Geologic Map of the Niobe Planitia Region (I-2467), Venus.

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Abstract

We present a 1:10M scale map of the Niobe Map Area (NMA) of Venus (0N-57N/60E-80E). Geologic mapping employed NASA Magellan synthetic aperture radar and altimetry data. The NMA geologic map, and its companion Aphrodite Map Area (AMA), cover ~25% of Venus' surface, providing with an important and unique perspective to study global and regional geologic processes. Both areas display 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 NMA preserves a limited record of the fracture zone era, contrary to the AMA. However, the NMA host a diverse and rich assemblage of material and structures of the ancient era, and structures that define the Artemis superstructure era, with a footprint covering more than 25 percent of the surface of Venus. These two eras likely overlap in time and account for the formation of basement materials and lower plain units. Impact craters formed throughout the NMA recorded history. Approximately 40% of the impact craters show interior flood deposits, indicating that a significant number of NMA impact craters experienced notable geological events after impact crater formation. This and other geologic relations record a geohistory inconsistent with postulated global catastrophic resurfacing. Together, the NMA and the AMA record a rich geologic history of the surface of Venus that provide a framework to formulate new working hypotheses of Venus evolution, an to plan future studies of the planet.

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Key Points:

- We present a geologic map of the Niobe map area (0N-57N/60E-180E), representing about 13 percent of Venus' surface

- The map area displays an important imprint of the Artemis superstructure associated tectonic suites.

- Different volcanic styles locally resurface the map area, where different basement materials record the history of an ancient era.

Abstract

We present a 1:10M scale geologic map of the Niobe Map area (NMA) of Venus (0N-57N/60E-80E). Geologic mapping employed NASA Magellan synthetic aperture radar and altimetry data. The NMA geologic map, and its companion Aphrodite Map Area (AMA), cover ~25% of Venus' surface, providing with an important and unique perspective to study global and regional geologic processes. Both areas display 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 NMA preserves a limited record of the fracture zone era, contrary to the AMA. However, the NMA hosts a diverse and rich assemblage of material and structures of the ancient era, and structures that define the Artemis superstructure era, with a footprint covering more than 25 percent of the surface of Venus. These two eras likely overlap in time and account for the formation of basement materials and lower plain units. Impact craters formed throughout the NMA recorded history. Approximately 40% of the impact craters show interior flood deposits, indicating that a significant number of NMA impact craters experienced notable geological events after impact crater formation. This and other geologic relations record a geohistory inconsistent with postulated global catastrophic resurfacing. Together, the NMA and the AMA record a rich geologic history of the surface of Venus that provide a framework to formulate new working hypotheses of Venus evolution, and to plan future studies of the planet

1. Introduction

The NASA's Magellan mission collected a near-global synthetic aperture radar (SAR) data of the surface of Venus between 1990 and 1994, and revolutioning the knowledge of our sister terrestrial planet. One of the main results of this first global reconaissance of Venus is that our neighbour planet lacks a system of moving plates like the one that operates here on Earth. However, an undertanding of how Venus has evolved through time remains elusive. Paramount to unraveling the geodynamic evolution of a planet, Earth included, is to constrain the structures, materials and processes that have molded its surface, for which regional geologic mapping has proven to be a fundamental tool. Regional mapping provides a means to to document and synthesize our current knowledge of a region or planet, and also serves as a tool to test working hypotheses, formulate questions, and devise new concepts to be studied in the future.

In this work we present a geologic map of the 1:10M Niobe Planitia Map Area (I-2467; 0N-57N/60E-180E). This map is part of a collaborative mapping project that includes the companion Aphrodite Map Area (AMA, I-2476), the object of a separate contribution [*Hansen & López*, 2020]. Together, both maps cover > 25% of Venus. The area includes different types of terrains, units, structures and volcanic styles representative of the surface of Venus. The map scale is well-suited for the discovery of regional to global scale processes, and to test current models of Venus geologic processes and evolution.

2. The Niobe Planitia Map Area (NMA)

The Niobe Planitia Region of Venus (I-2467) covers a surface of ~ 60,000,000 km^2 extending from lat 0° N to 57° N and from long 60° to 180° E (Figure 1). We refer to the map

66 area as the Niobe map area, or NMA, herein. NMA takes its name from Niobe Planitia, a large
67 volcanic lowland province that occupies the central map area.
68   The NMA includes the northern part of western Aphrodite Terra, a topographically high
69 region that extends ~10° (~1000 km) on either side of the equator, including the crustal plateaus
70 of western and central Ovda Regio and Thetis Regio, and several planitiae to the north. Tellus
71 Regio, the third crustal plateau in the NMA dominates northwest NMA, defining the boundary
72 between western planitiae. Elsewhere ridge belts (also called deformation belts) and/or large
73 tessera-terrain inliers, forming locally higher regions, define the boundaries between planitiae in
74 northern, central and eastern NMA.
75   Topographically the NMA ranges in altitude from over 5 km above mean planetary
76 radius (MPR) in the equatorial highland regions to around 2.5 km below MPR in the lowlands of
77 Leda and Atalanta Planitiae within northwestern and northeastern NMA, respectively. Llorona,
78 Niobe, and Sologon planitiae, located north of the equatorial crustal plateaus, may form the
79 northern part of a broad Artemis-concentric topographic trough [*Hansen & López*, 2020].
80 Akhtamar Planitia occupies southwestmost NMA whereas Rusalka Planitia occupies the
81 southeast corner. Northern NMA includes from east to west: Atalanta, Vellamo, Tilli-Hanum,
82 Lowana and Leda planitiae.

83
84 **3. Data and Methods**
85
86   **3.1.   Image Data**
87
88   Data for this study were provided by the U.S. Geological Survey (USGS) Astrogeology
89 Team in the projection parameters (Mercator projection) for the Niobe Planitia Region (I-2467).
90 The   data   are   available   online   from   the   USGS   Map-a-planet   website
91 (https://astrocloud.wr.usgs.gov/).
92   Cycle 1 (east-directed illumination, or left-looking) SAR images cover essentially the
93 entire I-2467 map area, with local data gaps, particularly within central NMA. Cycle 2 (west-
94 directed illumination, or right-looking) SAR data covers western NMA (60ºE-120ºE); cycle 3
95 left-look stereo SAR data is scarce and banded [*Ford et al.*, 1993]. Digital Compressed Once
96 Mosaicked Image Data Records (C1-MIDR; 225 m/pixel) SAR data from the regional database
97 and map base and digital full-resolution radar map (FMAP; 75–125 m/pixel) dataset were used in
98 constructing the geologic map.
99   We also employed other ancillary non-SAR Magellan data available though the USGS
100 Map-A-Planet website. The datasets include: (a) Topography (Global Topographic Data Record
101 3; GTDR 3); (b) Slope data (Global Slope Data Record; GSDR); (c) Reflectivity (Global
102 Reflectivity Data Record; GRDR); and (d) Emissivity (Global Emissivity Data Record; GEDR).
103   GTDR data has an effective horizontal resolution of 10 km, and were combined with
104 SAR images to produce synthetic stereo anaglyphs [*Kirk et al.*, 1992] using NIH-Image macros
105 developed by D.A. Young. Synthetic stereo images played a critical role in elucidating the
106 relations between geology and topography and, in particular, the interaction of flows, primary
107 and secondary structures, and topography.
108
109   **3.2.   Image Interpretation and geologic mapping**
110

111   The interpretation of features in SAR images is key to developing a NMA geologic
112   history. *Ford et al.* [1993] explored the subject of SAR image interpretation in depth. The
113   methodology for defining geologic units and structural fabrics builds on standard geologic
114   analysis detailed by *Wilhelms* [1990] and *Tanaka et al.* [1993], and employs cautions of *Hansen*
115   [2000], *Zimbelman* [2001], *Skinner and Tanaka* [2003], and *McGill and Campbell* [2004]. Map
116   units represent material emplaced within an increment of geologic history, to which standard
117   stratigraphic methods have some limited application. Other units may be composite, in that the
118   units might not be stratigraphically coherent over the entire represented area and (or) the material
119   may have been emplaced over an extended period of time, particularly in relation to other units
120   and (or) formation of secondary structures. In such cases the map units are descriptive units
121   rather than temporal units. Attempts were made to clearly separate secondary structures from
122   material units; location, orientation, and relative density of primary and secondary structures are
123   shown independent of material units. Evidence for reactivation of secondary structures is
124   common across the map area, which further complicates the process of unraveling both temporal
125   constraints and geologic history. In addition, in many cases the designation of a material unit
126   does not carry an implication of concurrent or synchronous emplacement [e.g., *Hansen*, 2000].
127   Indeed, absolute time is essentially impossible to constrain with regard to Venus geology at the
128   time of this study.
129   Criteria for distinguishing discrete geologic units in the map area include (but are not
130   limited to): (1) the presence of sharp, continuous contacts; (2) truncation of, or interaction with,
131   underlying secondary structures and topography; and (3) primary structures, for example flow
132   channels or edifice topography, that allow a reasonable geologic interpretation and which may
133   also provide clues to three-dimensional geometry. Some mapped units do not fit these
134   constraints, which limits their use in constructing stratigraphic interpretations. Composite units,
135   in particular, do not provide reasonable temporal constraints, even of a relative nature.
136   Composite character of the units is noted in the decsription of map units.
137   Estimating absolute geologic age is not currently possible for the surface of Venus.
138   Unlike surface crater statistics for planetary bodies that have old surfaces and high crater
139   densities, such as the Moon and Mars, Venus impact crater statistics cannot place constraints on
140   the age of surface units that cover the small areas visible in the map area given the low density of
141   craters and lack of small craters [*McKinnon et al*, 1997; Hauck et al, 1998; Campbell, 1999].
142   Relative age constraints may be established only where units are in mutual contact and (or)
143   interact with the same suite of secondary structures. Such relative temporal constraints are only
144   locally applicable and cannot be extended across the map area with confidence, nor are they
145   valid for composite (time-transgressive) geologic units.
146   Geologic maps at all scales should provide the basis for interpreting geologic histories,
147   which in turn provide critical relations for understanding the range of processes that contributed
148   to the evolution of planets. Construction of a geologic map is a critical first step in unraveling
149   geologic history. Geologic maps are interpretive products used in turn for further interpretation
150   of geological processes [*Butler & Bell*, 1988; *Maltman*, 1990]. Therefore, mapping must be
151   conducted in a fashion that ensures that any operative process can be discovered—that is, the
152   mapping method must not predetermine the resulting geologic map [*Hansen*, 2000]. It is
153   imperative, for example, that secondary structures (strain) be distinguished from geologic units
154   because materials and structures record different 'time slices' in the evolution of Venus' surface,
155   and each reflect different aspects of the operative processes which formed overall geology
156   [*Wilhelms*, 1972, 1990; *Hansen*, 2000; *North American Stratigraphic Code*, 2005]. 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 [e.g., *Gilbert*, 1886; *Wilhelms*, 1972, 1990; *Compton*, 1985; *Butler & Bell*, 1988; *Maltman*, 1990; *Tanaka et al.*, 1993, 2010; *Hansen*, 2000; *Skinner & Tanaka*, 2003; *Zimbelman*, 2001; *McGill & Campbell*, 2004; *Grindrod & Guest*, 2006; *Hansen & López*, 2018].

In this contribution we identify and map: (a) geomorphic features and named features within the map area; (b) primary and secondary structures, most commonly lineaments formed during unit emplacement, or after unit emplacement, respectively; (c) material units; (d) non-material units such as ribbon-tessera terrain or shield terrain [e.g., lithodemic units; *North American Stratigraphic Code*, 2005]; (e) shock features or thin deposits that overlay material units or terrains (e.g., impact crater haloes, mantling material), shown as transparent stippled areas.

4. The NMA Geologic Map

This section describes the NMA geologic map (Plate 1). The NMA is composed of an assemblage of materials and structures that together record a spatially and temporally varied geohistory: (a) local basal terrains (crustal plateaus, lowland tessera inliers and other local basal units); (b) a suite of geological elements—tectonic and magmatic—associated with the formation of the Artemis superstructure [*Hansen & Olive*, 2010]; (c) regionally extensive suites of tectonic structures exposed across the lowlands, and local tectonic suites associated with individual tectonomagmatic features; (d) volcanic materials including: basal-shield transitional terrain and shield terrain [*Aubele*, 1996; *Hansen*, 2005], local volcano- and corona-related flow materials, and undivided volcanic materials; and (e) 146 impact craters.

4.1.   Primary Structures, Secondary Structures, and Tectonic Fabrics

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

4.1.1. Primary structures

Primary structures are mostly related to volcanic and impact processes and include features such as channels, shields, pits/pit chains, lobate flow fronts and flow levees, and crater rims and impact-related haloes and splotches [*Ford et al.*, 1993].

