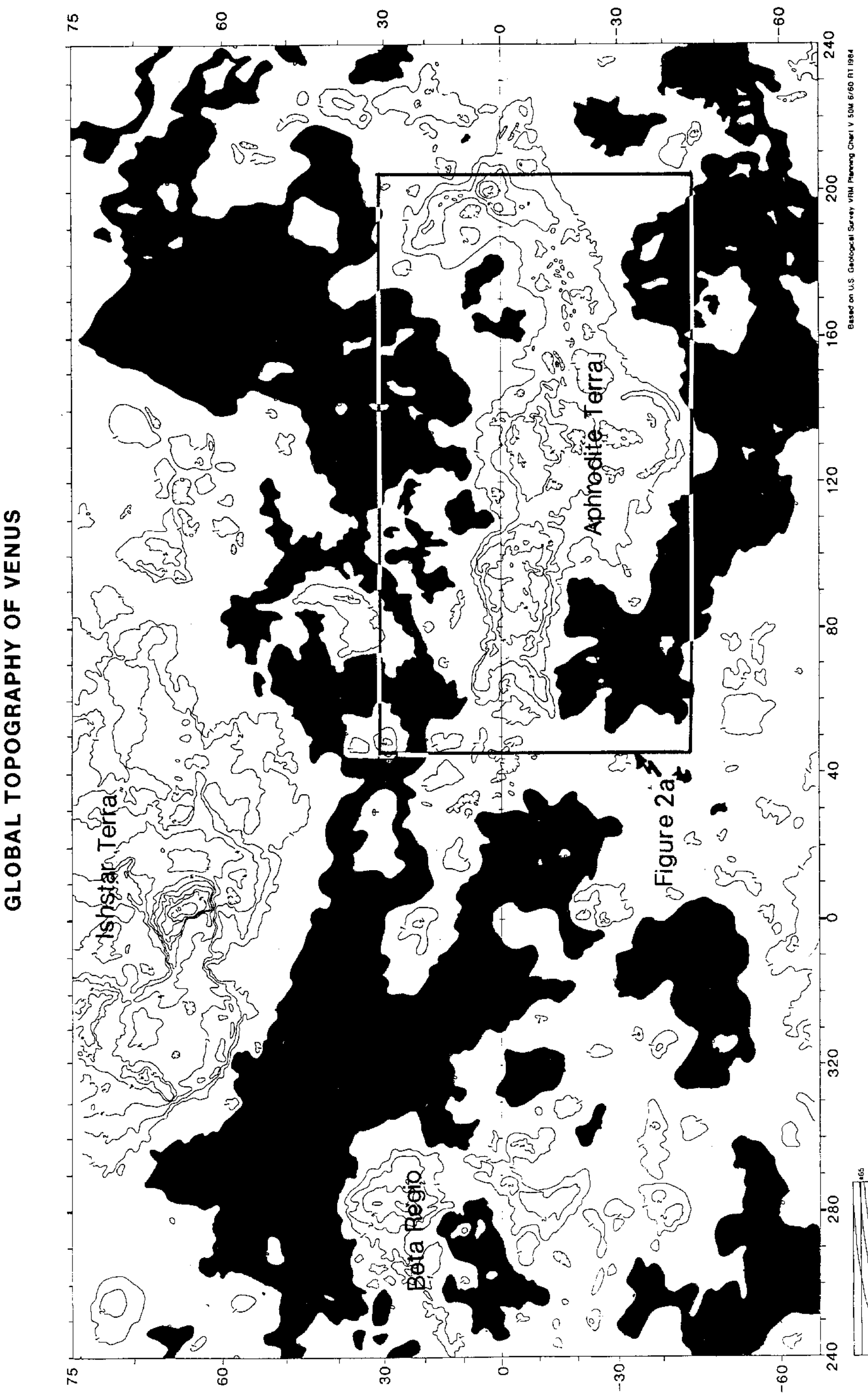

Fig. 1. Global topography of Venus from Pioneer Venus spacecraft altimetry (Pettengill *et al.*, 1980) showing location of Aphrodite Terra and Figure 2. Areas indicated in black lie below the 0-km datum. Contour interval is 1 kilometer.

