# Geologic Map of Aphrodite Map Area (AMA; I-2476), Venus

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**Key Points:**

- We present a geologic map of the Aphrodite map area (0N-57S/60E-180E), representing about 15 percent of Venus' surface
- The map area records three successive geologic eras: the ancient era, the Artemis superstructure era, and fracture zone complex formation.
- Deformation and magmatism were the most spatially focused during the youngest era, marked by fracture zone complex formation.

**Abstract**

We present a 1:10M scale geologic map of the Aphrodite Map area (AMA) of Venus (0N-57S /60E-80E). Geologic mapping employed NASA Magellan synthetic aperture radar and altimetry data. The AMA geologic map, with detailed structural elements and geologic units covering over one eighth of Venus' surface, affords an important and unique perspective to test models of global scale geologic processes through time. Geologic relations record a history inconsistent with global catastrophic resurfacing. The AMA displays a regional coherence of preserved geologic patterns that record three sequential geologic eras: the ancient era, the Artemis superstructure era, and the youngest fracture zone era. The ancient era and Artemis superstructure, with a footprint covering more than 25 percent of the surface, are recorded in the Niobe map area to the north. The latter two eras likely overlap in time. The fracture zone domain, part of a globally extensive province, marks the most spatially focused tectonomagmatic domain within the AMA. Impact craters are both cut by, and overprint, fracture zone structures. Twelve percent of AMA impact craters that occur within the fracture zone domain predate or formed during fracture zone development. This observation indicates the relative youth of the fracture zone era and is consistent with the possibility that this domain remains geologically active. The AMA records a rich geologic history of large tract of the surface of Venus and provides an important framework to formulate new working hypotheses of Venus evolution, and contribute to planning future studies of the surface of planets.

## 1 Introduction

Nearly 25 years ago, NASA's Magellan mission revealed that Venus lacks plate-tectonic processes [*Solomon et al.* 1992*; Solomon,* 1993*; Phillips & Hansen,* 1994], yet Venus' evolution and geodynamic processes remain elusive. Insight into the evolution of Venus and operative geodynamic processes is embedded in the planet surface, laid bare due to Venus' lack of: oceans and hydrosphere and thus extensive erosion and/or associated burial by eroded material; and plate tectonic processes that would result in major portions of the lithosphere (and hence surface) being recycled to the mantle. In addition, Venus' dense atmosphere has protected the surface from globally extensive surface gardening by bolide impact—processes that might result in the formation of thick local to regional regolith.

NASA's Magellan SAR data (synthetic aperture radar) provides an unprecedented view of Venus' surface, and provides the primary data for the construction of Venusian geologic maps, which in turn form a fundamental database for a wide range of investigations and future exploration. (We use SAR herein to indicate Magellan SAR).

In this contribution we present a geologic map of the Aphrodite Map Area (*I-2476;* 0N-57S/60E-180E). A geologic map of the Niobe Planitia Map sheet (*I-2467*; 0N-57N/60E-180E referred to herein as Niobe Map Area, NMA), adjacent to the AMA but north of the equator will be presented in a separate companion contribution. Geologic mapping of the AMA and NMA were undertaken in a collaborative project. The 1:10M scale of the AMA and NMA is well suited to the large regional scale of Venus geologic domains (Figure 1) [*Hansen & López,* 2018*; Hansen,* 2018]. A comparatively similar region on Earth would cover numerous tectonic plate boundaries and include both continental and oceanic crust. The area of the AMA, which covers a 120° longitudinal swath across a latitudinal area comparable to a region of the Earth from the equator to ~10° north of the Antarctic Circle, is large enough to capture tectonic domains, yet small enough to provide a relatively detailed view of geologic relations. Geologic maps, unlike raw data sets (e.g., SAR, altimetry and gravity) capture the evolution of a planet's surface.

Therefore, geologic maps allow geoscientists to both discover and test models of geologic surface histories and operative geologic processes through time.

## 2 The Aphrodite Map Area (AMA)

Venus' surface is divided cartographically into 62 1:5M-scale *VMaps* and eight 1:10M-scale *IMaps* (https://planetarymapping.wr.usgs.gov/Target/project/Venus). Currently just over half of the VMaps have been published. The eight 1:10M map sheets include six sheets each covering 120° longitude on either side of the equator and a N- and S-polar sheet (to N57° and S57°, respectively). This contribution presents the first geologic *IMap* of a Venus.

The U.S. Geological Survey published a suite of four 1:10M-scale radar-image mosaics and shaded relief maps of the Aphrodite Planitia region of Venus (*USGS MAP I-2476, 1988*). The four maps are variably referred to as Aphrodite Planitia Region (jacket) and Aphrodite Terra Region (map sheets). Aphrodite Planitia is a misnomer given that no such planitia exists on Venus. In addition, *planitia* refers to a regionally extensive lowland and relatively featureless plain. Aphrodite Terra is also somewhat misleading given that Aphrodite Terra, Venus' most expansive topographically high region, covers a region well beyond the defined cartographic limits of *I-2476* (Figure 1; Mollweide projections). Therefore, we refer to the Aphrodite Planitia/Terra cartographic map area (*I-2476*) herein as the Aphrodite Map Area, or AMA.

The AMA encompasses ~60,000,000 $km^2$ from 0° N–57° S and 60° E–180° E, encompassing much of *western Aphrodite Terra* south of the equator. Aphrodite Terra, characterized by high topography, straddles the equator and consists of a suite of different geologic features including crustal plateaus western Ovda, Ovda, and Thetis Regiones, volcanic rise Atla Regio, the Diana-Dali corona-chasma chain and Artemis (Figure 1). Artemis Chasma, an ~2000 km-diameter circular trough south of Thetis Regio, lies just east of the center of the AMA and serves as a point of geographic reference for the map area (Figure 2). Topographically the AMA ranges from > 4 to <7 km relative to mean planetary radius (MPR). Crustal plateaus in northern AMA mark the highest elevations, whereas the lowest elevations fall within Diana and Dali Chasmata. A broad trough (~1500-200 km wide, 1-2 km below MPR) concentric to, but outboard of Artemis Chasma and separated from the chasma by a broad concentric high (~1000 km wide, up to 1 km above MPR), hosts the regional lowlands within the AMA. The broad trough includes, counterclockwise from the west: Tahmina, Aino, Laimdota, Imapinua, Zhibek, and Nsomeka Planitiae. The Diana-Dali chain cuts the broad topographic trough, with Rusalka Planitia stranded to the north of the other AMA planitiae. North of the equator within the NMA, Llorona, Niobe, Sogolon, and Akhtamar Planitiae might form a northern extension of the broad Artemis-concentric topographic trough (Figs. 1 and 2). Rusalka Planitia marks the northeast corner of the AMA; Manatum Tessera (in western Ovda Regio) anchors the northwest corner. Xaratanga Chasma and Dsonkwa Regio anchor the southwest and southeast corners of the AMA, respectively. The AMA displays a regional zone of chasmata with arms of broadly Artemis-radial chasmata in the southwest to the more regionally focused Diana-Dali chain in the northeast (Figure 2).

The AMA contains an assemblage of: (1) ribbon tessera terrain [*Hansen & Willis,* 1998], and other local basal units; (2) suites of radial and concentric structures associated with the formation of the Artemis superplume [*Hansen & Olive,* 2010]; (3) volcanic material including: shield terrain [*Aubele,* 1996*; Hansen,* 2005], mons/volcano- and corona-related materials, fracture-fed flows, tholi, and undivided flows; (4) regionally extensive 'lineament/fracture zones' that parallel the corona-chasma chains; and (5) 124 impact craters. Ribbon-tessera terrain, Artemis superplume structural suites and fracture zone terrain extend globally beyond the limits of the AMA (Figure 1b).

## 3 Data and Methods

Global data sets collected during NASA's Magellan mission (1989-1994) provide the basis for modern studies of Venus. *Ford et al.* [1993a] describe Magellan data collection, coverage and interpretation. The Magellan spacecraft, which carried a 12.6-cm wavelength (S-band) radar system to map the surface of Venus, collected three datasets: (1) synthetic aperture radar (SAR) surface images, (2) passive microwave thermal emissivity, and (3) altimetric data. High-resolution Doppler tracking yielded gravity observations. Gravity-topography data provide clues to the nature of long-wavelength (100's of km) subsurface topographic support. Altimetry data (spatial resolution of ~8 km by ~20 km; vertical resolution ~50 m) resolve long-wavelength surface features (10's to 100's of km). SAR data (~100 m/pixel) cover 98% of the surface and provide detailed topographic information suitable for identifying primary and secondary features used for making geologic maps [*Stofan et al.,* 1993*; Hansen & López,* 2018]. Magellan data do not provide robust compositional information.

### 3.1 Data employed for geologic mapping

The primary data employed in this study, SAR and altimetry data, are available online: https://atrocloud.wr.usgs.gov/ and https://webgis2.wr.usgs.gov/Venus_Global_GIS/ ). SAR Cycle 1 (east-directed illumination or left-looking) images cover most of the AMA, with rare local data gaps. Cycle 2 (west-directed illumination, or right-looking) SAR data also covers much of AMA, with three main exceptions from west to east (0N–20S/65–64E; 0N–18S/123–137E; 0N–2S/155–180E). Cycle 3 (left-look stereo) SAR data is quite banded across the AMA, and unavailable south of 43S and from ~93–130E. Digital Compressed Once Mosaicked Image Data Records (C1-MIDR; 225 m/pixel) SAR data from the regional database and map base and digital full-resolution radar map (FMAP; 75–125 m/pixel) data were used in constructing the AMA. Ancillary data include Global Topographic Data Record 3 (GTDR 3) with effective horizontal resolution of 10 km and similar products representing Fresnel reflectivity at 12.6-cm wavelength, average 1- to 10-m-scale slope, and derived 12.6-cm emissivity data (GRDR, GSDR, and GEDR, respectively). GTDR data were combined with SAR images to produce synthetic stereo anaglyphs (*Kirk et al., 1992*) using NIH-Image macros developed by D.A. Young. These images played a critical role in elucidating the relations between geology and topography and, in particular, the interaction of flows, primary and secondary structures, and topography.

Although SAR and altimetry data form the foundation for geologic map construction, we note here a few observations with respect to ancillary slope, reflectivity and emissivity data highlighting broad patterns correlative with various features. Slope data (GSDR) values range from 0 to 15 deg across AMA [*Ford et al.,* 1993a*; Plaut,* 1993] the range in values reflects the wide variation in features. Ridges display linear high RMS slope values, whereas tesserae correlate with a wormy pattern marked by subdued variations in RMS slope values, and coronae typically show circular RMS slope patterns marked by high to intermediate values, with some coronae showing double RMS slope rings. Planitiae exhibit the lowest and most regionally consistent RMS slope values.

Reflectivity data (GRDR) display a broad range of values across the AMA. Notable features include ribbon-tessera terrain within Ovda and Thetis Regiones, which are extremely bright in contrast to inliers of ribbon-tessera terrain that correspond to some of the darkest features in the reflectivity data (e.g., Nuahine Tessera and Sudice Tessera). Manatun Tessera (i.e., western Ovda Regio), which sits topographically lower than Ovda and Thetis Regiones (although not in a lowland position), displays reflectivity similar to that of the lowland tessera inliers, although Manatun is quite large relative to the lowland inliers. Chasmata also appear dark in the reflectivity images. Regions of the crustal plateaus with a high density of intratessera flood basin material show intermediate values. Planitiae in southeastern AMA show mostly uniformly intermediate values. Mahuea Tholus (a local high, SE AMA) stands out as an extremely dark feature.

Emissivity data (GEDR) shows ribbon-tessera terrain of Ovda and Thetis Regiones as extremely dark, surrounded by regions of intermediate values. Most of the AMA displays intermediate values, with tessera-terrain inliers and chasmata-coronae displaying intermediate-high values. As in the other ancillary data, southeastern AMA displays uniformly intermediate values, with the exception of Mahuea Tholus, which displays intermediate-high values, similar to that of tessera inliers and chasmata.

Tessera terrain within the AMA displays different signatures in slope, emissivity, and reflectivity data as a function of regional elevation. Tessera terrain in the high-standing crustal plateaus Ovda and Thetis Regiones have a similar high-value signature in the slope data to the tesserae of western Ovda (e.g., Manatun Tessera) and tessera-terrain inliers (e.g., Nuahine Tessera, Sudice Tessera), however Ovda and Thetis Regiones display low emissivity and extremely high reflectivity compared to (low lying) tesserae that display high emissivity and low reflectivity.

### 3.2 Mapping methodology

Geologic maps at all scales should provide the basis for interpreting geologic histories, which in turn provide critical relations for understanding the range of processes that contributed to the evolution of planets [*Gilbert,* 1886]. Construction of a geologic map is a critical first step in unraveling geologic history. Geologic maps are interpretive products used in turn for further interpretation of geological processes [*Compton,* 1985*; Butler & Bell,* 1988*; Maltman,* 1990*; Powell,* 1992]. In the construction of this map we attempt to adhere to historical and contemporary terrestrial mapping methods, with particular attention to complementary criteria, format and cautions outlined for Venus [*Compton,* 1985*; Wilhelms,* 1972, 1990*; Tanaka et al.,* 1994, 2009*; Hansen,* 2000*; Zimbelman,* 2001*; Grindrod & Guest,* 2006]. Throughout mapping we attempt to ensure that map methodology allows that *any* operative process can be *discovered*—that is, the mapping method does not predetermine the resulting geologic map [*Hansen,* 2000]. We distinguish secondary structures (strain) from geologic units given that materials and structures record different 'time slices' in the evolution of Venus' surface, and each reflect different aspects of operative geologic processes [*Wilhelms,* 1972, 1990*; Hansen, 2000*; *Easton et al*., 2005, 2016].

*Hansen & López* [2018] discuss the philosophy and methods of geologic map construction employed herein, including a brief review of Magellan data, SAR image interpretation, and identification and delineation of geologic units and structural elements. Geologic maps constructed using SAR represent high-order derivative products interpreted from clues provided by multiple views (where possible) of the same surface. Given the side-looking nature of SAR, the specific geographic location of mapped features may vary based on employed SAR images; however, the local and regional scale patterns that emerge from mapping using SAR are robust. The methodology for defining geologic units and structural elements/fabrics builds on standard geologic and structural analysis [*Wilhelms*, 1990; *Tanaka*, 1994; *Hansen*, 2000; *Zimbelman*, *2001*; *Hansen & López,* 2018*; Peacock & Sanderson,* 2018]. Map units represent material interpreted to have been emplaced within an increment of geologic history with limited application of standard stratigraphic methods. However, composite units might lack temporal equivalence across the AMA. In these cases, map units represent descriptive, rather than temporal, units. Thus, designation of a material unit might not imply concurrent or synchronous emplacement. The location and orientation of secondary structural elements are shown independent of material units across the AMA. Evidence for reactivation of secondary structures is common [e.g., *DeShon et al.,* 2000], which further complicates the process of unraveling relative temporal constraints and, ultimately, geohistory.

Criteria for distinguishing geologic units include (but is not limited to): (1) the presence of sharp, continuous contacts; (2) truncation of, or interaction with, underlying secondary structures and topography; and (3) primary structures, such as channels or edifice topography that allow a reasonable geologic interpretation and hint at three-dimensional geometry. Some units do not fit these constraints, limiting robust stratigraphic interpretations/implications.

Identification and description of map units and structural features result in the generation of a *relative sequence* of material units *independent of absolute time*. This approach is consistent with terrestrial field geology where rock units and geospatial relations are initially identified independent of absolute time. In terrestrial studies, units might be correlated and fit into a historical framework based on universal (*absolute*) time markers (e.g., fossils, radiometric ages, paleomagnetic signatures). Currently there is no means to constrain absolute age on Venus [*Campbell,* 1999*; Hansen,* 2000*; Hansen & Young,* 2007], therefore interpretations of relative temporal relations should stop short of unit correlation, given that correlation requires absolute age constraints. Assessing 'absolute' ages of units and determining the duration of formative processes on planetary bodies (save the Moon) currently relies solely on surface crater density analysis. Given Venus' relatively low global density and large sizes of impact craters robust absolute unit age determination is not possible for Venus [*McKinnon et al.,* 1997*; Campbell,* 1999].

