GEOPHYSICAL RESEARCH LETTERS, VOL. 17, NO. 9, PAGES 1369-1372, AUGUST 1990

RIDGE BELTS: EVIDENCE FOR REGIONAL- AND LOCAL-SCALE DEFORMATION ON THE SURFACE OF VENUS

M.T. Zuber

Geodynamics Branch, NASA/Goddard Space Flight Center

Abstract. We evaluate models for the formation of the ridge belt fan assemblage on Venus through consideration of the orientation, spatial distribution, topographic expression and wavelengths of observed tectonic surface features. We favor a compressional mechanism for long wavelength deformation corresponding to the spacing of ridge belts ($300 \leq \lambda \leq 400$ km). However, short wavelength ridges and grooves ($10 \leq \lambda \leq 20$ km) that are contained within belts and trend parallel to them are likely to be compressional and extensional, and to reflect both regional and local stress fields. We hypothesize that large-scale (>> ridge spacing) early-stage mantle downwelling is the source of regional compression responsible for the establishment of the long wavelength of deformation.

Introduction

Ridge belts are quasi-linear features with lengths of several hundred to two thousand km and widths of 100-150 km [*Barsukov et al.*, 1986]. These features have complex morphologies, but many are characterized by broad topographic arches and 10-20 km wide lineations that trend parallel to the strike of the belts [*Basilevsky et al.*, 1986]. The ridge belts form a spatially extensive assemblage in the rolling plains in part of the northern hemisphere of Venus imaged by the Venera 15/16 radar system (Figure 1). The assemblage is characterized by north-south trending belts arrayed in a sub-parallel, fan-shaped pattern that extends from the North Pole to the southern limit of the Venera 15/16 coverage (~30N). Within the fan, individual ridge belts have a regular spacing of approximately 300-400 km [*Zuber*, 1986; *Frank and Head*, 1989a], and are separated by smooth plains that are often wider than the belts. Other features mapped as ridge belts are distributed in Venus' northern hemisphere in the vicinity of the Lakshmi Planum plateau and complex tectonic terrains known as tessera [*Barsukov et al.*, 1986].

Because of their broad spatial distribution, their proximity to other major tectonic terrain types, and details of their morphology, the ridge belts have important implications for Venus' global state of stress [*Head*, 1986; *Kozak and Schaber*, 1989; *Sukhanov and Pronin*, 1989] and mechanical structure of the lithosphere [*Zuber*, 1987; *Banerdt and Golombek*, 1988]. However, interpretations of the origin of the ridge belts vary markedly. Recent analyses have focused on distinguishing whether the features formed in an extensional or compressional environment [*Basilevsky et al.*, 1986; *Kozak and Schaber*, 1989; *Frank and Head*, 1990; *Kryuchkov*, 1990; *Zuber and Parmentier*, 1990].

Paper number 90GL01559
0094-8276/90/90GL-01559$03.00

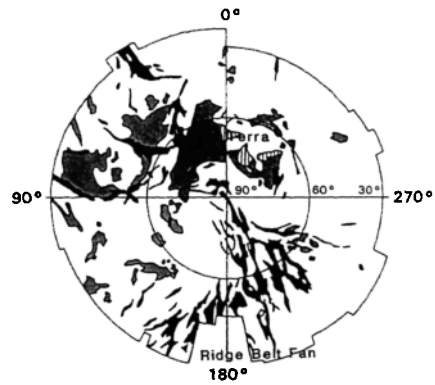

Fig. 1. Geologic map of the northern hemisphere of Venus simplified from *Barsukov et al.* [1986] and *Frank and Head* [1990]. White areas correspond to plains, black areas to ridge belts, stippled area to tessera, and crossed areas to mountain belts. The ridge belt fan is located between longitudes 135° and 250°.

Explanations of the state of stress and mechanism of origin of ridge belts must be consistent with the orientation, spatial distribution, topographic character, and wavelengths of deformation of the ridge belt fan. In this paper we evaluate current models for the formation of the ridge belts in the context of these observations. We infer that the long wavelength of ridge belt deformation is a consequence of regional-scale compressive stresses and that the short wavelength deformation is likely to be both extensional and compressional in nature, and to reflect both regional and local stress fields. We hypothesize that the source of regional compression is early-stage mantle downwelling.