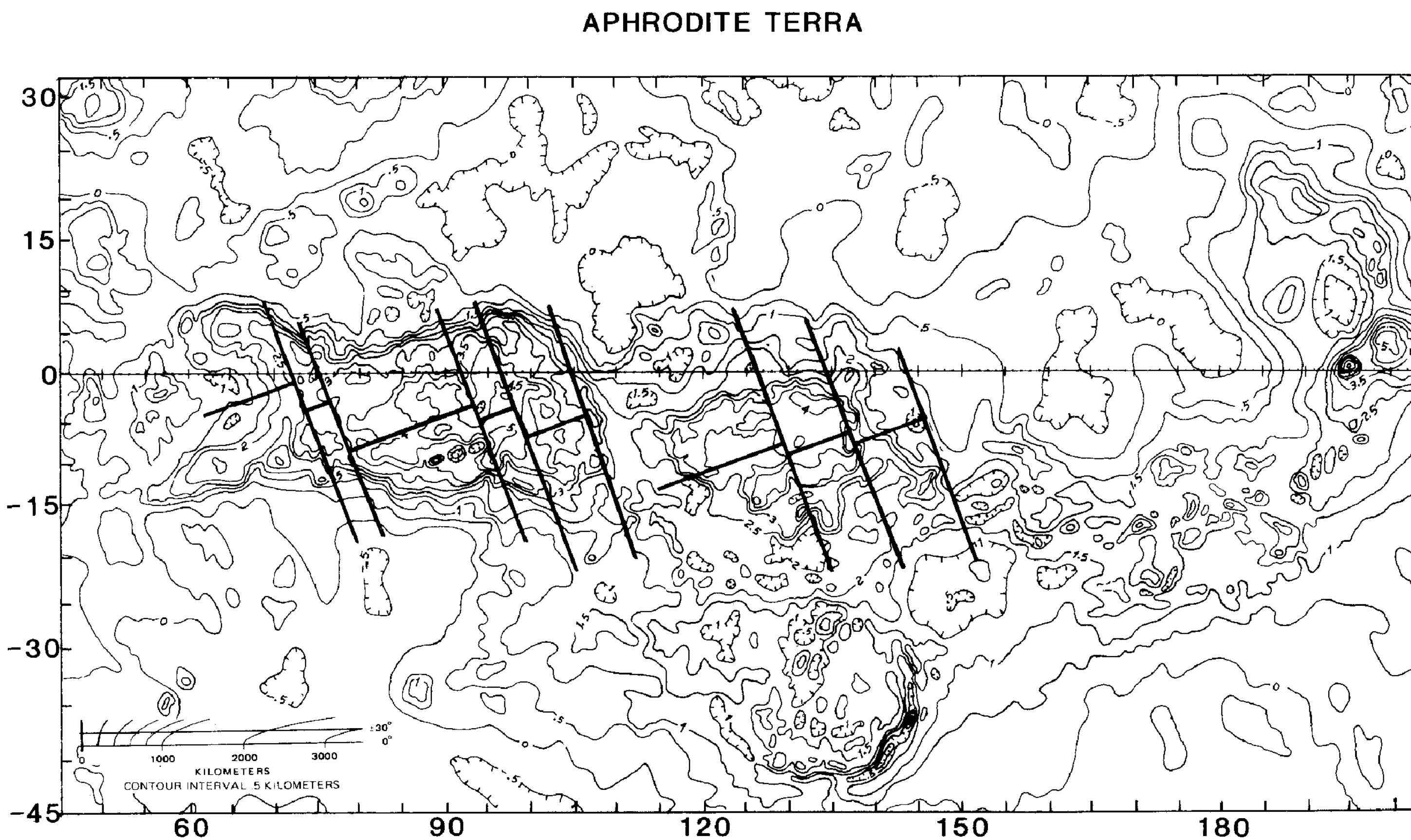

Fig. 2. Western Aphrodite Terra and the location of cross-strike discontinuities (CSD's) (solid black lines) striking NNW across Aphrodite. Lines normal to and connecting CSD's mark the axis of the centers of symmetry (rise crests) in each domain between CSD's. Contour interval is 500 meters.

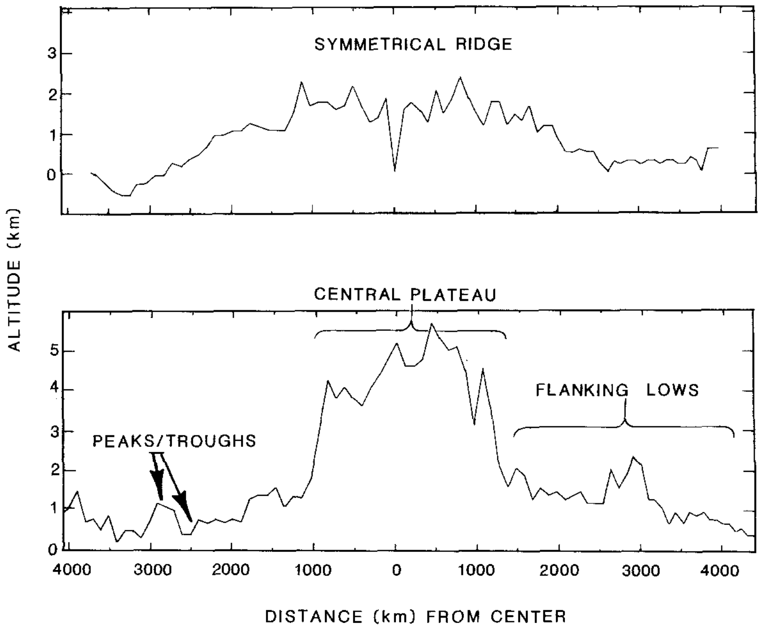

Fig. 3. Bilateral symmetry of topography parallel to cross-strike discontinuities.