Channels or canali are sinuous, low-backscatter troughs tens to thousands of kilometers long and a few kilometers wide; locally, they may lack apparent topographic relief; they are similar to terrestrial fluvial channels, interpreted to form by channelized fluid flow [*Baker et al.*, 1992, 1997; *Komatsu & Baker*, 1994]. A large section of Baltis Vallis, the longest channel on Venus (~6800 km), transects Atalanta Planitia in eastern NMA. Both the nature of the fluid and formational mechanism (constructive or erosional) are unknown [e.g., *Gregg & Greeley*, 1993; *Bussey et al.*, 1995; *Williams-Jones et al.*, 1998; *Jones & Pickering*, 2003; *Lang & Hansen*, 2006; *Waltham et al.*, 2008]. Canali could be primary constructional structures, related to levee

202 development during flow emplacement, secondary erosional structures that cut earlier emplaced
203 material, or a combination of both.
204   Shields,interpreted as small volcanic edifices, are small (generally 1 to 15 km in
205 diameter, rarely 20 km in diameter), quasi-circular to circular, radar-dark or radar-bright features
206 with or without topographic expression and with or without a central pit [*Guest et al.*, 1992;
207 *Crumpler et al.*, 1997; *Addington*, 2001]. The size of individual shields is difficult to constrain
208 because bases of individual shields are typically poorly defined, and deposits commonly blend
209 smoothly into a composite layer that cannot be treated as a time line or marker unit with any
210 certainty [*Hansen*, 2005].
211   Intermediate volcanoes, such as steep-sided domes or tholi, represent volcanic features
212 indicative of a relatively higher viscosity either due to a more felsic composition and/or
213 differences in the texture or rate of the extruded magma [e.g., *Stofan et al.*, 2000; *Pavri et al.*,
214 1992].
215   Lobate flow fronts and flow levees developed within flow units can indicate surface flow
216 direction, which in turn can provide information about flow emplacement and local topography
217 at the time of flow emplacement.
218   Impact craters are perhaps most prominently marked by rims that sit above circular
219 interiors and within/at the boundary of ejecta material marked by extremely radar-bright deposits
220 [*Weitz*, 1993]. Some impact craters display haloes, radar-bright (rough) or radar-dark (smooth)
221 deposits that extend outward from the rim and ejecta deposits up to many crater diameters
222 [*Izenberg et al.*, 1994]. Haloes are thought to form as a result of the shock-induced crushing of
223 host material just preceding or accompanying bolide impact or due to accumulation of fine-scale
224 ejecta. Some craters have parabolic haloes that extend up to 20 crater radii to the west; these thin
225 deposits(?) are interpreted as due to the interaction of east-to-west zonal winds [*Whitten &
226 Campbell*, 2016; *Campbell et al.*, 2015; *Campbell et al.*, 1992; *Arvidson et al.*, 1991]. Numerous
227 dark splotches also occur within the map area; these could represent bolides that exploded before
228 impact [*Kirk & Chadwick*, 1994].
229   Crater haloes, parabolic deposits and dark splotches appear to degrade with time resulting
230 in a decrease in radar contrast relative to surrounding terrain [*Izenberg et al.*, 1994]. Impact
231 craters that display both extreme haloes and radar-bright crater interiors are generally interpreted
232 as relatively young, whereas craters with degraded haloes, or lacking haloes entirely, and
233 displaying radar-smooth filled interiors are interpreted as relatively old [*Phillips & Izenberg*,
234 1995; *Herrick & Rumpf*, 2011]. Impact crater haloes and dark splotches are indicated with a
235 transparent map pattern so that underlying units and structures can be represented along with the
236 extent of crater haloes.
237
238   **4.1.2. Secondary structures**
239
240   Secondary structures or tectonic structures form after the emplacement of geologic units,
241 and typically record tectonic processes. In addition, the distribution and (or) character of
242 secondary structures may provide clues for the delineation of material units, as well as temporal
243 relations between different material units [*Hansen*, 2000]. Secondary structures within NMA
244 include various types of lineaments: (a) fractures and faults; and (b) broad ridges, folds, and
245 wrinkle ridges. Given that the map area covers ~60,000,000 km^2 we cannot and do not show all
246 lineaments. The focus here is an attempt to capture the essence of recognized structural suites.
247 Therefore, in some cases lineament trends will be shown, in other cases each lineament is shown,

248 in yet other cases a collection of the lineaments is shown. There is no single unique scale of
249 lineament or feature identification, just as there is no single unique scale of observation in the
250 case of field-based mapping on Earth, particularly for maps that cover huge areas of Earth's
251 surface.
252   Fractures are sharply defined lineaments with a negative, or null, topographic signature,
253 commonly grouped into suites based on orientation, pattern (i.e., parallel or near parallel, radial
254 or concentric) and/or spacing (that is, widely spaced or closely spaced). Fractures are generally
255 interpreted as extensional structures [*Banerdt et al.*, 1997]. In some cases fractures appear as sets
256 of paired lineaments, and may mark graben. Locally fractures consist of *en echelon* fractures
257 indicative of either a shear fracture origin, or the emergence of a fracture at depth to the surface
258 with the *en echelon* fractures marking hackles.
259   Some fractures in local radial suites transition to pits or pit chains, sharply defined
260 depressions, or pit chains. Linear arrays of pits likely represent regions marked by subsurface
261 excavation; they may mark the surface expression of dilatational faults or dikes [*Grosfils &*
262 *Head,* 1994; *Okubo & Martel*, 1998; *Bleamaster & Hansen,* 2005; *Ferrill et al.*, 2004; *Schultz et*
263 *al.*, 2004] or they could represent stoping features that would not require associated crustal
264 extension [e.g., *Cushing et al.*, 2015]. Pits or pit chains can be considered primary structures or
265 secondary structures, depending on the question at hand; pits are primary structures relative to
266 pit-related materials, yet they may be secondary structures relative to the units they cut or are
267 emplaced within.
268   Folds are ridges with a gradational radar character normal to their trend, and wave-like
269 topographic expression; they are generally interpreted as contractional structures [*Stofan et al.*,
270 1993]. Small ridges are topographic ridges with low relief and width, similar in appearance to
271 folds except that the nature of the lineaments is ambiguous—though possibly of contractional
272 origin (marked by folds or thrust faults).
273   Wrinkle ridges define low sinuous structures spaced a few kilometers to tens of
274 kilometers apart and up to a few hundred kilometers long. These lineaments, which represent low
275 values of layer contractional strain (<2%), are found on most terrestrial worlds, especially on
276 large flat expanses of volcanic flow materials [*Watters*, 1988; *Banerdt et al.*, 1997]. Locally
277 wrinkle ridges occur as inversion structures formed by the inversion of fracture-fill material due
278 to post burial contraction [*DeShon et al.*, 2000]. Wrinkle ridges typically form suites of near
279 parallel structures (and occasionally orthogonal suites) formed over large regional expanses.
280
281   **4.1.3. Tectonic fabrics**
282
283   Tectonic fabrics are an assemblage of related structural elements that together
284 characterize a rock unit, as in the case of ribbon-tessera terrain [*Hansen & Willis*, 1996, 1998;
285 *Hansen*, 2006].
286   Ribbon-tessera fabric is characterized by orthogonally developed suites of ribbons, or
287 ribbon structures and folds. For a complete description of this tectonic fabric and its implications
288 on the origin and evolution of tessera-terrain and crustal plateaus see *Hansen & Willis* [1996,
289 1998], *Ghent & Hansen* [1999], *Brown & Grimm* [1999], *Hansen* [2006] and *Ruiz* [2007]. For a
290 discussion of ribbon-terrain controversies, see *Gilmore et al.* [1998], *Hansen et al.* [2000], and
291 *Hansen* [2006].
292   Within the NMA we delineate ribbon-tessera ribbon and fold trends. Ribbon structures
293 are shown as trends of ribbon ridges and troughs; fold structures demarcate fold crest or trough

294 trends. In most cases short-, intermediate, and long-wavelength folds define locally parallel
295 trends [*Hansen*, 2006]. Graben complexes, common elements of ribbon-tessera terrain fabric,
296 typically parallel ribbon trends. Graben complexes can be differentiated from ribbons on the
297 basis of smaller length-to-width ratios—that is, graben complexes are generally wider and
298 shorter than ribbon structures. Ribbon-tessera graben complexes typically cut at high angles to
299 long-wavelength fold crests, commonly resulting in a lens-shape plan view. Some graben
300 complexes define broad patterns (radial, concentric) that can could offer information on the
301 evolution of the crustal plateaus after and during the formation of the ribbon-tessera fabric.
302 *Bindschadler et al.* [1992] recognized ribbon, fold and graben structures within tessera terrain.
303 These workers describe described ribbon structures as "narrow troughs", clearly differentiating
304 ribbon structures from generally parallel but morphologically different graben complexes.
305
306 **4.2. Map Units**
307
308 Map units interpreted across the NMA are broadly defined in this section. The map
309 legend provides a complete description of units.
310 The contacts between adjacent units vary from well defined, whereas in other cases are
311 approximate or gradational, due to the angular nature of individual contacts or the style of the
312 units or terrains. For example, shield terrain (unit st), consists of a thin veil of numerous *in situ*
313 locally sourced deposits associated with individual shields, typically on the order of a few km or
314 less across [*Guest et al.*, 1992; *Hansen*, 2005]; the location of the mapped contact could vary
315 across 10s and locally perhaps even 100s of kilometers given the inherent challenges in
316 recognizing individual shields and the wide variation in shield density [e.g., *Hansen*, 2005;
317 *Hansen*, 2009; *Hansen & Tharalson*, 2014]. In the case of some basal terrains that were cut by
318 fractures following basal unit formation and then later are locally buried by younger material, the
319 contact between the basal terrain and younger units can be sharp, marked by fracture truncation.
320 They can also be gradational, such as in cases in which the fractures are visible as lineaments,
321 yet do not obviously cut the overlying material. In this case the overlying material is interpreted
322 to form a thin layer across regions where earlier formed buried fractures are apparent as
323 lineaments through the thin cover. The transition from a gradational to sharp contact can itself be
324 very sharp or gradational. In addition, the amount/character of fracture burial can also be
325 gradational.
326
327 **4.2.1. Terrain Units**
328
329 The term "terrain" describes a texturally defined region, for example, where tectonism
330 imparted a surface with a penetrative deformation that disallows interpretation of the original
331 unit or units [*Wilhelms*, 1990]. The characteristic texture of a terrain could imply a shared
332 history, such as a terrestrial tectono-thermal history or an event that melds possibly previously
333 unrelated rock units (any combination of igneous, metamorphic, and sedimentary rocks); no
334 unique history is inferred or required prior to the event(s) that melded potentially separate units
335 into the textural terrain (i.e., lithodemic unit). Events prior to terrain formation are unconstrained
336 in time or process unless specifically noted. Three general classes of terrain units occur across
337 NMA: ribbon-tessera terrain and associated units, basal terrain, and shield terrain and associated
338 basal-shield transitional terrain.
339

4.2.1.1. Ribbon-tessera terrain and associated units

Ribbon tessera terrain and associated intratessera basin units are widespread across the NMA marking the characterisitic surface of crustal plateaus (Western Ovda/Manatun Tessera, and Ovda, Thetis, and Tellus regiones), and also occuring as lowland inliers. Units includes the descriptive moniker plus the name of the host tessera region (e.g., Ovda or Tellus ribbon tessera terrain, rtO and rtT, respectively; or itbO and itbT). A descriptive term such as undivided (rtu) is applied to the relatively small exposures located in unnamed locations. Ribbon-tessera terrain exposures are typically characterized by orthogonal ribbon-fold tessera fabric [*Hansen & Willis*, 1998; *Hansen*, 2006]. Fold wavelengths range from less than one kilometer—essentially to the effective resolution of SAR data, to tens of kilometers. Ribbon wavelengths range from 2 to 5 km, and below, locally also to SAR effective resolution. Orthogonal ribbon-fold fabrics are the most common tessera fabric across NMA as they are for ribbon-tessera terrain globally [*Hansen & López*, 2010], but local shear fabrics [*Hansen*, 1992; *Hansen & Willis*, 1996] occur in central Ovda Regio and in tessera inliers in Niobe Planitia (e.g. Shimti-Kutue tesserae). Intratessera basin material, which typically fills short- to long-wavelength tessera-fold troughs (short-wavelength fold troughs are below the scale of the NMA), are best preserved and identified within crustal plateaus, although we delineate such units within large tesserae inliers. Tesserae inliers describe regional-scale linear to arcuate patterns in lowland basins. Given that inliers reside at low elevation and are locally embayed by younger volcanic materials, unique identification of intratessera basin material (as opposed to undivided volcanic material) can be difficult. For a more complete description of intra-tessera basin materials or the origin of crustal plateaus see *Banks & Hansen* [2000] and *Hansen* [2006].

