Artemis, Venus: The largest tectonomagmatic feature in the solar system?

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ABSTRACT

New geologic mapping reveals that Artemis, a unique 2400-km-diameter feature on Venus, is much larger than previously recognized, including a wide outer trough (>5000 km diameter), a radial dike swarm (12,000 km diameter), and a concentric wrinkle ridge suite (13,000 km diameter). Artemis's evolution included formation of its interior and chasma, accompanied by lateral propagation of radial dikes. The escape of dike magma to the surface formed local cover deposits that buried parts of the remaining radial fracture suite. Cover deposits are cut, in turn, by wrinkle ridges that likely formed by coupling of convective mantle flow with the lithosphere. The outer trough formed late relative to radial fractures, cover deposits, and wrinkle ridges. We suggest that Artemis represents the magmatic signature of a deep mantle plume acting on relatively thin lithosphere. As such, it appears to represent the largest tectonomagmatic feature in the solar system. The newly recognized vast extent of Artemis holds implications for the formation of giant radial dike swarms, wrinkle ridge formation, terrestrial planet mantle-lithosphere coupling, and Venus's surface and geodynamic evolution.

INTRODUCTION

Artemis, a unique feature on Venus, is one of the largest circular structures on a rocky planet in our solar system. Artemis includes an interior topographic high surrounded by Artemis Chasma (a 2100-km-diameter, 25–100-km-wide, 1–2-km-deep circular trough) and an outer rise (2400 km diameter) that transitions outward into the surrounding lowland. The chasma describes a nearly complete circle, lacking definition to the north and northwest. The enigmatic nature of Artemis has perplexed researchers since acquisition of *Pioneer Venus* data in the late 1970s. Hypotheses for Artemis's formation include the following. (1) Artemis Chasma records convergence and subduction (McKenzie et al., 1992a; Brown and Grimm, 1995, 1996; Schubert and Sandwell, 1995). (2) Artemis's interior is analogous to a terrestrial metamorphic core complex (Spencer, 2001). (3) Artemis formed due to a huge bolide impact on cold strong lithosphere before 3.5 Ga (Hamilton, 2005). (4) Artemis represents the surface expression of a mantle plume (Griffiths and Campbell, 1991; Smrekar and Stofan, 1997; Hansen, 2002; Bannister and Hansen, 2010). We present evidence here that Artemis also includes a long-wavelength outer trough (>5000 km diameter), a radial dike swarm (12,000 km diameter), and a suite of concentric wrinkle ridges (13,000 km diameter). The vast scale of these newly recognized features leads us to reevaluate the origin of Artemis.

BACKGROUND

Aphrodite Terra, Venus's largest highland, extends along an equatorial band between ~50°E and ~210°E (Fig. 1). Aphrodite is a composite of several major features, formed by different mechanisms at different times: (1) an extensive fracture zone, comprising a region marked by extremely closely spaced fractures including the Diana-Dali chain (stippled in Fig. 1); (2) a series of highland features, including the Ovda and Thetis plateaus to the west and Atla rise to the east, connected by the fracture zone; and (3) Artemis, south of Thetis. Crustal plateaus Ovda and Thetis, supported by thick crust or low-density upper mantle, represent ancient features formed on thin lithosphere; volcanic rise Atla, thermally supported in the mantle, represents a modern feature on a thick lithosphere (Simons et al., 1997; Phillips and Hansen, 1998). The thermally supported fracture zone system includes splays that crosscut earlier formed Ovda and Thetis (Head et al., 1992; Bleamaster and Hansen, 2005); fractures both predate and postdate Artemis formation (Bannister and Hansen, 2010). A portion of the fracture zone is associated with Atla's evolution, as shown by Atla's triple junction (Smrekar et al., 1997). Collectively these first-order relations suggest that Artemis formed after Ovda and Thetis, but before Atla.