characteristics of the topography and topographic patterns, including bilateral topographic symmetry generally parallel to CSD's within domains, the existence of linear rise crests defined by the axes of bilateral symmetry within domains, and the offsets of these linear rise crests between domains (Figure 2), all suggest that Western Aphrodite Terra on Venus shows characteristics similar to terrestrial oceanic divergent plate boundaries and that the cross-strike discontinuities are analogous to oceanic fracture zones rather than strike-slip faults (Crumpler and Head, 1988).

Other similarities to oceanic divergent zones and spreading centers have been documented (Head and Crumpler, 1987). The adjacent centers of symmetry within individual domains that define the linear axial regions of rises (oriented normal to the CSD's and terminating against them) have axial regions that are often characterized by median valleys (Figure 3). The 200–1200 km right lateral offsets of the linear axial regions create a spatial pattern and topographic relationship comparable to terrestrial oceanic transform faults, i.e., step-down in a direction consistent with older lithosphere occurring at greater distances from the axis of symmetry. Individual domains between CSD's contain a variety of bilaterally symmetrical topographic elements (Crumpler and Head, 1988) which have been interpreted as topographic features that have been created at rise crests, separated, and moved laterally to their present symmetrical positions (Head and Crumpler, 1987). These additional factors, together with the broadly similar map patterns (Figure 2), are evidence that Western Aphrodite Terra shares the characteristics of oceanic divergent plate boundaries, and is the site of crustal spreading on Venus. Topographic profiles (adjusted for Venus conditions; Phillips and Malin, 1982) suggest that spreading rates are on the order of tens of millimeters to centimeters per year (Head and Crumpler, 1987; Sotin *et al.*, 1988b).

Western Aphrodite Terra (65° to 150°) forms a 9 400 km segment of an extensive, near-global equatorial topographic high designated the "Equatorial Highlands" by Phillips *et al.* (1981) (Figure 1). Do the morphologic features interpreted to represent divergence and crustal spreading extend to other areas of the Equatorial Highlands? Schaber (1982) has shown that much of the Equatorial Highlands are characterized by troughs which he interpreted to be of extensional origin. Recent analysis of Eastern Aphrodite shows the presence of cross-strike discontinuities, bilateral topographic symmetry, and the systematic segmentation and offset of altimetry and map characteristics (Crumpler and Head, 1988). This region is located adjacent to and is topographically continuous with Western Aphrodite. Eastern Aphrodite extends for an additional 4 200 km along the equator, and together with Western Aphrodite, comprises a length of about 14 000 km. Therefore, on the basis of analyses conducted thus far, over one-third of the circumference of the Equatorial Highlands is characterized by features similar to those at divergent plate boundaries and spreading centers on Earth.

3. A Test of Some Predictions

If divergence and crustal spreading occur in Aphrodite Terra and the adjacent equatorial regions of Venus, then a number of predictions based on this hypothesis can be made, and a number of tests of these predictions can be carried out. First, if spreading is widespread in the equatorial region and crust and lithosphere are transported toward the polar regions, and spreading rates are in the range of a few centimeters per year (Head and Crumpler, 1987; Sotin *et al.*, 1988b), then the average age of the surface of Venus should be relatively young, certainly less than 1.5 billion years. Secondly, the age of the surface should increase away from the equatorial Aphrodite Terra toward the poles; lower latitudes should be younger, on the average, than the higher latitudes. Thirdly, as a consequence of equatorial divergence and spreading in Aphrodite Terra, one would expect to see evidence for convergence and compressional deformation at higher latitudes. We now proceed to test each of these three predictions.

3.1. Relatively Young Average Age for the High Latitudes

If it is assumed that divergence and crustal spreading characterize much of the equatorial region of Venus (the one-third of the circumference represented by Aphrodite Terra and additional parts of the Equatorial Highlands), then the time for a segment of newly created crust to travel from the equator to the pole can be calculated. The relationship of travel time and distance/latitude is shown for several half-spreading rates in Figure 4. Crust moving at rates of 0.5 cm yr^{-1} will reach the pole in less than 2 Ga, while crust moving at rates of 3 cm yr^{-1} will reach the pole between 300 and 400 m.y. after leaving the equator. Estimates for spreading rates in the Western Aphrodite Terra region on the basis of topographic profiles adjusted for the high surface temperatures of Venus (Phillips and Malin, 1982) suggest that half-spreading rates for this region lie between 0.5–0.3 cm yr^{-1} (Head and Crumpler, 1987; Sotin *et al.*, 1988b). This rate suggests that crust would take somewhere between 300 m.y. and 1.8 b.y. to reach the pole, and that crust lying between the equator and the pole along this hypothetical line would therefore all be less than about 1.8 Ga old.