4.2.1.2. Local basal terrain

Local basal terrain is a term used to describe surfaces that lie within locally low stratigraphic positions relative to adjacent map units in planitiae. Similar to the naming scheme used in other terrain units we include the moniker basal terrain, and the name of the host planitia (e.g., Niobe or Leda basal terrain, btNi and btLe, respectively), or a descriptive term such as undivided (btu). These surfaces are termed terrains because it is unclear how many individual units might be represented, but the regions share suites or a suite of tectonic structures that formed prior to the emplacement of adjacent material. Local basal terrain exposures are just that, local, and there is no implication of shared histories between spatially separated basal terrain units across the NMA. However, it is also possible that isolated basal terrain exposures could locally represent temporal equivalent surfaces, or more likely perhaps, represent temporally equivalent unconformity bound packages (i.e., allostratigraphic surfaces/packages).

4.2.1.3. Shield terrain

Shield terrain consists of thousands of individual shields and coalesced flow materials, 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 rocks with an interpreted shared emplacement mechanism (represented by primary structures),

385 which differs from ribbon-tessera terrain whose elements include an interpreted shared
386 deformation history represented by secondary structures.
387   Within NMA, shield terrain material (unit st) is marked by distributed small (~1–10 km
388 in diameter) shield edifices and their associated deposits. Unit st generally hosts a high density of
389 shields although individual shield are not delineated within NMA due to the map scale. The
390 contact of unit st with adjacent units can locally be sharp but is mostly gradational due to the
391 point source nature of the volcanic activity. Unit st almost certainly represents a time-
392 transgressive unit across the NMA [e.g., *Addington*, 2001; *Stofan et al.*, 2005], comprised of
393 thousands of small edifices that may represent point-source, in situ, partial melting [*Hansen*,
394 2005]. This unit name is used in a descriptive fashion and does not imply temporal constraints.
395   We defined a unit transitional between shield and basal terrains, *basal-shield transitional*
396 *terrain* (unit bst), wherein the discontinuous presence of shields and the low thickness of
397 associated deposits reveal the tectonic structures of the underlying basal terrain. Similarly we
398 locally observe other volcanic features (e.g., intermediate volcanoes and small coronae) partially
399 embayed by shield terrain. Locally stratigraphic relations between such units and shield terrain
400 are difficult to constrain due to the presence of shields in both units and to the point-source
401 character of volcanism; we interpet a diachronic temporal relation between such units.
402
403   **4.2.2. Material Units**
404
405   **4.2.2.1. Volcanic material undivided**
406
407   Volcanic material undivided (unit vmu) represents a composite unit without stratigraphic
408 significance that combines materials of different origin, and probably different age, that cannot
409 be confidently differentiated with the available data. We use the unit name, volcanic material
410 undivided, because the unit includes many different volcanic styles and radar textures, including
411 corona-, volcano-, and shield-related material of low to intermediate-high backscatter and
412 homogeneous to mottled texture. Volcanic and large tectonomagmatic features are distributed
413 across unit vmu. Large flow units are difficult to delimit, perhaps due to the radar
414 homogenization of the flows with time [*Arvidson et al.*, 1992]. Primary structures (e.g. channels,
415 shields and flow fronts) provide evidence of the multiple genetic processes and distinct source
416 locations for the materials that form the unit. Except for younger materials with clear contact
417 relationships with these volcanic materials, most of the contacts of this unit are delineated as
418 approximate or gradational when these units are in contact with basal-shield transitional and
419 shield terrains; individual shields are also present in this unit. This unit correlates with unit flows
420 undivided (unit fu) in the AMA [*Hansen & López*, 2020]. Both units are composite and lack
421 stratigraphic significance across NMA and the AMA.
422
423   **4.2.2.2. Volcano-related flows, fracture fed flows**
424
425   Several flow units in the NMA are variably associated with different types of volcanic
426 structures (e.g., montes, tholi, paterae and fields of small volcanoes or colles) and can be
427 differentiated from the undivided material. Each of these material units include the name of their
428 associated volcanic feature (e.g., fmL, Lahar Mons flow material; fthE, Ezili Tholus flow
429 material; fpM, Malintzin Patera; fsA, Aserat Colles shield fields and associated flows). The
430 nature of the contacts vary for the different units; some units display clear flow margins that

431 allow delineation of contacts with sharp transitions; in other cases approximate contacts reflect
432 situations in which the areal limit of the unit is not clear due to the nature and orientation of the
433 radar contact and the interaction with secondary structures. Flow units associated with shield
434 fields (e.g., units fsL, fsJ, etc.) display gradational contacts due to the point sourced nature of this
435 type of volcanism. We differentiate these units from the shield terrain due to the larger size of the
436 shields that form the volcanic field, the presence of associated flows and the local temporal
437 relationship with unit vmu and other corona- and volcano-related units (i.e. locally postdate unit
438 vmu). This differentiation between shield terrain and younger shield fields have been noted
439 elsewhere on Venus [*Addington*, 2001].
440
441 **4.2.2.3. Corona-related material**
442
443 Many units within the NMA are corona-related deposits. The majority of the corona-
444 related material units are spatially associated with individual coronae as indicated by the material
445 unit name (e.g., fcI, Ituana Corona flows; fcE, Ereshkigal Corona flows), but in some cases
446 where coronae are close or clustered, the unique origin of flows is unclear, and unit names
447 indicate the names of the coronae or the region where these coronae are located (e.g. fcAt,
448 Atalanta Planitia coronae flows). Some coronae have more than one unit delineated when it is
449 possible to differentiate units at the map scale (e.g. Kunhild Coronae), but this is rare among
450 coronae in the NMA. This could indicate different stages of corona evolution [e.g., *Copp et al.*,
451 1998, *Smrekar & Stofan*, 1999]. Nevertheless, absence of subunits does not mean that multistage
452 corona evolution did not occur, but rather that we cannot identify multiple flows with existing
453 data.
454 Contacts of corona-related material with locally older units bst and st are delineated as
455 gradational given that individual shields are also present in the corona-related flows. The same
456 applies to contacts between corona-related materials and shield fields and associated flow
457 material.
458
459 **4.2.2.4. Crater material.**
460
461 The NMA includes two units that represent crater materials. Crater material undivided
462 (unit cu) includes radar-bright material associated with impact crater formation, including crater
463 ejecta and material inside the crater. Some craters present radar-dark interior deposits indicative
464 of embayment by younger flows that cannot be represented at the scale of the map, although
465 these deposits are visible in medium- and high-resolution images. The presence of such materials
466 in individual craters is noted in the associated crater table (Table 1) but not differentiated in the
467 map. This unit is descriptive with no implications for temporal equivalence across the map area.
468 A second unit, crater associated flows undivided (unit cfu), represents impact melt or fluidized
469 ejecta created by meteorite impact associated with the formation of individual impact craters; the
470 melt could be impact related, fluidized ejecta, or formed as a result of tapping pre-existing
471 subsurface magma. Exposures of this unit in most of the cases are small, and as such, not
472 delineated as individual units associated with specific impact craters. Both units are descriptive,
473 with no implications for temporal equivalence across the map area, these units are time-
474 transgressive having formed in association with individual impact craters and not as
475 lithostratigraphic packages.
476

4.3. Tectonic Structural Suites

Suites of tectonic structures define local or regional patterns that provide clues to operative tectonic or tectonomagmatic processes. We use the terms local and regional tectonic suites to delineate the different scale of tectonic suites. Local structural suites are generally spatially or geometrically associated with individual tectonomagmatic features such as coronae or montes. The timing of local structural suites likely corresponds to the formation, or stages of formation, of the individual features with which they are associated, although the development of these features and the related structural suites can be time-transgressive.

Regional structural suites describe coherent patterns across larger areas and commonly lack spatial or geometric correlation with individual geomorphic or geographic features. Temporal evolution of regional structural suites can be difficult to constrain given that these suites could form time-transgressively, and not necessarily formed at the same time across the expansive region where they are developed. Different surface units may be cut by a suite of regional structures, yet there is no guarantee that the entire suite of structures formed in a geological instance (or that there were not episodes of reactivation), frustrating efforts to interpret robust temporal constraints [*Hansen*, 2000].

4.3.1. Regional Tectonic Suites

NMA's regional tectonic suites are best preserved within planitiae. Although planitiae are commonly considered featureless, NMA planitiae are characterized by numerous suites of distributed deformation features. The most obvious of these regional suites are contractional wrinkle ridges, low topography sinuous structures spaced a few kilometers apart and up to a few hundred kilometers long that record low (<2%) layer contractional strain. We define two groups or patterns of regional wrinkle ridges: (1) a broadly arcuate wrinkle ridge suite that extends from east to west across the NMA, broadly concentric to Artemis Chasma to the south [*Hansen & Olive*, 2010]; (2) a second regional wrinkle ridge suite, orthogonal to the first one, that fans from NW-trending in western NMA to NE-trending in eastern NMA; this suite is broadly radial to Artemis Chasma to the south. Four suites of distributed lineaments (interpreted broadly herein as fractures) also within the planitiae: (1) a fracture suite radial to Artemis Chasma to the south; (2) a suite of NW-tending lineaments that marks the western termination of Ganis Chasma to the east [*Senske et al.*, 1992]; (3) a suite of closely-space NE-trending lineaments; and (4) a suite of closely-spaced NW-trending lineaments. The perspective gained through the collaborative mapping of the AMA [*Hansen & López*, 2020] and the NMA allow us to assign the regional tectonic suites within the NMA to two groups: (a) suites related to the Artemis superstructure [*Hansen & Olive*, 2010]; and (b) other regional suites.

4.3.1.1. Artemis superstructure-related suites

Structural suites related to the Artemis superstructure include extensive areal footprints: Artemis radial fractures (ARF; 12,000 km-diameter) and Artemis concentric wrinkle ridges (ACWR, 13,000-km diameter) [*Hansen & López*, 2018; *Hansen & López*, 2020; *Hansen & Olive*, 2010]. The first suite is broadly defined to include fractures, graben, dikes, lineaments, pit chains, stoping troughs, and describes a pattern radial to Artemis Chasma. This suite extends across most of NMA—well-preserved in central NMA and partly present in the west and

southeast. The suite is mostly absent in the northeast, as discussed in the geologic history. In Niobe, Sologon and Llorona planitiae several small coronae appear geographically related with ARF (e.g. Kubebe Corona in Llorona Planitia; Allatu, Bumiya and Dhisana coronae in Sologon-Niobe Planitiae). These features, referred to as circular-lows [*Shankar*, 2008], typically lack radial fractures.

The ACWR suite, previously described as circum-Aphrodite wrinkle ridges [*Billoti & Suppe*, 1999], defines a footprint concentric to Artemis Chasma [*Hansen & Olive*, 2010]. Wrinkle ridges are notably absent within ribbon-tessera and basal terrains, even in high-resolution SAR images; although wrinkle ridges locally cut intratessera basin material. Wrinkle ridges occur right up to the contact between ribbon-tessera terrain, basal terrain, and surrounding units, such as bst, st and vmu. These relations indicate that ribbon-tessera and basal terrain are not rheologically amenable to wrinkle ridge formation (that is, these units lack a thin deformable layer), whereas the thin basal-shield transitional terrain, shield-terrain, and unit vmu can form wrinkle ridge structures.

The ACWR suite cuts numerous flows associated with individual coronae or montes, providing clear evidence that such flows predated formation of this huge wrinkle-ridge suite. However, some corona-/mons-associated flows do not host wrinkle ridges; these relations could indicate that these flows formed after the Artemis-concentric wrinkle-ridge forming event, or that 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 Uti Hiata Mons (unit fmU1) do not show obvious development of wrinkle ridges, however, wrinkle ridges clearly cut the distal edges of these flows (unit fmU2). Thus, at least distal flows predated ACWR formation. If these flows post-dated formation of the ACWR suite, we might expect numerous examples illustrating the interaction of flows and pre-existing wrinkle ridge topography; however such relationships are not apparent. Some of the flows (e.g., proximal flows) might be too thick to have been affected by wrinkle ridge formation. It is also possible that Uti Hiata Mons formed during a period when some flows formed before and others formed after the Artemis - concentric wrinkle ridge- suite. The evolution and construction of a large volcano such as Uti Haita Mons, and the formation of a regional suite of wrinkle ridges are both likely to be time-transgressive, and plausibly each could last 10's to even 100's of millions of years.