Models of Origin

Crustal Spreading Model

Sukhanov and Pronin [1989] proposed that the ridge belt fan represents a zone of crustal spreading on the basis of observed bilateral symmetry within a prominent N-S trending ridge belt near the center of the fan (Pandrosa Dorsa), and other evidence for pervasive extension including linear intrusions, dikes, and volcanic domes. *Kozak and Schaber* [1989] supported this interpretation, citing two additional observations: the identification of graben-like features (Bellona Fossae), and similarities of paterae associated with certain ridge belts to features in a zone of obvious extension elsewhere on Venus. *Kozak and Schaber* further suggested that the ridge belt system forms part of a trans-polar tectonic zone, connecting with

Schaber's [1982] Aphrodite Terra-Beta Regio equatorial extension zone at Eisila Regio.

Other morphological observations are inconsistent with the spreading hypothesis. First, while some evidence for bilateral symmetry in the ridge belts has been identified, other longitudinally-trending features within the fan, including some near the proposed central axis, are distinctly asymmetrical. In addition, some of the features interpreted as extensional by *Sukhanov and Pronin* [1989] have alternatively been interpreted as compressional [*Frank and Head,* 1990].

If the fan represents a zone of spreading, then terrains should be progressively older with increasing distance from the proposed symmetry axis. However, the predicted age progression (or a lack thereof) cannot be distinguished on the basis of the number of impact craters currently recognized within the fan [*Sukhanov and Pronin,* 1989].

In summary, neither crater statistics nor morphological observations are sufficiently compelling to either prove or disprove the crustal spreading model. However, two other observations are in greater conflict with this hypothesis. First, at the resolution of Pioneer Venus altimetry, the ridge belt fan does not exhibit the pattern of thermal boundary layer topography expected to be associated with lithospheric cooling away from the proposed spreading center [*Kaula and Phillips,* 1981]. Second, the crustal spreading model as currently posed cannot explain the periodic development of tectonism. *Sukhanov and Pronin* [1989] suggested the possibility of multiple parallel spreading centers located along axes centered either within ridge belts or in the intervening smooth plains. In these scenarios the observed spacing of long wavelength deformation would be controlled by the locations of upwelling limbs of convection cells. However, as discussed in the next section, the mechanism and style of convection responsible for a sub-parallel distribution of spreading centers at the observed wavelength is not easily understandable given our present knowledge of Venus.

Convection Models

Kaula [1990] proposed that wavelengths comparable to the spacing of ridge belts ($\lambda > 300$ km) could be a consequence of convective effects. To explain the spatial distribution of deformation at the observed wavelength would require shallow, regionalized convection. The wavelength of the ridge belts is of a similar spatial scale to that of small-scale convection beneath Earth's oceanic lithosphere [*Haxby and Weissel,* 1986]. Small-scale convection results from instability of the upper thermal boundary layer due to horizontal shear in the mantle induced by plate motion. This style of convection is observed only in the vicinity of terrestrial mid-ocean ridges, and is therefore regional in nature. However, if the ridge belts represent an area of E-W directed crustal spreading as hypothesized above, then the belts cannot be a manifestation of this process. Small-scale convective lineations would be expected to trend in the direction of plate motion (E-W), rather than perpendicular to the proposed spreading direction (N-S), as is observed.

An alternative mechanism is convection within the crust. *Kaula* [1988] used boundary layer scaling arguments to demonstrate that a thick venusian crust would be convectively unstable. However, if the convecting layer thickness is comparable to half the wavelength of deformation, then a crustal thickness of 150-200 km is required to explain the observed wavelength of the ridge belts if the entire vertical extent of crust is convecting. If less than the full thickness of the crust convects, then even higher thicknesses are necessary. Such large values are unlikely given the elevation of the ridge belt fan, the expected depth of the basalt-eclogite transition at 60-80 km [*Kaula,* 1990], and estimates of 10-30 km crustal thicknesses in the rolling plains [e.g., *Zuber,* 1987]. The possibility of convection in a crust significantly thinner than the half-wavelength of deformation has yet to be explored. However, numerical studies of temperature-dependent convection indicate that large increases of viscosity with depth would be required to confine convection to a thin fluid layer [*Lin and Parmentier,* 1985]. An increase of viscosity with depth is not indicated by rheological models of the ductile Venus crust.

