GEOLOGIC MAPPING OF INARI: A LARGE VENUSIAN CORONA DOMINATED BY SUBSURFACE PROCESSES

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To Kimm
for her
everlasting love,
immeasurable strength,
and for teaching me to turn lemons
into lemonade
ABSTRACT

Venus and Earth are planets similar in size, mass, and presumed internal heat budget, and thus one might expect similar processes of heat transfer recorded at the surface. However, Venus lacks plate tectonics and therefore its heat transfer mechanisms are unknown. Due to the planets’ similarities, understanding heat transfer processes on Venus can give insight into Earth’s processes and those of other planets. NASA’s Magellan mission employed synthetic aperture radar (SAR) to penetrate Venus’ dense atmosphere to view and image 98% of the surface. Linear mesolands form broad zones, characterized by fracture zone terrain, that connect contemporary volcanic rises. Inari Corona is a unique tectonomagmatic structure within the fracture zone. Unlike many fracture zone coronae, Inari Corona sits relatively isolated and it lacks obvious evidence of volcanic activity at the surface; both of these characteristics contribute to preservation of its rich geologic history. I constructed broad and detailed geologic maps of Inari Corona in order to understand its geologic history and thus gain insight into geologic processes of heat transfer through the lithosphere at this location. Geologic mapping of structural elements revealed three key points: 1) Inari Corona is much larger than previously proposed (>1,000 km vs 300 km diameter); 2) Inari Corona is dominated by subsurface processes, as opposed to extensive surface flows; and 3) Inari Corona evolved dynamically through time and space.

In addition, Inari Corona preserves two types of features/deposits that play a critical role in Inari evolution: 1) the extensive development of pit chains, and 2) possible extensive pyroclastic flow deposits. Radial and concentric pit chains, evidence of
subsurface processes, dominate Inari Corona’s center. Pit chains occur on numerous planetary surfaces including Earth, Moon, and Mars; however, the pit chains on Venus differ from those on other bodies based on width, length, spacing, and penetrative development across extensive regions (up to 100,000 km$^2$). Surface deposits that cover preexisting features are mainly focused on Inari Corona’s outermost flanks; however, patches of surface cover (veneer) appear randomly across Inari, only partially obscuring features. Patches of veneer may result from selective deposition and erosion from pyroclastic flow deposits. Veneer patches are huge (potentially covering 150,000 km$^2$) compared to relatively minor deposits recently reported (covering up to 40,000 km$^2$).
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INTRODUCTION

Venus and Earth are planets similar in size, mass, age, composition, distance from the Sun, and presumed internal heat budget (Solomon et al., 1992; Nimmo & McKenzie, 1998), and thus one might expect similar processes of heat transfer recorded at the surface. However, Venus lacks evidence of plate tectonics, Earth’s current mode of cooling (Solomon et al., 1992; Solomon, 1993; Phillips & Hansen, 1994). Plate tectonics is marked by the distinct topography of linear highs and lows that correlate with spreading centers and subduction zones, respectively. The former, where new oceanic crust forms, and the latter where crust is recycled.

Venus’ surface (referenced to mean planetary radius, MPR 6051.8 km) is divisible into three topographic domains; highlands (~20%), mesolands (~40%), and lowlands (~40%) (Barsukov et al., 1986; Phillips & Hansen, 1994) (Figure 1 (a)). The highlands include Ishtar Terra (a unique continent-like region), crustal plateaus and volcanic rises. Crustal plateaus, isostatically supported features, host ancient ribbon-tessera terrain (Bindschadler et al., 1992; Phillips & Hansen, 1994; Bindschadler, 1995; Hansen et al., 2000). Volcanic rises represent contemporary surface expressions of deep mantle plumes (Smrekar & Phillips, 1991; McGill, 1994; Stofan et al., 1995; Nimmo & McKenzie, 1998). Volcanic rises are thermally supported at depth and display extensive volcanic flows at the surface (Smrekar et al., 1997). The mesolands dominantly form broad linear zones connecting contemporary volcanic rises. The lowlands mark broad basins. The broadly linear mesolands are characterized by fracture zone terrain (Figure 1 (b))—marked by zones of penetratively developed fractures, chasmata (troughs), and circular tectonomagmatic features called coronae (Hansen & López, 2018). Except for
crustal plateaus and Ishtar Terra, Venus’ regional topography is thermally supported, similar to the bathymetry of Earth’s oceanic lithosphere (Figure 2) (Rosenblatt et al., 1994; Hansen & Phillips, 1995; Hansen, 2018).

The broadly linear mesolands are topographically (and thermally) comparable to terrestrial spreading centers, where new oceanic lithosphere forms (Hansen & López, 2018; Hansen, 2018). Venus’ mesolands fracture zone terrain forms a connective tissue between volcanic rises Atla, Beta, and Themis, and Artemis (surface expression of a deep mantle plume) (Herrick & Phillips, 1990; Griffiths & Campbell, 1991; Sandwell & Schubert, 1992; Bannister & Hansen, 2010). Therefore, I posit that the fracture zone terrain is critical to the understanding of contemporary geologic heat transfer mechanisms on Venus.

Fracture zone terrain includes three variably developed components: penetratively developed fractures, coronae (circular tectonomagmatic features), and chasmata (troughs) (Hansen & López, 2018). Coronae in corona-chasmata chains typically display evidence of surface volcanic activity in the form of flows, such as the mesoland regions that connect volcanic rises Atla and Beta (Hecate Chasmata), Atla and Themis (Parga Chasmata), and Atla and Artemis (Diana-Dali Chasmata) (Figure 1). The fracture zone that traverses just south of crustal plateaus Thetis and Ovda Regiones mostly lacks coronae and is marked by fractures and chasmata. Inari Corona lies nested among fracture suites and chasmata, relatively rare in both its isolation from other coronae, and its relative lack of obvious evidence of volcanic (i.e. surface) magmatism, in the form of lava flows. The lack of lava flows results in the preservation of structural elements that would otherwise be covered by coronae-related flows. Inari therefore provides a unique
opportunity to gain insight into the subsurface processes through geologic mapping. Inari Corona, defined by suites of radial and concentric lineaments, and nested topographic basins, preserves a visible record of its subsurface and thermal evolution, due in large part to its relatively rare lack of obvious volcanic flows which might otherwise obscure its surface.

I constructed broad and detailed geologic and structural element maps of Inari Corona in order to understand its evolution and thus to gain insight into geologic processes of heat transfer through the lithosphere at this location. I mapped broad trends at Inari Corona and identified representative target areas for detailed mapping with a focus on radial and concentric structural elements and topographic troughs, basins, and ridges. Detailed geologic maps reveal the patterns of distinct structural element suites, provide clues to the relations between different suites of structures through time and space, and illustrate relations between structural elements and topography through time.

BACKGROUND

Venus is referred to as Earth’s sister planet due to first order similarities despite dramatic differences (Table 1). Venus’ dense CO₂-rich atmosphere shields its surface from extensive cratering by small bolides. Venus’ surface is basaltic in composition, similar to Earth’s oceanic crust; however, Venus is ultra-dry and therefore ultra-strong, despite high surface temperatures (~470°C) (Mackwell et al., 1998). Venus lacks evidence of plate tectonics, which is the surface expression of the dominant mechanism by which Earth dissipates heat from the interior to the surface (Solomon et al., 1992; Solomon, 1993, Phillips & Hansen, 1994). A protective atmosphere, no hydrosphere causing major erosion, and no plate tectonics recycling the crust results in a preservation
of Venus’ surface, and thus an excellent record of its formational geohistory (Solomon et al., 1992; Phillips & Hansen, 1994). The surface in turn records subsurface tectonic processes; therefore, studying the surface of Venus provides insight into subsurface processes.

Global data sets collected by NASA’s Magellan mission (1989-1994) provide the foundation for studying the surface of Venus (Ford et al., 1993). Synthetic aperture radar (SAR) data, required to see through Venus’ atmosphere, cover 98% of the surface with a resolution of ~100 m/pixel. SAR data provide the most detailed view of the surface and are extremely well-suited for the construction of geologic maps. Altimetry (topography) data resolve long-wavelength geomorphic features 10s to 100s of km. Gravity data offer insight into longer-wavelength topographic support (>400 km). Emissivity data measuring reflectivity is highly variable and not discussed herein.

The surface of Venus is divided into three domains (referenced to mean planetary radius, MPR 6,051.8 km): highlands (2 km above MPR) represent less than 20% of the surface, lowlands (below MPR) represent ~40% of the surface, and mesolands represent ~40% of the surface. Highlands include Ishtar Terra (a unique continent-like region), crustal plateaus, and volcanic rises (Figure 1 (a)). Crustal plateaus are circular, flat-topped and steep-sided features hosting ancient ribbon-tessera terrain (Bindschadler et al., 1992; Phillips & Hansen, 1994; Bindschadler, 1995; Hansen et al., 2000). Volcanic rises are broad and domical features representing contemporary surface expressions of deep mantle plumes (Smrekar & Phillips, 1991; McGill, 1994; Stofan et al., 1995; Nimmo & McKenzie, 1998). The mesolands dominantly form extensive linear zones connecting volcanic rises Atla, Beta and Themis, and Atla and Artemis Chasma—a circular marking
the surface expression of a mantle plume (Herrick & Phillips, 1990; Sandwell & Schubert, 1992; Bannister & Hansen, 2010). The lowlands mark broad basins. The broadly linear mesolands are characterized by fracture zone complex, consisting of fracture zone terrain—marked by regions of penetratively developed fractures, chasmata (troughs)—and circular tectonomagmatic structures called coronae (Hansen & López, 2018) (Figure 1 (b)). Inari Corona, the topic of this study, lies within the fracture zone complex nestled between Artemis Chasma and Thetis Regio.