The ARF and ACWR suites together define the Artemis superstructure, interpeted to have formed in association with the Artemis superplume [*Hansen & Olive*, 2010]. The ARF broadly pre-dates formation of the ACWR. At any one location concentric wrinkle ridges and radial fractures are mutually orthogonal. A second large suite of wrinkle ridges in NMA, orthogonal to ACWR, is interpreted to have formed due to inversion of buried ARF structures. Numerous Artemis-radial fractures locally 'end' abruptly where they are buried by younger deposits (e.g. volcanic material, undivided; corona-related flows); the fractures end, but transition into straight wrinkle ridges along trend. We interpret this occurrence of fractures and wrinkle ridges as early formed fractures that were buried and subsequently inverted during regional contraction to form topographically positive lineaments [e.g. *DeShon et al.*, 2000]. Thus, we interpret the orthogonal pattern of wrinkle ridges in various planitiae to be the results of Artemis-concentric wrinkle ridges and orthogonal inversion structures.

4.3.1.2. Other regional structural suites

569 We identify two regional fractures suites. These suites principally deform basal materials,
570 but also occur locally in thin deposits that postdate basal units.
571 The NW-trending regional fracture suite extends across most of the NMA cutting units
572 bst, st and vmu; it is dominately developed within bst in central and eastern NMA, and also
573 occurs in Leda Planitia, northwest NMA. In Akhtamar Planitia (SW NMA), these fractures are
574 locally restricted to basal materials in Lemkechen Dorsa and surrounding basal terrains. The
575 fractures are closely spaced and relatievely short, compared to ARF. Where these fractures cut
576 basal materials and local volcanic materials adjacent to ribbon-tessera terrain, they parallel the
577 trend of adjacent ribbon structures (e.g. locations around Gegute Tessera and Uni Dorsa in Niobe
578 Planitia), consistent with structural reactivation of earlier-formed ribbon structure anistotropy.
579 NE-trending regional fractures mostly occur in Leda Planitia, and in isolated locations
580 cutting units bst and st in Lowana and Llorona planitiae. Fractures in Leda Planitia are long and
581 locally recognizable as paired lineaments, indicating that these are mostly likely graben;
582 however, lineament orientation with respect to SAR acquisition is not optimal for
583 characterization. Elsewhere these structures can only be resolved as lineaments, and display
584 shorter lengths and closer spacing than in Leda Planitia. It is possible that these lineaments
585 represent different genetic suites with similar orientation.
586 We suggest that the NW- and NE-trending suites predate ARF. Perhaps the most robust
587 evidence for this relative timing emerges from broad geologic relations in which units vmu and
588 st that locally bury the NW- and NE-trending fracture suites, are cut by ARF (e.g., 5°N-
589 20°N/135°E-145°E).
590
591 ### 4.3.1.3. Fracture zones
592
593 The only fractures zone in the NMA is associated with the northwestern termination of
594 Ganis Chasma, contrary to the AMA where fracture zones define an extensive tectonic domain
595 [*Hansen & López*, 2020]. The part of Ganis Chasma expressed in the NMA lacks the topographic
596 expression and fracture density that characterize the chasma closer to Atla Regio from which it
597 radiates. Within the NMA spaced fractures and graben preserve the identity of host material they
598 cut: ribbon-tessera terrain (Athena and Nemesis tesserae), basal terrain, and volcanic materials.
599 Locally fractures covered by thin volcanic materials form inversion wrinkle ridges.
600
601 ### 4.3.2. Local Tectonic Suites
602
603 Local tectonic structures display linear, radial or concentric spatial patterns, typically
604 associated with individual deformation belts, coronae or large volcanic features. We briefly
605 describe areas of concentrated deformation, followed by suites associated with large
606 tectonomagmatic features.
607 The NMA hosts several deformation belts (also called ridge belts) mark topographic
608 boundaries between planitiae; parallelism of belt and internal structural trends that vary from belt
609 to belt. Collectively the belts might be considered regional given their broad distribution across
610 the NMA, but we consider them as local tectonic features herein: NW-tending Lemkechen and
611 Unelanuhi dorsum in southwest NMA; NE-trending Mardezh-Ava Dorsa in central western
612 NMA; N-trending Poludnista Dorsa in the southeastern most NMA; and the largest belts
613 consisting of NNE-trending Vedma and Oya dorsum, and Nephele and Frigg dorsum, in Atalanta
614 and Vellamo planitiae, respectively.

615   NW-trending Uni Dorsa and Lumo and Barballe dorsum differ from the deformation
616 belts described herein. Uni Dorsa (800 km long) consists of ribbon-tessera with folds parallel to
617 the dorsa (and ribbons normal to the dorsa); the tessera inlier is part of a larger quasi-circular
618 ring of ribbon-tessera terrain together with Likho Tesserae, marking the boundary between
619 Niobe Planitia and Vellamo Planitia. NW-trending Lumo and Barballe dorsum (500 and 1200
620 km long, respectively), spaced ~1000 km apart, comprise unit btu cut by NW-trending regional
621 fractures.
622   NW-trending Lemkechen and Unelanuhi dorsum (200 and 2600 km long, respectively)
623 form outcrops of discontinuous unit btu that predates local volcanic materials in Akhtamar
624 Planitia. The outcrops are characterized by broad anastomosing dorsum-parallel ridges and folds.
625 Wrinkle ridges that cut the young volcanic materials parallel the ridge belts and internal folds,
626 but differ in morphology, size and spacing.
627   In northern Akhtamar Planitia, NE-trending Mardezh-Ava Dorsa (900 km long) includes
628 NE-trending folds and fractures formed prior to the emplacment of material of the adjacent
629 volcanic plains.
630   In southeasternmost NMA, and continuing to the AMA, Poludnista Dorsa (1500 km long)
631 within Rusalka Planitia comprises a N-trending deformation belt that predated regional wrinkle
632 ridges of the Artemis concentric suite (for a detailed structural analysis of Poludnista Dorsa see
633 *Young & Hansen*, [2005].
634   Large deformation belts in Vellamo and Atalanta planitiae describe a fan-shaped pattern
635 with N-trending Nephele Dorsa (1900 km long) to the west and NNE-trending Vedma (3350 km
636 long) and Oya (480 km long) dorsum in the east, and NNE-trending Frigg Dorsa in between.
637 Nephele Dorsa forms a narrow belt of isolated exposures of btu; Frigg Dorsa is twice as wide but
638 half the length. Vedma and Oya dorsum, which collectively extend from ~15° N to 55° N, are
639 characterized by btu, cut by belt-parallel folds. Ribbon-tessera terrain occurs locally within
640 Vedma Dorsa, although at a scale below map resolution. NW-trending lineaments within btu
641 parallel local ribbon-tessera fabric trends. AWCR in the surrounding units trend orthogonal to
642 the deformation belt folds. Locally wrinkle ridges parallel the deformation belts and the expected
643 trend of Artemis-radial fractures at such locations. These relations could be interpreted as
644 reorientation of wrinkle ridges around still active deformation belts, or as reactivation of Artemis
645 radial fractures. Both interpretations support a time-transgressive and non-singular history of
646 wrinkle ridge formation in the NMA.
647   Local structural suites associated with individual coronae or volcanic features stand out
648 prominently on the geological map. These suites are mostly radial and concentric fractures, with
649 some isolated examples of volcanotectonic structures that show radial wrinkle ridges or
650 concentric ridges. Individual radial or concentric suites formed during the evolution of their host
651 feature, however there is no temporal equivalence inferred for spatially distinct radial or
652 concentric suites.
653   Tectonomagmatic features that display local radial suites are grouped in four locations:
654 (1) Akhtamar Planitia; (2) northern Lowana Planitia; (3) Atalanta Planitia; and (4) the equatorial
655 highlands. Some radial fracture suites can extend great distances from their foci, and therefore
656 might be useful as local temporal markers for unit delineation (i.e., Cinacoatl Mons in Atalanta
657 Planitia and Kurukulla Mons in Till-Hanun Planitia).
658   In Akhtamar Planitia radial fracture suites connect large, otherwise isolated,
659 tectonomagmatic centers (Hatshepsut Patera-H'uraru Corona, Uti Hiata Mons, Kaltash Corona,
660 Kunhild Corona, Ereshkigal Corona), forming an extensive interconnected suite that might

661 appear similar to regional fracture zones. However, contrary to fracture zones in the AMA, these
662 radial fractures do not obscure the identity of host materials. This tectonomagmatic chain extends
663 southward into the AMA, connecting with an unnamed structured centered at 8º S/72º E and
664 terminating in Ix Chel Chasma south of Ova Regio. This corona chain divides Manatum Tessera
665 (western Ovda) from central Ovda Regio. Potential implications of this segmentation of the
666 equatorial highlands remain to be studied.

667   In northern Lowana Planitia, radial fractures of Kurukulla Mons progressively change
668 orientation to a N-S trend away from the magmatic center, parallel to the local ARF trend.

669   In Atalanta Planitia radial fractures with a focus of Cinacoatl Mons, extend >1000 km to
670 the west with a ENE trend, likely the result of the operative regional stress field away from the
671 volcanic source, at the time of fracture formation.

672   Similar to radial fractures associated with coronae in Akhtamar Planitia, other large local
673 radial fracture suites occur in the equatorial highlands in the area that separates Thetis Regio and
674 Haastte-baad/Gegute tesserae. Rosmerta and Blai coronae display radial fractures that extend
675 100's to 1000's of kilometers. Blai Corona connects with Ceres Corona to the southeast, part of
676 the Diana-Dali corona-chasma chain in the AMA [*Hansen & López*, 2020]. The relationship of
677 Rosmerta Corona with corona-chasma chains in the AMA is less clear. To the north, in the
678 volcanic plains of Llorona planitia, radial fractures of Rosmerta and Blai coronae trend N.

679   Other local radial fracture suites associated with small features are typically areal
680 restricted to the vicinity of their respective volcanic centers (e.g. Zaltu Mons and Heqet Corona).

681   Local concentric fractures are associated with many volcanic features (e.g. paterae-
682 caldera and coronae). Most coronae in central NMA are ascribed to the calderic or circular lows
683 subclass of coronae [e.g. *DeLaughter & Jurdy*, 1999; *Shankar*, 2008], characterized by
684 concentric fractures similar to that of volcanic caldera, and lacking clear radial fracture suites.

685   Local folds suites that form concentric to some coronae (e.g. Ituana Corona), could be
686 inversion structures (earlier-formed concentric fractures subsquently covered by thin volcanic
687 flows), or gravity related structures [e.g. *Sandwell et al.*, 1997].

688   A local suite of radial wrinkle ridges is restricted to Fedosova Patera; outward from the
689 volcanic edifice the wrinkle ridges align with the adjacent ACRW. Different formation
690 mechanisms for the formation of radial wrinkle ridges were discussed by *Buczkowski* [2006] for
691 the case of Irnini Mons.
692
693   **4.4. Impact Features**
694
695   NMA hosts 146 impact craters, ranging from 1.9 to 98.1 km diameter. Table 1 lists
696 impact crater location, diameter, elevation, crater density [e.g., *Herrick et al.*, 1997], host
697 material units, etc. Most of the craters are included in existing Venus crater data bases [e.g.,
698 *Schaber et al.*, 1992; *Herrick et al.*, 1997]. Each impact crater displays an interior, rim and ejecta
699 deposit (unit cu); 40 percent have parabolic or halo deposits [e.g., *Izenberg et al.*, 1994]. Central
700 peaks are rare for craters with diameters <10 km. Impact crater deposits are shown as unit cu,
701 crater material undivided, representing interior and ejecta deposits associated with local bolide
702 impact. Each impact crater formed during a unique spatial and temporally localized event,
703 therefore, composite unit cu is diachronous across the map area. Thus, unit cu is a descriptive
704 unit, and does not imply temporal correlation. About 35-40% of the craters display interiors with
705 radar-smooth material similar to the surrounding lowland material. Interior materials are too
706 small to be represented at map scale but their presence is indicated in Table 1. These deposits are

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]. 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 meters and rim height (measured from rim to the adjacent surroundings) of 240 meters, 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 (*Hansen*, [2000], figure 3 therein, for a possible mechanism). This means that the occurrence of an impact crater on a host unit cannot robustly indicate relatively timing of unit and crater emplacement. Geologic mapping using high-resolution DEMs [e.g., *Herrick & Rumpf*, 2011] has not been employed in NMA construction.

Temporal relations between impact craters and tectonic events can be difficult to robustly constrain. If an impact 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 nine craters show evidence of deformation, however, an apparent lack of deformation is not a robust positive test for impact crater formation after local tectonic activity given the spaced nature of tectonic deformation fabrics and the point location of individual craters. Of the craters that show deformation, six occur on ribbon-tessera and basal terrains, one on shield terrain and two on corona-related units.