All published 1:5 M-scale USGS Venus geologic maps (Figure 2) were consulted during map construction including: V35/I-2808 [*Bleamaster & Hansen,* 2005a], V37/I-2752 [*Hansen & DeShon,* 2002], V46/I-2779 [*Stofan & Guest,* 2003], and V48/SIM 3099 [*Bannister & Hansen,* 2010]. However, in some cases, map interpretations differ, as happens in the case of geologic mapping on Earth. Discussion of each situation is outside the boundaries of this report.

## 4 The AMA Geologic Map

This section, which broadly describes the AMA geologic map (Plate 1), is organized from broad to specific. We first present a broad geologic overview, followed by a description of four geologic domains that emerged from map construction. We discuss primary and secondary structures (including tectonic fabrics), and geologic units—including both lithodemic units and material units. We then discuss tectonic suites of structures—that is, structural elements interpreted as displaying genetic relations (e.g., radial or concentric suites). We divide the tectonic suites into local and regional suites, based on suite patterns and geographic distribution. We then briefly describe impact features; impact crater characteristics are presented in Table 1. Map unit descriptions are included on the geologic map, as is a graphical representation of the interpreted sequence of maps units. A brief geologic history of the AMA that emerges from the geologic map completes this report. Feature names referred to herein are shown in figures 1 or 2 or on the geologic map. Impact crater names are indicated on the map, with specific location information provided in Table 1. The contribution concludes with first-order observations that emerge from the AMA geologic map.

### 4.1 AMA geologic setting

The AMA (Figure 2) encompasses the southern part of western Aphrodite Terra, including western Ovda, Ovda and Thetis Regiones, the Diana-Dali corona-chasmata chain, and Artemis. Southern AMA is dominated by planitiae that collectively define a broad (~150 to 200-km wide) topographic trough concentric to, but outboard of, Artemis Chasma (Figures 1a, 2). A fan of generally ENE-trending chasmata transect the AMA, with the narrow part of the fan (NE AMA) marked by the Diana-Dali corona-chasma chain. The northern chasmata/fracture zone terrain cuts mostly south of Ovda and Thetis Regiones and north of Artemis (Ralk-umigu and Quilla Chasmata); whereas the fan of chasmata radial to Artemis spays along three zones: Gamsilg and Juno chasmata, Xaratanga Chasma, and Reita Chasma, counterclockwise from ~8:30 to 6:30. Chasmata are more widely spaced and distributed, and less well-defined topographically in the southwest, as compared to Diana-Dali Chasmata. Southeastern AMA, a relatively featureless region, hosts Dsonkwa Regio marked by subdued topography (challenging its 'regio' moniker), and Mahuea Tholus notable in its isolation, steep local slopes and well-defined flow features [*Moore et al.,* 1992].

### 4.2 Geologic domains

The AMA is divisible into four major geologic domains (1-4) that locally overlap: (1) crustal plateaus (western Ovda, Ovda, and Thetis Regiones) and lowland inliers of ribbon tessera terrain [*Hansen & Willis,* 1998*; Hansen & López,* 2010]; (2) Artemis, including Artemis Chasma and the interior region, and a huge radial dike swarm and a concentric wrinkle ridge suite, 12,000- and 13,000-km diameter, respectively [*Hansen & Olive,* 2010]; (3) 'fracture zones'—broad zones (100's of km wide and thousands of km long) of deformation marked by a combination of fractures (broadly defined), coronae, and chasmata; and (4) southeastern AMA, which is cut by Artemis-radial fractures, and hosts both shield terrain [*Aubele,* 1996*; Hansen,* 2005] and extensive tracts of thin flows cut by Artemis-concentric wrinkle ridges.

#### 4.2.1 Domain 1

Ribbon tessera terrain [*Hansen & Willis,* 1998], and other basal regions mark some of the oldest recognizable crustal exposures across the AMA. These are best preserved in elevated crustal plateaus, although exposures occur across much of the AMA preserving an early record of crustal evolution [*Hansen & López,* 2010]; southeastern AMA generally lacks ribbon-tessera terrain, although other basal units occur locally. These basal units could be temporally correlative to ribbon-tessera formation; relative time is unconstrained.

#### 4.2.2 Domain 2

Domain 2, marked by two suites of Artemis-centric structures—radial fractures and concentric wrinkle ridges, as recognized by *Hansen & Olive* [2010], occurs across essentially the entire AMA and NMA. These two suites of structures, and their relations with regional units are best preserved in southeastern AMA, an area relatively unaffected by younger events. In some locations Artemis-radial fractures are well developed; elsewhere, Artemis-concentric wrinkle ridges dominate. Regardless, it is clear that these two suites of concentric and radial structures are genetically related to one another [*Hansen & Olive,* 2010] Detailed and regional cross-cutting relations indicate that fractures began to form before wrinkle ridges, and that the fractures likely served as conduits for Artemis-fed flows (unit Afu) distributing flows locally across huge regional areas. Areas buried by these flows, as well as regions covered by a thin cover of shield terrain [*Aubele,* 1996*; Hansen,* 2005], were later deformed by the suite of Artemis-concentric wrinkle ridges. Locally Artemis-radial fractures are buried, and in some cases these fractures were reactivated as inversion structures [e.g., *DeShon et al.,* 2000]. Artemis-radial fractures locally occur as buried lineaments. Artemis-fed flows lack indications of flow morphology, perhaps due to simple leaking to the surface as a result of the magmatic head intersecting the local surface [*Head & Wilson,* 1991]. These flows were likely characterized by low viscosity, based on the general lack of flow features. Alternatively, flow feature definition was lost through time [e.g., *Ardivson et al.,* 1992].

A broad topographic trough (~6,500-km diameter), concentric to Artemis Chasma, hosts wrinkle ridges within the trough low. Radial fractures are locally preserved in a concentric region on either side of the trough. Collectively relations indicate that the trough and outer topographic high probably formed during Artemis superstructure evolution with Artemis-fed 'flows' occurring, or collecting, more in the broad trough.

#### 4.2.3 Domain 3

This domain cuts diagonally across the AMA from the southwest to the northeast, where it intersects with fracture zones that radiate from the volcanic rise Atla Regio. Fracture zones, including those in the AMA, recognized in early studies of Magellan global data are referred to as rifts, or rift zones in some published literature [e.g., *Price & Suppe,* 1994, 1995]. However, detailed mapping within portions these zones indicates that the zones do not record large extensional strain perpendicular to regional fracture trends, as is the case of terrestrial rift zones [*Hansen & Phillips,* 1993*; Hansen & DeShon,* 2002]. Furthermore, these zones are typically much wider (i.e., normal to trend) than terrestrial rift zones (locally >1000 km wide), and the nature of the linear structures (in map view) within the zones differ from normal faults developed in typical terrestrial rift zones. Therefore, we refer to these regions as 'fracture zones', following terminology of *Hansen & DeShon* [2002]. The fracture zone domain is characterized by penetratively deformed zones marked by lineaments consisting of fractures, graben, pit chains, stoped troughs, hybrid structures (*see description below*), and coronae and chasmata. The fracture zones and associated structures dominantly post-date the formation of the Artemis-centric fractures and wrinkle ridges (e.g. domain 2). AMA hosts three types of coronae, with hybrids between three end members: (A) coronae marked by concentric structures; (B) radial fracture coronae; and (C) coronae with obvious corona-sourced flows. Radial and concentric fractures represent fractures/graben/dikes and/or magmatic stoping structures; in general, magma locally remained at depth, but emerged to the surface in the case of coronae with surface flows. Coronae type may be related to local lithospheric thickness, and the ability to support volcanic edifices and surface flows [*McGovern et al.,* 2015].

The fracture/corona/chasma zones define regions of variable deformation along linear to fan-shaped areas with the shape and orientation of each fracture zone broadly paralleling the trend of its internal structural lineament fabric. The most prominent zone, the Diana-Dali corona-chasma chain, trends ENE in the east extending northeast to volcanic rise Atla Regio (outside AMA; Figs. 1 and 2); west of Miralaidji Corona this zone splays into two zones. The southern arm trends WSW to SSW marked by the alignment of Bona, Mayauel, Colijnsplaat, Annapurna, and Teteoinnan Coronae. The northern arm extends west through Ceres Corona. West of Ceres the zone splays again, with one arm trending NW to Blai Corona. A more prominent arm, which we refer to informally as the Vir-ava/Ralk-umgu chasma zone*,* extends westward from Ceres Corona, trending WSW to W and curving to the WNW northwest of Artemis. The Vir-ava/Ralk-umgu chasma zone, which displays extensive development of extremely closely-space lineaments, includes Quilla, Vir-ava, Jana, Ralk-umgu, and Kuanja Chasmata. Inari Corona lies along this trend between Vin-ava Chasma to the north and Quilla Chasma to the south. Much of the zone cuts south of Thetis and Ovda Regiones, but NW-trending portions dissects ribbon-tessera terrain both within Ovda Regio, and the region between Thetis and Ovda Regiones. Directly north and west of Artemis the Vir-ava/Ralk-umgu chasma zone is characterized by extreme penetrative development of linear troughs and pit chains, which collectively likely represent magmatic stoping [*Hansen & López,* 2014a, 2014b]. The Vir-ava/Ralk-umgu chasma zone is similar in character to the Diana-Dali corona-chasma chain, although it is generally lacking in the development of coronae (with the exception of Inari Corona). The fracture zones take on a different character where the zones dissect ribbon-tessera terrain and crustal plateaus. The lineaments, which are more widely spaced as compared to other portions of the fracture zone, become more difficult to delineate, due in part to the tessera-terrain host, and its characteristic ribbon-tessera terrain fabric. A possible north-trending zone anchored by Rosmerta Corona in the south, may also form part of a fracture zone, although this zone lies mostly in the NMA, and is characterized by coronae rather than fractures or other lineaments [*López & Hansen,* 2015; *Hansen & López,* 2018].

West of Artemis Chasma, fracture zones take on a more fan-like character. One spoke, marked by penetratively-developed lineaments, trends SW (7 o'clock relative to Artemis Chasma) includes Reitia Chasma and Triglava Corona. A second spoke that trends west from Artemis Chasma (9 o'clock) is marked by Juno Chasma, Gefjun and Tai Shan Coronae, and Kunapipi Mons. Southwestern AMA hosts numerous coronae that are broadly aligned along these fracture zones; coronae structures and flows locally mask extensive parts of the fracture zones.

The Diana-Dali arm, which sits along a ~3000 km-wide linear topographic high that trends toward Atla Regio, is characterized by extremely penetrative deformation across an ~2000-km wide band. This zone hosts AMA's largest coronae; associated chasmata form deep troughs marked by steep scarps. These coronae display radial and concentric fractures, with variable development of flows. The easternmost coronae display more flows; whereas fractured surfaces and a notable lack of flows, characterize the coronae closer to Artemis. Coronae developed along the fracture zone periphery display more prominent flows, perhaps due more to the relatively lower intensity of deformation than to the nature of the flows. The relatively high elevation across the Diana-Dali belt is consistent with the occurrence of relatively thin lithosphere [*Rosenblatt et al.,* 1994], which is in turn consistent with the formation of coronae characterized by subsurface magmatism, as opposed to surface flows [*McGovern et al.,* 2015]. The relative size of the coronae is likely due to the broad width of thin lithosphere (i.e., high elevation)—that is, thin lithosphere across an expansive region allows for the development of large coronae given that the relatively thin lithosphere favors development of coronae over large volcanic constructs [*McGovern et al.,* 2015].

The broad fan-shape region west of Artemis Chasma hosts both coronae and fracture zones; overall deformation here is more distributed, or less penetratively developed than in the other fracture zones. This region is also topographically subdued, consistent with thicker lithosphere [*Rosenblatt et al.,* 1994]. Coronae in this part of AMA variably display radial and concentric structures and surface flows. Corona-radial fractures and corona-concentric fractures are best developed along trends parallel to the local orientation of Artemis-radial fractures, or the spokes of the fracture zones; in contrast, corona-concentric fold suites are best developed parallel to the local orientation of Artemis-concentric wrinkle ridges (that is, perpendicular to the trend of the aforementioned fracture suites). Most coronae within this region display corona-sourced flows, and observation consistent with a thicker lithosphere across this region [*McGovern et al.,* 2015], compared to that of the Diana-Dali corona-chasma chain, or to the mostly corona-free, Vir-ava/Ralk-umgu chasma zone.

The Vir-ava/Ralk-umgu chasma zone, ~1,000 kilometers wide and up to 3,000-4,000 kilometers long, includes a single corona, Inari. This fracture zone is characterized by extremely penetratively developed (that is, closely-spaced) pit chains, linear troughs, fractures, and hybrid features (described in tectonic structures section). The lineaments are so penetratively developed that host material cannot be defined. However, despite the incredible high lineament density, flows that locally bury earlier-formed lineaments are notably rare [*Hansen & López,* 2014a, 2014b; *Tovar et al.,* 2015].

#### 4.2.4 Domain 4

Southeastern AMA differs from the other domains in that it is defined by area, and a general lack of features. Southeastern AMA is free of crustal plateaus and hosts limited basal terrain, and lacks both true coronae and fracture zones. This area preserves an excellent record of the spatial and temporal development of Artemis-radial fractures and Artemis-concentric wrinkle ridges. The limited exposures of basal terrains offer windows in time—providing local, fragmented records of surface evolution prior to the formation of the Artemis superplume. Within domain 4, Artemis-radial fractures display incredible continuity, extending for 2000-3000 km; the structures are locally buried, yet reappear along trend, either as exposed fractures, or as veiled, shallowly buried lineaments. Where Artemis-radial fractures are best developed, wrinkle ridges do not form; and where wrinkle ridges are best developed, fractures are clearly buried. Dsonkwa Regio (probably not a true regio as noted previously) hosts Tonatzin and Utset 'Coronae' and limited exposures of ribbon-tessera terrain (including Shait Tessera) and other basal terrains, which may represent shallowly-buried ribbon tessera. Tonatzin Corona lacks radial fractures and concentric structures, defined instead mostly by a shield field; it is not clear why Tonatzin is considered a corona, and this classification should be revisited. However, we preserve the name of Tonatzin Corona herein given that detailed mapping of this feature is outside the scope of the current project. Utset Corona is marked by concentric structures, and two suites of fractures, one parallel to local Artemis-radial fractures and another suite near orthogonal to this trend (NNE). Classification of Utset as a corona might also be suspect. Dsonkwa Regio marks a local exposure of regional basal terrain cut by Artemis-radial fractures and surrounded by lower regions covered by thin flows deformed by Artemis-concentric wrinkle ridges. Domain 4 provides an excellent example of the type of terrain/unit contacts across the AMA, as discussed in the section Terrain Units. Mahuea Tholus is perhaps the most prominent feature in domain 4. Urd Tessera, which lies nearly due east of Mahuea Tholus, marks a basal terrain, a small local high surrounded by younger flows cut by Artemis-concentric wrinkle ridges. Contrary to its name Urd Tessera does not host ribbon-tessera terrain, but rather is characterized by closely-spaced NNW-trending folds and NNE-trending lineaments. The NNE-trending lineaments are not ribbon structures however, nor are these structures orthogonal to the fold trends, as would be expected in the case of typical ribbon tessera terrain [e.g., *Hansen & Willis,* 1998].

### 4.3 Primary structures, secondary structures, and tectonic fabrics

Structures, both primary (depositional or emplacement-related) and secondary (tectonic), are identified in SAR data. Tectonic fabrics represent suites of genetically related secondary structures that together define a coherent structural pattern.

#### 4.3.1 Primary structures

Primary structures on Venus are mostly related to volcanic features and include channels, shields, pits and pit chains, lobate flow fronts and flow levees, and impact crater haloes and rims [*Ford et al.,* 1993b]. However, some of these features may result from sediment deposition/erosion processes. More detailed work will be required to clarify the formation of all these features.

Channels (or canali) are sinuous, low-backscatter troughs tens to hundreds of kilometers long and a few kilometers wide; locally, they may lack apparent topographic relief, and are interpreted to form by channelized fluid flow [*Baker et al.,* 1992, 1997; *Komatsu & Baker,* 1994]. The nature of the fluid is undefined, as is the type of erosion, whether mechanical or thermal, cutting downward from the surface, or upward from depth [e.g., *Gregg & Greeley,* 1993*; Bussey et al.,* 1995*; Williams-Jones et al.,* 1998*; Jones & Pickering,* 2003*; Lang & Hansen,* 2006]. Channels could be primary structures, related to levee development during flow emplacement, or channels could be erosional structures in which case they would post-date the emplacement of the units they cut. The formation of these features is not understood [*Baker et al.,* 2015]. Multiple mechanisms could contribute to channel formation—that is, channels across the AMA might not share a singular origin [*Hansen & López,* 2018].