**Hypsometry.** Hypsometric curves provide a graphical representation of surface elevation distributions on a planet. Hypsometric curves used in geography and geomorphology analyze three-dimensional surface profiles with a two-dimensional approach. The process involves partitioning a planet’s surface into determined elevation intervals (bins) and normalizing the distribution against the entire surface to get the percentage contained within a given bin. Poorly chosen bin width introduces systematic error; large bin width generalizes the surface and distinguishing characteristics, and small bin width introduces more noise, making it difficult to separate features from the background. Therefore, in order to accurately compare hypsometric data of Venus and Earth, bin widths must match. In addition, Earth’s bathymetry data must be corrected for ocean weight, and geophysical reference levels chosen must reflect the shape of each planetary surface.

Rosenblatt et al. (1994) compared global hypsometric distributions of Venus and Earth (Figure 2). Venus displays unimodal hypsometry, whereas Earth displays a bimodal distribution with high elevations marking continental crust and low elevations representing oceanic crust. Venus’ geophysical reference level corresponds to mean
planetary radius (MPR; 6,051.8 km); Earth’s geophysical reference level corresponds to sea level (0 m) (Figure 2 (a)). Earth’s bimodal distribution correlates to distinct continental (>0 m) and oceanic (<0 m) regions, with continental values more focused than broadly distributed oceanic values. Comparison of Venus and Earth hypsometric curves reveals that Venus’ broad unimodal distribution resembles the broad oceanic distribution on Earth. This comparison is limited, however, in that no elevation bin on Venus exceeds twenty percent and no elevation bin on Earth exceeds eleven percent coverage.

Plotting Venus and Earth’s hypsometric data against the square root of cumulative area percentage further allows for comparison of surface distributions (Figure 2 (b)). On Earth’s curve, continental and oceanic crusts are distinguished by a break in slope. Graphing Venus’ distribution the same way accentuates its unimodal distribution, which mirrors that of Earth’s oceanic basins. The best fit linear regression on each plot confirms the similarity between Venus’ mesolands and lowlands and Earth’s oceanic region. The similarity between Earth’s oceanic spreading centers and heat expression to Venus’ mesolands indicates a comparable relationship between Venus’ heat expression and the mesolands.

**Fracture Zone Complex.** The mesolands are characterized by fracture zone complex, consisting of fracture zone terrain marked by penetratively developed fractures, circular tectonomagmatic features called coronae, and chasmata (troughs) (Figure 1 (b)). Coronae in the mesoland regions connecting volcanic rises Atla and Beta (Hecate Chasmata), Atla and Themis (Parga Chasmata), and Atla and Artemis (Diana-Dali Chasmata) occur in chains and typically exhibit extensive coronae-related lava flows.
Diana-Dali Chasmata, east of Artemis, contains chains of coronae that split near the eastern edge (Figure 3). Artemis is large enough that it interrupts both chasmata. Quilla Chasma, located northwest of Artemis, is distinct from Diana-Dali Chasmata in that it is flanked to the north by the ancient crustal plateaus, Ovda and Thetis Regiones, and contains a lone corona—Inari.

**Inari Corona.** Inari Corona sits alone compared to the chains of coronae typically found elsewhere in the region. Inari Corona is characterized by radial and concentric structures (Figure 4). Inari lies within a fracture dominated zone, which exhibits few obvious lava flows, preserving an exposed surface record of subsurface evolution.

**DATA**

Geologic mapping employed NASA Magellan SAR (synthetic aperture radar) data and altimetry data using Adobe Illustrator™ with linked data at full resolution. Mapping identified primary and secondary structures, represented by lineaments. Correctly identifying lineaments in SAR requires an understanding of the data collection method and possible radar distortion.

**Magellan SAR.** NASA’s Magellan Mission (1989-1994) employed synthetic aperture radar (SAR) to image 98% of Venus’ surface at a 100 m/pixel resolution (effective ground resolution ranging from 120 to 300 m) (Senske et al., 1993). The Magellan spacecraft orbited Venus, reflecting microwaves off its surface and using reflection time and intensity to create images highlighting the short-wavelength

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¹ Spatial resolution (or ground resolution) corresponds to the smallest distance on a target surface that can be resolved as a separate point in an image (Mutch et al., 1976). Ground resolution is comparable to detection resolution, where an object can be detected but not classified (Masurky et al., 1970; Zimbelman, 2001).
topography of secondary structures, dominantly represented as lineaments. As Magellan traveled suborbital paths around Venus, its sensor “looked” to the surface, forming a data collection window (Figure 5 (a)). The radar wave interacted with the planet’s surface, reflecting and scattering energy; the resulting image displayed the relative energy sent back to the sensor. Radar-brightness represents strong energy return and radar-darkness represents weak return. Rough surfaces increase radar scatter by returning more energy, and therefore appear as bright, whereas smooth surfaces reflect energy away from the receiver and thus appear dark.

Because of Magellan’s elliptical orbit, SAR imaging geometry (look angle/incidence angle) and viewing direction varied across the planet during three mapping cycles (Cycles 1 & 3 left-looking and Cycle 2 right-looking). The incidence angle, or the angle the radar wave reflects off the surface measured from true vertical, depends on latitude; the local incidence angle, or the angle measured between the surface normal and the radar wave, depends on local topography (Figure 5 (b)). There exists both inherent systematic collection distortions and target area distortions present in all SAR data; the relationship between the incidence angle and the local incidence angle characterizes the type of distortion. Figure 6 illustrates a typical trough and its associated radar interactions. The low local incidence angle on the trough slope facing the receiver causes a strong radar return, resulting in a bright feature. The high local incidence angle on the trough slope facing away from the receiver, however, causes less radar return, resulting in a dark feature. Abrupt changes in topography are marked by sharp transition between “colors” (radar-brightness or -darkness), whereas gentle changes appear gradational.
The height of a feature also affects radar distortion in SAR images. High areas return radar pulses sooner than lower areas, and thus are displaced towards the spacecraft in the image plane. Low areas return radar pulses more slowly, and thus are displaced away from the spacecraft in the image plane. These effects are known as “foreshortening” and “elongation,” respectively. An extreme case of foreshortening, called “layover,” occurs when the top of a feature is imaged before the bottom, superimposing the top on the base.

The direction of radar illumination relative to a feature also affects its visibility in SAR. Features perpendicular to radar look direction cause an increased change in local incidence angle, and therefore appear brighter (Figure 7). Features aligned parallel to radar look direction cause minimal change to local incidence angle, and thus such features are more difficult to image (Figure 8).

One full cycle of SAR data collection (or when the target body completes one full rotation under the radar’s surveillance) shares the same look direction. Although one data collection cycle alone contains many radar distortions that must be accounted for, one can tease out some surface details from radar distortions by combining different map cycles to create a more comprehensive understanding of surface morphology (Tanaka et al., 2009). Combining data from different SAR mapping cycles creates red-blue anaglyphs that provide a three-dimensional view (Plaut, 1993). Careful analysis of data from all available mapping cycles in an area is vital to gaining the most accurate view of the surface.

**Lineament Types in SAR.** The extensive lineament suites associated with Inari Corona can be generally characterized as radial or concentric (Figure 4). Furthermore,
lineaments can be distinguished by type (Figure 9). Linear arrangements of circular to elliptical depressions, called pit crater chains, are especially distinct in SAR (Figure 9 (a)). Pits in pit chains may coalesce or merge together forming troughs (Figure 9 (b)). Troughs also merge, forming branching, anastomosing patterns (Figure 9 (c)). Lineaments can be straight or sinuous (Figure 9 (d), (e)) and widely or closely spaced (Figure 9 (f), (g)). Inari contains a band of troughs that exhibit radar layover (Figure 9 (h)). These troughs represent a small-scale topographic change and have steep enough slopes that top of the slope is imaged before the bottom of the slope, causing an alignment of the ‘bends’ in opposite trough walls in the image, indicating it is a radar artifact. Accounting for the layover, the troughs would appear straight and not jagged (Hansen & Willis, 1998).