These results show the implications of equatorial spreading for the ages of surfaces at higher latitudes. However, it is not known that divergence and crustal spreading characterize the equatorial highlands outside of Aphrodite Terra, or if they do, that they occur at these rates. Secondly, the obvious geometrical complexities of a simple equatorial divergence and polar convergence (i.e., a 'room problem' toward higher latitudes) would preclude the majority of newly created crust from ever reaching the poles unmodified, thus requiring a complex mosaic of boundaries in the northern latitudes. Thirdly, any process of crustal thickening or other processes of crustal stabilization (i.e., analogous to the

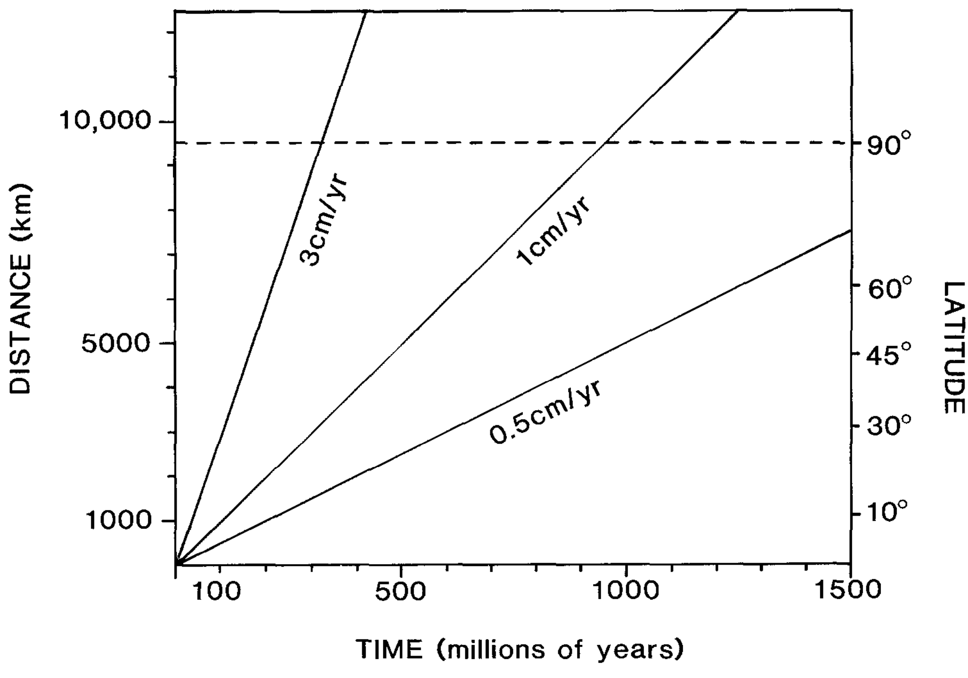

Fig. 4. Distance/latitude vs time on Venus. Crust/lithosphere formed at the equator and travelling at one centimeter per year (one-half spreading rate) would reach the pole in slightly less than one billion years.

formation of continents on Earth) could result in the formation of some stabilized regions which would escape destruction and thus be characterized by older ages. Therefore, average ages for high latitudes of less than two billion years generally represent minimum ages for the case of widespread equatorial spreading occurring at rates of 0.5–3 cm yr^{-1}.

Data for the age of the high latitude areas of Venus exist only for the northern regions generally above 30° North latitude, which were imaged by the Soviet Venera 15/16 missions (Barsukov *et al.*, 1986). On the basis of crater counts for these northern mid-to-high latitudes, Ivanov *et al.* (1986) report an average surface age of 1.0 billion years (±0.5 Ga) using lunar crater production curves corrected for Venus. Schaber *et al.* (1987) have reexamined these data and suggest that the 1 Ga average crater age for the northern hemisphere may be too high by a factor of two or more. On the basis of the population of large craters, considerations of the type of projectiles involved in the cratering process, the presence of an atmosphere, and comparisons to the terrestrial cratering record, Schaber *et al.* (1987) prefer the interpretation that the surface observed by Venera 15/16 is younger than the 450 Ma mean age of the Earth's crust. In either case, the northern high latitudes of Venus are one of the least-cratered regions in the inner solar system (Barlow, 1988).