Instability Models

It has also been suggested that the observed length scales of ridge belt deformation represent long and short dominant wavelengths caused by stretching or buckling instabilities [*Zuber,* 1987; *Banerdt and Golombek,* 1988; *Zuber and Parmentier,* 1990]. Unstable extensional or compressional deformation is theoretically possible if the venusian lithosphere contains one or more rheologically strong layers that could plausibly correspond to the upper crust and upper mantle. Instabilities may also develop within the thermal boundary layer in response to the combined effects of thermal buoyancy and horizontal extension or compression [*Marshall and Parmentier,* 1989]. The latter mechanism could explain the long wavelength component of deformation for boundary layer thicknesses on the order of 100 km.

One issue in assessing the viability of these mechanisms is the timing of deformation. Specifically, if the ridge belt fan developed sequentially, then the instability mechanisms, which are characterized by simultaneous development of deformational wavelengths, may not be appropriate. Sequential development of short wavelength lineations within several individual ridge belts has been identified [*Sukhanov and Pronin,* 1989], and may reflect modifications by local stresses of the regional field responsible for the establishment of the longer wavelength corresponding to the belt spacing. However, as noted earlier, there are no resolvable age differences across the fan, and therefore no current evidence either for or against a progressive sequence of long wavelength deformation.

A second issue is the nature of the smooth plains which separate the ridge belts. Unstable deformation models predict the harmonic development of deformation, which implies that topographic highs (ridge belts) and lows (plains) should be characterized by equal amplitudes and widths. In addition, both highs and lows should exhibit deformation. In the ridge belt fan the intervening plains in some areas are wider than the ridge belts, and in most areas they are undeformed. These observations can be reconciled in the context of the instability models if

topographic lows are infilled by volcanic materials. Evidence for volcanic embayment of ridge belts in several areas has been reported [*Sukhanov and Pronin*, 1989; *Frank and Head*, 1990; *Kryuchkov*, 1990;], though the mechanism of resurfacing remains an outstanding question.

In summary, some current observations of the ridge belt fan are not easily explained within the context of the crustal spreading or convection models. Instability growth in a horizontally-stressed lithosphere therefore constitutes our favored mechanism, though such models contain important caveats. One significant matter is the mechanism for large-scale horizontal stress.

Source of Large-Scale Horizontal Stress

Given the average to low elevation of the fan, extension associated with dynamic or thermal uplift and associated crustal spreading or hot spot plumes is an unlikely mechanism for ridge belt formation. In-plane transmission of remote stress is another possibility. The most obvious locus of large-scale stress in the Venus northern hemisphere is Ishtar Terra, a prominent highland region (see Figure 1). Ishtar has alternatively been hypothesized as a region of downwelling [*Bindshadler and Parmentier*, 1989; *Kiefer and Hager*, 1990] and upwelling [*Grimm and Phillips*, 1990], and may thus be a source of either remote extension or compression.

The fan elevation, combined with upper crustal strength levels implied from deformation models of a horizontally stressed lithosphere constrained by observed dominant wavelengths [*Zuber and Parmentier*, 1990], lead us to favor a compressional origin. On Earth, regional compressive stresses are commonly associated with plate tectonic forces, however, plate tectonics has not been definitively recognized on Venus. A possible subduction zone has been identified within the fan [Lukelong Dorsa; *Frank and Head*, 1989b], however, this interpretation is not unique. In-plane transmission of remote stresses, perhaps associated with Ishtar Terra, is another possible source of compression. However, the viability of stress transmission over thousands of kilometers through the weak, pervasively deformed Venus lithosphere has yet to be demonstrated.

We suggest that mantle downwelling may be the source of large-scale compressive stress. Downwelling is characterized by topographic subsidence followed by tectonic thickening of the crust [*Bindshadler and Parmentier*, 1989; *Kiefer and Hager*, 1990]. Stresses due to initial subsidence are compressional while stresses due to thickened crust are extensional. To accommodate the observed topography and a compressional origin for the fan, downwelling must be in its early stages. That is, deformation has not yet evolved to the point where the crust has thickened sufficiently to significantly increase the surface elevation and produce a state of extension.

To explain the long wavelength component of the deformation, the length scale of the downwelling must be much greater than the ridge belt spacing (i.e. order thousands of km). Thus, evidence for such a process should be observable in Venus' long wavelength gravity field. Global-scale models constrained by the observed gravity and topography fields [*Banerdt*, 1986; *Herrick and Phillips*, 1990] indicate positive upper mantle density anomalies beneath the ridge belt fan that are consistent with broad-scale downwelling of cold mantle in this region.