**MAPPING METHODOLOGY**

Constructing structural geologic maps at Inari Corona presents a challenge because of the area’s rich geologic history. Inari Corona (centered at 18S/120.3E) resides in the mesolands hugging the southern edges of crustal plateaus Ovda and Thetis Regiones and northwest of Artemis (Figure 3). The fracture zone complex characterizing the mesolands extends across Venus’ equator, connecting Inari to Artemis, Artemis to volcanic rises Atla Regio. Structurally defined by radial and concentric features, Inari Corona is stated as 300 km diameter (http://planetarynames.wr.usgs.gov/). However, Inari is, in fact, significantly larger, as shown in a stereo image (Figure 10); both topographic elements and radial and concentric lineaments extend far beyond the stated, but nominal, 300 km diameter of Inari Corona. The proximity and interaction of Inari-related structures with Artemis-related structures to the southeast makes the distinction
between these two large features hard to robustly define, however, Inari Corona likely
approaches a diameter on the order of 1,000 km. Generally, concentric basins, ridges, and
scarps surround Inari’s central high; suites of radial and concentric lineaments broadly
(correspond) to a similar central region.

I constructed geologic maps of Inari Corona to better understand: the definition
and limits of this large feature, its evolution, and to gain insight into mechanisms of Inari
Corona formation, and perhaps, clues with regard to processes of contemporary heat
transfer through the lithosphere at this location. Broad-scale regional mapping of
structural and topographic elements at Inari Corona helped pinpoint representative target
areas for detailed mapping (Figure 4). Whereas the regional geologic map provides a big-
picture rendering of the various structural element suites, the detailed geologic maps
provide clues for the interactions between different suites of structures, and relations
between structural suites and topography. Constructing geologic maps, and correctly
interpreting available data, requires careful mapping methodology.

Geologic maps provide the foundation for interpreting geologic history, and
interpretation requires assumption. Mapping methodology, conducted in a way that
ensures any operative geologic process is discoverable, cannot sacrifice data. For Venus,
any mapping method must allow that tectonic processes play an important role in its
surface evolution; therefore, distinguishing geologic material units from geomorphic
features is crucial (Hansen, 2000). Furthermore, differentiating between primary vs
secondary (tectonic) features is critical as primary structures form during unit
emplacement, whereas secondary structures form after emplacement. Material geologic
units, primary structures, and secondary structures record different processes occurring at
different times, and therefore need clear delineation to understand geologic history (Wilhelms, 1990).

**Mapping Criteria.** Geologic mapping was conducted following guidelines set forth by Hansen (2000). Material units/terrain types and geomorphic features (primary and secondary structures, basins and ridges) are delineated and defined as follows.

**Geologic Map Units/Terrain Types.** I delineate four map units/terrain types in the area occupied by Inari Corona: fracture zone terrain; ribbon-tessera terrain; Artemis domain; and surface veneer (Figure 11).

*Fracture zone terrain:* This characterizes the fracture zone complex that globally connects volcanic rises (Hansen & Lopez, 2018). Defined by closely spaced lineaments representing fractures along with coronae and chasmata, fracture zone terrain occurs in linear zones.

*Ribbon-tessera terrain:* Occurring in ancient crustal plateaus and lowland regions, ribbon-tessera terrain is characterized by a unique, penetratively developed tectonic fabric that exhibits at least two sets of intersecting structural elements (Barsukov et al., 1985; Hansen & Willis, 1996).

*Artemis domain:* This terrain type includes radial and concentric features extending from Artemis Chasma, southeast of Inari Corona. Straight, NW-SE trending lineaments are radial to Inari Corona; sinuous lineaments trend concentric to Inari.

*Veneer:* Patches of undifferentiated, radar-smooth material called “veneer” occur in locally thin layers. Veneer may interrupt or partially obscure structures. Veneer boundaries vary from sharp to diffuse.
Geomorphic features at Inari Corona include primary structures, secondary (tectonic) structures, basins, ridges, and breaks in slope.

**Primary Structures.** Primary structures are structures that formed during the emplacement of geologic units. Examples of primary structures at Inari Corona are impact crater rims, pit crater chains, flow channels, and lobate flow terminations (Figure 12).

*Impact Crater Rims:* Impact craters are defined by a raised rim enclosing an interior basin. Impact craters at Inari Corona include Yonge (32 km diameter; centered at 14S/115E), Maltby (38 km; 23.3/119.7E), and Winnemucca (30 km; 15.3S/121E).

*Pit Crater Chains:* Pit chains are linear arrangements of circular to elliptical pits. Individual pits within a chain can be articulated or merging together, and commonly coalesce into troughs. Pit chains are interpreted as the result of collapse of surface material into a subsurface cavity (Okubo & Martel, 1998). Pit chains evolve from fractures (secondary structures, see below) and pit chains can in turn evolve into troughs. Pit chains can be considered primary or secondary structures (Hansen, 2000). Pit chains are delineated from other lineaments in detailed map areas.

*Flow Channels:* Flow channels are narrow (<5 km), steep-sided, shallow (<1 km), long (up to 500 km), sinuous troughs similar in morphology to terrestrial lava channels (Baker et al., 1992; Komatsu et al., 1994). Channels may appear complex and branching.

*Lobate Flow Terminations:* Lobate flow terminations describe the lobate margins of a radar-smooth flow front. Lobate flow terminations can have sharp or diffuse boundaries.
**Tectonic Structures.** Secondary (tectonic) structures form after the emplacement of geologic units. In SAR, lineaments are interpreted as tectonic structures (e.g. fractures, faults, dikes, graben, etc.) due to their character (i.e. forming after unit emplacement). Lineaments are radar-bright with ambiguous topographic expressions. The width of such structures (1 to 2 pixels) make them difficult to classify explicitly at radar resolution. Lineaments representing tectonic structures are characterized by their orientation relative to Inari Corona (radial, concentric, and neither radial, nor concentric) and described by character, pattern, and/or spacing. Lineaments in detailed map areas are interpreted as fractures and pit chains.

**Basins.** Basins are topographic lows with low relief and varying lengths (200 to 600 km) and widths (25 to 100 km). Basins are often filled with radar-smooth material and are defined by their orientation relative to Inari Corona (radial or concentric).

**Ridges.** Ridges are topographic highs with moderate relief and varying lengths (10 to 600 km) and widths. Closely spaced individual ridges (2 to 10 km wide) group together to form ridge belts 10 to 50 km wide. Ridges and ridge belts are defined by orientation relative to Inari Corona. Basins and ridges are easier to identify near Inari’s center or where they are broad or well-defined.

**Breaks in Slope.** Breaks in slope are distinct changes in slope that cannot be classified as basins or ridges. Breaks in slope are mapped along sharp changes in slope angle, and generally occur along Inari’s flanks.

**INARI STRUCTURAL ELEMENT MAP**

The geologic map of Inari Corona (14S-27S/110E-132E) encompasses over 2,500,000 km$^2$ (Figure 4). Artemis domain is delineated to the southwest. Non-Inari
fracture zone terrain and ribbon-tessera terrain variably interact with Inari structures.

Suites of radial and concentric geomorphic and structural elements define Inari. Inari’s center, which sits topographically high, is defined by a circular basin containing wide troughs surrounded by a circular ridge, and an outer moat-like basin, defined by another outer ridge. Nested concentric ridges and basins form three distinct off-center packages. Suites of concentric lineaments broadly parallel these geomorphic elements. Radial lineaments variably extend from the central region outward, well beyond the concentric elements. Surface deposits, with dominantly outward directed channelized flows, occur at the lowest levels in the most distal flanks.

The distal flanks of Inari are variably dominated by radial lineaments and surface deposits. In the southeast, Inari-radial lineaments interact with lineaments radial to Artemis Chasma. Inari’s southern, outermost flank is characterized by surface flows with an unclear origin, but which appear to flow downslope, generally normal to ridge and trough axes. Immediately to the west, a structure defined by radial lineaments appears distinct from Inari Corona, although this suite of radial lineaments interacts with Inari-radial lineaments within the lowest reach of Inari’s SW flank. Inari’s western lower flank is dominated by flows that flow downslope normal to Inari-related ridge and basin axes. The flows appear to emerge from Inari-radial lineaments. To the NW of Inari’s center, the distinction between structures related to Inari and non-Inari fracture zone terrain become difficult to distinguish. Inari is poorly defined to the north and northeast due to spatial overlap with fracture zone terrain, although Inari-radial lineaments extend a few hundred kilometers outward from suites of Inari-concentric structures, likely indicating an affinity to Inari.
Mapping broad geologic structures at Inari Corona highlights some important first-order observations. First, Inari Corona is much larger than previously stated. Conventionally 300 km in diameter, the radial and concentric structures defining Inari extend to at least 1,000 km in diameter. Inari’s exact boundaries are difficult to constrain due to its proximity with Artemis Chasma (SE) and Inari’s merging into fracture zone terrain (NW, N, N). Second, the large, off-center packages of nested concentric basins and ridges to the southwest illustrate that Inari Corona likely formed in a dynamic manner, with Inari’s center having moved through time. Third, extensive (lava?) flow deposits are largely confined to the distal flanks at low elevation, where deposits seem to emerge from Inari-concentric and Inari-radial lineaments. Fourth, more locally defined surface deposits with diffuse boundaries are mostly confined to mid-flank regions. Most notably, Inari Corona is a large feature with rich geologic history. Geologic relations are investigated further in seven detailed map areas.