Shields are small (generally 1 to 15 km in diameter, rarely 20 km in diameter), quasi-circular to circular, radar-dark or radar-bright features with or without topographic expression and with or without a central pit, interpreted as small volcanic edifices [*Guest et al., 1992; Crumpler et al.,* 1997*; Addington,* 2001]. The size of individual shields is difficult to constrain because the bases of individual shields are typically poorly defined, and deposits commonly blend smoothly into a composite layer [*Hansen,* 2005].

Lobate flow fronts and flow levees can indicate local surface flow direction providing information about flow emplacement and local paleo-topography at the time of flow emplacement, unless deposits represent pyroclastic flows. Flow directions, interpreted from lobate flow fronts and levees, are shown on the map.

Impact craters are perhaps most prominently marked by rims that sit above circular interiors and within/at the boundary of ejecta material that occurs as extremely radar-bright deposits [*Weitz,* 1993]. Impact craters can also display haloes, radar-bright (rough) or radar-dark (smooth) deposits that extend outward from the rim and ejecta deposits up to many crater diameters [*Izenberg et al.,* 1994]. Haloes are thought to form as a result of the shock-induced crushing of host material just preceding or accompanying bolide impact or due to accumulation of fine-scale ejecta. Some craters have parabolic haloes, which can extend up to 20 crater radii to the west; these thin deposits(?) are interpreted as due to the interaction of east-to-west zonal winds [*Arvidson et al.,* 1991, 1992; *Campbell & Campbell,* 1992]. The nature and extent of impact haloes might be leveraged to provide unique clues about regional geologic histories [*Campbell et al.,* 2015*; Whitten & Campbell,* 2016].

Crater haloes and parabolic deposits appear to degrade with time losing their radar contrast with surrounding terrain [*Izenberg et al.,* 1994]. Impact craters that display both extreme haloes and radar bright crater interiors are generally interpreted as relatively young, whereas craters with degraded haloes, or lacking haloes entirely, and displaying radar smooth filled interiors are interpreted as relatively old [*Phillips & Izenberg,* 1995; *Herrick & Rumpf,* 2013]. Impact crater haloes are indicated on the map with a stippled map pattern so that underlying units and structures can be represented along with the extent of crater haloes.

#### 4.3.2 Secondary structures

Secondary structures form after the emplacement of geologic units and typically record tectonic processes; accordingly, these structures provide clues for formational tectonic processes. The distribution and (or) character of secondary structures may also provide clues for the delineation of material units, as well as temporal relations between different material units [*Hansen,* 2000*; Tanaka et al.,* 2009*; Hansen & López,* 2018]. Most radar lineaments represent secondary structures. Stofan et al. [*1993*] provided an excellent introduction to the interpretation of secondary structures in SAR imagery. Secondary structures within AMA include various types of lineaments, fractures and faults; pits and pit chains, stoping troughs, and hybrid structures; folds, ridges, chasmata, and wrinkle ridges. Given that the AMA covers ~60,000,000 km$^2$ we do not show all lineaments. However, we attempt to capture the essence of recognized structural suites. Therefore, in some cases lineament trends will be shown, in other cases each lineament is shown, in yet other cases a collection of the lineaments is shown on the map. There is no single unique scale of lineament or feature identification, just as there is not a single unique scale of observation in the case of field-based mapping on Earth, particularly for maps that cover huge areas of Earth's surface.

Fractures are sharply defined lineaments with a negative, or null, topographic signature, commonly grouped into suites based on orientation, pattern (i.e., radial or concentric) and/or spacing (i.e., widely spaced or closely spaced). Fractures are generally interpreted as extensional structures [*Banerdt et al.,* 1997] although there might be very little measurable extension normal to their trends. Locally fractures consist of *en echelon* fractures indicative of either a shear fracture origin, or the emergence of a fracture at depth to the surface with the *en echelon* fractures marking hackles. Any consideration of fractures as evidence of tectonic extension should be independently and robustly proven; we do not consider fractures to be extensional structures in the same mode as, for example, normal faults, herein.

Pits—sharply defined depressions, occur individually, or more commonly as pit chains—linear arrays of pits. Pit chains can have a distinctive scalloped plan-view, or be marked by straight, sharply defined parallel walls forming a generally flat-floored trough, given complete connection or coalescing of a chain of pits. Pits or pit chains can be considered primary structures or secondary structures, depending on the question at hand. Pit chains are primary structures relative to pit-related materials, yet they may be secondary structures relative to the units they cut or are emplaced within. Pit chains, which represent regions marked by subsurface excavation, may mark the surface expression of dilatational faults or dikes [*Grosfils & Head,* 1994*; Okubo & Martel,* 1998*; Bleamaster & Hansen,* 2005b*; Ferrill et al.,* 2004*; Schultz et al.,* 2004] or they could represent stoping features that would not require associated crustal extension [e.g., *Cushing et al.,* 2014]. Pit chains, or stoping troughs may evolve from fractures, dikes, or faults; these features may or may not result in crustal extension. Pit chains may evolve into shallow troughs, marked by paired, closely spaced (<5 km and commonly $\leq$1 km) lineaments marking a shallow (tens of meters) flat depression bounded by steep sides; they are interpreted herein as the result of subsurface magmatic activity [e.g., *Bannister & Hansen,* 2010*; Hansen &*

*López,* 2018]. A full discussion of pit chains and trough structures is outside the goals of this contribution.

Folds are ridges defining wave-like topographic expression marked by a gradational radar character normal to their trend [*Stofan et al.,* 1993]. Folds are generally interpreted as contractional structures, although folds locally form in extensional environments in terrestrial settings. Small ridges are topographic ridges with low relief and width, similar in appearance to folds except that the nature of the lineament is ambiguous—although possibly of contractional origin (marked by folds or thrust faults). Large ridges are topographic ridges with moderate relief and width. Ridges and chasmata (relatively wide topographic troughs) commonly occur as paired structures within AMA, particularly within the corona/chasmata chains and fracture zone domain. Scarps are marked by a steep slope.

Wrinkle ridges define low sinuous spines spaced a few kilometers to tens of kilometers apart and up to a few hundred kilometers long; these lineaments, which represent low (<2%) layer contractional strain, are found on most terrestrial worlds, especially on large flat expanses of volcanic flow materials [*Watters,* 1988*; Bandert et al.,* 1997]. Wrinkle ridges typically form suites of near parallel structures (and occasionally orthogonal suites) formed over large regional expanses. Locally within the AMA, wrinkle ridges occur as inversion structures formed by the inversion of buried fractures due to post burial contraction [*DeShon et al.,* 2000]; inversion wrinkle ridges typically have straighter less sinuous trends reflecting the nature of their parent fractures.

#### 4.3.3 Tectonic fabrics

Tectonic fabrics comprise an assemblage of related structural elements that together characterize a rock unit, as in the case of ribbon-tessera terrain [*Hansen & Willis,* 1996, 1998; *Hansen,* 2006], or Artemis interior fabrics [*Bannister & Hansen,* 2010].

Ribbon-tessera fabric is characterized by orthogonally developed suites of ribbons, or ribbon structures and folds. Ribbon structures record layer extension, whereas orthogonal fold suites record layer contraction. Ribbon terrain is marked by parallel bright and dark lineaments that represent alternating parallel ridges and troughs with typical wavelengths of 2 to 5 km [*Hansen & Willis,* 1996, 1998]. Ribbon structures are commonly spatially associated with folds; parallel fold crests and troughs typically trend at a high angle (generally 90°) to ribbon lineaments. These ribbon-tessera folds defined parallel fold suites ranging in wavelength from short (≤1 km), to intermediate, to long (order >10 km); longer wavelength folds host shorter-wavelength folds, carrying them piggyback [*Hansen,* 2006]. Within the AMA we delineate the trends of ribbon-tessera ribbons and folds. Ribbon trends parallel ribbon lineaments, whereas fold trends parallel fold crests or troughs. In most cases short-, intermediate, and long-wavelength folds display parallel local trends [*Hansen,* 2006]. Together, ribbons and folds characterize ribbon-tessera terrain [*Hansen & Willis*, 1996, 1998]. Graben complexes, an additional possible structural element of ribbon-tessera terrain, typically parallel ribbon trends. Graben complexes are wider and shorter than ribbon structures, and thus display smaller length-to-width ratios. Graben complexes that occur within ribbon-tessera terrain typically cut across long-wavelength fold crests, which results in a lens-shape plan view [*Ghent & Hansen,* 1999*; Hansen,* 2006]. *Bindschadler et al.* [1992] recognized ribbon, fold and graben structures within tessera terrain. These workers describe described ribbon structures as “narrow troughs”, clearly differentiating ribbon structures from generally parallel but morphologically different graben. Some workers do not delineate ribbon and graben, which can lead to confusion with regard to the temporal and kinematic evolution of ribbon-tessera fabric [e.g., *Gilmore et al.,* 1997, 1998], whereas others simply map tessera terrain but do not identify the nature of the tessera fabric structures, nor their trends [e.g., *Ivanov & Head,* 2011].

Collectively referred to as ribbon-tessera terrain, or ribbon terrain for short, this distinctive composite tectonic fabric (e.g., ribbons and parallel graben, and orthogonal fold suites) commonly marks tessera terrain. The composite fabric records a progressive change in the rheological character of the deformed layer with time, from an early-formed thin layer to an increasingly thicker layer with time and fabric development, likely a result of thermal history [*Hansen & Willis,* 1998; *Ghent & Hansen,* 1999; *Brown & Grimm,* 1999; *Hansen,* 2006; *Ruiz,* 2007]. For a discussion of ribbon-terrain controversies, see *Gilmore et al.* [*1998*], *Hansen et al.* [*2000*], and *Hansen* [*2006*].

Artemis hosts a second type of tectonic fabric within the AMA, as noted by *Bannister & Hansen* [2010]. Artemis interior penetrative fabric represents closely spaced (0.5–1 km] lineaments with slight gradation in radar brightness across strike. The lineaments are interpreted in some cases as short-wavelength low-amplitude folds, and in other cases as fracture-like structures; however, in many cases the fabric character is ambiguous given that the fabric approaches the effective resolution [*Zimbleman,* 2001] of SAR. This distinctive tectonic fabric has, to date, only been recognized within the interior of Artemis. The fabric may be analogous to structural fabric development along terrestrial divergent plate boundaries [*see Bannister & Hansen,* 2010]. Lineament trends are noted for Artemis interior tectonic fabric.

### 4.4 Map units

Map units are broadly defined in the following section. Readers should refer to the description of map units for a complete description of all map units and specific material unit characteristics (Plate 1).

In some cases, contacts between adjacent units are sharp and well defined, elsewhere contacts are gradational, resulting from the low angle nature of individual contacts, as well as the style of the units or terrains. For example, shield terrain (unit st), consists of a thin veil of numerous *in situ* locally sourced deposits associated with individual shields a few km across [*Guest et al.,* 1992; *Hansen,* 2005]; the location of the mapped contact could vary across 10s to 100 kilometers [e.g., *Hansen,* 2005; *Hansen,* 2009; *Hansen & Tharalson,* 2014]. The contacts of basal terrain and overlying units also varies from sharp to gradational. Basal terrain cut by fractures and later locally buried, typically displays sharp contacts marked by fracture truncation. In other cases, lineaments appear in the overlying material, although the lineaments (fractures) do not obviously cut the overlying material. In these cases, the overlying material is interpreted to form a thin layer deposited on a basal unit cut by earlier-formed, now buried fractures. In addition, the amount/character of fracture burial can also be gradational. Given these relations, and the variation of fracture burial—from no burial to complete burial, the mapped contact (viewed in planform), is typically shown as a gradational contact.

#### 4.4.1 Terrain units (or lithodemic units)

The term "terrain" describes a texturally defined region, for example, a region where tectonism imparted a surface with a penetrative deformation that disallows interpretation of the original unit or units [*Wilhelms,* 1990]. Terrain units are examples of lithodemic units [*Hansen & López,* 2018]. Characteristic texture could imply a shared history, such as a terrestrial tectono-thermal history or an event that melds possibly previously unrelated rock units (any combination of igneous, metamorphic, and sedimentary rocks) into gneissic terrain; no unique history is inferred or required prior to the event(s) that melded potentially separate units into the textural terrain (i.e., lithodemic unit). Events prior to terrain formation are unconstrained in time or process unless specifically noted. Three general classes of terrain units occur across AMA: ribbon-tessera terrain and related material, shield terrain and associate basal-shield terrain transition, and fracture zone terrain.

*Ribbon-tessera terrain and related material* are delineated within AMA. Each of these units includes the moniker ribbon-tessera terrain modified by the name of the host tessera region (e.g., Ovda or Thetis ribbon tessera terrain, rtO and rtT, respectively), or a descriptive term such as inlier of ribbon tessera (rti). These later terms are used for relatively small exposures or occurrences in unnamed locations.  Ribbon-tessera terrain units are differentiated using regional location and structural trends. It is unclear how the various units are related to one another temporally because interpretations of crosscutting relations are not unique. We also define units associated with ribbon-tessera terrain: intratessera basin material unit itb [see *Banks & Hansen,* 2000*; Hansen,* 2006]. Similar to unit rt, unit itb is further divided based on location and/or tessera terrain host (e.g., itbO, itbT, itbN).

Ribbon-tessera terrain typically displays orthogonal ribbon-fold tessera fabric [*Hansen & Willis,* 1998*; Hansen,* 2006]. Fold wavelengths range from less than one kilometer—essentially to the effective resolution [*Zimbelman,* 2001] of SAR for folds, to tens of kilometers. Ribbon wavelengths generally range from 2 to 5 km, although wavelengths locally occur to the effective resolution of SAR. Intratessera basin material (unit itb) commonly fills intermediate- to long-wavelength fold troughs. Unit itb also locally fills short-wavelength fold troughs, although such deposits are not delineated here due to scale limitations. See *Hansen* [2006] for detailed geologic maps of ribbon-tessera terrain within Ovda Regio; map relations, emergent temporal relations and geological implications derived from that study are applicable to AMA ribbon-tessera terrain.

Orthogonal ribbon-fold fabrics are the most common tessera fabric across AMA as they are for ribbon-tessera terrain globally [*Hansen & Willis,* 1996*,* 1998*; Hansen & López*, 2010]. S-C ribbon-tessera fabrics occur locally. S-C tessera fabric, first described by *Hansen* [*1992*] and later by *Hansen & Willis* [1996], shows a fabric asymmetry comprised of ductile and brittle structures that together define coherent pictures of noncoaxial strain reflecting relative shear displacement, similar to S-C fabrics within terrestrial ductile shear zones [e.g., *Berthé et al.,* 1979].

Both orthogonal ribbon-fold fabric and the S-C tessera fabric occur within ribbon-tessera terrain preserved within crustal plateaus. S-C tessera fabric represents ductile shear zones in central Ovda Regio, along its southern margin and along its eastern margin with Thetis Regio [*Ghail,* 2002*; Tuckwell & Ghail,* 2003*; Kumar,* 2005*; Romeo et al.,* 2005]. Orthogonal ribbon-fold fabric and S-C tessera fabric could represent the deformation of the surface scum of huge crystallizing lava ponds [*Hansen, 2006*]. Hawaii's lava lakes show dynamic flow fabrics of extension, convergence, and strike-slip translation similar to terrestrial plate tectonic kinematic patterns, presumably driven by convection within the lava lake. Similarly, Ovda's ancient lava pond surface could record layer-parallel shortening and orthogonal extension (forming orthogonal ribbon-fold tessera fabric), along with localized horizontal shear distributed over several hundreds of kilometers (forming S-C tessera fabric) [*Hansen*, 2006].

*Local basal terrains*, or local basal terrain undivided, herein, is a term used to describe surfaces that lie within locally low stratigraphic positions relative to adjacent map units. These surfaces share suite(s) of tectonic structures that formed prior to the emplacement of adjacent material; there is no implication of shared histories between spatially separated basal terrain units across the AMA. However, it is possible that isolated (yet adjacent) basal terrain exposures may represent temporally equivalent unconformity bound packages (i.e., allostratigrphic surfaces/packages).