Sixty craters locally cover Artemis-related structures. Twenty-two locally cover or follow Artemis radial fractures; forty locally cover Artemis concentric wrinkle ridges; two craters locally cover both. 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 twenty-seven of the craters that locally cover Artemis tectonic suites have interior fill that matches the radar reflectivity of their surroundings. These relations likely indicate a history of early Artemis-structure formation, followed by impact crater formation, following in turn by interior flooding of these individual craters.

Fifteen craters display crater-associated flow material, unit cfu. Ferrier and Cochram craters present flows are large enough to be mapped as individual units; however, these flows are included in unit cfu for mapping consistency. Ferrier and Himiko craters reside in regions marked by concentric fracture suites on the flanks of coronae. Both impact craters tapped into subsurface magma chambers, presumably associated with their respective coronae. 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 locations relative to host coronae. The rest of the impact craters are not associated with magmatic centers; these features formed by impact on basal terrains and units bst and st. In these cases, the presumed sources of flows are subsurface magma chambers or magma accumulations near the surface but without manifestation in form of concentric fractures, or material produced due to the impact process (i.e. melting of the impacted materials).

These data and observations, independently and taken together with the observation that ~ 40% of the craters within the NMA show interior flooding, indicate that a significant number of impact craters within NMA experienced notable geological events (i.e., interior fill emplacement) after crater formation. These results are contrary to initial surveys of the Venus

753 crater population conducted using NASA Magellan data that concluded that only a few percent
754 of Venus craters were deformed or embayed by volcanic material [*Schaber et al.*, 1992; *Phillips*
755 *et al.,* 1992; *Strom et al.*, 1994; *Collins et al.*, 1999]. These new data are consistent with findings
756 of *Herrick and Rumpf* [2011], and are difficult to accommodate within the context of
757 catastrophic resurfacing models or any resurfacing models that require the vast majority of
758 Venus impact craters to mark the top of the stratigraphic column [e.g., *Turcotte*, 1993; *Strom et*
759 *al.*, 1994; *Solomatov & Moresi*, 1996; *Turcotte et al.*, 1999; *Basilevsky & Head*, 1998, 2000,
760 2002a, 2002b, 2006; *Basilevsky et al.*, 1997, 1999; *Reese et al.*, 2007; *Romeo & Turcotte*, 2010;
761 *Romeo*, 2013; *Ivanov & Head*, 2015a,b; *Kreslavsky et al.*, 2015]. Thus, crater relations within the
762 NMA cast doubt on the conclusions of these studies. In addition to the data described herein, a
763 growing number of studies similarly indicate that hypotheses of catastrophic resurfacing, or
764 hypotheses that call for late formation of most impact craters on Venus are inconsistent with
765 geologic relations and/or modeling [e.g., *Guest & Stofan, 1999*; *Herrick & Sharpton*, 2000,
766 2002; *Hansen & Young*, 2007; *Hansen & López*, 2010; *Hansen & Olive*, 2010; *Herrick & Rumpf*,
767 2011; *Bjonnes et al.*, 2012; *O'Rourke & Korenaga*, 2015], and collectively challenge
768 assumptions that the Venus crater population represents a limited, young, geologic time period.
769
770 **5. Geologic History**
771
772   A rich geologic history emerges from the geologic map of the NMA. Given the absence
773 of elements of regional correlation we define local temporal relationships that help to constrain
774 local geologic histories; however, these local histories cannot confidently be extrapolated across
775 NMA or to Venus globally. Tessera terrain and other basal materials formed locally early,
776 followed broadly by the time-transgressive evolution of the Artemis superstructure, coronae,
777 montes, and lowland volcanic deposits.
778   Basal ribbon-tessera terrain units formed early across NMA and in a time-transgressive
779 manner. That is, not all ribbon-tessera formed in one event, although these distinctive terrains
780 likely formed within a geological era marked by specific geologic conditions, most notably an
781 era marked by thin global lithosphere [*Phillips & Hansen*, 1994; *Bindschadler*, 1995; *Hansen et*
782 *al.*, 2000; *Hansen*, 2006].
783   We distinguish three different groups of ribbon-tessera terrain: (a) within the equatorial
784 crustal plateaus including west and central Ovda Regio and Thetis Regio, (b) within Tellus
785 Regio, and (c) as inliers distributed across the NMA. All three groups of ribbon-tessera terrain
786 present similar tectonic fabrics with local variations in trend and degree of embayment.
787   Ribbon-tessera tectonic fabric evolved through progressive deformation of a strong thin
788 layer above an extremely low-viscosity layer over a strong substrate [*Hansen*, 2006], indicating a
789 high heat flow across the areal extent of individual crustal plateaus [*Ruiz*, 2007], which are
790 characterized by ribbon-tessera terrain. Tectonic fabric evolution was accompanied by formation
791 of local intratessera volcanic basins filled with low-viscosity volcanic materials [*Bindschadler et*
792 *al.*, 1992; *Hansen & Willis*, 1996, 1998; *Gilmore et al.*, 1998; *Hansen et al.*, 2000; *Banks &*
793 *Hansen*, 2000; *Hansen*, 2006]. Evidence for this style of volcanic activity is preserved in Ovda,
794 Thetis, and Tellus regiones due to high topography. However, clear differentiation between
795 intrastessera basin material and significantly younger volcanic material is difficult in tessera
796 inliers due subdued topography (e.g. Haasttse-baad Tessera).
797   Tectonic patterns in the ribbon-tessera inliers (e.g. Gegute and Haasttse-baad tesserae in
798 Llorona Planitia, Shimti, Kutue and Ananke tesserae crossing through Lowana, Niobe and Tilli-

799 Hanun planitiae; and Nemesis and Athena tesserae in Atalanta Planitia) show coherent patterns
800 across regions similar in size to that of crustal plateaus [*Hansen & López*, 2010]. Such regionally
801 coherent patterns across such expansive regions is consistent with the idea that ribbon-tessera
802 inliers represent ancient packages similar to crustal plateau surfaces [*Bindschadler*, 1995; *Ivanov*
803 *& Head*, 1996; *Phillips & Hansen*, 1998; *Hansen & López*, 2010].

804 Assemblages of basal terrain are exposed locally (e.g., unit btL), commonly in contact
805 with ribbon-tessera terrain, and as isolated outcrops or kipukas. Origin of these basal terrains is
806 not clear, nor is it required that all basal terrain formed in the same fashion. Basal terrains could
807 have formed before, during, or after the era during which ribbon-tessera terrain formed, and
808 could mark areas between regions of ribbon-tessera terrain. Exposures of basal terrain are cut by
809 different tectonic structures. In some locations, these tectonic structures can be resolved only as
810 close-spaced lineaments, but in most cases the tectonic structures appear to be comprised of
811 closely-spaced fractures. In eastern NMA (e.g., Vedma Dorsa) NNE-trending outcrops of basal
812 terrain are deformed by folds and broad ridges.

813 In central and western NMA regional NW-trending fractures cut basal terrain, with
814 fractures parallel to adjacent tessera fabric trends; units bst, st and vmu postdate basal terrain.
815 NW-trending fractures within younger volcanic units are due to incomplete burial, or structural
816 reactivation, or both.

817 In northwest NMA NE-trending fractures cut basal terrain with fracture trends parallel to
818 adjacent tessera fabric trend; NE-trending fractures both cut, and are covered by unit bst. Other
819 local units (e.g., units st and fpHC) display NE-trending wrinkle ridges, parallel to, and in
820 continuation of, fractures of the basal terrain; we interpret these wrinkle ridges as inversion
821 structures of buried fractures [e.g. *DeShon et al.*, 2000]. All these previous materials and events
822 would belong to the ancient era.

823 Various volcanic units, emplaced after tessera and basal terrain deformation, form the
824 NMA volcanic plains. It is difficult to establish a singular chronology across the map area.
825 Although the large tectonic suites of the Artemis superstructure (ARF and ACWR) constrain
826 some temporal relations, evolution of the Artemis superstructure is not temporally constrained,
827 and is likely time transgressive. Therefore, these suites cannot impose robust temporal
828 constraints.

829 In the lowlands due north of Aphrodite Terra—the volcanic plains, composed mostly of
830 units bst and st, also lack robust temporal relations. Unit st in composed exclusively by small
831 shields, but local exposures of unit bst also present embayed intermediate volcanoes [e.g. *López*,
832 2011] and small coronae without evident associated flows (i.e. circular lows).

833 In general, ARF and ACWR cut units bst and st, although locally individual shields could
834 postdate these tectonics structures. One possible mode of the formation of unit st (or bst) is
835 heating from below by the Artemis superplume, driving *in situ* partial melting of the overlying
836 crust and subsequent emergence of point-source shield formation. There is a possible spatial
837 association, consistent with (but not requiring) a genetic association, between ribbon-tessera
838 terrain and shield terrain. In western and central NMA, spatial association between units bst and
839 st and ribbon-tessera terrain appears obvious, with large expanses of units bst and st located in
840 and around large ribbon-tessera terrain blocks and inliers. In contrast, units bst and st are rare in
841 Rusalka, Vellamo and Atalanta planitiae, all regions that generally lack ribbon-tessera terrain.

842 Large corona-related flow units that locally postdate units bst and st occupy a large
843 region adjacent to Aphrodite Terra. These units (fcK, fcRo and fcOv) consist of low viscosity
844 flows that extend great distances and postdate tessera, bst and st. Unit fcOv is a huge composite

845 unit composed of flows from several coronae and volcanic structures; this unit cannot be used as
846 a detailed a temporal marker. Some of material is easily traced to specific coronae, such as
847 Kaltash (unit fcK), Rosmerta (fcRo) and Blai (fcB) coronae. These coronae, which formed on
848 ribbon-tessera terrain, are characterized by large local radial fracture suites and topographically
849 low corona annulus.
850   In this area it is also difficult to constrain temporal relations between coronae-related
851 fractures and ARF structures. Flows of unit fcOv both cover and are deformed by ARF and
852 ACWR; however, the composite nature of unit fcOv precludes the establishment of reliable
853 temporal relations. Kaltash and Rosmerta coronae also display well-developed radial fracture
854 suites, which further frustrate efforts to robustly constrain temporal relations with the Artemis-
855 superstructure related suites. Given that ARF do not clearly transect these coronae, we expect
856 that the coronae broadly post-date the formation of ARF; or rather, that the evolution of these
857 coronae outlasted formation of ARF. However, ACWR cut distal flows sourced from Rosmerta
858 Corona (e.g. unit fcRo). Thus it is possible that the Artemis superstructure began to form prior to
859 the formation of Rosmerta, and formation of Rosmerta temporally overlapped with, and
860 outlasted, that of the Artemis-superstructure.
861   In Akhtamar Planitia a cluster of tectonovolcanic structures postdate emplacement of
862 local lowland materials. Temporal relations with regard to ARF and ACWR are difficult to
863 constrain given that the local tectonic structures mimic the trends of these regional structures.
864 The cluster formed by Ereshkigal and Kunhild coronae and their associated materials (units fcE,
865 fcKu1 and fcKu2) has been interpreted as result of the formation of a now-extinct hot-spot
866 [*Herrick & McGovern*, 2000]. Coronae-related materials are locally covered by younger volcanic
867 flows associated with Ezili Tholus (unit fthE), a flat-topped volcano located northeast of the
868 center of proposed extinct hot-spot (Ezili Tholus could be interpreted as part of late hot-spot
869 evolution). Other large volcanic structures postdate the ARF and ACWR suites in Akhtamar
870 Planitia. Uti Hiata Mons is a complex magmatic system with associated flow units (units fmU1
871 and fmU2) that locally postdate units bst, st and vmu and other previous volcanic structures
872 (embayed intermediate volcanoes; see figures 4a and 4f in *López*, [2011]). Hatshepsut Patera
873 (northern Akhtamar Planitia) represents a complex magmatic system composed of concentric
874 fractures that define a caldera surrounded by flow material (unit fpH) and late steep-sided domes.
875   Collectively Kurukulla Mons, Hiei Chu Patera, Amra Tholus and several other unnamed
876 volcanic structures comprise a large volcanic cluster located between northern Lowana Planitia
877 and Tilli-hanun Planitia. Contact relations between materials associated with Kurukulla Mons
878 and Hiei Chu patera (units fmK and fpHC) are difficult to constrain due to the absence of clear
879 radar contacts and the presence of shields in both units; contacts are mapped as approximate.
880 Flows from Amra Tholus and an unnamed volcanic edifice postdate radial fractures of Kurukulla
881 Mons; however, it is not clear if these flows postdate all the activity in Kurukulla Mons or
882 simply the formation of radial fractures. Temporal relations of all these units with respect to ARF
883 and ACWR suites are difficult to determine given that radial fractures of Kurukulla Mons
884 parallel ARF. ACWR cut some parts of units fmK, fpHC and fpu1, however local wrinkle ridges
885 suites, interpreted as inversion structures, also deform these materials.
886   In Lowana Planitia volcanic units associated with shield clusters or volcanic fields (units
887 fsSh and fsLw) postdate units bst, st and vmu. The point-sourced nature of shields and the
888 presence of shields in each unit renders contact delineation difficult; contacts are mapped as
889 gradational.