**DETAILED AREAS**

I selected seven regions to map in detail at Inari Corona to explore detailed geologic relations (Figure 4). The first region, referred to as map area A, includes Inari’s topographically high center surrounded by a circular ridge and basin. Map area B partially overlaps map area A and includes the concentric ridge surrounding the circular ridge and basin at Inari’s center. Map area C, southwest of (and partially overlapping) map area B, includes nested off-center concentric ridges and basins on Inari’s mid-flank that spatially overlap with ridges and basins defining Inari’s central region. Map area D, overlapping area C to the southwest, contains the confluence of two off-center packages of concentric ridges and basins on Inari’s extensive southwestern flank. Map area E,
northwest of Inari’s center, shows Inari-related structures merging with lineaments within the non-Inari fracture zone complex. Map area F, on Inari’s southeastern flank adjacent to map area B, highlights surface deposits. Map area G, partially overlapping map area F, features nested breaks in slope on Inari’s southeastern flank.

Detailed map areas A-G exhibit various structural elements (Figure 13). Map area A includes Inari’s center and radial and concentric fracture and pit chain suites. Immediately southeast, map area B displays characteristic penetratively developed radial fractures and pit chains. Southwest of map area B, map area C shows the interaction of radial and concentric features south of Inari’s center. In addition, area C preserves evidence of localized flows emerging from fractures and pit chains. Further west, map area D hosts the confluence between two packages of lineaments following off-center concentric ridges along Inari’s southwest flank. Northwest, map area E displays radial fractures and pit chains connecting Inari to non-Inari fracture zone terrain. Map area F, on Inari’s southeast flank, displays lineaments that appear to be, at least in part, buried. Further southeast, map area G exhibits abrupt topographic changes and associated unique downslope geomorphic features.

**Area A.** Map Area A is located in Inari’s center where a topographic high is nested within a concentric basin (Figure 14). Right-look inverted SAR of the area provides a point of reference for mapping geologic elements (Figure 14 (a)). Comparison of SAR data with geologic element maps illustrates the spatial and temporal relations of geologic elements, and relations between the different elements. Lineaments include: wide troughs, radial fractures and pit chains, and concentric fractures and pit chains. Surface domains include radar-smooth regions, interpreted as areas covered by a thin
veneer, and radar-rough regions that lack a smooth veneer. The spatial patterns and interaction of structures provide clues to geologic history. The nature of some features can be difficult to identify in densely lineated (radar-rough) regions (NW, NE), and where radar-smooth patches of veneer partially obscure features (NW, SW, SE, map center).

Branching and intersecting troughs represent the most prominent features (Figure 14 (b)). The troughs, marked by sharp, steep walls, display scalloped boundaries and rounded terminations. One trough appears as an isolated circular pit. Troughs are wide (up to 30 km) with varying lengths (>5 km to 100’s of km long). The troughs are widest where they intersect (NE, SW), and narrowest (>5 km) to the south where they take on a more linear and concentric trend. Trough depth is difficult to constrain; however, realistic estimates are on the order of a kilometer or more. The depth within troughs appears to be relatively consistent; radar-smooth material marks the bottom of the troughs, possibly representing trough fill. Faint, yet visible, fractures and pit chains locally crosscut the troughs and apparent fill. In other cases, fractures and pit chains appear covered by the trough fill given that the fracture and pit chains stop on one side of the trough and appear along trend on the other side. Troughs can be connected by fractures and pit chains oriented radially and concentrically to Inari’s center.

The radial features include fractures and pit chains, with pit chains dominating (Figure 14 (c)). Visual “removal” of the troughs reveals a well-developed, closely spaced (100’s of m) pattern of radial features that range in length from 5 to 100’s of km. Fractures are only a pixel or two wide (~100 m); pit chains vary in width from >2 to <10 km. Pit chain width locally varies the length of a particular pit chain. There are no
obvious patterns in changes in pit chain width across the area. Some fractures and pit chains appear faint (SW, SE, and center), as if covered by a thin veneer. Radial fractures and pit chains interact with concentric features.

The concentric features include fractures and pit chains occurring in fairly equal numbers (Figure 14 (d)). Both class of features range in length from 5 to 100’s of km and are relatively closely spaced (100’s of m). Fractures are a pixel or two wide (~100 m), whereas pit chains vary in width from >2 to <5 km. Pit chains vary in width along the length of a particular pit chain. The distribution of pit chain width displays no obvious pattern. Similar to the radial features, some concentric fractures and pit chains appear covered by a thin veneer, particularly in the northwest, southwest, and southeast.

Radar-smooth patches of veneer occur within the southwest, northeast, southeast, and center of the area (Figure 14 (e)). The sharpness of veneer boundaries varies. The veneer patch in the southwest has sharp boundaries. All boundaries of the northeastern veneer appear diffuse; this region also corresponds to the highest concentration of visible fractures and pit chains. The veneer in the southeast has a sharp, distinct western boundary, and a diffuse eastern boundary. A small patch of veneer in the center has the sharpest boundaries and the least number of visible fractures and pit chains. An interpretation consistent with these observations is that veneer boundary sharpness corresponds to veneer thickness, with the central region marking the thickest veneer, and the northeast region hosting the thinnest veneer.

Assembling the geologic elements in the area into a single geologic map reveals the relationships between the different elements (Figure 14 (f)). Troughs and associated fill are cut by and also cut radial and concentric fractures and pit chains. Overall, the area
displays roughly an equal number of radial and concentric features; however, pit chains dominate the radial features, whereas concentric fractures and pit chains exist in equal numbers. Radial pit chains appear wider on average (>2 to <10 km) than concentric pit chains (>2 to <5 km). Areas of veneer mark regions where fractures and pit chains (both radial and concentric) appear faint. Interestingly, there is no apparent pattern between areas with veneer and areas with fewer radial and concentric fractures or pit chains, except perhaps in the southeast. In fact, the veneer to the northeast and southeast display well-developed (or preserved) radial and concentric fractures and pit chains.

**Area B.** Map area B, located southeast of Inari’s center, partially overlaps map area A and provides a view of the upper flank region of this large corona (Figure 15). Area B includes more of the nested concentric ridge and basin in the southeast corner of map A, as well as an additional concentric ridge. As with map area A, right-look inverted SAR provides a point of reference for accompanying geologic lineaments (troughs, radial fractures and pit chains, concentric fractures and pit chains, and neither radial, nor concentric fractures and pit chains) and surface domains, with element interactions recording geologic history (Figure 15 (a)). Area B is particularly densely lineated (radar-rough), which makes robust identification of some features difficult.

Long, linear troughs, marked by sharply defined, steep walls with scalloped boundaries and rounded terminations, highlight the map area pattern (Figure 15 (b)). Most troughs are radial to Inari’s center, although a few concentric troughs are present. Trough widths range from >2 to <10 km, and lengths range from 20 to 200 km. Trough depth is difficult to constrain; however, realistic estimates are on the order of a kilometer
or more. The depth within troughs appears to be relatively consistent, and trough bottoms are generally marked by radar-smooth material, which may indicate fill.

Radial features include NW-SE trending fractures and pit chains, with pit chains dominating the area (Figure 15 (c)). Radial features range in length from 5 to 100’s of km. Fractures are ~100 to 200 m wide (essentially at the effective resolution of the data); pit chains are 1 to 5 km wide. Pit chain width locally varies along the length of a particular pit chain; although, no obvious patterns in pit chain width emerge. Fractures and pit chains are extremely closely spaced (too closely spaced to determine width between features). Some fractures and pit chains appear faint (SW, NE, center), as if covered by a thin veneer. Radial fractures and pit chains interact with the three suites of concentric features.

Concentric features include E-W trending fractures and pit chains; pit chains dominate (Figure 15 (d)). Concentric features define three nested suites. Fractures and pit chains range in length from 5 to 100 km. Fractures are ~100 to 200 m wide; pit chains vary in width from 1 to 5 km. Pit chains vary in width along the length of a particular pit chain, with no particular distribution. Fractures and pit chains are closely spaced (100’s of m) within individual suites; however, no concentric features occur between suites. Spacing between the three suites is on the order of a few to tens of kilometers. Similar to the radial features, locally concentric fractures and pit chains appear covered by a thin veneer (SW).

Neither radial, nor concentric (NRNC) fractures and pit chains appear in the map area (SW) trending NW-SE; pit chains dominate (Figure 15 (e)). NRNC fractures and pit chains range from 10 to 100 km in length. Fractures are ~100 to 200 m wide; pit chains
vary in width from 1 to 5 km. Pit chains vary in width along the length of a particular pit chain, with no particular distribution. Fractures and pit chains are fairly closely spaced (100’s of m), and also appear covered by a thin veneer.

Radar-smooth veneer defines a concentric band (NW) that extends to the southwest, and three areas outward from that band (NE, E, SW) (Figure 15 (f)). The sharpness of veneer boundaries varies. The concentric band of veneer exhibits sharp boundaries. Veneer patches in the northeast and east have sharp western boundaries. The veneer in the southwest has a sharp, distinct northern boundary, and a diffuse eastern boundary. Veneer boundary sharpness may correspond to veneer thickness, with the concentric region marking the thickest veneer, and the southwest hosting thinner veneer.

