

**FINAL TECHNICAL REPORT***The Tectonics and Evolution of Venus***"Summary of Research"**

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The research can be summarized under five headings: (1) Planet formation; (2) Thermal and Compositional Evolution; (3) Tectonic structures and processes; (4) Determination and interpretation of gravity; (5) Analyses of Ishtar Terra. Thirty-four publications were produced. References to publications supporting the summary are by year and letter: e.g., (1990c,d) for the emphasis on the terminal phases in formation studies.

1. *Planet Formation.* The consensus that the terrestrial planets formed by accretion of planetesimals was followed, and emphasis was placed on the terminal phase of great collisions as most important in determining the differences of Venus from the other terrestrial planets, particularly the Earth (1990c,d; 1995c). The greatest cause of difference between the two planets is the great impact that created the Earth's moon, required by the low iron content of the moon. This also appreciably affected the difference in atmospheres between the two planets. A persistent problem is the much greater abundance of primordial neon and argon in Venus, compared to that in krypton and xenon. We follow the Owen hypothesis of delivery by a body of 100-300 km size from the outer solar system, but find it has dynamical difficulties (1995a); however, recent work by Newman (under another grant) on large impacts into atmospheres indicates that much more of the bolide is retained than believed heretofore (1997a).

2. *Thermal and Compositional Evolution.* Two general reviews, emphasizing differences between Venus and Earth, were published in *Science*, one before Magellan and one after (1990c, 1995d). The most striking differences in the solid planets were already known from the Pioneer Venus project: the lack of any plate tectonic pattern (i.e., no system of concave ridges), and the much higher ratio of gravity to topography, implying a much stiffer upper mantle. We were first to advance the generally accepted hypothesis that this difference arises from the lack of water in Venus (1990a, c). The implications for a compositional evolution dominated by CO<sub>2</sub> were explored (1993d). The main data produced by Magellan of import to the long term evolution of Venus is the dense and near-random distribution of 912 impact craters, and the small fraction of them that are modified, implying either a global resurfacing around 500 Ma, or an extremely localized tectonics. The former seems more plausible, and an attempt was made to develop an empirical modeling of clustering of resurfacing, taking into account the moderate departures from randomness (1993g), but it was not pursued to a satisfying conclusion. Simple

models of catastrophic resurfacing are unpersuasive (1994c). Hence we have emphasized the development of finite element models for multi-compositional flow, as discussed in section 3 below. A persistent problem is the low abundance of radiogenic argon in the Venus atmosphere; only 18 percent of that produced, if the K:U ratio of 9000 measured by the Venera landers persists throughout the mantle. This forbids the simple solution of packing the radioactive heat sources in the crust, since at temperatures of more than 740 K it should be transparent to interstitial argon. (1994a, 1995d, 1997a).

3. *Tectonic Structures and Processes.* We have participated in some general discussions of Venus tectonics (1990a; 1991d; 1992c, d), and developed an empirical model of Atla and Beta (1993a). But the main emphasis has been on finite element computation of multi-compositional flows. This has required appreciable technical development in accurately tracking material interfaces (1993e), as well as in coping with non-linear rheology. Several applications have been made to Venus (1991c; 1993b, c, f; 1994b; 1995b; 1996b), with emphasis on plume formation and crustal recycling. Some of this work was with particular application to Ishtar, as described in section 5 below. The high viscosities of crustal rocks inferred by the experiments of Mackwell et al stretch the time scale of formation of major features such as Ishtar to well over 1 Gy; hence we welcome the indications by MacKinnon et al that atmospheric effects may lengthen the time scale well beyond 500 Ma. The latest finite element work (1996b) is of more generic character, with significant implications for crustal effects on mantle convection in the Earth as well.

4. *Determination and Interpretation of Gravity.* The Doppler residuals to the MGN-90 solution of Cycles 5 and 6 of Magellan tracking were obtained, and used to determine regional fields, typically of 1600 km extent, as an equivalent surface coating representation (1996a). The principal technical innovation was to substitute a known surface field with the same solution residuals to infer the resolution. It was found to vary from about 110 km (half wavelength) near the equator to 180 km at latitude 70 degrees. This could only be accounted for by the electromagnetic environment of Venus, as confirmed by correlation of residuals with the  $Kp$  index of solar activity. With the availability of Cycle 4 residuals, a global mesh of 182 1500 km squares was determined, and a spherical harmonic analysis to degree 180 was made. The degree to which each 110x110 km element was used in the analysis varied from about 10th to 180th, in accordance with the estimates of residuals (1995e). Some statistical studies comparing Venus's gravity and topography with those of other terrestrial planets were made; Venus's field is cuspidate--i.e., positively skew--like the other three bodies, and intermediate between the Earth's & Mars's in stress implication. (1991b; 1992e; 1993g). The thin-plate model of Forsyth was adapted to interpret the field, but the resolution is too poor to infer flexural rigidity, and applications mainly limited to Ishtar: see below.

5. *Analyses of Ishtar Terra.* Ishtar Terra has the highest topography and the third highest geoid on Venus. However, it is much more difficult to interpret than the other big features, Atla and Beta. Clearly, Ishtar has been the site of tectonism and volcanism over several Gy, with shifts in character that have led to sharp variations in morphology on a scale of a few hundred kilometers. In general, early simple models of convergent flow (1990b; 1991a; 1992a, b) have been confirmed by subsequent work. A very detailed analysis of the imagery was carried out (1992f). The sharp boundaries between geomorphologic provinces made it difficult to infer a stratigraphy, but the mountain belts appear to be most recent. The marked ridge patterns therein demand convergent flow. The smoothness of Lakshmi Planum suggests basic flows, hence upper mantle sources. Plausibly a keel of upper mantle residuum is the main support of the entire plateau, while lateral variations in crustal density may help support the mountain belts, particularly Maxwell Montes. Gravity and topography data were used to constrain a model of Maxwell Montes involving convergence driven by a dense sinker arising from the basalt: eclogite transition. (1997b).

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