*Shield terrain* consists of thousands of individual shields and coalesced flow material, referred to as "shield paint" for its apparent low viscosity during emplacement [*Hansen,* 2005*;* see also *Aubele,* 1996]. Shield paint could be formed from any combination of lava flows, air-fall deposits, or pyroclastic flows [*Guest et al.,* 1992*; Crumpler et al.,* 1997]. Shield terrain contains material with an interpreted shared emplacement mechanism (represented by primary structures), which differs from ribbon-tessera terrain whose elements include an interpreted shared deformation history (represented by secondary structures).

Within the AMA, shield terrain material (unit st) is marked by distributed small (~1–10 km in diameter) shield edifices and associated local deposits. Unit st generally hosts a high density of shields; although individual shields are not delineated due to map scale, and shield density is difficult to robustly delineate [*Hansen,* 2005]. The contact of unit st with adjacent units can be sharp or gradational over 10's to 100's of km as noted above. Unit st almost certainly represents a time-transgressive unit across the AMA [e.g., *Addington,* 2001*; Stofan et al.,* 2005], comprised of thousands of local point-source eruptions that may represent point-source, *in situ*, partial melting [*Hansen,* 2005]. This unit name is descriptive and does not imply temporal equivalence.

Basal-shield transitional terrain (unit bst, southeastern AMA), marks a transition between basal terrain and stratigraphically higher shield paint, delineated due to its transitional character in which both the basal terrain and shield deposits are apparent.

Three lithodemic terrain units occur within the region including and encompassed by Artemis Chasma: Artemis trough terrain (tAt) and Artemis tectonic terrains, tAa and tAb. The latter correlate with units by the same names originally described by Bannister & Hansen [*2010*]. Artemis trough terrain—defined by trough parallel lineaments that variably correspond to normal faults, thrust faults and folds crest/troughs—formed during the development of the Artemis trough [*Bannister & Hansen,* 2010].

#### 4.4.2 Mantling material

A mantling material occurs at high elevation locally blanketing ribbon-tessera terrain of southern Ovda Regio. The mantling material occurs as both radar-bright and -dark regions (shown as stipple pattern on host rtO) interpreted as elevation limited metal frost deposits [*Bleamaster & Hansen,* 2005a], representing tellurium 'snow' [*Pettengill et al.,* 1996; *Kerr,* 1996] or heavy metal precipitates of lead and bismuth [*Schaefer & Fegley,* 2004].

#### 4.4.3 Material units

Material units are geologic materials interpreted to represent emplacement or deposition as a coherent body or entity. Material units can be (1) lithostratigraphic units, which obey the Law of Superposition and mark distinct temporal units (e.g., individual volcanic flows); (2) bounded packages of similar emplacement character but formed at different times (e.g., impact crater ejecta), and thus are not time equivalent; or (3) allostratigraphic, or unconformity-bounded, composite units that cannot be robustly divided given available data and/or map scale [*Hansen & López*, 2018].

*Artemis-related material* encompasses a suite of Artemis interior units fAa, fAb, and fAc associated with tectonomagmatic features [*Bannister & Hansen,* 2010] and Artemis flows undivided, unit Afu. Unit Afu is the most widely distributed material related to the Artemis superstructure [*Hansen & Olive,* 2010]. Unit fAu, characterized by low-backscatter and low RSM slope extends well beyond Artemis Chasma, covering much of southern AMA; unit fAu both covers, and is locally cut by, the ~12,000 km diameter suite of Artemis-radial lineaments [*Hansen & Olive,* 2010], interpreted as source structures for unit fAu material. Unit fAu is cut by the ~13,000 km diameter suite of wrinkle ridges concentric to Artemis trough, which record late collapse of the Artemis superplume [*Hansen & Olive,* 2010].

*Undivided flow material* includes three units: unit fchu (chasmata flow material undivided), unit flu (localized lowland flows undivided), and unit fu (flows undivided). Unit fchu is spatially associated with the regional fracture zone/corona-chasma system that cuts AMA from east to west, occurring generally north of Artemis Chasma. Unit fchu shares a gradational contact with unit fAu; the two units are delineated on the basis of spatial location, with unit fchu occurring within the fracture zone regions. This unit likely includes a host of materials including material emplaced prior to fracture zone development (which could include unit Afu), and local flows contemporaneous with and genetically associated with fracture zone evolution. Units flu and fu are characterized by generally low radar backscatter, low-RMS slope; unit flu occurs in local topographic lows, whereas unit fu need not be topographically localized. None of these units represent coherent time-specific lithostratigraphic units across AMA.

*Tholus, mons, and fracture fed flow* material are, as the name implies, material units variably associated with tholus, mons, or fractures. Each unit show spatially limited extent consistent with a genetic relationship to individual geomorphic features, and the unit name includes the associated feature (e.g., fG, Gauri Mons flow material; fMh, Mahuea Tholus flow material; fH Henwen Fluctus flow material; fLS, Lo Shen Valles flow material). Specific characteristics are noted in map unit descriptions. In contrast to the other units, unit ff, flows from fractures, is a descriptive unit—flows fed from fractures—it is not meant as a temporally correlative unit. Unit ff material variably occurs as bright to dark on SAR images with lobate to digitate flow fronts, channels, levees, breached levees, and well-preserved features indicative of flow direction.

*Corona-related material and chasmata flow material* comprise the largest number of units. Most are corona-related deposits—the majority of which are spatially associated with individual coronae as indicated by the unit name (e.g., fAra, Aramaiti Corona flow a; fCe, Ceres Corona flow material). Individual characteristics are noted in map unit descriptions (Plate 1). Some coronae have more than one unit delineated; typically, such units are noted with a, b, c, rather than 1, 2, 3. Numerical notation infers temporal constraints, which are typically lacking. In some cases, specific corona flows define more proximal, or more distal facies. Location does not carry robust temporal implications, given that distal and proximal facies could develop at different times possibly related to corona evolution stages [e.g., *Smrekar & Stofan*, 1997, 1999*; McGovern et al.,* 2015]. We cannot independently and robustly determine the relative age of flows given the currently available data. It is possible that flow facies formed time-transgressively over the evolution of the host corona. We also map two units not defined as coronae-specific, but rather that occur within many coronae—unit cc (corona center) and unit cif (corona interior flow material). Both units occur in the center of coronae and each likely formed relatively late during the formation of their host corona. Unit cc is typically radar-dark and may include many small shields; unit cif typically displays digitate to lobate flow structures. Both units are descriptive with no temporal equivalence implications across the AMA.

Material unit fcha (chasmata flow material a) is moderately bright on SAR images and with digitate flow fronts, and local shield-type edifices; this unit is only rarely cut by secondary structures, and is interpreted as comprised of relatively late, generally confined, flows associated with formation of the Kuanja, Ralk-umgu, and Vir-ava Chasmata system.

### 4.4.4 Crater material

The AMA includes three regional distributed crater material units (units cfl, cf, and cu). These units are time-transgressive having formed in association with individual impact craters and not as lithostratigraphic packages. Unit cfl represents low viscosity, gently emplaced material that locally flood the lowest portions of individual impact crater basins following, and unrelated to, impact crater formation [*Izenberg et al.,* 1994; *Herrick & Sharpton* 2000; *Herrick & Rumpf,* 2011]. Unit cf represents impact melt or fluidized ejecta created by meteorite impact associated with the formation of individual impact craters; exposures are typically small. Unit cu, crater material undivided includes radar bright material associated with impact crater formation including crater ejecta and interior deposits.

Units cfM (Markham crater flow material) and cfAd (Addams crater flow material) represent flows formed as a result of bolide impact associated with Markham and Addams craters, respectively. The flows could be impact related, fluidized ejecta, or represent tapping of pre-existing subsurface magma.

## 4.5 Tectonic structural suites

Tectonic (or secondary) structures form after the emplacement of a host material unit. Suites of tectonic structures define local and regional patterns that collectively record a shared deformation history and provide clues to operative tectonic or tectonomagmatic processes. We use the terms local and regional tectonic suites to delineate different scales of tectonic suites.

### 4.5.1 Local tectonic suites

Local structural suites are spatially or geometrically associated with specific features such as coronae or montes. Their timing likely corresponds to the formation, or stages of formation, of the features with which they are associated, recognizing that feature development could have been time-transgressive. These suites can be comprised of radial fractures (dikes at depth, graben, faults), or concentric fractures, or both. Locally folds suites form concentric to some coronae. In cases where concentric folds occur, folds generally are developed in north-trending portions of an overall corona-centric pattern, whereas concentric fractures develop along the east-trending portions of the same overall corona-centric pattern (e.g., Copia Corona; 42.5 S/75.5 E). Within the AMA, coronae with radial fracture suites dominate; although some coronae are marked by prominent suites of concentric structures and generally lack radial fracture suites (e.g., Ohogetsu, Aramaiti, Cailleach, and Khotun Coronae). In some cases, local fractures change trend away from the host structure and become parallel to regional trends, reflecting changes in local to regional stress fields [*Ernst et al.,* 1995; *López et al.,* 2008]. For example, fractures concentric to Nishtigri Corona (24.5 S/72 E), which are developed best along ENE-trends, lose their concentric geometry away from Nishtigri Corona becoming parallel to the trend of regional fracture zone structures. In the case of Makh Corona (48.7 S/ 85 E), radial fractures become parallel to regional fracture zone fracture (NE-trending). Chasmata and/or troughs also occur spatially associated with many coronae, likely genetically related to their host features. Chasmata and ridges are developed concentric to individual coronae, as well as aligned between coronae; in such cases these features broadly define corona-chasma chains. We infer no collective temporal equivalence of local radial and concentric suites across the AMA. (Note: local suites of radial or concentric structures are associated with individual features, but collectively these tectonic suites can be part of fracture zones and corona-chasma chains).

4.5.2 Regional tectonic suites

Regional structural suites describe coherent patterns across larger areas, lacking specific spatial or geometric correlation with individual features. We identify two suites of regional tectonic structures clearly associated with large-scale features; one group of structural suites is related to the formation of the Artemis superplume [*Hansen & Olive,* 2010], and the other group is related to the fracture zones and corona-chasma chains. We also delineate three suites of orientation-defined fractures: NW-trending fractures transect southwestern AMA; generally N-trending fractures are developed in south-central and southeast AMA. Each of these suites occur within large, but limited areas, and are not obviously associated with other fractures suites.

4.5.2.1 Artemis-related structural suites

Two distinct suites of structures define the Artemis superstructure: fractures that describe a pattern radial to Artemis Chasma with an overall radial fracture diameter on the order of 12,000 km, and wrinkle ridges that define a huge regionally-developed suite concentric to Artemis Chasma, with an overall suite diameter on the order of 13,000 km [*Hansen & Olive,* 2010; *Hansen & López*, 2018; see also *Hansen,* 2002; *Bannister & Hansen,* 2010]. The fracture suite, here referred to as Artemis-radial fractures, broadly pre-dated formation of the wrinkle-ridge suite, referred to here as Artemis-concentric wrinkle ridges.

*Artemis-radial fractures* define a suite of fractures radial to Artemis Chasma cuts unit in both the AMA and the NMA (I-2467) (Figure 1). The nature of this suite (broadly defined to include fractures, dikes, lineaments, pit chains, stoping troughs) is particularly well-preserved in southeastern AMA (domain 4) because that this region is relatively free of other features. Individual fractures can extend several hundred kilometers. On the map fractures locally may appear to end where the fracture package intersects with local basal units or with ribbon-tessera units, due to difficulty in tracing the fractures across these basal terrains. Such abrupt truncation of the fractures is likely an artifact of mapping. Packages of fractures also locally ‘end’ abruptly where the fractures are buried by younger deposits; elsewhere the character of the fractures become muted, due to shallow burial. Collectively the fracture suite defines a coherent pattern of radial fractures, with the locus sharing the same center as the locus of Artemis Chasma. Regional patterns of fully exposed fractures delineate exposures of pre-fracture basal terrain. Shallowly buried fractures mark transitional basal terrain and overlying thin cover material. Regions where fractures end abruptly along trend indicate areas of relatively thick cover resulting in essentially complete burial of the fractured basal terrain. Fractures trend perpendicular to local wrinkle ridges, which collectively define the Artemis-concentric wrinkle ridge suite. Artemis-radial fractures are interpreted as having served as feeders for Artemis-related flows (e.g., unit Afu), which were, in turn, deformed by Artemis-concentric wrinkle ridges along with numerous other pre-existing flows.

Some Artemis-radial fractures can be difficult to distinguish from fractures within the fracture zone domain. In general, where fracture zones parallel the trend of the Artemis-radial fracture suite, we designate the fractures as Artemis-radial fractures. Fracture zones mark regions of more focused zones of fracture development, referred to herein as spokes, given their overall radial geometry with respect to Artemis Chasma. In cases where the fracture zones are not parallel to the Artemis-radial fractures it is clear that the fractures are instead fracture zone fractures. This may be a moot point in that the fracture zones radial to Artemis may be broadly related to the Artemis superplume, and as such, these more defined 'spokes' of radial deformation, may simply mark a different expression of the Artemis-radial fracture suite. The fracture zone spokes may also have formed after Artemis-radial fractures, or out-lasted the evolution of the Artemis-radial fracture suite. Robust detailed temporal relations are unconstrained.

*Artemis-concentric wrinkle ridges* define a suite of wrinkle ridges concentric to Artemis Chasma. Wrinkle ridges define low sinuous spines spaced a few kilometers apart and up to a few hundred kilometers long, recording low (<2%) layer contractional strain. Wrinkle ridges are developed across much of AMA, with the most striking suite concentric to Artemis Chasma. This wrinkle ridge suite, with a diameter on the order of 13,000 km (Figure 1), affects most of AMA and NMA. Like the fractures, wrinkle ridges occur at a range of spacing, down to small-scale wrinkle ridges too closely spaced to show on the AMA geologic map.

Wrinkle ridges are notably absent within exposures of ribbon-tessera terrain, even in high-resolution images, although wrinkle ridges occur locally in intratessera basin material (unit itb). Wrinkle ridges occur right up to the contact between ribbon-tessera terrain and surrounding units, such as Afu and st. These relations indicate that ribbon-tessera terrain is not rheologically amenable to wrinkle ridge formation (that is, it lacks a thin deformable layer), whereas the thin shield-terrain veneer or unit Afu can readily form wrinkle ridges. Similarly, some exposures of local basal terrain (unit blu) are cut by Artemis-radial fractures but lack wrinkle ridges; thus, these units are not rheologically amenable to wrinkle ridge formation.

Wrinkle ridges are also absent, or mostly absent, along the fracture zone 'spokes' broadly radial to Artemis. The most striking example of this is the Diana-Dali arm, where wrinkle ridges end abruptly to the south of Atahensik Corona in northern Zhibek and Nsomeka Planitiae, and in southern Rusalka Planitia north of Miralaidji Corona. Wrinkle ridges are also mostly absent within the fracture zones in southwestern and western AMA. It is unclear whether this absence results because the fracture zones dominantly post-date wrinkle ridge suite development, or if these spokes, which typically lie at slightly higher elevations than the surrounding regions, are typically not buried by thin flows, and as such, not rheologically amenable to the formation of wrinkle ridges. Both explanations are possible. Locally flows associated with coronae in the Diana-Dali region appear to both predate (deformed by) and post-date (bury) Artemis-concentric wrinkle ridges. Corona-flows located at the off-axis distal edges of the fracture zones (e.g. southernmost Atahensik and Flidais Coronae and northernmost Sith Corona).