Assembling the geologic elements in the area into a single geologic map reveals the relationships between the different elements (Figure 15 (g)). Long troughs (20 to >200 km) and associated fill are cut by and also cut fractures and pit chains of varying orientation. Overall, the area displays more radial features than concentric or NRNC features. Pit chains dominate the radial features and are closely spaced and well-developed. Concentric fractures and pit chains appear in three nested suites, spaced a few to tens of kilometers apart; pit chains outnumber fractures. NRNC fractures and pit chains to the southwest are fairly closely spaced and curve towards a basin (outside this map area). Radial, concentric, and NRNC pit chains are similar widths (1 to 5 km), but radial pit chains are longer (5 to 100’s of km) on average than concentric and NRNC pit chains (5 to 100 km; 10 to 100 km). Areas of veneer mark regions where fractures and pit chains (radial, concentric, and NRNC) appear faint. Veneer in the southwest partially obscures concentric and NRNC features, whereas veneer along the eastern border locally obscures
radial fractures and pit chains. There is no apparent pattern between areas with veneer and areas with fewer radial, concentric, and NRNC fractures or pit chains.

**Area C.** Map area C, located just southwest of Inari’s center, partially overlaps map area B and provides a view of the interaction between a concentric ridge (NE) and a nesting concentric ridge and basin (SW) (Figure 16). As with previous map areas, right-look inverted SAR provides a point of reference for accompanying geologic lineaments (troughs, radial fractures and pit chains, concentric fractures and pit chains, and neither radial, nor concentric fractures and pit chains) and surface domains (radar-smooth (veneer) and radar-rough) (Figure 16 (a)).

Long, linear, intersecting troughs, marked by sharply defined steep walls with scalloped boundaries and rounded terminations are prominent in the eastern half of the area (Figure 16 (b)). Troughs to the west are shorter and more sinuous than other troughs. Troughs are both radial and concentric to Inari’s center. Trough widths range from 2 to 8 km, and lengths range from 5 to 200 km. Trough depth is difficult to constrain; however, reasonable estimates are on the order of a kilometer or more. The depth within troughs appears relatively consistent, with trough bottoms generally marked by radar-smooth material, possibly fill.

Radial features include N-S trending fractures and pit chains; pit chains dominate (Figure 16 (c)). Closely spaced (too closely spaced to determine width between features), penetratively developed radial pit chains appear in the northeast corner of the map area; few, more widely spaced (100’s of m) radial fractures and pit chains appear in the center and northwest corner. Little to no radial fractures or pit chains are visible in the southwest. Radial features range in length from 5 to 100 km. Fractures are ~100 to 200 m
wide; pit chains are 1 to 5 km wide. Pit chain width locally varies along the length of a
particular pit chain, but no obvious pattern in pit chain width emerges. Radial fractures
and pit chains in the northwest locally appear faint, as if covered by a thin veneer. Radial
fractures and pit chains interact with concentric and neither radial, nor concentric
features.

Concentric fractures and pit chains appear in fairly equal numbers (Figure 16 (d)).
The concentric features define two packages; E-W trending pit chains dominate the
northern suite; NW-SE trending fractures dominate the southern suite. Few linear features
cut the central map area. Fractures and pit chains in both packages are closely spaced
(100’s of m) and range in length from 5 to 100’s of km. Fractures are ~100 to 200 m
wide, whereas pit chains in all suites vary in width from 1 to 5 km. Pit chains vary in
width along the length of a particular chain, but with no particular pattern. Like the radial
features, locally concentric fractures and pit chains appear covered by a thin veneer
(SW).

Fractures and pit chains in the southeast trending WNW are neither radial nor
concentric (NRNC) to Inari (Figure 16 (e)). Dominated by fractures, features in this suite
are relatively closely spaced (100’s of m). Fractures and pit chains range in length from 5
to 100 km. Fractures are ~100 to 200 m wide; pit chains vary from 1 to 5 km wide. Pit
chains vary in width along the length of a particular pit chain, but with no particular
pattern. NRNC fractures and pit chains appear faint, as if covered, especially in the south-
central map area. NRNC fractures and pit chains interact with radial and concentric
features.
A radar-smooth region of veneer dominates the map area center (Figure 16 (f)). Veneer boundary sharpness varies, with sharp boundaries to the north and west and more diffuse in the east and south. Small patches of veneer in the very southwestern and northeastern corners of the area display sharp, fairly distinct boundaries.

A detailed geologic map of all elements highlights the relationships between different features, as well as new information (Figure 16 (g)). Arrows representing flow direction added to the map indicate potential source(s) of flow. Lobate flows distinguished in the SAR images range in length from 10 to 75 km. Stemming from map center, the flows widen towards the southwest, indicating the overall flow direction is southwest towards a large ridge and basin concentric (but a little off-center) to Inari.

Long troughs (5 to 200 km) and associated fill are both cut, and are cut by, radial and concentric structures as well as NRNC fractures and pit chains. Radial features are more penetratively developed across the map area, whereas concentric features are more spatially restricted, occurring primarily in two major packages. Pit chains dominate concentric features in the northern suite; fractures dominate the southern suite and follow the trend of a large ridge and basin concentric to Inari. There are few radial features in the southwest and map center, and few concentric features in the center of the area. Radial features are dominated by pit chains, whereas concentric features contain fairly equal numbers of fractures and pit chains and NRNC features are dominated by fractures.

Radial, concentric, and NRNC pit chains are similar widths (1 to 5 km), but concentric features are longer (5 to 100’s of km) on average than radial and NRNC features (5 to 100 km). Radial, concentric, and NRNC fractures and pit chains appear faint in areas of veneer, especially in the map center. Arrows representing flow direction in map center
indicate possible sources of flow as troughs, concentric pit chains, and NRNC fractures and pit chains. Overall, flows trend southwest towards a large concentric basin and ridge.

**Area D.** Map area D, southwest of Inari’s center, partially overlaps map area C and provides a view of the interaction between two sets ridges and basins concentric to Inari (Figure 17). This area is more complicated than the other map areas discussed so far due to changes in topography and the presence of short, linear features with numerous intersections. Right-look inverted SAR presents a point of reference for associated geologic map lineaments (troughs, radial fractures, concentric fractures and pit chains, and neither radial, nor concentric fractures) and surface domains (radar-smooth (veneer) and radar-rough) (Figure 17 (a)).

Troughs define a concentric pattern on either side of a ridge to the east of the map area (Figure 17 (b)). Troughs have sharply defined, steep walls with a sinuous character and rounded terminations. Troughs are technically radial to Inari’s center, but lie on either side of a ridge concentric to Inari. Troughs are typically narrow (2 to 5 km wide) and short (8 to 20 km long). Trough bottoms are generally marked by radar-smooth material, possibly indicating fill. Trough depth is difficult to constrain and appears to vary within individual troughs.

Radial fractures in map area D are focused in two suites; one suite in the southwest trends E-W and another in the northeast trends N-S (Figure 17 (c)). Few fractures occur in the center and southeast portions of the area. Radial fractures range in length from 5 to 60 km, are ~100 to 200 m wide and relatively closely spaced (100’s of m). Radial fractures in the southwest and northeast appear faint, as if covered by a thin veneer. Radial fractures and concentric features interact.
Concentric features include fractures and pit chains; lineaments dominate (Figure 17 (d)). Concentric features define two suites. NW-SE trending fractures in the eastern suite appear to trend radially in the map area, but actually follow the trend of a concentric ridge and basin. The western suite follows a more obvious concentric trend (NE-SW). Fractures to the east (following trend of ridge) are more closely spaced than fractures and pit chains to the west (too closely spaced to determine vs 100’s of m), except in the southwest where fractures follow the trend of a second concentric ridge and basin. Fractures and pit chains (in both suites) range in length from 5 to 100 km. Fractures are ~100 to 200 m wide and pit chains are not much wider (1 to 3 km). Like radial features, locally concentric features appear covered by a thin veneer (south-central map area).

Neither radial, nor concentric (NRNC) fractures appear in the northwest and center of the area following a trend similar, but different, to radial lineaments (NW-SE) (Figure 17 (e)). NRNC fractures are fairly closely spaced (too closely spaced to determine width between features) but appear more widely spaced on the southwestern and northeastern borders of the suite (1,000’s of m). Fractures range in length from 2 to 50 km and are ~100 to 200 m wide. Like radial and concentric features, NRNC fractures appear covered by a thin veneer (NW corner). NRNC fractures interact with concentric fractures and pit chains.

Radar-smooth veneer dominates the south-central map area between the two sets of concentric ridges and basins (Figure 17(f)). A patch of veneer to the northeast follows the concentric ridge and basin to the east, and a patch of veneer in the southwest follows the concentric ridge and basin to the west. Another area of veneer appears in the
northwest corner. Veneer boundary sharpness varies; boundaries are sharp in all areas besides the patch in the northwest corner, where boundaries are more diffuse.