890   Central NMA is dominated by units bst and st, which predate ARF and ACWR, and
891   corona- and volcano-related units (fcA, fmUa and fpJ); the later units locally bury ARF but are
892   cut by ACWR. In Niobe Planitia we interpret N-trending wrinkle ridges in unit vmu as having
893   formed by structutral inversion of ARF structures, with unit vmu locally postdating units bst and
894   st, with Maa-ema Corona serving as a possible source for unit vmu.
895   In eastern NMA ribbon-tessera and basal terrain predate emplacement of composite units
896   bst, st and vmu, and local corona- and volcano-related units (units fcI,fcV and unit fsL). In
897   Rusalka Planitia corona-related flows locally postdate unit vmu (unit fu of *Young & Hansen*,
898   [2003]). These corona-related materials (units fcRu1 and FcRu2) are in turn locally postdated by
899   small volcano related flows (units fmI, fmLa and fmM) and volcanic materials associated with
900   shield fields (units fsA, fsR and fsZy). The areal extent of unit vmu in the eastern NMA is more
901   extensive than elsewhere; however, vmu is a composite unit with potentially many different
902   sources. Unit vmu hosts numerous circular topographic rims that could represent buried coronae
903   and that indeed could be source of at least part of this composite unit in this region. Eastern
904   NMA also hosts a large number of volcanic channels or canali. Baltis Vallis, Venus' longest
905   volcanic channel, runs through most of this part of the map area in unit vmu. Within Rusalka
906   Planitia areally localized volcano-related units (fmZ) and materials related to shields fields
907   (fsRk) postdate unit vmu. These shield-related volcanic materials are locally cut by Ganis
908   Chasma fractures. Ganis Chasma is considered a young feature in the geologic evolution of
909   Venus [*Basilevsky*, 1998]. Both the fracture density and topographic signature of the terminous
910   of Ganis Chasma in the NMA are more muted than in Atla Regio, where recent volcanic activity
911   has been proposed [*Shalygin et al.*, 2015].
912   In Atalanta Planitia a large corona-related composite unit formed by flows from different
913   volcano-tectonic structures (Holde and Mari coronae, and Cinacoatl Mons) (unit fcAt) occupies
914   much of northeastern NMA. This unit locally postdates basal materials and unit vmu; distal
915   flows of unit fcAt postdate Baltis Vallis in Atalanta Planitia. These corona-related materials are
916   locally covered by small shields and associated flows from Jurate Colles (unit fsJ), that also
917   postdate unit vmu and tessera terrain of Ananke Tessera. Other local volcanic units sourced from
918   fractures and volcanic centers postdate unit vmu in Atalanta Planitia (unis fpF, fpu2 and ffr).
919   In western NMA the ACWR suite is well developed. NW-trending fractures could
920   represent ARF, or fractures related to coronae and/or montes, or both; the trends fit both
921   interpretations. Vellamo, Atalanta, and Rusalka planitiae display two suites of mutually
922   orthogonal wrinkle ridges—ACWR, and parallel to ARF. It is likely that the latter suite
923   represents buried ARF (by unit vmu) reactivated as inversion structures [e.g. *DeShon et al.*,
924   2002].
925   In general, the geologic history of the NMA is complex and diverse, with multitude of
926   volcanic units that postdate basement materials. Most of these volcanic materials form composite
927   units and we stress the importance that point-sourced volcanic activity played in the geologic
928   evolution of the NMA (units bst and st), as first noted by *Aubele* [1996]. There also appears to be
929   a broad spatial association of these units to ribbon-tessera inliers. Numerous coronae and large
930   volcanoes form local clusters that postdate basement materials and basal plain materials (units
931   bst and st). The main regional tectonic suites are related to the formation and evolution of the
932   Artemis superstructure and can be used as a local relative temporal marker; however, one must
933   be cognizant that the duration of Artemis superstructure evolution is unknown. Other regional
934   and local tectonic suites deform the NMA materials and interact with volcanic flows depicting a
935   rich and complex geologic history that can only be constrained locally in absence of reliable

936 temporal markers. Geologic relations preserved within the NMA do not support catastrophic
937 resurfacing models, but instead are consistent with complex geologic evolution of the Venusian
938 lowlands.

939   **6. Conclusions**

940   The geologic mapping of the NMA provide first-order observations and/or geologic
941 implications enumerated below.
942   1. Geologic mapping of the NMA supports observations made in the AMA that
943   show broad geologic domains, and broad cross-cutting temporal relationships in this part of
944   the planet. Patterns are mostly defined by the mapping of structural elements that show
945   coherent patterns across both map areas [*Hansen & López*, 2018]. The three tectonic domains
946   defined in both map areas include, from oldest to youngest (Figure 2): 1) an Ancient era
947   represented by ribbon-tessera terrain (including intra-tessera basin material) in both crustal
948   plateaus and lowland inliers, and locally developed basal terrain; 2) Structures associated
949   with the development of the Artemis superstructure, including Artemis-radial fractures and -
950   concentric wrinkle ridge suites; and 3) a younger era characterized by the development of
951   fracture zone terrain, including chains of coronae and chasmata.
952   2. The Ancient era is well represented by different lithodemic units distributed
953   across the NMA (Figure 2). Ribbon-tessera terrain is found within the equatorial crustal
954   plateaus (west and central Ovda Regio and Thetis Regio), Tellus Regio, and as inliers of
955   different size scattered acroos the map area. Ribbon-tessera terrain units formed early across
956   NMA and in a time-transgressive manner in an era marked by thin global lithosphere
957   [*Phillips & Hansen*, 1994; *Bindschadler*, 1995; *Hansen et al.*, 2000; *Hansen*, 2006]. Other
958   assemblages of basal terrain are locally exposed Basal terrains that could have formed before,
959   during, or after the era during which ribbon-tessera terrain formed, and could mark areas
960   between regions of ribbon-tessera terrain.
961   3. Shield terrain, a unique style of volcanic unit first recognized and described by
962   *Aubele* [1996] in Niobe Planitia and later characterized in detail by *Hansen* [2005], occurs
963   across much of NMA. Shield terrain postdates ribbon-tessera terrain inliers and basal terrains
964   in lowland locations, however its evolution requires further study. This lithodemic unit likely
965   formed broadly time-transgressive; it is not clear if formation of shield terrain started in the
966   ancient era or later in the history of the volcanic plains, or both. Evidence for formation of
967   shield terrain late within the ancient era, but perhaps relatively early within the Artemis
968   superplume era includes: the occurrence of transitional materials between shield terrain and
969   the basal units, and that shield terrain both cuts and is cut by Artemis Chasma-radial
970   fractures; and yet Artemis Chasma-concentric wrinkle ridges (which post-date the ARF
971   suite) generally cut shield terrain deposits. These relations lead most directly to temporal
972   constraints in which shield within the NMA formed prior to and/or early during the evolution
973   of the Artemis superstructure (that is, overlapping in time with the formation of the ARF
974   suite), and was broadly emplaced prior to development of the extensive Artemis Chasma-
975   concentric wrinkle-ridge suite—which represents late-stage evolution of this huge structure
976   (*Hansen & Olive*, 2010). One would /could expect that the geologic transition between the
977   ancient era and the Artemis superstructure era might be time-transgressive, rather than
978   geologically catastrophic.
979   4. Artemis-radial fractures and Artemis-concentric wrinkle ridges defined regional
980   patterns relative to Artemis Chasma (12,000 km and ~13,000 km diameters, respectively)

981 irrespective of the material units they deform (Figure 2), consistent with geologic relations
982 documented within the AMA. Artemis radial fractures are more difficult to define in the
983 NMA than in the AMA due to: the distance to Artemis Chasma; the location of the Aphrodite
984 Terra crustal plateaus between Artemis Chasma and the NMA lowlands; and the occurrence
985 of, and interaction with, other local tectonic suites. However, regional-scale map relations
986 documents in both the AMA and the NMA together illustrate a clear pattern. Somewhat in
987 contrast, the regional pattern of the Artemis-concentric wrinkle ridge suite is quite clearly
988 defined within the NMA, particularly in southern and central NMA; equally important, this
989 extensive wrinkle ridge suite is difficult to define in the north part of the NMA, which
990 provides a boundary or spatial termination of this extensive suite. By comparison, the
991 boundaries of this suite lie outside the spatial limit of the AMA.
992   5. Undivided volcanic materials and materials and local tectonic suites associated
993 with individual tectonovolcanic structures postdate materials and structures of the ancient
994 era. Much of this material likely formed during the era related to the evolution of the Artemis
995 superstructure, or during the transition of this era to the youngest facture zone era. It is
996 difficult to establish a singular chronology across the map area. Although the large tectonic
997 suites of the Artemis superstructure constrain some temporal relations, evolution of the
998 Artemis superstructure is not temporally constrained, and likely time transgressive.
999 Therefore, these suites cannot impose robust temporal constraints. Some tectonovolcanic
1000 structures seem to postdate, or at least have outlasted, formation of the Artemis
1001 superstructure given that associated flows are not apparently deformed by the Artemis-
1002 concentric wrinkle-ridge suite. However, such flows could also predate wrinkle-ridge
1003 formation, given that that individual flows, or parts of flows, could be rheologically
1004 unfavorable to the formation of wrinkle ridges. Geologic relations documented within NMA
1005 are consistent with a time-transgressive transition from the Artemis superstructure era to the
1006 fracture zone era.
1007   6. The Fracture Zone Domain era is little represented in the NMA compared to the
1008 AMA. In the NMA we observe the termination of fracture zones (e.g. Ganis Chasma) where
1009 fracture density is lower that in the fracture zones observed in the AMA, and where precursor
1010 materials can be observed. Coronae within NMA, particularly those near the southern
1011 boundary with AMA (e.g., Blai, Rosmetra, Kaltash) could represent distal limits of the
1012 fracture zone domain, which includes coronae and chasmata. Further study, including more
1013 detailed geologic mapping may shed light on these relationships.
1014   7. Impact craters clearly formed time-transgressively across the NMA relative to
1015 each of the three major geologic eras noted above, with near half of the craters within the
1016 NMA show interior flooding, indicating that a significant number of impact craters within
1017 NMA experienced notable geological events (i.e., interior fill emplacement) after impact
1018 crater formation. Thus, there is no geologic evidence within the NMA that impact craters lie
1019 at the highest level of NMA stratigraphy, and thus that impact craters formed as the youngest
1020 'event' across the NMA. Furthermore, geologic relations do not require, and in fact provide
1021 strong evidence against, global-scale catastrophic resurfacing of Venus.
1022   8. NMA materials and structures depict a rich and complex geologic history that can
1023 only be constrained locally in absence of reliable temporal markers. Geologic relations
1024 preserved within the NMA do not support catastrophic resurfacing models, but instead are
1025 consistent with complex geologic evolution of the Venusian lowlands.

1026   In summary, the picture that emerges is the regional coherence of preserved geologic
1027 patterns in this part of the planet (both AMA and NMA), that record three relatively distinct
1028 geologic eras with the first two particularly well recorded within the NMA [*Hansen & López,*
1029 *2018*]. The three eras are relatively distinct in terms of the geologic elements that define them.
1030 However, the temporal transition from one era to the next does not appear to be sharply defined,
1031 and as such may represent global-scale geodynamic transitions indicative perhaps of transitional
1032 geodynamic processes. Future geologic mapping of the rest of Venus, at a similar scale to that
1033 presented herein, will add important spatial and temporal information regarding the evolution of
1034 these three geologic eras and could also lead to the identification of other geologic eras within
1035 the evolution of Earth's sister planet Venus.