As historically defined, Artemis includes an interior region, Artemis Chasma, and an outer high. Previous mapping defined Artemis's major characteristics, including the interior, circular chasma, and outer high, that evolved coevally (Brown and Grimm, 1995, 1996; Spencer, 2001; Hansen 2002; Bannister and Hansen, 2010). The interior hosts magmatic centers, a northeast-trending fracture zone, and a penetratively developed tectonic fabric. The chasma displays normal faults along the inner wall and fold hinges in the center and outer wall. External wrinkle ridges parallel the chasma, and fracture suites include both concentric and radial orientations relative to the chasma.

NIOBE-APHRODITE MAPPING

We are constructing 1:10,000,000 scale geologic maps of the Niobe and Aphrodite regions (57°N–57°S; 60–180°E) that straddle Aphrodite Terra as part of the National Aeronautics and Space Administration–U.S. Geological Survey planetary mapping program. We mapped local fractures (defining radial or concentric patterns associated with coronae, mons, or volcanoes), regional fractures (elements not obviously part of a local suite, and that are outside of the fracture zone), and wrinkle ridges (Figs. 1B, 1C). We refer here collectively to fractures, fissures, and graben as "fractures." These features form sharp lineaments in synthetic aperture radar data; graben and fissures show resolvable troughs, whereas fractures do not. Fractures (including fissures and graben) represent subsurface dikes (Head et al., 1992; McKenzie et al., 1992b; Grosfils and Head, 1994a; Ernst et al., 2001). Wrinkle ridges, marked by distinctive sinuous ridges, represent modest (<2%–5%) distributed surface-layer contraction (Watters, 1992; Mége and Reidel, 2001).

Here we discuss patterns defined by wrinkle ridge trajectories and a specific regional fracture suite that have particular implications for Artemis. Wrinkle ridge trajectories, consistent with global-scale map efforts, reveal a uniform concentric pattern south of Aphrodite, and more complex patterns to the north (Fig. 1A; a detailed lineament map is available in the GSA Data Repository[1]). Wrinkle ridges also deform fill of local basins located at high elevations within Ovda and Thetis. Wrinkle ridge trajectories reveal regional-scale patterns, the largest of which is concentric to Artemis. Regional fracture suites occur across the map area; of particular interest are fractures that trend at high angles to the concentric wrinkle ridges, referred to here as radial fractures.

Concentric wrinkle ridges and radial fractures together define a coherent pattern centered on Artemis Chasma (Figs. 1A, 1D, 1E; note that

[1]GSA Data Repository item 2010126, a detailed lineament geologic map, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Geology, May 2010; v. 38; no. 5; p. 467–470; doi: 10.1130/G30643.1; 1 figure; Data Repository item 2010126.