A detailed geologic map of all geologic elements reveals the relationships between different features (Figure 17 (g)). Short troughs (8 to 20 km long) follow the inside and outside of a large ridge and basin (E) that are generally concentric to Inari. Troughs are confined to the eastern half of the area, and do not appear following the trend of the concentric ridge and basin in the west. The troughs and associated fill are both cut by and also cut radial, concentric, and NRNC fractures. Radial fractures are mainly spatially focused in two small suites (in the SW and NE). Concentric fractures form two suites; closely spaced fractures form the eastern suite that appears radial but follows the trend of a concentric ridge and basin. Fractures in the western suite are generally more widely spaced, except in the southwest corner where they follow the trend of another concentric ridge and basin. Concentric pit chains only appear in the western suite, focused in the northeast corner of the area. NRNC fractures in the southwest and center of the area trend similarly to radial fractures, but greatly outnumber them. Radial and NRNC fractures are generally shorter (5 to 60 km; 2 to 50 km) than concentric fractures and pit chains (5 to 100 km). Overall, there are more concentric fractures and pit chains than radial and NRNC fractures. Radial fractures, concentric fractures and pit chains, and NRNC fractures appear faint in areas of veneer, especially within the basins (SE and SW) between the two concentric ridges.

**Area E.** Map area E, located northwest of Inari’s center, provides a view of how features associated with Inari interact with the fracture zone complex (Figure 18). Generally consistent NW-SE linear trends characterize map area E. A ridge and basin,
trending roughly N-S, run parallel through the center of the area. Another smaller basin appears in the northeast corner. Right-look inverted SAR provides the basis for geologic lineaments (troughs, radial fractures and pit chains, concentric fractures, and neither radial, nor concentric fractures) and surface domains (radar-smooth veneer and radar-rough) (Figure 18 (a)).

Linear troughs delineated by sharply defined, steep walls with scalloped edges and rounded terminations comprise a suite radial to Inari (Figure 18 (b)). Troughs are generally long (30 to 100 km) and range in width from 2 to 10 km. The center of the area lacks troughs. Trough bottoms are usually radar-smooth, possibly signifying fill. Trough depth is difficult to constrain, but relatively consistent, with reasonable estimates on the order of a kilometer or more.

Radial features include fractures and pit chains trending WNW, with fractures dominating (Figure 18 (c)). Both fractures and pit chains are generally long (5 to 100’s of km), closely spaced (too closely spaced to determine width between features), and penetratively developed. Fractures are ~100 to 200 m wide, whereas pit chain width varies from 2 to 5 km. Pit chain width locally varies along the length of a particular pit chain, but no obvious pattern in pit chain width emerges. Radial fractures and pit chains (NE and center) appear faint, as if covered by a thin veneer. Radial fractures and pit chains interact with concentric fractures and neither radial, nor concentric fractures.

Only a few concentric fractures appear in eastern half of the area (Figure 18 (d)). Trending N-S, concentric fractures are short (4 to 10 km), ~100 to 200 m wide, moderately spaced (10’s of km), and difficult to see. No obvious concentric pit chains occur in this area. All concentric fractures appear covered, as if by a thin veneer.
Neither radial, nor concentric (NRNC) fractures in the southwest corner of the area trend similarly to radial features (WNW), but at a slightly different angle (NW-SE) (Figure 18 (e)). The fractures range in length from 3 to 100 km, are ~100 to 200 m wide and closely spaced (100’s of m). Some fractures in the far southwest corner appear faint, as if covered by a thin veneer.

Two large patches of veneer dominate the center and eastern portions of the area (Figure 18 (f)). Both patches of veneer have fairly sharp boundaries that become more diffuse to the northeast. Two smaller patches, one near the northeast corner of the area and the other in the southwest corner, have diffuse boundaries. All patches of veneer trend NW-SE.

A detailed geologic map of all elements exposes the relationships between different features (Figure 18 (g)). Long troughs (30 to 100 km) define a radial pattern interrupted in the center of the area by a ridge flanked by two basins. Troughs and associated fill both crosscut and are crosscut by radial fractures and pit chains, concentric fractures, and NRNC fractures. Radial fractures and pit chains are long (5 to 100’s of km) and penetratively developed. Concentric fractures are short, rare, and poorly developed. NRNC fractures with a slightly different trend than radial features are confined to the southwest. Radial fractures and pit chains are interrupted in the map center by a ridge. The ridge follows the western border of a large patch of veneer (E) that partially obscures radial fractures and pit chains and concentric fractures. A parallel basin lines up with another large patch of veneer to the west. Another smaller basin lines up with a smaller patch of veneer to the northeast.
**Area F.** Map area F on the southeast flank of Inari provides a view of the interaction between lineaments and patchy areas of veneer (Figure 19). This map area lies east of map area B, adjoining but not overlapping it. Right Look inverted SAR provides a point of reference for supplementary geologic lineaments (troughs and radial fractures and pit chains) and surface domains (radar-smooth veneer and radar-rough) (Figure 19 (a)). The pattern of radial features in the area differs from that of any other detailed map area; the trend of radial features undulates slightly, forming a rounded crenate pattern trending NE-SW that repeats throughout the area overlapping breaks in slope. Concentric fractures and pit chains in map area F are seemingly non-existent, however nesting breaks in slope trending NE-SW display a concentric pattern to overall Inari Corona.

Linear troughs delineated by sharply defined, steep walls with scalloped boundaries and rounded terminations define a mostly radial pattern in the area (Figure 19 (b)). Rare, intersecting troughs east of the map center take on a more concentric pattern. Troughs range in length from 5 to 100 km and in width from 2 to 8 km; troughs in the northwest and west of the map center tend to be longer and wider. There are no visible troughs in the southeast. The depth within troughs appears reasonably consistent, with trough bottoms commonly marked by radar-smooth material, probably indicating fill. Although trough depth is difficult to constrain, reasonable estimates are on the order of a kilometer or more.

Radial features include both fractures and pit chains, with fractures dominating (Figure 19 (c)). These features are divided into two groups; one consisting of closely spaced (too closely spaced to determine width between features) fractures and pit chains trending NW-SE that is well-developed near the northwestern and western border of the
area, and a second group consisting of long, straight moderately spaced (100’s of m) fractures and pit chains that trend WNW on the eastern border of the mapped area. The two groups of radial fractures and pit chains cross one another and interact. The slight change in trend between the two groups of features forms unique scalloped patterns. NW-trending fractures and pit chains dominate the west and range in length from 5 to 50 km whereas WNW-trending fractures and pit chains in the east range in length from 5 to 150 km. Both NW- and WNW-trending fractures are ~100 to 200 m wide, and both groups of pit chains range in width from 1 to 3 km. Pit chain width remains relatively constant along the length of a particular pit chain. Radial fractures and pit chains appear faint, as if covered by a thin veneer, everywhere barring the northwest corner.

Radar-smooth patches of veneer dominate the map area (Figure 19 (d)). The largest patch of veneer (NE and map center) has a semi-sharp northeastern boundary that displays an undulatory/jagged character. In the south, two patches of veneer exhibit more diffuse boundaries.

A detailed geologic map of all elements reveals the associations between different elements (Figure 19 (e)). Linear troughs take on a mostly radial pattern and are focused in the northern half of the map area. Troughs and associated fill are both cut and cut by radial fractures and pit chains. Radial fractures and pit chains form two groups with slightly different trends and with differing characteristics; one, focused in the northwest and west, is extremely closely spaced and follows the trend of most troughs (NW-SE), and the second, focused in the east and southeast, exhibits longer (5 to 150 km vs. 5 to 50 km) and straighter fractures and pit chains (trending WNW). Both groups of radial fractures and pit chains appear faint in areas of veneer, especially those in the south.
where patches of veneer are interrupted by nesting breaks in slope that trend concentrically to Inari’s center. The change in trend between the two suites of radial fractures forms a scalloped pattern corresponds with the concentric a concentric basin and breaks in slope.

**Area G.** This area, located on Inari’s southeast flank, displays distinct troughs bounded by breaks in slope that are mainly concentric to overall Inari Corona (Figure 20). This area partially overlaps the southern border of map area F. Left-looking inverted SAR provides a point of reference for accompanying geologic lineaments (troughs, radial fractures and pit chains, concentric fractures, and N-S trending lineaments) and surface domains (radar-smooth veneer and radar-rough) (Figure 20 (a)). The abrupt topographic changes and associated downslope geomorphic features in area G make it challenging to map.

The dominant feature in this area is a focused band of linear troughs radial to Inari that are developed in a concentric band (Figure 20 (b)). The band of troughs runs southeast and overlaps with nested breaks in slope concentric to Inari. The upper break in slope marks a change from gentle to steep, the lower break in slope marks a change to nearly flat or a horizontal slope. Troughs within the concentric band trend N-S. These are longest in the northwest (20 to 75 km) and become shorter to the east (10 to 50 km); trough width varies from 2 to 8 km throughout the map area. Troughs boundaries appear jagged, and trough bases level out into the adjacent breaks in slope north and south. Troughs in the east have relatively radar-smooth bottoms, likely indicating fill. However, lineaments track across troughs (including the bottoms). The overall slope that the troughs cut has small-scale lineaments, normal to trend of the troughs. The apparent
jagged slope of the troughs walls is a radar artifact due to the small-scale lineaments (ridges near-normal to trough trend, and near-parallel to radar look-direction), as evidenced by the alignment of “wiggles” from trough to trough (see Hansen & Willis, 1998). The troughs cut the ridges, and thus the high part of the trough wall imaged toward the radar, as a result of radar foreshortening. Trough depth in this area is difficult to constrain, and beyond the scope of the current project.