The geometry of downwelling is also an issue. Axisymmetric downwelling centered near the North Pole could explain the radial distribution of ridge belts within the fan, but would not account for the lack of similar structures in the rest of the high latitude northern hemisphere. A N-S oriented, quasi-linear pattern of downwelling could explain other, though by no means all, aspects of the deformation. Clearly, a more complex geometry than discussed here would be required.

In this model, some localized extension within the regional compressional regime is required to explain the existence of small-scale extensional features within the fan recognized by *Kozak and Schaber* [1989] and *Sukhanov and Pronin* [1989]. Such extension could be explained by modification of the regional field at various times by stresses associated with topography, volcanic intrusion, local variations in subsurface flow structure and/or mechanical properties, or localized lithospheric bending associated with instability growth. Thus, while the long wavelength of deformation is expected to be compressional and to develop simultaneously, short wavelength deformation features could be both compressional and extensional, and could exhibit temporal sequences due to variable and evolving local stresses.

If the observed long wavelength topographic variations within the fan are a consequence of the regional stress field, then the stresses are most likely either presently active or ceased in the geologically recent past. Surface topography produced by plastic or viscous flow persisting much beyond the cessation of compression would have to be "frozen-in" as stresses fall below yield. Whether or not stresses in the Venus lithosphere or boundary layer could be frozen in has not been investigated, however, freezing in of stresses may be difficult given the high surface temperature and low average strength of the lithosphere. The observation that the ridge belt fan is among the youngest surfaces on Venus [*Sukhanov and Pronin*, 1989] supports the suggestion of an ongoing process of formation such as early-stage downwelling.

It has also been suggested that Ishtar Terra formed in response to mantle downwelling [*Bindshadler and Parmentier*, 1989; *Kiefer and Hager*, 1990]. If this is the case, then the ridge belt fan must be in a much earlier stage of evolution than Ishtar, which is characterized by high topography and significant crustal thickening.

Role of Magellan Observations

The Magellan mission will yield the following observations that will permit this hypothesis to be tested. (1) High resolution (<300 m) radar images will facilitate distinction of the compressional vs. extensional nature of ridge belts. (2) Images also will permit the identification of relative ages of various terrains. In our preferred scenario, ridge belts developed simultaneously and should therefore exhibit a uniform average density of impact craters across the fan. Intervening plains should be younger than the fan as a whole and should therefore exhibit fewer impact craters. Short wavelength ridges and grooves within belts should exhibit a progressive sequence of deformation that

should be revealed by superposition relationships. (3) Altimetry combined with improved orbit determination and images will clarify the relationship of topography and tectonic deformation, and will thus assist in the identification of the style and mechanism of deformation of the ridge belts. This will be particularly important in understanding the nature of the short wavelength deformation, where local stresses are likely to have been significantly influenced by topography. (4) Altimetry combined with gravity will provide information on subsurface structure. While the spatial resolution of Magellan gravity during the nominal mission will not be sufficient to model the detailed structure of individual ridge belts (best resolution ~2 ridge belt widths), the data will permit the construction of broad-scale geodynamical models. Circularization of the Magellan orbit to 200 km altitude at the end of the nominal mission would greatly improve the resolution of the gravity models and would permit characterization of the isostatic response functions of gravity and topography. This would provide information on the elastic properties of the lithosphere and the distribution of lithospheric loads. It would further permit comparison to other areas of tectonic importance on both Venus and Earth.

Acknowledgements. I thank W.B. Banerdt, R.E. Grimm and an anonymous reviewer for helpful comments on the manuscript. This work was supported by the NASA Planetary Geology and Geophysics Program.

References

Banerdt, W.B., Support of long-wavelength loads on Venus and implications for internal structure, *J. Geophys. Res., 91,* 403-419, 1986.

Banerdt, W.B., and M.P. Golombek, Deformational models of rifting and folding on Venus, *J. Geophys. Res., 93,* 4759-4772, 1988.

Barsukov, V.L., *et al.,* The geology and geomorphology of the Venus surface as revealed by radar images obtained by Veneras 15 and 16, *J. Geophys. Res., 91,* D378-D398, 1986.