Grimm and Solomon (1987) have used impact crater densities on Venus to set limits on the modes of lithospheric heat transport. Rates of lithospheric recycling are inversely proportional to the mean age of the surface and since the mean age of the terrestrial oceanic lithosphere is about 60 m.y. (Sclater *et al.*, 1980), Grimm and Solomon (1987) concluded that the lowest estimate of the mean crater retention age on Venus (130 m.y.) means that any lithospheric recycling there is at least a factor of two slower than on Earth. This value is in the range estimated by Head and Crumpler (1987) from comparison of topographic profiles across Aphrodite Terra and terrestrial divergent plate boundaries topography under Venus conditions.

In summary, these estimates for the average age of the northern mid-to-high latitudes indicate a relatively young surface, one which is consistent with the range of ages predicted by spreading rates estimated by Head and Crumpler (1987) and Sotin *et al.* (1988b).

3.2. Younging Trend from Pole to Equator

The relatively young mean surface age for the northern latitudes is significant but does not address the question of individual ages within smaller areas or trends in age in relation to global tectonic patterns. The crater population has been shown to be too small to determine ages of *local regions* (i.e., on the scale of geologic units mapped by Barsukov *et al.*, 1986) within the area mapped by VENERA 15/16 using crater size/frequency distributions (Plaut and Arvidson, 1987). Using a different approach, however, Head *et al.* (1988) have examined *latitudinal* *trends* in absolute crater density. Again if we assume that the process of divergence and crustal spreading occurs along a large part of the equatorial highlands, then the area of the equatorial highlands should be the youngest and there should be increasingly older crust occurring toward higher latitudes. If this is indeed the case, we would predict the highest crater density in the polar regions and a general decrease in crater density from the polar regions toward the equatorial highlands. Using the data of Basilevsky *et al.* (1987) showing the locations of identified impact craters, Head *et al.* (1988) plotted absolute crater density as a function of latitude in equal area latitude bands (Figure 5). The resulting plot shows a distinctive and statistically significant trend from higher crater density in the polar region to lower crater density at 30° North latitude, where the VENERA 15/16 data coverage terminates. On the basis of this analysis, we conclude that there is evidence for a trend of decreasing age from the north polar region toward the equator. This trend is consistent with diver-

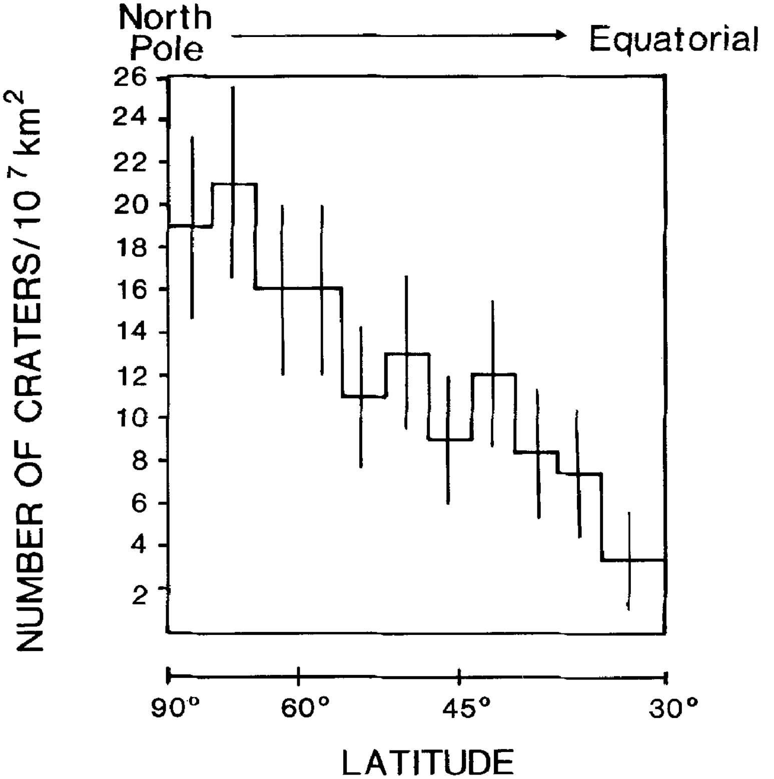

Fig. 5. The number of craters in equal area bands (10^7 km^2) from the north pole to about 30° north latitude on Venus, based on the data of Basilevsky *et al.* (1987). Greater latitude width of lowermost latitude band is due to the slightly uneven latitude coverage of the VENERA 15/16 data in this area. Vertical bars represent one-sigma confidence level.

gence in the equatorial regions, crustal spreading, and increasing age of crust and lithosphere towards higher latidudes.