Radial features include fractures and pit chains that form two distinct suites (WNW- and NW-trending, respectively); fractures dominate both suites (Figure 20 (c)). The WNW-trending suite dominates the map area; radial fractures and pit chains are relatively long (5 to 150 km) and straight features. Fractures and pit chains in this suite are more penetratively developed and closely spaced (too closely spaced too determine width between features) in the southwest corner of the area. Features are interrupted in the northwest, center, and northeast part of the map area. The second suite (NW-trending) of radial fractures and pit chains are closely spaced, shorter (5 to 30 km), commonly curved, and mostly confined to the southeast corner of the area. Fractures and pit chains in this suite are closely spaced (too closely spaced to determine width between features). Fractures in both suites are a ~100 to 200 m wide; pit chain width in both suites ranges from 1 to 3 km. Pit chain width remains relatively constant along the length of a particular pit chain. Radial fractures and pit chains appear faint, as if covered by a thin veneer, in the central and northeastern portions of the map area. Radial fractures and pit chains interact with concentric and N-S trending fractures.

Concentric fractures form two packages in the northeast and southeast corners of the map area (Figure 20 (d)). Both packages trend E-W, generally following the trend of
nested concentric breaks n slope. The northeastern package contains fewer fractures than
the southeastern package. These moderately spaced (100’s of m) fractures range in length
from 8 to 100 km, with widths ranging from ~100 to 200 m. Fractures of the southeastern
package are locally variably faint, as if covered by veneer. Concentric fractures in both
packages interact with radial and N-S trending features.

Faint lineaments trend N-S in a band concentric to Inari in the center of the map
area (Figure 20 (e)). Closely spaced (too closely spaced to determine distance between
features) lineaments parallel the band of linear troughs. These lineaments might not be
fractures (like in areas A-F), but their true nature is difficult to determine. These
lineaments range in length from 2 to 50 km and are ~100 to 200 m wide. Lineaments
appear especially faint, as if covered by a thin veneer, in the south-central and southeast
regions of the map area.

Radar-smooth patches of veneer in this area follow the trend of nested concentric
basins and a ridge (Figure 20 (f)). Two large patches (north-central and south-central) are
divided by radar-rough features but connect through a small strip of veneer in the east.
Two smaller patches of veneer appear in the southeast. Veneer in the north exhibits
diffuse boundaries, whereas veneer in the south displays sharper boundaries. The
northern boundary of the south-central veneer, however, is unique. Upon close
inspection, the northern veneer boundary shows a feathery, jagged appearance.

A detailed geologic map of all elements highlights the relationships between
different elements (Figure 20 (g)). Linear troughs are focused in a concentric band
between two breaks in slope. Troughs trend N-S and are longer in the west (20 to 75 km)
and shorter in the map center and east (10 to 50 km). Trough bases level out and appear
to merge with both the upper and lower slope boundaries (N and S, respectively). The southern edge of the troughs displays a feathery, jagged character at radar resolution. Radar distortion due to steep slopes causes trough walls to appear wavy and jagged instead of relatively straight. Troughs have relatively smooth bottoms, likely indicating fill; however, determining the depth of troughs is extremely difficult due to radar distortion (layover). Troughs are cut by radial fractures and pit chains and N-S trending lineaments, but do not interact with concentric fractures. Radial fractures and pit chains form two suites; one suite trends NW-SE and consists of short, closely spaced features (5 to 30 km), and the other trends WNW and contains long, straight features (5 to 150 km). Concentric fractures are rare, isolated to the southeast corner of the area, and follow the trend of the band of troughs and concentric basins and ridge. Faint lineaments trending N-S form a concentric band corresponding with troughs. Patches of veneer north and south of the troughs partially obscure radial fractures and pit chains and concentric and N-S trending lineaments. Veneer patches follow a concentric trend corresponding with the trend of local breaks in slope. The abrupt changes of topography make mapping this area challenging.

**Summary of Detailed Map Areas.** Detailed map areas A-G exhibit lineaments and surface domains with variable characteristics and interactions. Troughs, fractures and pit chains of varying orientations, and surface veneer throughout the areas are summarized and compared below. Feature details are compiled in Table 2. Refer to the Inari Corona structural element map (Figure 4) for spatial comparison.

**Troughs.** Troughs vary in length, width, pattern, orientation relative to Inari, radar-character, and interaction with other lineaments and surface domains. Starting at
Inari’s center (map area A), long troughs (up to 100’s of km) extend southwest into map areas B and F and southeast into map area C. Troughs in map area A are the widest (up to 30 km) where radial and concentric troughs merge, forming a branching pattern. Map area D, on Inari’s southwest flank, contains the shortest, most narrow troughs (8 to 20 km long, 2 to 5 km wide). Map area G, on Inari’s southeast flank, exhibits relatively short troughs (10 to 75 km) focused in a concentric band.

**Radial Features.** Radial features include fractures and pit chains that vary in length, width, trend, spacing, and interaction with other lineaments and surface domains. Radial fractures are present in all map areas, and radial pit chains are present in every map area except area D. Fractures and pit chains range in length from 5 to >100 km except in map area D, where fractures range in length from 5 to 60 km. Fractures in all map areas are a pixel or two wide (~100m), but pit chains are widest (2 to 10 km) at Inari’s center (map area A). Fractures and pit chains near Inari’s center (map areas B, C, D and F) generally trend N-S and are closely spaced and penetratively developed. Closely spaced fractures and pit chains on Inari’s northwest flank (map area E) trend WNW. All radial features interact with troughs and veneer. Radial features interact with concentric features in every map area except map area F on Inari’s southeast flank.

**Concentric Features.** Concentric features include fractures and pit chains that vary in length, width, and interaction with other lineaments and surface domains. Fractures appear in all map areas barring map area F; pit chains appear in map areas at and around Inari’s center and areas A, B, C, and D. Fractures and pit chains are generally 5 to >100 km in length, except northwest of Inari’s center in map are E where lineaments are 4 to 10 km in length. All fractures are a pixel or two wide (~100 m), but pit chains vary
slightly in width (1 to 5 km) and are widest at Inari’s center (2 to 5 km). Concentric features generally trend E-W and are closely spaced near Inari’s center and moderately spaced near the flanks. All concentric features interact with troughs, radial features, and veneer.

**NRNC Features.** Neither radial, nor concentric (NRNC) features include fractures and pit chains that vary in length, width, trend, spacing, and interaction with other lineaments and surface domains. NRNC fractures and pit chains on Inari’s southwest flank (map areas B and C) are up to 100 km in length. Fractures further southwest in map area D are shorter, ranging from 2 to 50 km long. Fractures on Inari’s northwest flank (area E) are up to 100 km long. All fractures are a pixel or two wide (~100 m), but pit chains in areas B and C range from 1 to 5 km wide. Fractures and pit chains trend generally NW-SE, except in map area G on Inari’s southeast flank where fractures trend N-S. All fractures and pit chains are relatively closely spaced and variably interact with troughs, radial and concentric features, and veneer.

**Veneer.** Radar-smooth patches of veneer in map areas A-G display boundaries with varying degrees of sharpness. Veneer in map area A at Inari’s center possess relatively sharp boundaries in the immediate center; however, the sharpness of veneer boundaries in map areas B-G vary and display no discernable pattern. Veneer interacts with all troughs (fill) and radial features and most concentric and neither radial, nor concentric features.

In summary, Inari’s center is dominated by the widest troughs; and troughs with a range of orientations. Radial and concentric troughs occur in Inari’s center and upper flanks. Map area G is an exception to this in that the troughs here form a distinctly
different suite of troughs. Inari’s central region and upper flanks are dominated by mostly radial (but both radial and concentric), closely spaced (at or near radar resolution) fractures and pit chains. Fractures and surface flows dominate the southwest flank, where there is a mixed-up confluence of ridges and basins that are broadly concentric to overall Inari, yet which also locally intersect. Fractures and pit chains on Inari’s northwest flank are radial to Inari and yet also parallel lineaments of the non-Inari fracture zone complex. Inari’s southeast flank is dominated by radial fractures and pit chains and patches of surface veneer overlapping nested breaks in slope concentric to overall Inari. Troughs on the southeast flank are distinct from troughs elsewhere at Inari. Patches of veneer in all detailed map areas often obscures lineaments and pit chains but does not necessarily correspond to areas with the fewest number of visible lineaments and pit chains. Veneer seems to be divided into three types, 1) along the lower flanks, and in the wide, concentric, off-center, crescent-moon shaped nested basin partially covered by map area D, where the cover is marked by flow features, and as such likely represents lava flows; 2) veneer in other regions, with commonly diffuse boundaries that appears to partially cover regions; and 3) veneer in the narrow band of alternating troughs and ridges concentric to overall Inari on the southeast flank bounded by breaks in slope.