Basilevsky, A.T., A.A. Pronin, L.B. Ronca, V.P. Kryuchkov, A.L. Sukhanov, and M.S. Markov 1986. Styles of tectonic deformations on Venus: Analysis of Veneras 15 and 16 data, *J. Geophys. Res. 91,* D399-D412, 1986.

Bindshadler, D.L., and E.M. Parmentier, Mantle flow tectonics and a weak lower crust: Implications for the formation of large-scale features on Venus (abstract), *Lunar Planet. Sci. Conf. XX,* 78-79, 1989.

Frank, S., and J.W. Head, Spacing of ridge belts in the plains-ridge belt assemblage: Venus (abstract), *Lunar Planet. Sci. Conf. XX,* 311-312, 1989a.

Frank, S., and J.W. Head, Lukelong Dorsa as a zone of underthrusting and possible subduction on Venus (abstract), *Lunar Planet. Sci. Conf. XX,* 309-310, 1989b.

Frank, S.L., and J.W. Head, Ridge belts on Venus: Morphology and origin, *Earth Moon Planet.,* in press, 1990.

Grimm, R.E., and R.J. Phillips, Tectonics of Lakshmi Planum, Venus: Tests for Magellan, *Geophys. Res. Lett.,* this issue, 1990.

Haxby, W.F. and J.K. Weissel, Evidence for small-scale convection from Seasat altimeter data, *J. Geophys. Res., 91,* 3507-3520, 1986.

Head, J.W., Venus global tectonics: Tectonic style and evidence for latitudinal distribution of tectonic features (abstract), *Lunar Planet. Sci. Conf. XVII,* 325-326, 1986.

Herrick, R.R., and R.J. Phillips, Planform of global mantle convection pattern for Venus (abstract), *Lunar Planet. Sci. Conf. XXI,* 499-500, 1990.

Kaula, W.M., Thermal effects on the tectonics of Venus (abstract), *Lunar Planet. Sci. Conf. XIX,* 593-594, 1988.

Kaula, W.M., Venus: A contrast in evolution to Earth, *Science, 247,* 1191-1196, 1990.

Kaula, W.M., and R.J. Phillips, Quantitative tests for plate tectonics on Venus, *Geophys. Res. Lett., 8,* 1187-1190, 1981.

Kiefer, W.S., and B.H. Hager, Crustal convergence and mantle downwelling in the Ishtar Terra region of Venus (abstract), *Lunar Planet. Sci. Conf. XXI,* 629-630, 1990.

Kozak, R.C., and G.G. Schaber, New evidence for global tectonic zones on Venus, *Geophys. Res. Lett., 16,* 175-178, 1989.

Kryuchkov, V.P., Ridge belts: Are they compressional or extensional structures?, *Earth Moon Planet.,* in press, 1990.

Lin, J., and E.M. Parmentier, Surface topography due to convection in a variable viscosity fluid: Application to short wavelength gravity anomalies in the Central Pacific Ocean, *Geophys. Res. Lett., 12,* 357-360, 1985.

Marshall, G.A., and E.M. Parmentier, Convective instabilities within a horizontally extending or shortening thermal boundary layer (abstract), *EOS Trans. Am. Geophys. Un., 70,* 471, 1989.

Schaber, G.G., Venus: Limited extension and volcanism along zones of lithospheric weakness, *Geophys. Res. Lett., 9,* 499-502, 1982.

Sukhanov, A.L., and A. Pronin, Ridge belts on Venus as extensional features, *Proc. Lunar Planet. Sci. Conf., 19,* 335-348, 1989.

Zuber, M.T., A dynamic model for ridge belts on Venus and constraints on lithospheric structure (abstract), *Lunar Planet. Sci. Conf. XVII,* 979-980, 1986.

Zuber, M.T., Constraints on the lithospheric structure of Venus from mechanical models and tectonic surface features, *J. Geophys. Res., 92,* E541-E551, 1987.

Zuber, M.T., and E.M. Parmentier, On the relationship of isostatic topography and the wavelengths of surface deformational features on Venus, *Icarus, 85,* 290-308, 1990.

M.T. Zuber, Geodynamics Branch, Code 921, NASA/ Goddard Space Flight Center, Greenbelt, MD 20771.

(Received May 1, 1990;
revised July 3, 1990;
accepted July 6, 1990)