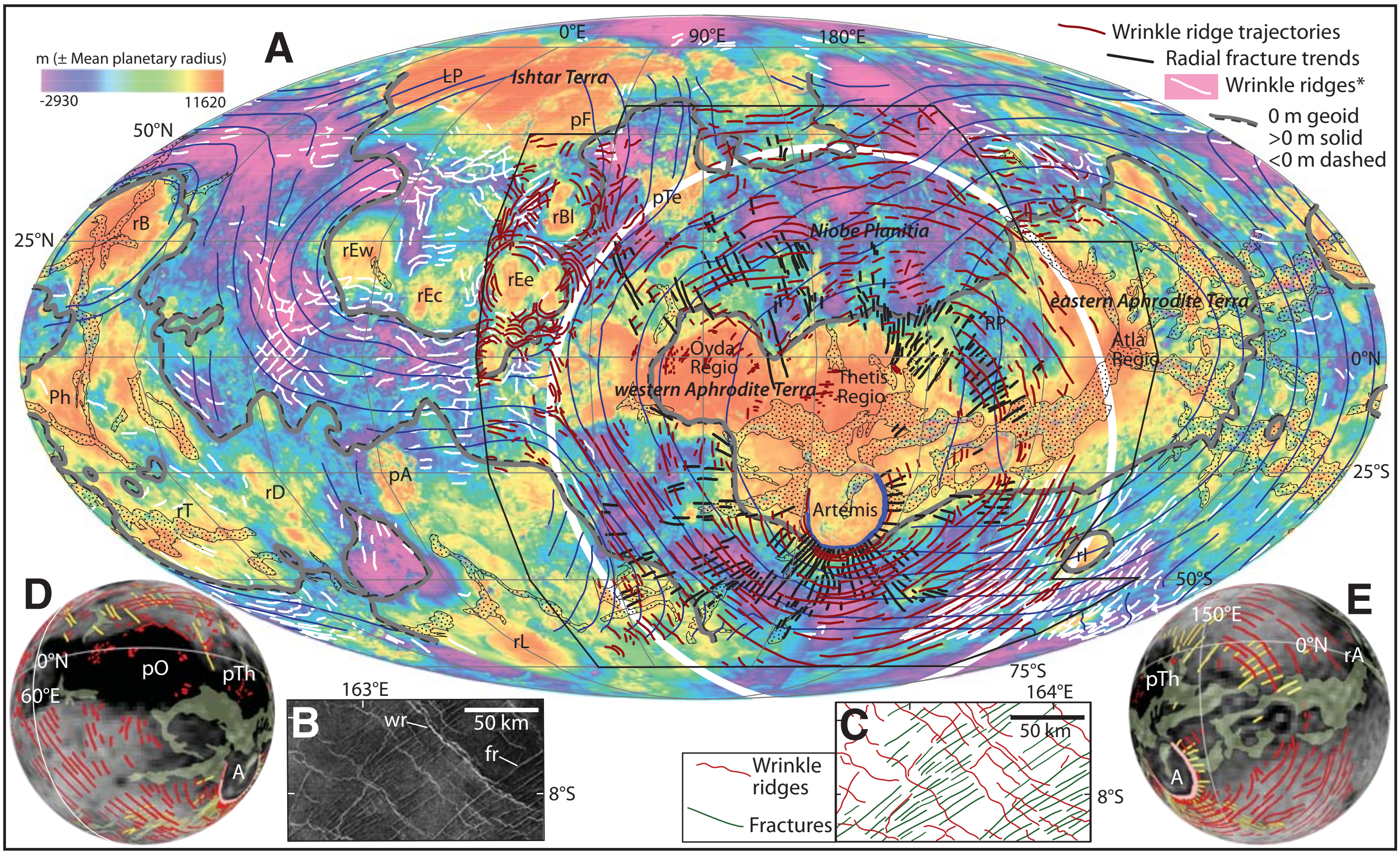

Figure 1. A: Mollweide projection of Venus showing Magellan altimetry, fracture zones (from Price and Suppe, 1995) (stipple), wrinkle ridge trajectories (red, and white*; from Price and Suppe, 1995), and radial fracture trends (black). Major geomorphic features: crustal plateaus (pA—Alpha Regio; pF—Fortuna Tessera; pO—Ovda Regio [in D]; pTe—Tellus Regio; pTh—Thetis Regio [in D, E]), volcanic rises (Atla Regio; rB—Beta Regio; rBl—Bell Regio; rD—Dione; rEc—central Eistla Regio; rEe—eastern Eistla Regio; rEw—western Eistla Regio; rL—Lada Terra; rI—Imdr Regio; rT—Themis Regio), Phoebe Regio (Ph), Lakshmi Planum (LP), Rusalka Planitia (RP), Niobe Planitia, Ishtar Terra, western and eastern Aphrodite Terra, and Artemis trough in dark blue. Wrinkle ridge trends in intratessera basins in western Aphrodite are exaggerated for illustration. Thin black polygon marks map area. Surface strain model features include (Sandwell et al., 1997) 0 m geoid shown between 65°N and 65°S, and predicted surface contraction (blue); according to the global surface strain model, wrinkle ridges should parallel blues lines and not form with geoid >0 m. Thick white line demarks newly defined Artemis. B: Example synthetic aperture radar image of fractures (fr) and wrinkle ridges (wr). C: Map of fractures and wrinkle ridges. D: Orthographic view of a virtual globe to the west of Artemis (A) with Magellan gravity (low—black; high—light), wrinkle ridge (red) and radial fracture (yellow) trends, fracture zones (from Price and Suppe, 1995) (green), and Artemis chasma (pink); symbols as in A. E: View of virtual globe to the east of Artemis. rA—Atla Regio.