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1349

1350 **Captions to Figures and Tables.**

1351

1352 *Figure 1.* Mollweide projections of Venus; the NMA (north) and AMA (south) are shown as
1353 polygons. (a) Altimetry: highlands, red; mesolands, yellow; lowlands, blues; Ishtar Terra and
1354 Aphrodite Terra are composite highlands; highland features include crustal plateaus and volcanic
1355 rises, and hybrid Phoebe Regio. Planitiae are indicated by 'P.', chasmata with 'C.' Topographic
1356 profiles (Ovda Regio, 90°E; Beta Regio 23.6°E), ~6 km vertical, 3500 km horizontal. b) Global
1357 distribution of: average model surface age provinces [*Phillips & Izenberg*, 1995; *Hansen &*
1358 *Young*, 2007]; fracture zone terrain ['rift' of *Price & Suppe*, 1995]; ribbon-tessera terrain
1359 [*Hansen & López*, 2010]; Artemis Chasma (green); trajectories of Artemis Chasma-radial
1360 fractures (gray lines) and wrinkle ridges (faded red lines), including Artemis Chasma-concentric
1361 wrinkle ridges and wrinkle ridges not concentric to Artemis [*Hansen & Olive*, 2010]. Labels as
1362 in (a). Modified from *Hansen* [2018].

1363

1364 *Figure 2.* Mercator projection summary of the tectonic regimes within the NMA.

1365

1366 *Table 1.* Niobe Region (I-2467) Impact Craters.

1367

1368 *Plate 1.* Geologic Map of the Niobe Planitia Region (I-2467), Venus.

1369

a

-2931 ▬ +11620
+/- MPR (m)

60°N

Ishtar Terra

Fortuna

Atalanta P.

Vinmara P.

Guinevere P.

30°N

Bell

Tellus

30°N

Beta

W.Eistla

Niobe P.

Ganis C.

Hecate C.

Guinevere P.

C.Eistla

E.Eistla

Rusalka P.

0°N

Devana C.

W.Ovda

Ovda

Aphrodite Terra

Atla

Phoebe

Thetis

Parga C.

Alpha

30°S

Artemis

Diana-Dali C.

30°S

Themis

Dione

Aino P.

Imdr

Lavinia P.

Zhibek P.

60°S

Lada

○ Crustal plateau (ancient)

○ Volcanic rise (contemporary)

90°E

b

Average Model Surface Age

Young ▬ Old

60°N

Ishtar Terra

Fortuna

Atalanta P.

Vinmara P.

Guinevere P.

30°N

Bell

Tellus

30°N

Beta

W.Eistla

Niobe P.

Ganis C.

Hecate C.

Guinevere P.

C.Eistla

E.Eistla

Rusalka P.

0°N

Devana C.

W.Ovda

Ovda

Aphrodite Terra

Atla

Phoebe

Thetis

Parga C

Alpha

30°S

Artemis

Diana-Dali C.

30°S

Themis

Dione

Aino P.

Imdr

Lavinia P.

Zhibek P.

60°S

Lada

○ Volcanic rise (contemporary)

○ Crustal plateau (ancient)

⬡ Fracture zone terrain

▬ Ribbon-tessera terrain

90°E

Ancient Era

~~~~~ Deformation belts

~~~~~ Tesserae folds

//// NE- & NW-fractures

� Basal terrain

▓ Tessera terrain

Artemis Superstructure Era

──── Artemis-concentric wrinkle ridge trajectories

──── Artemis-radial structure trajectories

Fracture Zone Domain Era

░ Fracture Zone Complex

Time

Table 1. Niobe Region (I-2467) Impact Craters

Name	Latitude (deg N)	Longitude (deg E)	Diameter (km)	Elevation	Vmap	Units	Ejecta blanket	Impact Halo	Central Peak	Rim	Dark Floor	Crater density	Crater Database	Deformed	Temporal implications
Adivar	8,9	76,2	29	6051.76	22	vmu	Y	70	Y	Y	Y	2,55	H,S?	N	Postdates ACWR formation
Adzoba	12,8	117	12,2	6051.50	23	bst	Y	x	N	Y	N	3,18	H,S	N	Postdates ARF and AWCR formation
Afua	15,5	124	11	6051.45	24	btL, bst	Y	x	N	Y	N	3,18	H,S	Y	
Aimee	16,1	127,2	16,8	6051.09	24	fcA	Y	50	Y?	Y	N	2,86	H,S	N	Postdates ACWR formation
Almeida	46,6	123,3	14,9	6051.92	12	st	Y	140	Y	Y	N	2,86	H,S	N	Postdates ARF formation
Altana*	1,5	69,9	5,7	6053.47	22	rtMa, fcK	Y	x	N	Y	N	2,23	H	N	
Amaya	11,3	89,3	34	6052.56	22	bst, fcOv	Y	120	Y	Y	Y	2,55	H,S	N	Postdates ARF and local radial fractures, with possible later structural reactivation
Anaxandra	44,2	162,3	20,2	6051.31	13	vmu	Y	80	Y	Y	Y	1,59	H,S	N	Postdates ARF, ARF burial and subsequent inversion, and ACWR
Antonina	28,1	106,9	11	6050.63	11	vmu	N	60	N	N	N	2,23	H,S	N	Postdates ACWR formation
Anush	14,9	86,5	12,2	6051.88	22	bst	Y	x	Y	Y	Y	1,91	H,S	N	Postdates ACWR formation
Asmik	3,9	166,5	18,6	6051.57	25	fcRu2	Y	130	N	Y	Y?	3,5	H,S	N	Postdates ARF, ARF burial and subsequent inversion, and ACWR formation
Avene	40,4	149,4	11	6051.08	13	vmu	Y	40	N	Y	N	2,55	H,S	N	Postdates ACWR formation
Ban Zhao	17,2	146,9	38,3	6050.80	24	vmu, btL	Y	x	Y	Y	N	2,86	H,S	N	Postdates ACWR formation
Barrera	16,5	109,4	26,8	6051.67	23	bst, st	Y	70	Y	Y	Y	3,18	H,S	N	Postdates ACWR formation
Barto	45,3	146,2	47,9	6051.30	12	vmu	Y	x	Y	Y	Y	3,82	H,S	N	Postdates ACWR formation?
Bernhardt	31,6	84,4	25	6052.02	10	bst	Y	x	Y	Y	Y	2,55	H	N	
Bourke-White	21,2	147,9	34,4	6050.96	24	vmu	Y	120	Y	Y	Y	2,55	H,S	N	Postdates ACWR formation
Budevska	0,5	143,2	18,7	6052.22	24	st	Y	70	Y	Y	N	2,55	H,S	N	Postdates ARF formation
Caccini	17,4	170,4	37,5	6051.68	25	vmu	Y	130	Y	Y	N	1,91	H,S	N	Postdates ACWR formation
Caldwell	23,6	112,5	52	6051.52	23	bst	Y	x	Y?	Y	N	3,18	H,S	N	Postdates ACWR formation
Callirhoe	21,2	140,7	32,9	6051.33	24	st	Y	x	Y	Y	Y	2,55	H,S	N	Postdates NW-fracture formation, although NW-fractures may show local evidence of later reactivation
Carter	5,3	67,3	19,3	6054.13	22	rtMa	Y	55	N	Y	N	2,23	H,S	N	
Cather	47,1	107	26,5	6051.60	11	st?	Y?	x	N	Y	Y	1,27	H,S	N	

Name	Lat	Long	Diam	Elev	Geo	Unit	C1	C2	C3	C4	C5	Val	Class	Flag	Comments
Chapelle	6,4	103,8	20,8	6051.86	23	fcOv	Y	x	Y	Y	Y	2,23	S	N	
Christie	28,3	72,7	24,3	6050.84	10	vmu	Y	170	Y	Y	Y	2,55	H,S	N	Postdates ACWR formation
Cochran	51,9	143,4	98,1	6051.77	4	vmu	Y	x	N	Y	Y	3,18	H,S	N	Postdates ACWR formation
Cori	25,4	72,9	54,7	6050.79	10	vmu	Y	x	N	Y	Y	2,86	H,S	N	Postdates ACWR formation
Corpman	0,3	151,8	45,1	6052.21	25	fcOv	Y	110	N	Y	Y	3,5	H,S	N	Postdates ARF formation, although ARF may also been locally reactivated
Datsolalee	38,3	171,8	17	6051.44	13	bst	Y	120	N	Y	N	1,27	H,S	Y?	
de Beauvoir	2	96,1	53,3	6054.79	23	rtO, itbO	Y	x	N	Y	Y	3,82	H,S	N	
Doris	2,3	90	15,5	6055.01	22,23	rtO	Y?	x	N	Y	Y	0	H,S	Y	Predates ARF or local radial fractures
du Chatelet	21,5	165	19	6051.73	25	vmu	Y	60	?	Y	?	1,91	H,S	N	big enough to show?
Erkeley	43,9	103,4	9,3	6051.69	11	vmu	N	x	N	N	N	1,27	H,S	N	
Escoda	18,2	149,5	19,5	6051.12	24	vmu, fcl	Y	x	N	Y	Y	2,23	H,S	N	Postdates ACWR formation
Estelle	1,1	93,7	17,8	6055.06	23	rtO, itbO	Y?	x	Y	Y	N	3,5	H,S	N	
Faiga	4,9	170,9	10,6	6051.48	25	fcRu2	Y	70	N	Y	N	3,5	H,S	N	
Fazu	32,4	106	7,1	6050.75	11	vmu	Y	60	N	Y	N	1,91	H,S	N	
Ferrier	15,7	111,3	29	6051.51	23	bst	Y	x	Y	Y	Y	3,18	H,S	N	Crater may postdate ARF formation, but ARF may have been locally reactivated after crater formation
Fiona	5	166,6	5	6051.40	25	fcRu2	Y	30	N	Y	N	3,5	H,S	N	
Firuza	51,8	108	4,9	6051.50	3	bst	Y	x	N	Y	N	0	H,S	N	
Frosya	29,5	113,4	9,6	6050.87	11	vmu	Y	50	N	Y	N	3,5	H,S	N	Postdates ACWR formation
Greenaway	22,9	145,1	92,3	6051.28	24	btLl, st, vmu	Y	x	N	Y	N	2,55	H,S	N	Postdates ACWR formation
Gregory	7,1	95,8	18	6053.17	23	bst	Y	x	N	Y	N	3,18	H,S	N	Postdates ARF formation
Hannah	17,9	102,6	19,1	6051.54	23	st	Y	x	Y	Y	Y?	2,55	H,S	N	Postdates ACWR formation
Helvi	12,4	82,7	11,2	6052.35	22	bst	Y	x	N	Y	N	2,55	H,S	N	Postdates ARF formation
Hepworth	5,1	94,6	62,5	6054.16	23	rtO, itbu	Y	x	N	Y	Y	3,5	H,S	N	
Himiko	19	124,3	36,7	6051.42	24	fcA, bst	Y	x	Y	Y	N	2,86	H,S	N	Postdates ARF and AWCR formation, and formation of concentric fractures of Abundia Corona and the steep sided dome
Horner	23,4	97,8	24,7	6051.36	23	bst, fcOv	Y	x	Y	Y	Y	2,86	H,S	N	Postdates formation of concentric fractures of Maya Corona
Hwangcini	6,3	141,7	30,8	6051.73	24	st	Y	230	Y	Y	Y	2,55	H,S	N	Postdates ARF formation
Icheko*	6,6	97,9	5,6	6053.53	23	bst	Y	x	N	Y	N	2,86	H,S	N	Postdates tessera ribbon fabric formation, but may be deformed by reactivation of ribbon structures?