Artemis-concentric wrinkle ridges also deform many flows associated with individual coronae or montes, particularly in western and southwestern AMA (e.g., Marzyana, Khotun, Cailleach, Makh and Copia Coronae and Kunapipi Mons). These relations provide clear evidence that the deformed corona/mons-related flows predated formation of this huge wrinkle-ridge suite. Some corona/mons-associated flows do not host wrinkle ridges. These relations might result because the flows formed after the Artemis-concentric wrinkle-ridge forming event, or these flows were rheologically not amenable to wrinkle ridge formation, possibly due to flow thickness, internal flow structure, or composition. For example, most flows associated with

Kunapipi Mons (unit fKu) do not show clear development of wrinkle ridges, however, wrinkle ridges clearly cut the distal, and presumably thinner, edges of these flows. More proximal flows might be too thick to form wrinkle-ridges, or, alternatively, portions of the Kunapipi flows could post-date formation of the Artemis-concentric wrinkle ridge suite. In any case, map relations within AMA highlight the challenge of robustly determining temporal relations between flows and regional deformation 'events', such as the formation of wrinkle ridges. Clearly the evolution and construction of a volcanic feature like Kunapipi Mons, and the formation of a regional suite of wrinkle ridges, with a diameter of 13,000 km, are both likely to be time-transgressive, and plausibly each could last tens to hundreds of millions of years.

Wrinkle ridges formed by inversion occur within Rusalka Planitia [*DeShon et al., 2000*]. Orthogonal patterns of wrinkle ridges in Rusalka Planitia east of Nuahine Tessera are the result of earlier formed Artemis-radial fractures, which were later buried; following burial the filled fractures were closed resulting in inversion of the fracture fill material and the formation of straight (as opposed to sinuous) wrinkle ridges along strike with parts of the fractures that were not buried. Fracture closure and resulting inversion of the fill likely occurred synchronous with the formation of Artemis-concentric wrinkle ridges, which, together with the inversion-formed wrinkle ridges define a suite of orthogonal wrinkle ridges. But it is also possible that the inversion event occurred after (or even before) concentric wrinkle ridge formation, although synchronous formation would be geologically reasonable.

#### 4.5.2.2 Fracture zone structural suites

Fracture zone structural suites collectively define domain 3. Lineaments within the fracture zones represent a range of planar structures that are manifested as lineaments in map view (e.g., fractures, dikes, pit chains, troughs, scarps, stoping troughs, hybrid structures). Individual zones display different mixes of structural elements, and some include coronae. For example, The Diana-Dali corona-chasma chain hosts numerous scarps and troughs (chasmata) that either parallel the zone or are curvilinear associated with individual large coronae. In contrast the fracture zone at about 7 o'clock with respect to Artemis Chasma is characterized by extremely closely-spaced lineaments, lacking ridges, troughs, or coronae. The Vir-ava/Ralk-umgu chasmata zone displays extremely closely-space lineaments marked by narrow topographic troughs including pit chains, stoping troughs, or hybrid lineament, and hosts a single corona, Inari Corona. Structural elements within individual fracture zones are likely genetically related, and the zones might also be collectively genetically related.

We delineate a new type of structural element, here referred to as, hybrid lineaments, within the fracture zones. The need for this delineation arose given that individual lineaments change along trend, and the effective resolution of the SAR data does not always allow for robust identification of the nature of the lineament. Hybrid lineaments, or hybrid structures, are the epitome of tectonovolcanic features; they can change along trend from zones of *en echelon* fractures, fractures, pit-chains, graben, leaky dikes, stoping troughs, and channels. Widths range from <1 km to >5 km; lengths can exceed several 100 km. Lineament spacing ranges from 10's of kilometers to lineament overlapping, intersecting, or coalescing. Hybrid structures can form along trend with other lineaments or result from reactivation of parts of different lineament suites, resulting in a stepped surface pattern, locally forming channels. Hybrid lineaments likely occur throughout much of the fracture zone domain; many lineaments mapped as fractures could be hybrid lineaments. Although hybrid structures locally source flows, evidence of this is quite rare. More noteworthy is a striking lack of evidence for associated surface flows. The major role of hybrid lineaments appears to be the transfer of material from the surface to depth (rather than from depth to the surface) as evidenced by widespread development of pit-chains, and topographic troughs and the lack of evidence for local burial [*Hansen & López,* 2014b]. If these structures transferred a significant amount of material from depth to the surface then we would expect to observe numerous examples of flooding/filling of troughs by surface flows, burial of troughs, and abrupt truncation of trough lineaments due to burial. However, few such examples exist. If surface eruption was a common occurrence, we would expect that earlier formed structures would be buried and effectively erased from the surface record. However, evidence for a rich history is preserved, consistent with transfer of material to the subsurface. Hybrid structures both predate and postdate various flows, providing evidence of their dynamic role in the extensive volcano-magmatic province of southern Aphrodite Terra. The subsurface nature of these structure remains unknown (i.e. fault, dike, or stoping-dominated), however the incredibly close spacing of the lineaments, the topographic character of steep-sided flat based troughs, the lack of associated surface flows, and the development over 100's of km of wide and 1000's of km long collectively indicate that these structures are unlikely to be associated with crustal extension (e.g, dikes and/or normal faults). We favor a stoping interpretation [*Hansen & López,* 2014a, 2014b, 2018; *Tovar et al.,* 2015]. Discussion of this topic is outside the limits of the map description text.

### 4.6 Impact features

AMA hosts 124 impact craters, ranging from 2.7 to 92.2 km diameter (Table 1). Table 1 lists crater location, diameter, elevation, crater density, host material units, etc. Most of the craters are included in existing Venus crater data bases [e.g., *Schaber et al.,* 1992; *Herrick et al.,* 1997]. Each impact crater displays an interior, rim and ejecta deposit; about 33% also have parabolic or halo deposits [e.g., *Izenberg et al.,* 1994]. Impact craters with rim diameter <14 km generally lack central peaks. Impact crater deposits are shown as unit cu, crater material undivided, representing interior and ejecta deposits associated with local bolide impact. Each impact crater formed during a unique spatial and temporally localized event; therefore, composite unit cu is diachronous across the map area. Over 40% of the craters display radar-smooth interiors, unit cf, interpreted as interior flood deposits that formed after, and unrelated to, initial impact crater formation [*Izenberg et al.,* 1994*; Phillips & Izenberg,* 1995*; Herrick & Sharpton,* 2000; *Herrick & Rumpf,* 2011]. For small diameter craters, unit cf is not shown; for very small diameter craters the presence of absence of interior fill cannot be confirmed. Crater haloes are shown as a stippled pattern.

None of AMA's craters show obvious signs of embayment by flows that breach an individual crater rim; however, this relation does not require that crater formation is the youngest local geologic event. Detailed mapping of Venus impact craters using high-resolution digital elevation models indicates that dark-floored craters with diameter >20 km have an average rim-floor depth of 290 m and rim height (measured from rim to the adjacent surroundings) of 240 m, less than bright-floored craters, indicating significant post-crater volcanic modification of radar-dark floored craters [*Herrick & Sharpton,* 2000; *Herrick & Rumpf,* 2011]. Thus, dark-floored craters likely predate, rather than post-date, the emplacement of at least some of the adjacent units (see figure 3 of *Hansen,* 2000, for a possible mechanism). Geologic mapping of individual craters using high-resolution DEMs [e.g., *Herrick & Rumpf,* 2011] has not been employed in the construction of the AMA.

Temporal relations between craters and tectonic events can be difficult to robustly constrain. If a crater lies between structural elements that comprise the local tectonic suite, such as wrinkle ridges or spaced fractures, the relative timing of crater formation and tectonic activity cannot be determined [*Hansen,* 2000]. Evidence for crater deformation (or lack thereof) is noted in Table 1 in cases where information can be extracted from map relations. At least 22 craters show clear evidence of deformation (and four craters show possible deformation) indicating that at least these craters formed before local tectonic activity ceased. However, an apparent lack of deformation is not a robust positive test for crater formation after local tectonic activity given the spaced nature of tectonic deformation fabrics and the point location of individual craters (see figure 3 of *Hansen*, 2000). In addition, craters with diameter ≤7 km are generally too small to be able to robustly determine if the craters are deformed; 25 craters within AMA (20%) have a diameter ≤7 km, and therefore cannot be used to evaluate the relative timing of tectonic activity. At least 22% (possibly >26%) of the AMA's craters with diameter >7 km are deformed. This observation is notable given that the AMA lies fully outside the Beta-Alta-Themis (BAT) region, which encompasses the area of Venus marked by the lowest crater density and highest percentage of craters obviously modified by tectonic or volcanic activity [e.g., *Phillips & Izenberg,* 1995; *Herrick & Sharpton,* 2000; *Hansen & Young,* 2007].

Specific geological events occurred *after* the formation of some impact craters, as indicated by cross-cutting relations (Table 1). Craters Abigail, Chiyojo, Gilmore, Huang Daopo, Khelifa, Shushan and Yokhtik appear to be cut by Artemis-radial fractures and/or Artemis-concentric wrinkle ridges; thus, these craters formed prior to these the cessation of the Artemis superplume [e.g. *Hansen & Olive,* 2010]. Craters Agrippina and Xiao Hong might also be cut by Artemis superstructure-related fractures and/or wrinkle ridges, and therefore could also have predated cessation of the Artemis superplume. In addition, the following craters appear to be cut by fracture-zone or coronae-chain structures, and therefore they were likely emplaced broadly prior to (or during) fracture zone terrain evolution: Austen, Langtry, Maltby, Pavlinka, Teura, Winnemucca, Whitney, and Yonge. Langtry Crater displays a flooded interior, which is cut by fracture zone structures; therefore, emplacement of the interior crater fill (which formed after the impact crater itself) occurred prior to fracture zone evolution, or at least prior to the end of fracture zone evolution. Austen crater is cut by fractures related to Atahensik Corona, thus predating final formation of Atahensik. Craters Yonge, Whitney, Maltby, Winnemucca, and Pavlinka predate adjacent fracture zone structures and or corona/chasma zones. In contrast, O'Connor, Halle, Martinez and Warren Craters both cover and are cut by fracture zone/corona/chasma structures, therefore these impact craters likely formed at some point during the time-trangressive evolution of these tectonomagmatic zones. Twelve percent of craters large enough to record geologic relations pre-date, or formed synchronously with, fracture zone structures and/or coronae. This observation indicates the relative youth of the fracture zone domain and is consistent with the possibility that this zone remains geologically active. A nearly equal number of craters (11 %) cross-cut local fracture zone structures, an observation—coupled with the previous observation—consistent with a relatively long geological history of the fracture zone domain, broadly speaking.

Twenty-two craters locally cover or bury Artemis-related structures or fracture zone structures, indicating that these craters formed after the waning of these events. Although many of these craters have radar-rough (bright) interiors and halo deposits, consistent with relatively young ages [e.g., *Izenberg et al.,* 1994], at least ten display filled interior regions. These craters record a history of early Artemis-structure formation, followed by impact crater formation, following in turn by interior flooding of these individual craters.

Markham Crater and Addams Crater in the northeast and southwest AMA, respectively, display impressive outflow deposits. Both formed on regions marked by suites of concentric fractures on the flanks of coronae—Markham on the eastern flank of Seia Corona, Addams on the eastern flank of Triglava Corona. Both impact craters display radar smooth interiors, and both have possible haloes deposits that 'mute' adjacent wrinkle ridge structures; and in both cases, associated outflow deposits likely postdate formation of Artemis-concentric wrinkle ridges. Both impact craters also display butterfly ejecta deposits indicative of oblique impact [e.g., *Schultz,* 1992]; Markham resulted from impact from the southwest, whereas Addams Crater formed due to impact from the northwest. Both craters apparently formed after, or possibly in the late stages of, the formation of Artemis concentric wrinkle ridges, and hence after, or late during, the waning stages of the Artemis superplume. Both impact craters likely tapped into subsurface magma chambers associated with their respective coronae-related structures. Given the location of these impact craters on the flanks of coronae, and their associated outflow material, it is likely that their radar smooth interiors also relate to their respective locations relative to their host coronae.

The impact crater data and observations, independently and taken together with the observation that >40% of AMA craters show interior flooding, indicate that a significant number of AMA impact craters experienced notable geological events (i.e., interior fill emplacement) after their formation. These results are consistent with the results of analysis of high-resolution digital elevation model data of Venus impact craters, that reveal significant geologic modification of numerous impact craters [*Herrick & Rumpf,* 2011]. These results are contrary to initial surveys of the Venus crater population conducted using NASA Magellan data, used to suggest that only a few percent of Venus craters were deformed or embayed by volcanic material [*Schaber et al.,* 1992; *Phillips et al.,* 1992; *Herrick & Phillips,* 1994; *Strom et al.,* 1994; *Collins et al.,* 1999]. These new data, along with the *Herrick and Rumpf* [2011] study are difficult to accommodate within the context of catastrophic resurfacing models, or with any resurfacing models that require the vast majority of Venus impact craters to mark the top of the stratigraphic column [e.g., *Turcotte,* 1993; *Strom et al.,* 1994; *Solomatov & Moresi,* 1996; *Turcotte et al.,* 1999; *Basilevsky & Head,* 1998, 2000, 2002a, 2002b, 2006; *Basilevsky et al*., 1997, 1999; *Reese et al.,* 2007; *Romeo & Turcotte*, 2010; *Romeo,* 2013; *Ivanov & Head,* 2015a, 2015b; *Kreslavsky et al.,* 2015]. Thus, impact crater relations within the AMA cast doubt on the conclusions of these studies. In addition to the data described herein, a growing number of studies similarly indicate that hypotheses of catastrophic resurfacing, or hypotheses that call for late formation of most impact craters on Venus are inconsistent with geologic relations and/or modeling [e.g., *Guest & Stofan,* 1999; *Herrick & Sharpton,* 2000; *Hansen & Young,* 2007; *Hansen & López,* 2010; *Hansen & Olive,* 2010; *Herrick & Rumpf,* 2011; *Bjonnes et al.,* 2012; *O'Rourke & Jun Korenaga,* 2014, 2015], and collectively challenge assumptions that the Venus crater population represents a limited, young, geologic time period.

## 5 Geologic History

The geologic history that emerges from the AMA is, broadly speaking, relatively simple, although a rich regional history emerges (Figure 3). An ancient era marked by formation of ribbon-tessera terrain and crustal plateaus (and perhaps basal terrain), predated time-transgressive evolution of the Artemis superstructure; Artemis superstructure formation was broadly followed by, more spatially focused, evolution of the fracture zone domain marked by fracture zones and corona-chasma chains. Fracture zone and corona-chasma chain evolution seems to have broadly outlasted Artemis superstructure evolution.

The broad regional history parallels the three major geological eras identified through structural-element mapping across the combined Niobe and Aphrodite map areas [*Hansen & López,* 2018]. The three eras—the ancient era, the Artemis Superstructure era and the fracture zone complex era—are discussed briefly below. Basal ribbon-tessera terrain units formed early across AMA and in a time-transgressive manner comprising the hallmark of the ancient era. Not all ribbon-tessera formed in one event, although ribbon-tessera terrain likely formed within an ancient geological era marked by specific geologic conditions, most notably an era marked by thin global lithosphere [*Phillips & Hansen,* 1994, 1998*; Bindschadler,* 1995; *Hansen et al.,* 2000; *Hansen,* 2006; *Hansen & López,* 2018]. Composite yet local basal terrain (unit blu), which might mark areas between regions of ribbon-tessera terrain, could have formed before, during, or after the era during which ribbon-tessera terrain formed. Exposures of unit blu mark the lowest (local) exposed surfaces in each specific area of exposure; however, no data required that isolated exposures are geologically or temporally correlative. The exposures of unit blu are commonly cut by lineaments—mostly fractures, broadly defined. We do not recognize coherent patterns in these lineaments between exposures, unlike ribbon-tessera terrain, in which the structural fabrics are define by a unique and distinctive assemble of structural elements [e.g., *Hansen & López,* 2010].

Artemis, the hallmark of the Artemis Superstructure era, includes an interior high, a deep (~2 km) narrow (50–150 km) 2100-km-diameter trough (Artemis Chasma), 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 accompanied radial fracturing. (2) Fractures (subsurface dikes) propagated laterally, driven by magma buffering, producing dikes with widths and sizes independent of chamber size [*Parfitt & Head,* 1993; *Grosfils & Head,* 1994; *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 (unit Afu), resulting in local burial of some radial fractures. (4) It is likely that an extensive region of the surface was uplifted as a result of superplume structure evolution. (5) Wrinkle ridges deformed the cover deposits (driven by coupling of convective mantle or plume flow to the lithosphere [e.g., *Phillips,* 1990*; Rosenblatt et al.,* 1994]; and/or due to collapse of the huge regional uplift). (6) Late topographic collapse (and/or loading) resulted in formation of the broad outer trough (the trough might also record mantle flow). (7) Artemis Chasma and its interior region mark the decay of the Artemis superplume into a smaller (but still large) plume-type structure, resulting in regional localization of the Artemis interior and chasma [*Bannister & Hansen*, 2010; *Hansen & Olive,* 2010].