the chasma is not defined between the northwest and north). Directly outside of the chasma from the north-northeast clockwise to the west, both wrinkle ridges and radial fractures are progressively more closely spaced with proximity to the chasma; wrinkle ridges transition into chasma folds (Bannister and Hansen, 2010). West and northeast of the chasma, wrinkle ridges are preserved in patches at high elevation (>0 m geoid). Outward from the chasma to the west and south, distal wrinkle ridges trend at a high angle to the fracture zone and radial fractures. Outward from the chasma to the east, wrinkle ridges track across and perpendicular to the fracture zone, and across geoid and topographic contours into Rusalka Planitia. In Rusalka, wrinkle ridges at low to intermediate elevations describe a broad Artemis-concentric curve; fractures, typically at intermediate elevation, fan broadly to maintain a high angle relative to wrinkle ridges. Counter-clockwise to the west, wrinkle ridges trend east and northeast in Niobe Planitia; there fractures define a fan pattern. In northern Niobe orthogonal fractures and wrinkle ridges track across intermediate elevation. Farther west, wrinkle ridges curve to the north-northeast and fractures fan to the northwest. South of western Ovda, wrinkle ridges trend to the north-northwest with orthogonal fractures completing the circum-Artemis pattern.

Generally across the map area, temporal relations between radial fractures, cover deposits, and wrinkle ridges appear similar to those documented in Rusalka (DeShon et al., 2000). There, fractures broadly predate emplacement of cover deposits, which broadly predate wrinkle ridge formation. However, some fractures show evidence of reactivation, whereas others form inversion structures (early formed fractures were filled; fill was later inverted, forming fracture-parallel wrinkle ridges) indicating broadly coeval evolution of fractures, cover deposits, and wrinkle ridges. The deposits, which typically lack obvious sources, likely result from the intersection of radial dikes (fractures) with the surface and resulting magma escape (McKenzie et al., 1992b; Grosfils and Head, 1994a; Ernst et al., 1995). In some cases coronae form the source of local cover deposits (e.g., Llorona Corona; Young and Hansen, 2003).

Circum-Artemis or Circum–Western Aphrodite?

The concentric wrinkle ridge suite was previously described by Bilotti and Suppe (1999) as a circum–western Aphrodite suite, and attributed to topographic loading of western Aphrodite Terra (Sandwell et al., 1997). We suggest that the suite is better described as circum-Artemis. Aphrodite Terra is variably defined by high topography or the region above the 0 m geoid (Fig. 1A). Sandwell et al. (1997) calculated the present-day global surface strain field (assuming isostatic topography) in order to compare model surface strains with documented wrinkle ridge and fracture zone occurrences. According to their model, areas of positive and negative geoid height are in states of surface tension and compression, respectively. Thus, fracture zones should correspond with regions at high geoid elevation (>0 m) and wrinkle ridges should only form in regions with geoid <0 m, if these features reflect current-day topography-induced strain; in addition, wrinkle ridge trajectories should broadly parallel model surface strain trajectories and topographic contours. To the first order, model predictions appear to fit the data; however, close examination reveals critical mismatches. First, contrary to model predictions, wrinkle ridges occur across areas with geoid >0 m, and they trend perpendicular, rather than parallel, to gravity-topography boundaries in several places (south of Ovda, west of Artemis, and north and south of the Diana-Dali chain; Fig. 1A). Second, although wrinkle ridges parallel model trends to the north of western Ovda, and south and southwest of Artemis, this correspondence is lacking to the southeast and east of Artemis, near Atla, and within Rusalka and Niobe Planitiae. Thus, concentric wrinkle ridges do not fit model predictions. In contrast, Artemis Chasma is at the center of the concentric wrinkle ridge pattern, including wrinkle ridges that trend at high angle to the 0 m geoid, and that are at geoid >0 m (Figs. 1A, 1D, and 1E).