3.3. Latitudinal distribution of geological structure: extensional deformation in the low latitudes and compressional deformation in the mid-to-high latitudes

If the equatorial highlands represent regions of divergence and crustal spreading, then one would anticipate geological structures associated with extensional deformation to be dominant in the equatorial highlands and structures associated with convergence, compressional deformation, and crustal thickening to occur at mid-to-high latitudes. The extensional structural environment of the equatorial highlands has been known for several years (Schaber, 1982) and numerous studies have documented the detailed nature of rifting and volcanism in local areas such as Beta Regio (McGill *et al.*, 1981; Campbell *et al.*, 1984; Stofan *et al.*, 1988), in addition to the spreading center-like structure characteristic of Western Aphrodite Terra (Head and Crumpler, 1987).

Pioneer Venus altimetry data for northern high latitudes revealed linear mountain belts in the Ishtar Terra region (Pettengill *et al.*, 1980; Masursky *et al.*, 1980) and Arecibo high-resolution imaging data showed the presence of linear bands in these mountains which were interpreted to represent folds associated with compressional deformation (Campbell *et al.* 1983). Further analyses of these mountains showed that they shared the characteristics of terrestrial orogenic belts (Crumpler *et al.*, 1986), and analysis of Maxwell Montes showed evidence for large-scale strike-slip movement accompanying the general regional and local compressional deformation (Von der Bruegge *et al.*, 1985, 1986).

Further data on the tectonic structure north of 30° North latitude was provided by the Venera 15/16 mission. Barsukov *et al.* (1986) and Basilevsky *et al.* (1986) reviewed the characteristics of features revealed by this mission and showed that they were dominated by compressional deformation (mountain belts, ridge belts) and the complex areal deformation of the parquet or tessera terrain. Evidence for extension was limited to the areas associated with the lower latitude equatorial highlands (i.e., Beta Regio), or to very limited areas of the higher latitude terrain. Head (1986) reviewed the available data for the surface of Venus and concluded that extensional deformation dominates in equatorial latitudes (< 30° latitude) and that compressional deformation dominates at northern high latitudes (>30° N) and possibly at southern high latitudes (>30° S). In contrast to the interpretation of Barsukov *et al.* (1986) and Basilevsky *et al.* (1986), Sukhanov and Pronin (1987, 1988) have interpreted the ridge belts in the Atalanta Planitia region of the northern hemisphere (Figure 1) to be of extensional origin, and to represent zones of spreading. The mountain belts of Ishtar Terra (Figure 1) are almost uniformly considered to represent compressional deformation, and there is little evidence in the VENERA 15/16, Pioneer Venus, or Arecibo data for development of Beta-like rift zones in the northern middle to high latitudes. However, there is no concensus on the origin of many of the ridge belt areas in the Atalanta Planitia region, and there is insufficient data in the southern hemisphere to conclusively assign an origin to the ridge-like features observed there (Head, 1986; Stofan *et al.*, 1985). We therefore conclude that there is evidence for the widespread development of extensional deformation in the equatorial latitudes and that there is abundant evidence for compressional deformation in the northern high latitudes in Ishtar Terra. However, there is insufficient data to establish the nature and global configuration of the full range of tectonic zones on Venus. Such a determination must await the analysis of the global high-resolution data set planned for the Magellan mission (Dallas and Nickle, 1987).

4. Summary and Conclusions

On the basis of (1) the young average age of the northern mid-to-high latitudes, (2) the trend from higher crater density in the north polar regions to lower crater density toward the equator, and (3) the preliminary analysis of the latitudinal distribution of extensional and compressional deformation features, we find that several of the main predictions of the implications of divergence and crustal spreading in the Western Aphrodite region of Venus (Head and Crumpler, 1987) are supported by observations. Further tests of these predictions for the southern hemisphere can be made using data from the upcoming Magellan mission (Dallas and Nickle, 1987).

Acknowledgements

We greatly acknowledge the financial support of National Aeronautics and Space Administration grants NGR-40-002-116 and NAGW-713. Sharon Frank assisted in the assessment of latitudinal distribution of crater densities and Angel Hilliard, Peter Neivert, and Mary Ellen Murphy assisted greatly in the preparation of the manuscript. Particular thanks are extended to Christophe Sotin, Duane Bindschadler, David Senske, Richard Vorder Bruegge, and Scott Murchie for reviews of earlier versions of this manuscript.

References

Anderson, D. L.: 1981, 'Plate Tectonics on Venus', *Geophys. Res. Lett.* **8**, 309–311.

Arvidson, R. E. and Davies, G. F.: 1981, 'Effects of Lateral Resolution on the Identification of Volcanotectonic Provinces on Earth and Venus', *Geophys. Res. Lett.* **8**, 741.

Barlow, N. G.: 1988, 'Relative Plots of Venusian Impact Craters: Comparison with the Inner Solar System Cratering Record (Abstract), *Lunar and Planetary Science* **XIX**, 33.