The fracture zones and corona-chasma chains that define radial spokes relative to Artemis Chasma broadly post-date the formation of Artemis-radial fractures, and variably overlap in time with Artemis-concentric wrinkle ridge formation. In western AMA coronae mostly align along the fracture zones spokes, suggestive of a genetic relationship between coronae and fracture zones. We suggest that these features may have formed in a continuum with the Artemis superplume, perhaps forming in the waning stages of the superplume, and at the same time, or soon after, the Artemis plume came into existence. Evolution of the Diana-Dali corona-chasma chain outlasted the formation of Artemis-concentric wrinkle ridge suites as evidence by truncation/interruption of the wrinkle ridge trends across this zone. However, as noted, Artemis-concentric wrinkle ridges, which mark collapse of the Artemis superplume, cut some corona-sourced flows in Rusalka, Zhibek and Nsomeka Planitiae. The picture that emerges is one in which tectonism (deformation), and magmatic activity became spatially more focused with time. Initially the Artemis superplume resulted in uplift of a huge circumferential region coupled with formation of radial fractures with a footprint of at least 12,000 km diameter extending north into the NMA [*Hansen & Olive,* 2010; *Hansen & López,* 2018; *López & Hansen,* 2020]. Locally magma emerged from these radial fractures forming unit Afu. In some regions the radial fractures were reactivated, in some regions the fractures were not covered (similar to regions of ribbon-tessera terrain and local basal exposures which were not buried by these flows), and in some regions, the radial fractures were completely buried by these flows. Formation of the Artemis-concentric wrinkle ridge suite occurred broadly after formation of the Artemis-radial fractures, but wrinkle-ridge formation was outlasted in turn by more localized spokes of fracture-zone development. Some of the fracture zones were dominated by the formation of near-parallel fractures, whereas other zones were dominated by corona-mons formation. Elsewhere coronae, chasmata and fractures developed in concert with one another along these fracture zones (e.g., Diana-Dali). With time, the Artemis superplume decayed to the Artemis plume, and Artemis tectonic and volcanic activity became limited to the evolution of the interior of Artemis and Artemis Chasma [see *Bannister & Hansen,* 2010].

The timing of shield terrain formation, unit st, is probably not the same across the AMA; however robust temporal constraints are not forthcoming. Locally Artemis-radial fractures cut shield terrain material; elsewhere shield terrain appears to cover Artemis-radial fractures. Shield terrain occurs in a broad band south of, and concentric to, Artemis Chasma. One possible mode of the formation of this unit is heating from below by the Artemis superplume, resulting in *in situ* partial melting of the overlying crust and emergence of point-source shield formation. It is possible that there is a spatial association, which might signal a genetic association, between ribbon-tessera terrain and shield terrain, but more focused research is required to evaluate this possibility.

Mahuea Tholus, southwestern AMA, forms a unique volcanic feature given its isolation from other volcanic features and fracture zones. *Moore et al.* [1992] suggested that Mahuea Tholus flows might be highly siliceous based on the texture of its flow surfaces and terminations, and its isolated location and high topography character relative to the adjacent lowlands. Whatever the composition of Mahuea Tholus flows, distal unit fMhb is deformed by Artemis-concentric wrinkle ridges. Thus, Mahuea was at least partially active prior to the latest stages of the Artemis superplume. However, flow emplacement of unit fMha, located in a proximal location, either postdated formation of the Artemis-concentric wrinkle ridge suite, or is rheologically unsuited to host wrinkle ridges.

The youngest regional-scale geological provinces and/or events within the AMA seem to be continued evolution of the Diana-Dali corona-chasma chain, and the Vir-ava/Ralk-umgu chasma zone including Inari Corona. Both zones, which are generally along strike with one another, extend ~2000 km in width and over 6000 km in length, and collectively define a zone marked by extensive tectonomagmatic activity. The Diana-Dali corona-chasma chain extends eastward to volcanic rise Atla Regio, which represents the surface expression of a large contemporary mantle plume [*Smrekar & Phillips,* 1991; *Hansen et al.,* 1997; *Smrekar et al.,* 1997]. Atla Regio displays other tectonomagmatic fracture zones including Ganis Chasma, and the Hecate and Parga chasma-corona chains. Tectonic and magmatic activity along each of these spokes is likely genetically related to Atla Regio, and thus of similarly young age [*Hansen,* 2018]. The Diana-Dali zone is dominated by large coronae, yet this region is also affected by a pervasively developed fracture zone. Coronae within the Diana-Dali zone may have sourced early surface flows (?), or not; but more recent activity appears to have been tectonic in nature, marked by the development of radial and concentric fractures, and fractures parallel to the regional trend of the zone. Fractures (broadly defined) and hybrid structures characterize the Vir-ava/Ralk-umgu chasmata zone; fracture-fed flows are relatively rare, or rarely preserved, occurring mostly along the edges of zones of pervasive fracture development; the region is characterized by pervasively developed fractures broadly parallel to the regional trend of the host zone. As noted, the general lack of young surface flows across the Diana-Dali and Vir-ava/Ralk-umgu chasma zones, is consistent with the development of topographically high and thin lithosphere [*Rosenblatt et al.,* 1994; *McGovern et al.,* 2015].

## 6 Conclusions

We conclude with a summary of a few first-order observations and/or geologic implications that emerge from the AMA geologic map.

1. Coherent patterns across the AMA define broad geologic domains, and broad cross-cutting temporal relationships, illustrating the evolution of this portion of Venus' surface through time. These patterns were initially recognized through structural element mapping [*Hansen & López*, 2018], but the AMA geologic map further highlights these patterns, and adds important constraints and details. The three tectonic domains include, from oldest to youngest: 1) Ancient era ribbon-tessera terrain (including intratessera basin material) in both crustal plateaus and lowland inliers, and locally developed basal terrain. 2) Geologic units and structures associated with the development of the Artemis superstructure, including Artemis-radial fractures and -concentric wrinkle ridge suites, and Artemis-related flows (undivided); the later likely emerged to the surface via radial fractures prior to the formation of the wrinkle-ridge suite, which deforms the flows. Several material units associated with individual coronae or montes are also deformed by the extensive suite of Artemis-concentric wrinkle ridges (but not the Artemis-radial fracture suite). Collectively these relations indicate that flows sourced from localized features were emplaced (at least in part) prior to the final evolution of this regionally-developed Artemis-concentric wrinkle-ridge suite. Thus, the evolution of the coronae and montes overlapped with, but broadly outlasted the evolution of the Artemis superstructure (see below). Emplacement of lows that are not apparently deformed by the Artemis-concentric wrinkle-ridge suite could have post-dated wrinkle-ridge formation; however, such flows could also pre-date wrinkle-ridge formation, given that we must consider the possibility that individual flows, or parts of flows, were simply not rheologically amenable to wrinkle ridge development. 3) Development of the fracture zone terrain, including chains of coronae and chasmata, outlasted the cessation of the Artemis-concentric wrinkle-ridge suite. The fracture-zone terrain—marked by the Diana-Dali arm that extends east to volcanic rise Atla Regio, and fans into several arms to the west, clearly truncates (cross-cuts) the Artemis-concentric wrinkle ridge suite (Figure 3). Shield terrain within AMA (#5 below) formed prior to and/or early during the evolution of the Artemis superstructure given that shield terrain is both cut by, and locally covers, Artemis-radial fractures. The fractures could have been reactivated following shield terrain emplacement. Shield terrain is also generally cut by Artemis-concentric wrinkle ridges,

indicating that shield terrain material was emplaced prior to development of this extensive wrinkle-ridge suite. These coherent regional patterns provide strong support that neither plate tectonic processes, nor 'block processes' marked by large-scale horizontal translations [e.g. *Byrne et al.,* 2018] occurred at any time as recorded in by geologic relations within the AMA.

2. Given that Artemis-concentric wrinkle ridges cut numerous material units, many of which are flows that are clearly associated with individual coronae or mons, the identification of a singular plains unit/flow material characterized by wrinkle ridges is not a valid concept [e.g., *Basilevsky & Head*, 1998, 2000, 2002, 2006; *Ivanov & Head*, 2011, 2013, 2015a, 2015b; *Head*, 2014]. These relations further call into question the global stratigraphy hypothesis given that the postulated 'plains with wrinkle ridges' (and variations on this naming) is not a valid material unit, yet forms a critical center piece of the global stratigraphy hypothesis [e.g., *Basilevsky & Head*, 1998, 2000, 2002, 2006; *Ivanov & Head,* 2011, 2013, 2015a, 2015b; *Head*, 2014]. The concept of a coherent global stratigraphy through space and time is also a center piece to the hypothesis of (global) catastrophic resurfacing [*Bullock et al.,* 1993; *Strom et al.,* 1994; *Nimmo & McKenzie,* 1998; *Head,* 2014; *Ivanov & Head,* 2015b]. Thus, the geologic relations documented within the AMA provide further evidence against the catastrophic resurfacing hypothesis. This evidence against the occurrence of catastrophic resurfacing of Venus should be considered with regard to geodynamic models of Venus that employ catastrophic resurfacing [e.g., *Armann & Tackley,* 2012; *Gillman & Tackley,* 2014; *Moore et al.,* 2017], and mission proposals with the stated goal to understand catastrophic resurfacing of Venus [e.g., *Smrekar et al.,* 2017; *Dyar & Smrekar,* 2018; *Dyar et al.,* 2018].

3. Artemis-radial fractures and Artemis-concentric wrinkle ridges defined regional patterns relative to Artemis Chasma (12,000 km and ~13,000 km diameters, respectively) irrespective of the material units they define. These relations indicate that the wrinkle ridges are genetically related to an extremely large feature and not related to individual flows.

4. The Diana-Dali corona-chasma fracture zone broadly cross cuts the Artemis-radial fractures and -concentric wrinkle ridge suites. These first-order relations provide robust temporal evidence that tectonic evolution of the Diana-Dali corona-chasma fracture zone outlasted 'collapse' of the Artemis superplume.

5. Shield terrain, a unique style of volcanic unit first recognized and described by *Aubele* [1996] in Niobe Planitia and later characterized in detail by *Hansen* [2005], occurs as an extensive lithodemic terrain across the AMA in lowland locations. The evolution of this style of volcanism and the operative processes seem quite unique given the development of this type of terrain across huge regions, and yet the terrain is characterized by a thin surface layer marked by extremely local point-source volcanism. The volcanic and geodynamic significance of unit remains a mystery worth further study.

6. Impact craters clearly formed time-transgressively across the AMA relative to each of the three major geologic eras noted above. Thus, there are is no geologic evidence within the AMA that impact craters formed as the youngest 'event' across the AMA; nor do geologic relations require resurfacing of Venus. In fact, the range of temporal relations of impact craters provides evidence against catastrophic resurfacing hypotheses.

7. The fracture zone domain, the youngest and most spatially-focused region of tectonomagmatic activity, post-dated formation of twelve percent of the impact craters large enough to record relative geologic relations. This observation is consistent with the

possibility that the fracture zone domain could represent on-going geological activity.

In summary, the most first-order observation that emerges from the AMA is the regional coherence of preserved geologic patterns, which provide a variable record of three relatively distinct geologic eras: the ancient era, the Artemis super structure era, and the youngest fracture zone terrain era. The first two eras are also variably recorded within the NMA [*Hansen & López,* 2018]; all three eras can be extrapolated to the global scale, although the Artemis era is not strictly global as the Artemis superstructure covers about 30 percent of the planet surface [*Hansen*, 2018]. Geologic relations captured within the AMA illustrate the spatial and temporal relations of these three eras across time and space as described herein. Future geologic mapping, at a similar scale of the other four *IMap* areas east of the AMA—south and north of the equator (Helen Planitia [*I-2477*] and Guinevere Planitia [*I-2457*], respectively), and west of the AMA—south and north of the equator (Sedna Planitia [*I-2466*] and Lavinia Planitia [*I-2475*], respectively), will add important spatial and temporal information with regard to the evolution of these three geologic eras identified within the AMA. 1:10 M-scale mapping of these other regions, and the two polar 1:10 M cartographic sheets, might also lead to the identification of other geologic eras within the evolution of Earth's sister planet Venus.

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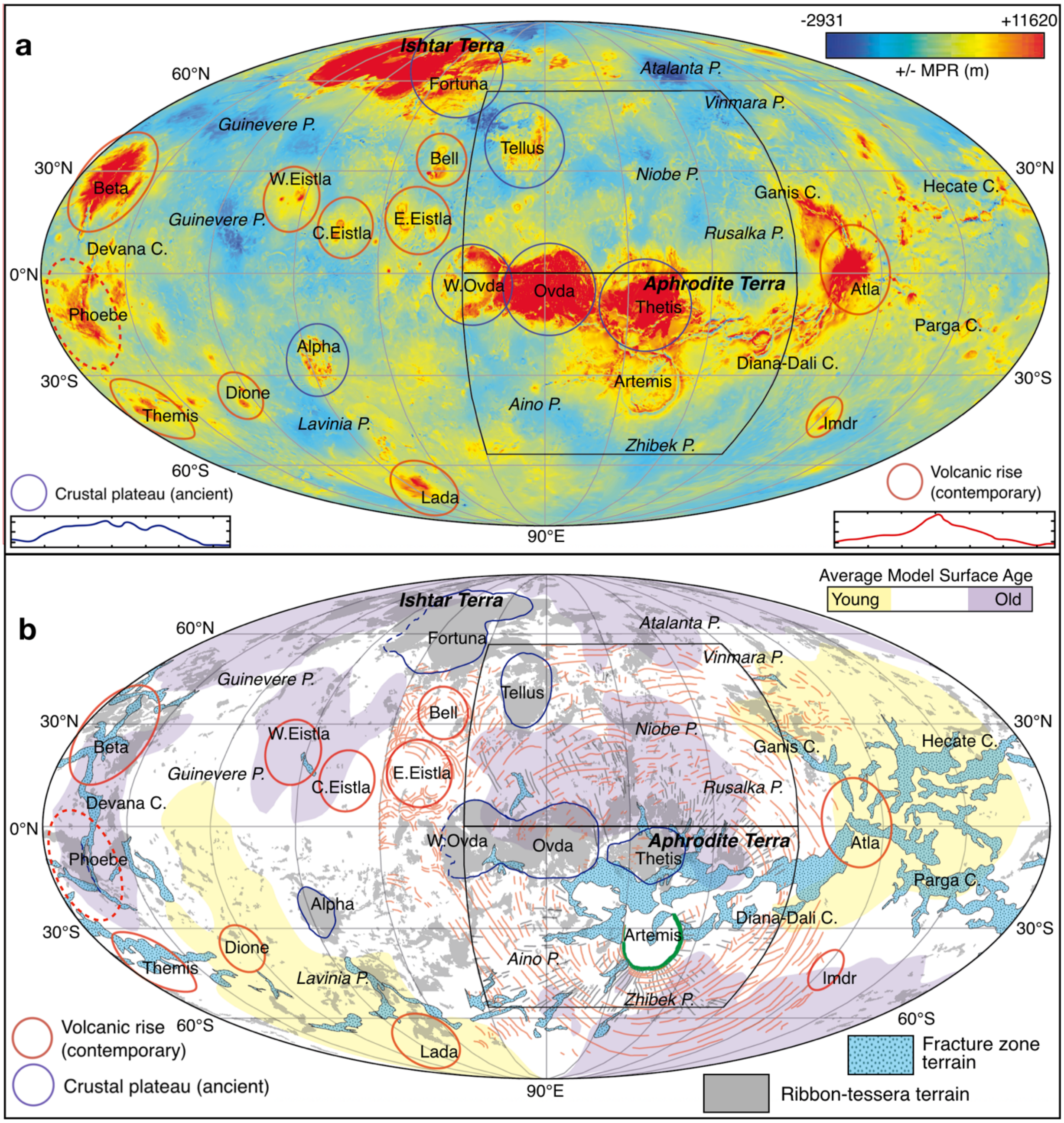


Figure 1. Mollweide projections of Venus; the NMA (north) and AMA (south) are shown as polygons. (a) Altimetry: highlands, red; mesolands, yellow; lowlands, blues; Ishtar Terra and Aphrodite Terra are composite highlands; highland features include crustal plateaus and volcanic rises, and hybrid Phoebe Regio. Planitiae are indicated by 'P.', chasmata with 'C.' Topographic profiles (Ovda Regio, 90°E; Beta Regio 23.6°E), ~6 km vertical, 3500 km horizontal. b) Global distribution of: average model surface age provinces [*Phillips & Izenberg,* 1995; *Hansen & Young,* 2007]; fracture zone terrain ['rift' of *Price & Suppe,* 1995]; ribbon-tessera terrain [*Hansen & López,* 2010]; Artemis Chasma (green); trajectories of Artemis Chasma-radial fractures (gray lines) and wrinkle ridges (faded red lines), including Artemis Chasma-concentric wrinkle ridges and wrinkle ridges not concentric to Artemis [*Hansen & Olive,* 2010]. Labels as in (a). Modified from *Hansen* [2018].