Name															Notes
Iraida*	27,8	108	6	6050.65	11	vmu	Y	x	N	Y	N	1,91	H	N	Postdates ARF, ARF burial and subsequent inversion as WRs
Irene	49,8	134	13,5	6052.15	12	rtA, st	Y	x	N	Y	N	4,14	H,S	Y?	
Irina	34,9	91,2	14,2	6051.47	11	st	Y	x	N	Y	Y	1,59	H,S	N	Postdates ACWR formation
Irinuca*	51,4	121,9	8,1	6051.80		fmJ	Y	x	N	Y	N	2,23	H,S	N	
Jaantje	46,5	123,1	7,3	6051.98		st	Y	140	N	Y	N	2,86	H,S	N	Postdates ARF formaion
Jamila	45,8	134,7	7,8	6051.72	12	vmu	Y	50	N	Y	N	3,5	H,S	N	Postdates ACWR formation
Khadako	54,2	139,4	7	6051.95	4	itbu	Y?	x	N	Y	Y	2,86	H,S	Y?	Posts formation or reactivation of NE and NW-trending fractures
Khatun	40,3	87,2	42,4	6052.55	10	rtT	Y	120	Y	Y	Y	1,27	H,S	N	
Kiris	20,9	98,8	13,3	6051.67	23	bst	Y	x	N	Y	N	2,23	H,S	N	Postdates formation of NW-trending fractures and ARF, but these fracture suites may have been reactivated after crater formation
Kollwitz	25,2	133,6	28,9	6051.23	12	btLl, bst, vmu	Y	x	Y	Y	Y	1,27	H,S	N	
Konopnicka	14,5	166,6	19,9	6051.74	25	vmu	Y	60	Y	Y	Y	2,55	H,S	N	
Kylii	41,1	67	12,8	6051.46	10	bst	Y	x	Y	Y	N	1,59	H,S	N	
Laura	48,9	141,2	18,4	6051.46	12	vmu	Y	x	N	Y	N	3,82	H,S	N	Temporal relations between crater and WRs unclear due to spacing of wrinkle ridges, low strain, and radar brightness of both ejecta and WRs
Li Quingzhao	23,7	94,6	22,4		23	bst		x	Y	Y	N	2,55	H,S	N	Crater postdates formation of NW-trending fractures
Lullin	23	81,3	24,9	6051.80	22	bst, fcKu2	Y	160	Y	Y	Y	2,86	H,S	N	Postdates ACWR formation
MacDonald	30	120,7	18,4	6051.70	12	st	Y	90	N	1	Y?	1,59	H,S	N	Postdates ACWR formation
Manzolini	25,7	91,3	43,7	6051.67	11	bst, st	Y	x	Y	Y	Y	2,55	H,S	N	Predates ARF
Maranda	4,9	169,7	17,1	6051.53	25	fcRu2	Y	x	Y	Y	Y?	3,5	H,S	Y?	Predate local radial fractures
Marere*	19,6	65,8	6,7	6051.15	22	vmu	Y	x	N	Y	N	2,23	H,S	N	
Maria Celeste	23,4	140,4	96,6	6051.38	24	vmu, st	Y	x	N	Y	Y	2,86	H,S	N	Temporal relations with WRs difficult to robustly constrain given the presence of extensive halo deposits
Marysya*	53,3	75,1	6,9	6051.39	3	btu	Y?	x	N	Y	N	1,91	H,S	Y	
Mbul'di*	23,8	74,7	5,5	6050.73	22	vmu	Y	x	N	Y	N	2,86	H,S	N	Postdates ACWR formation
Merian	34,5	76,2	21,9	6052.88	10	rtT	Y?	x	?	Y	N	1,59	H,S	Y	
Merit Ptah	11,4	115,6	17	6051.19	23	bst	N	x	N	N	N	2,86	H,S	N	Postdates formation of NW-trending fractures at this location
Millay	24,4	111,3	48,3	6051.33	23	bst	Y	x	Y	Y	Y	2,86	H,S	N	Postdates ACWR formation

Name															
Mosaido	17,3	75,2	7,3	6051.59	22	bst	Y	x	N	Y	N	3,5	H,S	N	Postdates ACWR formation
Moses	34,6	119,9	28,1	6051.09	11	bst, st	Y	x	Y	Y	Y	2,23	H,S	N	Postdates ACWR formation
Mu Guiying	41,2	81,1	32,7	6051.60	10	bst	Y	x	Y	Y	N	1,59	H,S	N	
Nana	49,8	75,4	8,3	6051.35	10	st	Y	x	N	Y	N	1,59	H,S	N	
Naomi	6	70,3	17,1	6053.07	22	rtMa, bst	Y?	x	N	Y	N	2,55	H,S	Y	Predates formation of radial fractures associated with Kaltash Corona?
Neeltje	12,4	124,5	10,3	6051.27	24	btL	N	x	?	Y	?	4,14	H,S	N	
Nemcova	5,9	125,1	21,4	6052.47	24	fcRo	Y	90	Y	Y	Y	1,91	H,S	N	Postdate formation of radial fractures associated with Rosmerta Corona
Nijinskaya	25,8	122,5	35,4	6051.09		vmu, bst	Y	x	Y	Y	Y	2,55	H,S	N	
Nsele*	6,7	64,2	4,9	6053.50	22	vmu	Y?	40	N	Y	N	2,23	H,S	N	
Nyal'ga*	17	64,5	5,2	6051.49	22	vmu	Y?	x	N	Y	N	1,59	H,S	N	
Odarka	40,7	138,2	7,2	6051,6	12	vmu	Y	70	N	Y	N	2,55	H,S	N	Postdates ACWR formation
Ogulbek*	2,4	145,1	6,6	6052.29	24	bst	Y?	70	N	Y	N	2,86	H	N	Postdates formation of ARF
Olena*	10,9	149	7	6051.42	22	bst	Y	x	N	Y	N	2,55	H,S	N	Postdates formation of local WR formation
Ortensia	7,6	155,7	6,6	6051.78	25	fsL	Y	50	N	Y	N	1,91	H,S	N	
Oshalche	29,7	155,5	9,6	6050.91	13	vmu	Y	x	N	Y	Y?	0,64	H,S	N	
Parra	20,5	78,5	42,8	6052.02	22	fcKu2	Y	140	N	Y	N	3,5	H,S	N	
Pasha	42,7	156,3	7,6	6050.66		vmu	Y	50	N	Y	N	2,55	H,S	N	Postdates ACWR formation
Phyllis	12,2	132,4	10,6	6051.74	24	bst, st	Y	130	N	Y	N	2,55	H,S	N	Postdates ARF formation
Polina	42,4	148,2	20,5	6051.18	11	vmu	Y	130	N	Y	N	2,86	H,S	N	
Puhioia*	20,6	69,4	6,4	6051.02	22	vmu	Y?	x	N	Y	N	0	H,S	N	
Qulzhan	23,5	165,4	10,8	6051.33	25	vmu	Y	140	N	Y	N	1,59	H,S	N	Postdates ACWR formation
Quslu	6,2	166,8	8,6	6051.34	25	fcRU2	Y	x	Y	Y	N	3,18	H,S	N	Postdates formation of ARF and ACWR
Rampyari	50,6	179,3	6	6050.75	4	vmu	Y	80	N	Y	Y	2,23	H	N	Postdates ACWR formation
Regina	30	147,3	25,5	6051.35	12	bst	Y	220	Y	Y	Y	1,59	H,S	N	
Riley	14	72,5	18,8	6051.91	22	fmU1	Y	80	Y	Y	Y?	2,86	H,S	N	
Romanskaya	23,2	178,5	31,7	6052.18	25	fRk	Y	80	Y?	Y	Y	0,95	H,S	Y	
Rowena	10,4	171,4	19,6	6051.48	25	fcRu2	Y	x	Y	Y	Y	3,82	H,S	N	Postdates WR formation
Surija	5,3	178,2	14,5	6051.36	25	vmu	Y	130	Y	Y	N	2,23	H,S	N	
Susanna	6	93,3	13,2	6053.37	23	fcOv	Y	71	N	Y	N	3,5	H,S	N	Postdates ARF formation
Taglioni	41,7	122,6	31	6051.47	12	bst	Y	90	Y	Y	Y	1,59	H,S	N	
Tahia*	44,2	73,7	9,1	6050.70	10	bst	Y	x	N	Y	N	2,55	H	N	

Name															Notes
Tekarohi	21,2	76,5	8,9	6051.69	22	bst	Y	x	N	Y	N	2,86	H,S	N	
Tinyl	9,7	132,1	11,7	6051.49	24	bst	Y	x	N	Y	N	2,55	H,S	Y	Likely postdates ARF formation, but affected by local reactivation of ARF
Tseraskaya	28,6	79,3	30,1	6051.64	10	rtT	Y	x	Y	Y	Y	2,86	H,S	N	
Tsiala*	2,9	100	16	6054.83	23	rtO	Y?	x	N	Y	N	3,82	H,S	N	
Ualinka	13,2	168,6	8,1	6051.97	25	vmu	Y	x	N	Y	N	2,86	H,S	N	
Udyaka	30,8	172,9	12,2	6051.36	13	vmu	Y	130	N	Y	N	1,59	H,S	N	Postdates ACWR formation
Unay	53,5	172,6	10,8	6050.83	4	vmu	Y	40	N	Y	N	1,59	H,S	N	
unnamed*	5,8	84,3	5,3	6052.16	22	vmu	Y?	60	N	Y	N	2,55	H,S	N	
unnamed*	8	148	7,7	6051.71	24	st	N	x	N	N	N	3,18	H,S	N	
unnamed*	35,8	164,4	5,9	6051.13	13	vmu	Y?	80	N	Y	N	1,59	H,S	N	
unnamed*	6,4	83,4	5,1	6052.00	22	vmu	Y?	80	N	Y	Y	2,55	H,S	N	
unnamed*	55	124,5	4,8	6051.51	4	fmJ	Y	x	N	Y	N	2,55	H,S	N	
unnamed*	40,3	105,9	4,4	6051.71	11	vmu	Y	x	N	Y	Y	1,59	H	N	
unnamed	38,7	114,7	4,3	6050.90	11	st	Y	30	N	Y	N	1,59	H	N	
unnamed*	7,9	74,2	4,2	6051.89	22	vmu	Y	x	N	Y	N	2,55	H,S	N	
unnamed*	52,1	123,2	4	6051.61	4	fmJ	Y	80	N	Y	N	2,23	H,S	N	
unnamed	43	150,9	3,9	6051.05	13	vmu	Y?	40	N	Y	N	2,86	H,S	N	
unnamed*	10,4	136,5	3,8	6051.48	24	vmu	Y	x	N	Y	N	2,23	H,S	N	Postdates formation of ARF
unnamed	42,7	141,7	3,8	6051.52	12	vmu	Y?	70	N	Y	N	3,5	H,S	N	
unnamed*	13,2	112,8	3,7	6051.24	23	bst	Y?	x	N	Y	N	1,91	H	N	
unnamed*	13,33	123,46	1,9		24	btu		x	N	Y	N		S	N	
unnamed*	11,9	132,3	3,6	6051.54	24	bst	Y?	x	N	Y	N	2,86	H,S	N	
unnamed*	15,1	116,8	3,6	6051.63	23	bst	Y	80	N	Y	N	3,5	H,S	N	
unnamed*	43,3	67,7	3,6	6050.70	10	vmu	Y	x	N	Y	N	1,91	H,S	N	
unnamed	22,6	94,1	3,1	6051.43	23	bst	Y	x	N	Y	Y	2,23	H,S	N	
unnamed	29,6	135,4	2,7	6051.14	12	vmu	Y	20	N	Y	N	0,95	H,S	N	
unnamed*	8,5	132,4	4,3	6051.60	24	bst	Y	x	N	Y	N	2,55	H,S	N	Postdates formation of ARF
Valentina	46,4	144,1	24,3	6051.39	12	vmu	Y	x	Y	Y	Y	4,14	H,S	N	
Vallija	26,3	120	15	6050.93	11	vmu	Y	200	N	Y	Y	2,86	H,S	N	Postdates formation of ARF and ACWR
Vigee-Lebrun	17,3	141,4	57,6	6051.06	24	vmu, bst	Y?	x	N	Y	Y	2,55	H,S	N	Postdates formation of NW fractures and ACWR
Wharton	55,6	61,9	50	6051.76	3	sf	Y	140	N	Y	Y	1,27	H,S	Y	
Wilder	17,4	122,6	35,3	6052.02	24	rtGe, bst	Y	x	Y	Y	Y	3,18	H,S	N	

Name															Notes
Winema	3	168,6	21,1	6051.58	25	fcRu2	Y	x	N	Y	Y	3,18	H,S	N	Postdates N-trending folds
Yakyt	2,1	170,2	13,8	6052.19	25	fcRu2	Y	x	Y	Y	Y?	3,5	H,S	Y	Predates final activity along N-trending fractures
Yazruk	21,2	160,2	10	6051.12	25	fcl	Y	170	N	Y	N	1,27	H,S	N	
Yolanda	7,8	152,7	11,1	6051.76	25	vmu	Y	40	Y	Y	N	1,91	H,S	N	Postdates ARF formation
Ytunde	49,9	81,1	7,7	6051.57	10	sf	Y	x	N	Y	N	1,59	H,S	Y?	
Zivile	48,8	113,1	11	6051.83	11	sf	Y	135	N	Y	N	2,55	H,S	N	Postdates ARF formation
Zulfiya	18,4	101,9	12,3	6051.63	23	bst, st	Y	x	N	Y	N	2,55	H,S	N	Postdates ARF formation, although ARF may also been locally reactivated
Zumrad	32,1	94,8	12,9	6051.16	11	bst	Y	60	N	Y	N	1,91	H,S	N	Postdates ARF formation

Abbrevations: N, no; U, unknown; Y, yes; ACRW, Artemis concentric wrinkle ridges; ARF, Artemis radial fractures.

Dark floor: Materials in the crater floor with the same radar reflectivity than surrounding volcanic materials. Interpreted as possible embayed.

* Craters not represented in map because of size and map resolution

Venus crater data bases: S, Schaber and others (1992); H, Herrick and others (1997)

Crater density values from Herrick and others (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 106 km2.