New Artemis

Artemis's true size emerges as regional-scale detailed geologic mapping is compiled on a virtual sphere, avoiding projection issues. Orthographic views of the virtual global surface (Figs. 1D and 1E) illustrate the global-scale patterns of radial fractures and circum-Artemis wrinkle ridges. The suites of concentric wrinkle ridges and radial fractures are each independently centered about Artemis Chasma, and each cover similar large regions away from Artemis. Wrinkle ridges define a 13,000-km-diameter pattern with nearly complete arcuate definition preserved across a full range of elevations. Radial fractures describe a 360° arc centered on Artemis; they also occur over a range of elevations across a 12,000-km-diameter region. Discounting geometric coincidence, we propose that the broadly coeval circum-Artemis wrinkle ridge suite and the radial fracture suite represent parts of Artemis not previously recognized, and that they provide clues for Artemis's evolution. Circum-Artemis wrinkle ridges formed after Ovda and Thetis, but before composite assembly of Aphrodite Terra; that is, before the addition of Atla.

A newly defined Artemis therefore includes an interior high, a deep (~2 km) and narrow (50–150 km) 2100-km-diameter trough, outer rise (2400 km diameter), long-wavelength outer trough (5000 km diameter), radial dike swarm (12,000 km diameter), and concentric wrinkle ridges (13,000 km diameter). These features record progressive evolution of Artemis, as follows. (1) Initial doming and subsurface magma emplacement was accompanied by radial fracturing. (2) Fractures (subsurface dikes) propagated laterally, driven by magma buffering, producing dikes with widths and sizes independent of chamber size (Parfitt and Head, 1993; Grosfils and Head, 1994b; Ernst et al., 1995). Emplacement of lateral dikes in the constant driving pressure (magma buffered) produced dikes with sizes and widths that are very large and are independent of chamber size. (3) Dike-magma effusion fed local cover deposits, burying some radial fractures. (4) Wrinkle ridges deformed these cover deposits (driven by coupling of convective mantle or plume flow to the lithosphere; Phillips, 1990; Rosenblatt et al., 1998). (5) Late topographic collapse (and/or loading) resulted in formation of the broad outer trough (the trough might also record mantle flow). Artemis Chasma and its interior evolved approximately synchronously with radial fractures and concentric wrinkle ridges adjacent to the chasma (Bannister and Hansen, 2010), and therefore evolved broadly coevally with the events described above. Accepting that all these features define Artemis, it is difficult to envision any mechanism of formation other than the surface expression of a deep mantle plume (or superplume; Courtillot et al., 2003). Subduction would not result in formation of radial fractures or concentric wrinkle ridges, nor would bolide impact. However, extensive regional development of radial factures and concentric wrinkle ridges are both consistent with plume emplacement (Mége and Ernst, 2001; Wilson and Head, 2002).

DISCUSSION

The newly recognized extent of Artemis holds implications for the formation of giant radial dike swarms, wrinkle ridge formation, terrestrial planet mantle-lithosphere coupling, and Venus surface and geodynamic evolution, forming the basis for future study.

Venus preserves many radial fracture suites, each representing radial dike swarms (Ernst et al., 1995, 2001). Artemis marks the largest such radial fracture suite extending across a remarkable ~25% of the planet surface. Circum-Artemis wrinkle ridges and the radial fracture suite far exceed any topographic expression of Artemis, or likely that of earlier doming, and instead record an axisymmetric global stress field. The circum-Artemis wrinkle ridge and radial fracture suites are individually and collectively consistent with a thin global lithosphere during Artemis evolution (with the exception of locally thick lithosphere associated with Ovda and Thetis) (Grosfils and Head, 1994b; Mége and Ernst, 2001), allowing transmission of mantle shear stress to the surface (Phillips, 1990; Rosenblatt et al., 1998).