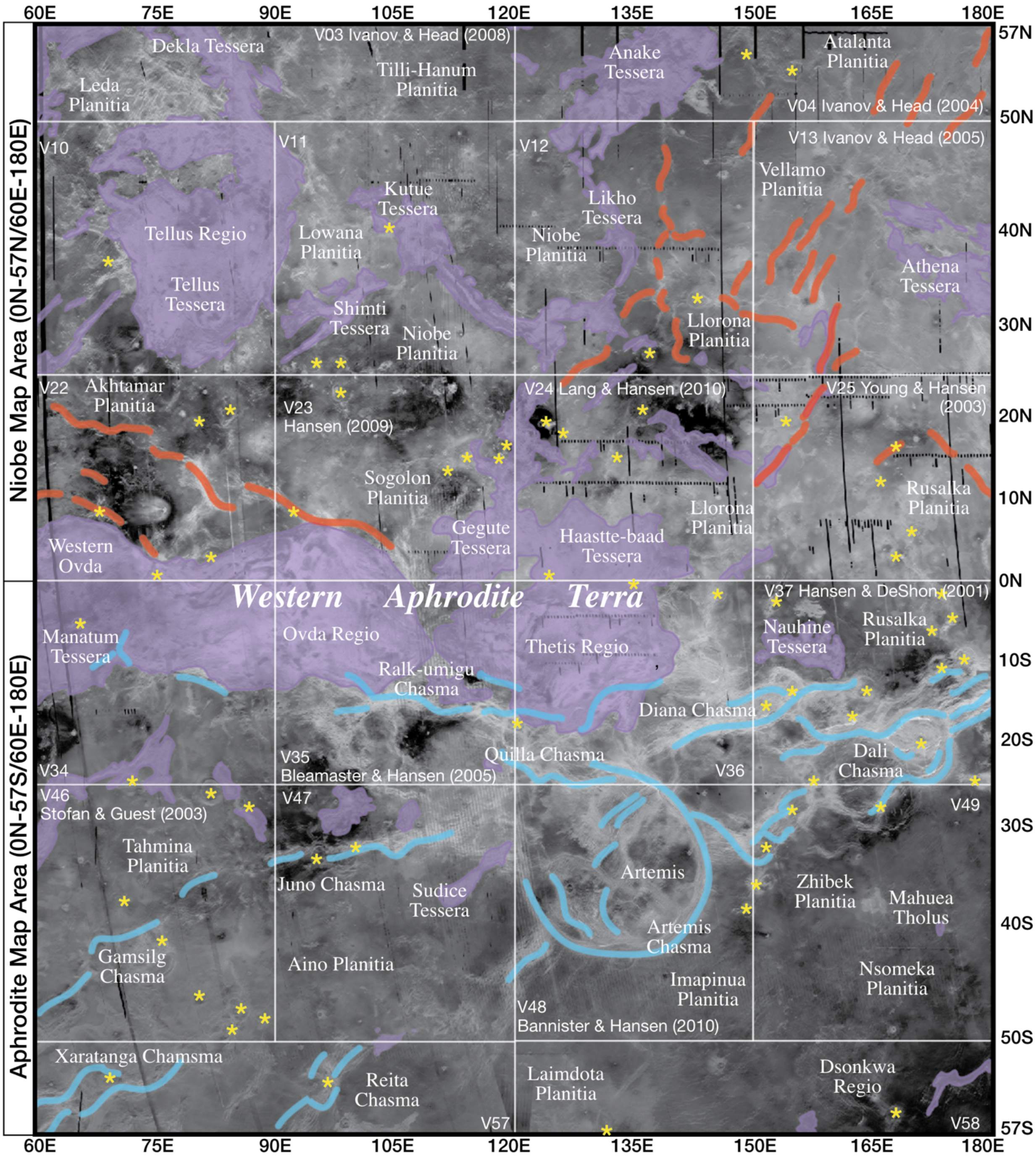


Figure 2. Mercator projection sketch map of Niobe and Aphrodite Map areas, SAR base with locations. Key: purple, tessera terrain; red lines, deformation belts; blue lines, chasmata; yellow stars, coronae; published VMap information in block text.

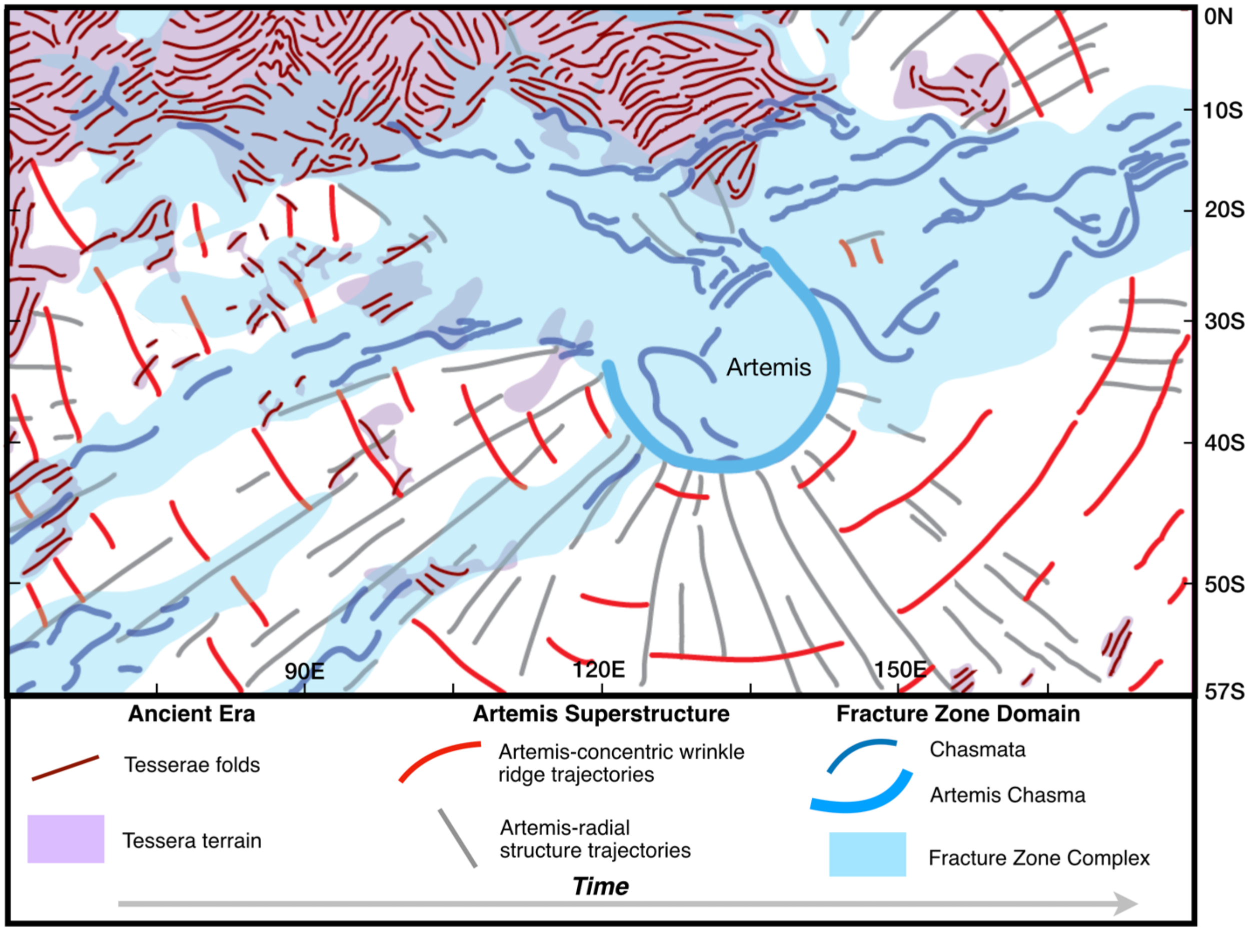


Figure 3. Mercator projection summary of the tectonic regimes within the AMA.

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**Table 1. Aphrodite Map Area Impact Craters**