Barsukov, V. L., Basilevsky, A. T., Burba, G. A., Bobina, N. N., Kryuchkov, V. P., Kuzmin, R. O., Nikolaeva, O. V., Pronin, A. A., Ronca, L. B., Chernaya, I. M., Shashkina, V. P., Garanin, A. V., Kushky, E. R., Markov, M. S., Sukhanov, A. L., Kotelnikov, V. A. Rzhiga, O. N., Petrov, G. M., Alexandrov, Y. N., Sidorenko, A. I., Bogomolov, A. F., Skrypnik, G. I., Bergman, M. Y., Kundrin,

L. V., Bokshtein, I. M., Kronrod, M. A., Chochia, P. A., Tyuflin, Y. S., Kadnichansky, S. A., and Akim, E. L.: 1986, 'The Geology and Geomorphology of the Venus Surface as Revealed by the Radar Images Obtained by VENERAS 15 and 16', Proc. Lunar Planet. Sci. Conf. XVI, Part 2, *J. Geophys. Res.* **91**, 378.

Basilevsky, A. T., Pronin, A. A., Ronca, L. B., Kryuchkov, V. P., and Sukhanov, A. L.: 1986, 'Styles of Tectonic Deformation on Venus: Analysis of VENERA 15 and 16 Data', *J. Geophys. Res.* **91**, 399.

Basilevsky, A. T., Ivanov, B. A., Burba, G. A., Chernaya, I. M., Kryuchkov, V. P., Nikolaeva, O. V., Campbell, D. B., and Ronca, L. B.: 1987, 'Impact Craters of Venus: A Continuation of the Analysis of Data from the VENERA 15 and 16 Spacecraft', *J. Geophys. Res.* **92**, 12 869.

Campbell, D. B., Head, J. W., Harmon, J. K., and Hine, A. A.: 1983, 'Venus: Identification of Banded Terrain in the Mountains of Ishtar Terra', *Science* **221**, 644.

Campbell, D. B., Head, J. W., Harmon, J. K., and Hine, A. A.: 1984, 'Venus: Volcanism and Rift Formation in Beta Regio', *Science* **226**, 167.

Crumpler, L. S. and Head, J. W.: 1988, 'Bilateral Topographic Symmetry Patterns across Aphrodite Terra, Venus', *J. Geophys. Res.* **93**, 301.

Crumpler, L. S., Head, J. W., and Campbell, D. B.: 1986, 'Orogenic Belts on Venus', *Geology* **14**, 1031.

Crumpler, L. S., Head, J. W., and Harmon, J. K.: 1987, 'Regional Linear Cross-Strike Discontinuities in Western Aphrodite Terra, Venus', *Geophys. Res. Lett.* **14**, 607.

Dallas, S. S. and Nickle, N. L.: 1987, 'The Magellan Mission to Venus', *Advances in Astronomical Sciences*, **64**, 33.

Grimm, R. E. and Solomon, S. C.: 1987, 'Limits on Modes of Lithospheric Heat Transport on Venus from Impact Crater Density', *Geophys. Res. Lett.* **14**, 538.

Head, J. W.: 1986, 'Venus Global Tectonics: Tectonic Style and Evidence for Latitudinal Distribution of Tectonic Features (Abstract), *Lunar and Planetary Science* **XVII**, 325.

Head, J. W. and Solomon, S. C.: 1981, 'Tectonic Evolution of the Terrestrial Planets', *Science* **213**, 62.

Head, J. W. and Crumpler, L. S.: 1987, 'Evidence for Divergent Plate Boundary Characteristics and Crustal Spreading on Venus', *Science* **238**, 1380.

Head, J. W., Yuter, S. E., and Solomon, S. C.: 1981, 'Topography of Venus and Earth: A Test for the Presence of Plate Tectonics', *Am. Sci.* **69**, 614.

Head, J. W., Crumpler, L. S., Bindschadler, D. L., Stofan, E. R., Vorder Bruegge, R. W., and Campbell D. B.: 1987, 'Venus Geology and Geophysics: A Review of Some Recent Studies', *Astron. Vestnik* **21**, 100 (in Russian).

Head, J. W., Crumpler, L. S., and Frank, S.: 1988, 'Regional Trends in Crater Density on Venus: Implications for Surface Processes (Abstract)', *Lunar and Planetary Science* **XIX**, 473.

Ivanov, B. A., Basilevsky, A. T., Kryuchkov, V. P., and Chernaya, I. M.: 1986, 'Impact Craters of Venus: Analysis of VENERA 15 and 16 Data', Proc. Lunar Planet. Sci. Conf. 16th, *J. Geophys. Res.* **91**, 413.

Kuala, W. K. and Phillips, R. J.: 1981, 'Quantitative Tests for Plate Tectonics on Venus', *Geophys. Res. Lett.* **8**, 1187.