Giant radial dike swarms on Earth are characterized by geologically rapid formation (Ernst et al., 2001). Artemis's radial dike swarm, and its huge spatial footprint, might therefore be used to a first order as a time marker (event) of sorts across ~25% of Venus's surface. The Artemis event, which might be expanded to include emplacement of local cover material, and subsequent deformation of this layer by concentric wrinkle ridges, would have formed on a thin lithosphere collectively covering at least 25% of Venus. Based on crosscutting relations, Artemis formed after Ovda and Thetis, and after tessera terrain of the Niobe-Aphrodite area, all of which likely formed on thin lithosphere (Hansen, 2006, and references therein). Therefore, Artemis may have formed late during the "thin-lithosphere" phase of Venus history (Phillips and Hansen, 1998).

Global temporal implications might be derived from interpreted global lithosphere thickness, or through geologic crosscutting relations. With regard to the former, other wrinkle ridge suites occur with large diameters circumferential to Lada (8000 km), Themis (4200 km), Bell (3200 km), and western (3700 km), central (2600 km), and eastern Eistla (3200 km) (Bilotti and Suppe, 1999). All of these features are interpreted as surface expressions of mantle plumes (Simons et al., 1997; Smrekar et al., 1997). In each case, wrinkle ridges occur in regions with geoid >0 m and modeled as tensile surface stress regimes (Fig. 1A; Sandwell et al., 1997). Therefore these wrinkle ridges cannot be attributed to a contemporary topographic stress regime. In contrast, Atla and Beta, the largest volcanic rises, lack concentric wrinkle ridge suites. Each hosts fracture zones that radiate from central highs, correlating well with tensile surface stress predictions and, as such, consistent with contemporary formation of these two rises related to topographically induced stress.

If we assume that the areal extent of radial fracture suites and wrinkle ridges relate, at least in part, to lithosphere thickness (Phillips, 1990; Grosfils and Head, 1994b; Rosenblatt et al., 1998; Mége and Ernst, 2001) and that Venus's lithosphere thickness increased with time (Solomon, 1993; Phillips and Hansen, 1998), then it is possible that Artemis (1) formed broadly before Lada (2), followed in turn by Themis (3), with later formation of western, central, eastern Eistla, and Bell (4; in an undefined order), and finally, contemporary evolution of Atla and Beta (5). Each group of rises would have formed on progressively thicker global lithosphere. Present-day lithosphere is too thick for wrinkle ridge formation, consistent with the lack of circum-Atla and circum-Beta suites. Clearly, other factors affect the areal distribution of concentric wrinkle ridge suites (such as plume size); however, lithosphere thickness might play a first-order role given a range of plume sizes.

Artemis's global-scale manifestation could have implications for lateral transfer of heat in the crust and to near-surface environments, and for climate models and mantle flow. In terms of mantle flow, it is perhaps plausible that Ishtar Terra, Venus's other large unique feature and a site of ancient mantle downwelling that collected mantle melt residuum (Hansen and Phillips, 1995), represents a near-antipodal feature formed in concert with Artemis. The size of Artemis's radial fractures exceeds radial swarms recognized elsewhere, but they are proportionally similar to Mars' Tharsis-radial dike system (Wilson and Head, 2002) as compared to host planet size. As with the Tharsis system, Artemis should provide rich fodder for modeling terrestrial planet dike propagation, plume-lithosphere interaction, and mantle geodynamics.

ACKNOWLEDGMENTS

Olive was a National Aeronautics and Space Administration (NASA) Planetary Geology and Geophysics Undergraduate Research Program participant. Hansen acknowledges support from the McKnight Foundation and NASA grant NNX06AB90G. We thank F. Bilotti, E. Grosfils, and M.B. Price for data files; R. Bannister, T. Hare, V. Lutes-Jégat, and B. Skinner for image files and geographic information system guidance; J. Goodge and I. Lopéz for discussions; and E. Grosfils, S. Wyld and two anonymous reviewers for comments.

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Manuscript received 31 August 2009
Revised manuscript received 25 November 2009
Manuscript accepted 11 December 2009

Printed in USA