| Name | Latitude (deg N) | Longitude (deg E) | Diameter (km) | Elevation (km) | V-map | Unit Location | Ejecta blanket | Impact halo | Central peak | Rim | Interior flooding | Crater density* | Crater data base | Deformed? | Temporal implications and comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abigail | -52.2 | 111.2 | 18.4 | 6050.84 | 57 | Afu | Y | N | Y | Y | Y | 1.59 | H, S | cut by ARF & ACRW | predates ARF & ACRW |
| Abika | -52.5 | 104.4 | 14.5 | 6051.01 | 57 | Afu | Y | N | N | Y | Y | 2.23 | H, S | can't tell timing with ACRW | |
| Addams | -56.2 | 98.9 | 87 | 6051.47 | 57 | Afu | Y | N | Y | Y | Y | 2.86 | H, S | outflow cut by ACRW | predates ACWR |
| Afiba | -47.1 | 102.7 | 9.5 | 6051.71† | 47 | rti | Y | N | N | Y | N | 1.59† | S | no deformation | |
| Agrippina | -33.2 | 65.7 | 38.6 | 6051.06 | 46 | fMe, fu | Y | N | Y | Y | Y | 2.55 | H, S | cut by ACRW? | predates ACWR |
| Ailar | -15.8 | 68.4 | 8.2 | 6051.47 | 34 | fu | Y | N | N | Y | N | 1.27 | H, S | no deformation | |
| Alison | -4 | 165.6 | 14.4 | 6051.51 | 37 | blu | Y | Y | Y | Y | Y | 2.55 | H, S | no deformation | |
| Amanda | -29.2 | 94.5 | 12.5 | 6052.07 | 47 | fu | Y | N | N | Y | N | 1.91† | H, S | no deformation | |
| Andreianova | -3 | 68.8 | 66.1 | 6052.97 | 34 | rtO | Y | N | Y | Y | Y | 1.91 | H, S | no deformation | |
| Austen | -25 | 168.4 | 45.1 | 6052.47 | 37/49 | fAta | Y | Y | Y | Y | N | 2.86 | H, S | cut by Atahensik Corona structures | predates Athensik Corona |
| Ayana | -29.2 | 175.5 | 13.8 | 6051.92 | 49 | Afu | Y | N | N | Y | Y | 2.55 | H, S | can't tell time wrt ACRW | composite crater |
| Badarzewska | -22.6 | 137.2 | 29.6 | 6053.46 | 36 | fchu | Y | N | Y | Y | Y | 1.91 | H, S | cuts & cut by FSZ | formed during FZ evolution |
| Bassi | -19 | 64.6 | 31 | 6051.02 | 34 | blu, fu | Y | Y | Y | Y | N | 1.91 | H, S | buries ACRW | postdates ACWR |
| Behn | -32.4 | 142 | 25.4 | 6052.87 | 48 | fAa | Y | N | Y | Y | Y | 1.91 | H, S | ejecta cut by Artemis Chasma faults; interior buries Artemis Chasma faults? | predates Artemis Chasma; interior flooding postdates Chasma structures |
| Blanche | -9.3 | 157 | 12.3 | 6054.08† | 37 | rtN | Y | N | N | Y | N | 1.91† | S | tstd | |
| Bonnevie | -36.1 | 127 | 92.2 | 6052.42 | 48 | fAa/fAa | Y | Y | Y | Y | Y | 0.95 | H, S | no deformation | postdates Artemis interior |
| Bonnin | -6.3 | 117.6 | 28.5 | 6054.89 | 35 | rtT | Y | N | N | Y | Y | 1.27 | H, S | no deformation | |
| Boulanger | -26.6 | 99.2 | 71.5 | 6052.76 | 47 | rtH | Y | N | Y | Y | N | 1.91 | H, S | no deformation | |
| Chiyojo | -47.8 | 95.7 | 40.2 | 6051.25 | 47 | st | Y | N | Y | Y | Y | 2.86 | H, S | covers & cut by ARF; cut by ACRW | date crater; crater predates ACWR |
| Chloe | -7.4 | 98.6 | 18.6 | 6055.93 | 35 | rtO | Y | N | Y | Y | Y | 2.23 | H, S | no deformation | |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Corpman | 0.3 | 151.8 | 46 | 6052.21 | 25/37 | fSa | Y | Y | N | Y | Y | 3.5 | H, S | mostly in Niobe | (outflow cut by N-fractures) |
| Dado | -13.9 | 87.6 | 11.2 | 6053.06 | 34 | fLS | Y | N | N | Y | N | 1.27 | H, S | no deformation | |
| de Beausoleil | -5 | 102.8 | 28.2 | 6054.93 | 35 | rtO | Y | N | N | Y | N | 2.55 | H, S | no deformation | |
| Deloria | -32 | 97.1 | 31.9 | 6052.13 | 47 | fu | Y | N | Y | Y | Y | 1.91 | H, S | buries fractures | postdates fractures |
| Dheepa | -21.6 | 176.3 | 4.7 | 6052.55 | 37 | ff | Y | Y | N | Y | N | 1.91 | H | tstd | |
| Eini | -41.6 | 96.4 | 5.9 | 6050.91 | 47 | Afu | Y | Y | N | Y | N | 2.86 | H, S | tstd | |
| Elena | -18.3 | 73.4 | 17.6 | 6051.53 | 34 | fu | Y | N | N | Y | N | 1.27 | H, S | buries N-trending fractures | |
| Elma | -10.1 | 91.1 | 10.2 | 6054.62 | 35 | fLS | Y | N | N | Y | N | 1.91 | H, S | tstd | |
| Emilia | -26.5 | 88.2 | 12.5 | 6051.55 | 46 | fu | Y | N | N | Y | Y | 0.64 | H, S | buries ENE-fractures & ARF | postdates ARF |
| Fava | -0.7 | 87.4 | 9.7 | 6055.28 | 34 | rtO | Y | N | N | Y | Y? | 2.23 | H, S | tstd | |
| Florence | -15.2 | 85 | 10.5 | 6052.89 | 34 | fu | Y | N | N | Y | N | 1.27 | H, S | no deformation | |
| Fredegonde | -50.5 | 93.3 | 25.2 | 6051.55 | 57 | Afu | Y | Y | Y | Y | Y | 2.55 | H, S | buries ACRW? | postdates ACWR? |
| Fukiko | -23.1 | 105.8 | 13.9 | 6052.6 | 35 | fG | Y | N | N | Y | Y | 2.55 | H, S | outflows bury FZS/CCS | postdates FZ/CC |
| Germain | -37.9 | 63.7 | 35.5 | 6051.09 | 46 | st | Y | Y | Y | Y | Y | 2.55 | H, S | ejecta cut by NW lineaments? | possibly deformed |
| Gilmore | -6.7 | 132.8 | 21.3 | 6055.25 | 36 | rtT | Y | N | N | Y | Y | 1.59 | H, S | cut by ARF | post ttT, pre-ARF or late ARF |
| Gulnara | -23.7 | 174 | 5 | 6051.68 | 37 | fAta | Y | N | N | Y | N | 1.91† | S | tstd | |
| Hadisha | -39 | 97.2 | 8.9 | 6051.25 | 47 | st | Y | Y | N | Y | Y | 2.55 | H, S | fills existing fracture troughs | composite crater |
| Halle | -19.8 | 145.5 | 21.5 | 6052.99 | 36 | ff | Y | Y | N | Y | Y | 1.59 | H, S | covers & cut by FZS/CCS | formed during FZ/CC evolution |
| Hanka | -27.3 | 114.3 | 5 | 6053.29 | 47 | fchu | Y | N | N | Y | N | 1.59 | H, S | no deformation | postdates FZ |
| Helga | -10.4 | 116.7 | 8.8 | 6054.28 | 35 | rtT | Y | N | N | Y | N | 0.95 | H, S | no deformation | |
| Henie | -51.9 | 146 | 70.4 | 6050.96 | 58 | st | Y | N | Y | Y | Y | 1.91 | H, S | buries ARF | postdates ARF |
| Howe | -45.7 | 174.8 | 38.6 | 6051.42 | 49 | st | Y | N | Y | Y | Y | 1.59 | H, S | ejecta cut by ACWR? | predates ACWR? |
| Huang Daopo | -54.2 | 165.3 | 29.1 | 6051.94 | 58 | st | Y | N | N | Y | Y | 2.86 | H, S | cut by ARF | predates ARF |
| Imagmi | -48.4 | 100.7 | 7.6 | 6050.82 | 47 | Afu | Y | Y | N | Y | N | 2.55 | H, S | flows into ARF | postdates ARF |
| Irma | -50.9 | 122 | 9.5 | 6051.23 | 58 | Afu | Y | Y | N | Y | N | 2.55 | H, S | no deformation | composite crater |
| Istadoy | -51.8 | 132.6 | 5.4 | 6051.18 | 58 | Afu | Y | Y | N | Y | N | 2.23 | H, S | tstd | |
| Izudyr | -53.9 | 135.2 | 6.6 | 6050.93 | 58 | st | Y | Y | N | Y | Y | 2.55 | H, S | tstd | |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jalgurik | -42.3 | 125.1 | 7.5 | 6052.51 | 48 | Afu | Y | N | N | Y | N | 1.59 | H, S | buries FZS | postdates FZ |
| Janina | -2 | 135.7 | 9.3 | 6053.27 | 36 | fBb | Y | Y | N | Y | Y | 1.91 | H, S | buries FZS | postdates FZ |
| Janyl | -28 | 138.8 | 5.6 | 6053.03 | 48 | fAb | Y | N | N | Y | N | 1.59 | H, S | tstd | |
| Jennifer | -4.6 | 99.8 | 9.6 | 6055.21 | 35 | rtO | Y | N | N | Y | N | 2.86 | H, S | tstd | likely postdates rtO |
| Jhirad | -16.8 | 105.6 | 50.2 | 6053.48 | 35 | fl1a, blu | Y | N | Y | Y | Y | 0.95 | H, S | buries FZ troughs | postdates FZ |
| Jodi | -35.7 | 68.7 | 10.2 | 6051.18 | 46 | st | Y | N | N | Y | N | 2.55 | H, S | buries ACRW? | postdates ACWR? |
| Joliot-Curie | -1.6 | 62.4 | 91.1 | 6052.48 | 34 | rtO, itbM, dD | Y | N | Y | Y | Y | 1.91 | H, S | not deformed? | predates dD? |
| Judith | -29.1 | 104.5 | 16.6 | 6052.71 | 47 | st | Y | Y | N | Y | Y | 2.23 | H, S | buries fractures & canali | postdates fractures & canali |
| Jumaisat | -15.1 | 135.6 | 7.5 | 6054.08 | 36 | rtT | Y | N | N | Y | Y | 0.95 | H, S | tstd | |
| Jutta | 0 | 142.6 | 7 | 6052.4 | 24/36 | st | Y | N | N | Y | N | 2.23 | H | tstd | |
| Kaikilani | -32.8 | 163.2 | 19.9 | 6051.76 | 49 | Afu | Y | Y | Y | Y | Y | 2.23 | H, S | buries ARF | postdates ARF |
| Kastusha | -28.6 | 59.9 | 13 | 6051.23 | 45/46 | fu | Y | Y | N | Y | N | 2.55 | H | no deformation | |
| Katrya | -29.5 | 108.7 | 9.2 | 6052.64 | 47 | fchu | Y | Y | N | Y | N | 1.59 | H, S | buries FZS | postdates FZ |
| Khelifa | -1.5 | 129.9 | 10.8 | 6054.76 | 36 | rtT | Y | N | N | Y | N | 1.59 | H, S | cut by ARF | predates ARF |
| Langtry | -17 | 155 | 50.3 | 6052.08 | 37 | fchu | Y | N | N | Y | Y | 1.59 | H, S | cut by FZS | predates FZ |
| Larisa | -18.47 | 131.06 | 3.7 | 6054.31† | 36 | ff | Y | N | N | Y | N | 1.59† | S | tstd | |
| Lazarus | -52.9 | 127.2 | 24.2 | 6051.25 | 58 | st | Y | Y | Y | Y | Y | 2.23 | H, S | buries ARF | postdates ARF |
| Leila | -44.2 | 86.8 | 18.8 | 6051.04 | 46 | Afu | Y | Y | Y | Y | Y | 2.23 | H, S | buries ACRW | postdates ACWR |
| Leona | -3.1 | 169 | 3 | 6051.57 | 37 | fE | Y | N | N | Y | N | 2.86 | H | tstd | |
| Ma Shouzhen | -35.7 | 92.5 | 18.9 | 6051.8 | 47 | Afu | Y | Y | Y | Y | Y | 1.59 | H, S | buries ARF & ACRW | postdates ACWR |
| Makola | -3.8 | 106.7 | 16.6 | 6053.96 | 35 | rtO | Y | N | N | Y | N | 2.23 | H | does not looked deformed | |
| Maltby | -23.3 | 119.7 | 36.6 | 6053.4 | 35 | fl1b, flc | Y | N | N | Y | Y | 0.64 | H | cut by FZS (stoping) | predates FZ |
| Mansa | -33.9 | 63.4 | 8.1 | 6051.08 | 46 | fu | Y | N | N | Y | N | 2.86 | H | covers ACRW? tstd | indeterminate |
| Markham | -4.1 | 155.6 | 71.8 | 6051.97 | 37 | fSa | Y | Y | Y | Y | Y | 1.91 | H, S | ARF &bank against ACRW | postdates ARF & ACWR |
| Martinez | -11.7 | 174.7 | 23.5 | 6052.6 | 37 | fK | Y | N | Y | Y | N | 0.64 | H, S | both covers and cut by FZS | formed during FZ evolution |
| Maurea | -39.5 | 69.1 | 9.9 | 6051.52 | 46 | fCoa | Y | Y | N | Y | Y | 2.23 | H, S | no deformation | |
| Ndella | -15.9 | 60.7 | 5.9 | 6051.22 | 34 | rtM | Y | N | N | Y | N | 1.91 | H, S | tstd | |
| Ngaio | -53.3 | 61.8 | 9.5 | 6052.64 | 57 | fMrdb | Y | Y | N | Y | Y | 1.91 | H, S | buries FZS | postdates FZ |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| O'Connor | -26 | 143.9 | 30.4 | 6052.43 | 48 | fchu | Y | N | Y | Y | Y | 2.55 | H, S | buries local fractures; pos. fracture reactivation? | formed late during FZ evolution? |
| Onissya | -25.6 | 150.2 | 8.2 | 6052.17 | 49 | ff | Y | Y | N | Y | N | 1.59 | H, S | outflow locally buried FZS | postdates FZ; cc |
| Opika | -57.1 | 151.9 | 9.8 | 6050.83 | 58 | st | Y | N | N | Y | N | 3.18 | H | no deformation? | |
| Parishan | -0.2 | 146.5 | 6.8 | 6052.23 | 24/36 | st | Y | N | N | Y | N | 2.23 | H, S | tstd | postdates fractures? |
| Patimat | -1.3 | 156.5 | 5.1 | 6051.84 | 37 | fSa | Y | N | N | Y | N | 1.91 | H, S | tstd | postdates ACWR?; cc |
| Pavlinka | -25.5 | 158.7 | 7.5 | 6053.22 | 49 | blu | Y | N | N | Y | N | 3.18 | H, S | cut by FSZ/CC | predates FZ/CC |
| Philomena | -40.7 | 151.9 | 14.8 | 6051.63 | 49 | Afu | Y | Y | N | Y | Y | 0.95 | H, S | buries ARF; buries ACRW? | postdates ACWR? |
| Qarlygha | -33 | 162.9 | 9.3 | 6051.66 | 49 | Afu | Y | Y | N | Y | N | 2.23 | H, S | covers ARF | postdates ARF |
| Quimby | -5.7 | 76.7 | 23.2 | 6054.24 | 34 | rtO | Y | N | Y | Y | N | 0.64 | H, S | no deformation | postdates rtO |
| Radhika | -30.3 | 166.4 | 7.9 | 6052.33 | 49 | Afu | Y | N | N | Y | N | 2.55 | H, S | no deformation? | postdates FZ? |
| Raki | -49.4 | 70 | 7.5 | 6052.23 | 46 | fMrdb | Y | Y | N | Y | N | 1.27 | H, S | buries ARF | postdates ARF |
| Ruit | -25.5 | 72.9 | 6.4 | 6051.29 | 46 | st | Y | Y | N | Y | N | 0.95 | H, S | tstd | |
| Safarmo | -10.8 | 161.4 | 7.4 | 6052.3 | 37 | fMa | Y | N | Y | Y | N | 1.91 | H, S | tstd | |
| Salika | -5 | 97.7 | 12.5 | 6055.53 | 35 | rtO | Y | N | N | Y | N | 3.18 | H, S | no deformation | |
| Samintang | -39 | 80.7 | 25.9 | 6051.37 | 46 | Afu | Y | N | Y | Y | Y | 1.91 | H, S | buries ARF | postdates ARF |
| Shushan | -43.8 | 70.2 | 8.5 | 6051.52 | 46 | fCoa | Y | N | N | Y | N | 1.91 | H, S | cut by ACRW | predates ACWR |
| Simonenko | -26.9 | 97.6 | 31.9 | 6052.48 | 47 | fu, fTh | Y | Y | Y | Y | Y | 1.91 | H, S | buries NE-fractures | postdates FZ |
| Sullivan | -1.4 | 110.9 | 32 | 6052.55 | 35 | rtO | Y | N | Y | Y | Y | 1.27 | H, S | no deformation | |
| Tehina | -30.4 | 76.4 | 5.4 | 6051.08 | 46 | st | Y | N | N | Y | N | 1.27 | H, S | tstd | |
| Temou | -10 | 83.4 | 9.3 | 6055.18 | 34 | rtO | Y | N | N | Y | N | 1.91† | H, S | no deformation | |
| Teumere | -38.3 | 88.1 | 5.4 | 6051.09 | 46 | fKu | Y | N | N | Y | N | 1.91 | H, S | tstd | |
| Teura | -12.3 | 90.2 | 9.3 | 6054.42 | 35 | fLS | Y | N | N | Y | N | 1.27 | H, S | cut by lava channel | predates lava channel |
| Ulpu | -35.7 | 179 | 7 | 6051.48 | 49 | Afu | Y | N | N | Y | N | 1.27 | H, S | tstd | cc |
| unnamed a | -46.3 | 125.6 | 5.4 | 6051.79 | 48 | st | Y | Y | N | Y | N | 2.23 | H, S | tstd | |
| unnamed b | -26.5 | 167.9 | 5.4 | 6052.78 | 49 | fAta | Y | N | N | Y | N | 2.86 | H, S | tstd | |
| unnamed c | -56.9 | 160.5 | 7 | 6051.27 | 58 | st | Y | N | N | Y | N | 2.86 | H, S | tstd | |
| unnamed d | -10.9 | 173.7 | 2.7 | 6054.538 | 37 | fK | Y | N | N | Y | N | 1.27† | S | tstd | |
| unnamed e | -41.9 | 149.6 | 6.4 | 6051.66 | 48 | Afu | Y | Y | N | Y | N | 0.96† | H, S | tstd | |
| unnamed f | -22.98 | 150.9 | 3.4 | 6052.47 | 37 | fchu | Y | Y | N | Y | N | 2.23† | H, S | tstd | |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| unnamed g | -26.1 | 130.4 | 6.3 | 6053.48 | 48 | fAb | Y | Y | N | Y | N | 1.59† | H, S | tstd | |
| unnamed h | -41.5 | 142.9 | 8.2 | 6052.3 | 48 | Afu | Y | Y | N | Y | N | 0.95 | H, S | tstd | |
| unnamed i | -55.4 | 129 | 14.3 | 6051.03 | 58 | st | Y | Y | N | Y | N | 2.23 | H, S | tstd | composite crater |
| unnamed j | -39.3 | 110 | 6.3 | 6051.7 | 47 | st | Y | Y | N | Y | N | 0.64 | H, S | tstd | |
| unnamed k | -13.7 | 131.6 | 8.4 | 6054.51† | 36 | fl1b | Y | N | N | Y | N | 1.59† | | tstd | |
| Valadon | -49 | 167.7 | 25.2 | 6051.71 | 49 | st | Y | N | Y | Y | Y | 1.91 | H, S | covers or cut by ARF? | |
| Veronica | -38.1 | 124.6 | 17.9 | 6052.4 | 48 | fAb | Y | N | N | Y | Y | 1.27 | H, S | undeformed (?) | |
| Warren | -11.7 | 176.5 | 50.9 | 6052.44 | 37 | fSi | Y | N | Y | Y | Y | 0.95 | H, S | covers & cut by FZ/CC | formed during FZ/CC evolution |
| Whiting | -6.1 | 128 | 35.7 | 6054.73 | 36 | rtT | Y | N | Y | Y | N | 1.27 | H, S | cut by ARF? | predates ARF? |
| Whitney | -30.2 | 151.3 | 42.5 | 6052.15 | 49 | fchu | Y | N | Y | Y | N | 1.59 | H, S | cut by FZS/CC | predates FZ/CC |
| Winnemucca | -15.4 | 121.1 | 30.3 | 6053.36 | 36 | rtT, fchu | Y | N | N | Y | N | 1.27† | H, S | cut by FZS/CC | predates FZ/CC |
| Xiao Hong | -43.5 | 101.7 | 38.7 | 6050.8 | 47 | Afu | Y | Y | Y | Y | Y | 2.55 | H, S | cut by ACRW? | predates ACRW? |
| Yasuko | -26.1 | 169 | 10.6 | 6053.12 | 49 | fAta | Y | N | N | Y | N | 2.86 | H, S | covers Atahensik fractures | postdates Atahensik Corona |
| Yokhtik | -50.1 | 158.1 | 11.4 | 6051.66 | 58 | bst | Y | N | N | Y | Y | 2.23 | H, S | cut by ARF | predates ARF |
| Yomile | -27.3 | 138.7 | 13.6 | 6053.03 | 48 | fAb | Y | Y | N | Y | N | 1.59 | H, S | no deformation | |
| Yonge | -14 | 115.1 | 42.8 | 6053.82 | 35 | fchu | Y | N | Y | Y | N | 1.27 | H, S | cut by FZS | predates end of FZ |
| Zeinab | -2.2 | 159.6 | 12.5 | 6051.38 | 37 | fE | Y | N | N | Y | Y | 2.86 | H, S | covers ACRW? | postdates ACWR? |
| Zemfira | -46.2 | 157.7 | 11.4 | 6051.28 | 49 | st | Y | N | N | Y | Y | 1.59 | H, S | no deformation | |
| Zosia | -18.9 | 109.2 | 10.5 | 6053.03 | 35 | fl1a | Y | N | N | Y | N | 1.27 | H, S | poor imagery; can't determine | |
| Zulma | -7.7 | 102 | 11 | 6055.15 | 35 | rtO | Y | N | N | Y | N | 1.91 | H, S | no deformation | |

Abbrevations: N, no; Y, yes; ACRW,Artemis concentric wrinkle ridges;ARF, Artemis radial fractures; CCS, corona-chasma structures; FZS, fracture zone structures; FZ/CC, fracture zone-corona-chasma; tstd, too small to determine; cc, composite crater

Venus crater data bases: S, *Schaber et al.* [1992]; H, *Herrick et al.* [1997]

*Crater density values from *Herrick et al.* [1997] at a crater's location. Value is the density of craters in the neighborhood of the specified crater; that is, the number of craters (including the specified crater) within a 1000 km radius circle normalized to give the number of craters per 1 x $10^6$ $km^2$.

† Values calculated using the methodology of *Herrick et al.* [1997].