Masursky, H., Eliason, E., Ford, P. G., McGill, G. E., Pettengill, G. H., Schaber, G. G., and Schubert, G.: 1980, 'Pioneer-Venus Radar Results: Geology from Images and Altimetry', *J. Geophys. Res.* **85**, 8232.

McGill, G. E., Steenstrup, S. J., Barton, C., and Ford, P. G.: 1981, 'Continental Rifting and the Origin of Beta Regio, Venus', *Geophys. Res. Lett.* **8**, 737.

Morgan, P. and Phillips, R. J.: 1983, 'Hot Spot Heat Transfer: Its Application to Venus and Implications to Venus and Earth', *J. Geophys. Res.* **88**, 8305.

Pettengill, G. H., Eliason, E., Ford, P. G., Loriot, G. B., Masursky, H., and McGill, G. E.: 1980, 'Pioneer-Venus Radar Results: Altimetry and Surface Properties', *J. Geophys. Res.* **85**, 8261.

Phillips, R. J. and Malin, M. C.: 1982, 'The Interior of Venus and Tectonic Implications', in D. M. Hunten, L. Colin, T. M. Donahue and V. I. Moroz (eds.), *Venus*, University of Arizona Press, Tucson, pp. 159–214.

Phillips, R. J., Kaula, W. W., McGill, G. E., and Malin, M. C.: 1981, 'Tectonics and Evolution of Venus', *Science* **212**, 879.

Plaut, J. and Arvidson, R.: 1987, 'Spatial Distribution of Circular Features on Venus (Abstract)', *Lunar and Planetary Science* **XVIII**, 782.

Schaber, G. G.: 1982, 'Limited Extension and Volcanism along Zones of Lithospheric Weakness', *Geophys. Res. Lett.* **9**, 499.

Schaber, G. G., Shoemaker, E. M., and Kozak, R. C.: 1987, 'The Surface Age of Venus: Use of Terrestrial Cratering Record', *Astron, Vestnik*, **21**, 144 (in Russian).

Sclater, J. G., Jaupart, C., and Glason, D.: 1980, 'The Heat Flow through Oceanic and Continental Crust and the Heat Loss of the Earth', *Rev. Geophys. Space Phys.* **18**, 269.

Solomon, S. C.: 1978, 'On Volcanism and Thermal Tectonics on One-Plate Planets', *Geophys. Res. Lett.* **5**, 461.

Solomon, S. C. and Head, J. W.: 1982, 'Mechanisms for Lithospheric Heat Transport on Venus: Implications for Tectonic Style and Volcanism', *J. Geophys. Res.* **87**, 9236.

Sotin, C., Senske, D. A., Parmentier, E. M., and Head, J. W.: 1988a, 'Terrestrial Spreading Centers under Venus Conditions: Effects on Thermal Structure and Crustal Thickness', *Lunar and Planetary Science* **XIX**, 1109.

Sotin, C., Senske, D. A., Head, J. W., and Parmentier, E. M.: 1988b, 'Terrestrial Spreading Centers under Venus Conditions: Application to Western Aphrodite Terra', *Earth and Planetary Sci. Lett.* (submitted).

Stofan, E. R., Head, J. W., and Campbell, D. B.: 1985, 'Multiple Ring Structures in Themis Regio: Evidence for Endogenic Origin', *Lunar and Planetary Sci.* **XVI**, 825.

Stofan, E. R., Head, J. W., Campbell, D. B., Zisk, S. H., Bogomolov, A. F., Rzhiga, O. N., Basilevsky, A. T., and Armand, N.: 1989, 'Geology of a Venus Rift Zone: Beta Regio and Devana Chasma', *Geol. Soc. Am. Bull.* **101**, 143.

Sukhanov, A. L. and Pronin, A. A.: 1987, 'Signs of Spreading on Venus', *Doklady Acad. Sci. USSR* **294**, 661, (in Russian).

Sukhanov, A. L. and Pronin, A. A.: 1988, 'Ridged Belts on Venus as Extensional Features', *Proceedings Lunar and Planet. Sci. Conf.* **19**, (in press).

Von der Bruegge, R. W., Head, J. W., and Campbell, D. B.: 1985, 'Evidence for Major Cross-Strike Structural Discontinuities: Maxwell Montes, Venus (Abstract), Reports of Planetary Geology and Geophysics Program, *NASA Tech. Mem.* **88383**, 369.

Von der Bruegge, R. W., Head, J. W., and Campbell, D. B.: 1986, 'Cross-Strike Discontinuities on Maxwell Montes, Venus: Evidence for Large-Scale Strike-Slip Faulting (Abstract)', *Lunar and Planetary Science* **XVII**, 917.