DISCUSSION

Broad and detailed structural geologic mapping at Inari Corona revealed three key points: 1) Inari Corona is large (~1,000 km diameter); 2) Inari Corona is dominated by subsurface processes (stoping via pit chains), particularly within the central region and within its upper and mid-flank regions; and 3) Inari Corona evolved dynamically through space and time.
**How Big is Inari Corona?** Inari Corona is considered 300 kilometers in diameter (USGS Gazetteer of Planetary Nomenclature, 2006); however, Inari-related radial and concentric fractures and pit chains, structures, patchy veneer, and distal surface flows extend far beyond 300 kilometers (Figs. 4, 13). Broad and detailed geologic mapping at Inari Corona reveal a diameter of at least 1,000 kilometers or possibly greater, however, interference from Artemis-related structures and non-Inari fracture zone complex make it difficult to identify Inari’s exact size. Smrekar & Stofan (1997) define coronae as, “nearly circular annuli of fractures and ridges that are interpreted as manifestations of small-scale mantle upwelling driven by thermal buoyancy.” However, considering Inari Corona as 300 kilometers in diameter only acknowledges its immediate center and disregards its most defining features: the vast number of penetratively developed pit chains that extend for hundreds of kilometers, patches of veneer that partially obscure features, and the surface flows that completely cover features on the outer flanks that altogether define the coherent structure that is Inari Corona.

**Pit Chains.** Detailed geologic mapping at Inari Corona highlighted an extensive number of closely spaced fractures and pit chains, especially near Inari’s central and mid-flank regions. The distinct linear arrangements of circular to semi-circular pits appear in all detailed map areas (A-G). In order to better understand the implications of the vast number of pit chains at Inari Corona, it is necessary to review the mechanisms of pit chain formation.

Pit crater chains are lines of circular to elliptical pits that can merge into troughs. Pit chain arrangement may be en echelon (closely spaced, parallel or subparallel, overlapping or step-like) or linear, discontinuous, or pits within a chain may coalesce into
troughs. Pit chains have been identified on planets, moons, and asteroids across the inner and outer solar system, including Earth (Okubo & Martel, 1998), Mars (Banerdt et al., 1992), and Venus (Bleamaster & Hansen, 2004). Pit chains result from the collapse of surface material into a subterranean void by a variety of hypothesized void-forming mechanisms including those driven by magma, tectonism, or water.

**Pit Chains on Earth.** Pit chains on Earth are rare, but have been documented in Hawaii, Iceland, and Israel/Jordan. In Hawaii at Kilauea volcano, pit chains formed from an intrusion of magma through a crustal fracture, or a dike, resulting in the stoping of the rock roof followed by collapse into the subsurface, forming deep, steep-sided pits and subsurface caves (Okubo & Martel, 1998). As the pit chains evolved from fractures above dikes at depths to articulated pits, individual pits merged together and formed troughs (Figure 21). Subsequent magma flow along the underlying fracture likely transported stoped material away, at depth, and continued to widen the fracture by thermal and/or mechanical erosion causing individual pits to merge and coalesce into troughs (Figure 22).

Pit chains have been mapped in rift zones in Iceland (Sigurdsson, 1980), where extension cracks formed in the underlying basalt, causing the unconsolidated fluvial sediment above to “drain” into the cracks (Ferrill et al., 2011). Pit chains along the coastlines of Israel and Jordan formed in the Dead Sea pull-apart basin, aided in formation by the dissolution of a buried salt layer by groundwater (Abelson et al., 2003).

**Pit Chains on Mars.** Pit chains on Mars are much larger than pit chains on Earth (100’s of km in length vs. 100’s of m), likely due to Mars’ lower gravity and erosion. Pit chains are often alongside normal faults and above dilational faults associated with
extensional stress (Ferrill et al., 2004), but also occur near the base of volcanoes and associated with igneous dike injection (Wyrick et al., 2004). Pit chains on Mars in the Tharsis region form in radial and concentric patterns and are interpreted as evidence for subsurface dikes (Mége & Masson, 1996; Scott & Wilson, 2002; Scott et al., 2002; Wilson & Head, 2002). In this interpretation, pit chain formation stems from a rising plume that reaches a neutral buoyancy level and propagates laterally and vertically as a dike. The dike continues to propagate upward, and strain concentrated at the dike tip produces fractures in the host rock and subsidence above the dike (Rubin, 1992). Pit chains often merge together into troughs.

**Pit Chains on Venus.** Pit chains on Venus range in length from a few up to thousands of kilometers, generally form in radial and concentric patterns, and are predominantly associated with coronae, chasmata (troughs), and fractures within fracture zone terrain (Bleamaster & Hansen, 2004). Similar in morphology to those at Kilauea volcano on Earth yet much larger (up to 1,000’s of km in length vs. up to 2 km in length) and those at Tharsis on Mars, Venusian pit chains likely formed by a similar mechanism involving thermal stoping, and are therefore likely capable of transporting material 10’s to 100’s of km away at depth.

**Implication of Pit Chains at Inari Corona.** Inari Corona likely displays an evolution of radial and concentric pit chains beginning with a fracture above a dike leading to the formation articulated pits via the stoping of material, to merging pits, to troughs with scalloped edges, and to troughs that branch and intersect (Figure 21). The wide troughs with scalloped edges and rounded terminations that intersect at Inari’s center and branch out into pit chains likely represent the most “long-lived” pit chains,
displaying advanced erosion over time via the stoping of material into the subsurface. Pit chains are the most closely spaced and penetratively developed surrounding Inari’s center (especially SE). Inari Corona is dominated by subsurface processes (stoping via pit chains), particularly within the central region and within its upper and mid-flank regions, where pit chains are extremely closely spaced and penetratively developed.

**Spatial Evolution of Inari Corona.** A picture of the spatial evolution of Inari becomes apparent in spatial relations between the various map elements (Figure 4). Radial lineaments (fractures and pit chains) extend outward from Inari’s center (at least 1,000 km), merging with non-Inari fracture zone complex in the northwest and merging with Artemis-related lineaments in the southeast. Radial lineaments appear throughout the map area, but concentric lineaments (fractures and pit chains) define focused packages. Concentric ridges, basins, and breaks in slope delineate domains. Lobate surface flows are mainly confined to the lower flanks and display extensive flow features (sinuous channels and lobate-flow fronts) and essentially completely cover and obscure preexisting structures. Some surface flows are clearly Inari-related, appearing to leak from Inari-radial and -concentric lineaments (NE). Veneer patches display a different character from these zones of burial. The veneer patches are developed along the upper and mid-flanks, exhibit no obvious flow features, are marked by diffuse boundaries, and do not completely bury or obscure preexisting structures. Alternating troughs and ridges on Inari’s southeastern flank (area G) differ from other troughs in the map area. These troughs appear similar to downslope, erosional features on Earth; in addition, these troughs exhibit a possible stripping of veneer or fill through remobilization, by erosion.
Nested ridges and basins concentric to overall Inari Corona on the southwestern flank imply that Inari’s center may move through time. Deep-rooted, compositionally supported crustal plateaus Ovda and Thetis Regiones likely prevent Inari from spreading towards the north, possibly explaining the overall concentric ridges and basins forming to the south as Inari developed through time. Additionally, mapping of Inari reveals the evolution of surface topography. Flow features within the radar-smooth area inside of the off-center concentric ridge just southwest of Inari’s center displays southwest directed flows originating from fractures and pit chains; however, altimetry data reveals this area currently sits high, implying that the radar-smooth area represents a former basin that existed when the surface flows occurred and traveled downslope that was later uplifted, currently sitting high. These relationships indicate Inari’s dynamic evolution through space and time.

**Geologic History.** Within the context of the geologic history, one might place the above observations into the following scenario. Given the evolution of lineaments (fractures) to pit chains to troughs via stoping above a dike at depth (Figs. 21, 22), it is logical that radial and concentric fractures formed at Inari’s center, and through time, some fractures evolved into pit chains, which subsequently further evolved into troughs. Thus, the evolution of Inari’s center might be characterized as a thermally-driven process. Troughs would be expected to widen over time via continued stoping, causing some troughs to merge. Whether during or after trough formation, the trough bases were locally filled with either melt from below or something deposited from above (or both). If filled with melt from below, presumably the melt could reach a point where it spilled over the sides of the troughs and flowed downslope forming the thin covering (veneer) in areas
surrounding the troughs. This veneer would presumably be thin enough to allow for radial and concentric fractures to be visible; the melt veneer could solidify with time, and new radial and concentric features could form and/or reactivate previous structures.

However, if the troughs were filled by deposition of material from above, the same material could be responsible for the surface veneer. Once deposited, the material could also record the formation of new radial and concentric fractures or reactivation of previous structures. If veneer formed by deposition from above, this would imply either incomplete deposition across the map area, or, alternatively, removal of veneer in some locations. Pyroclastic flow deposits exhibit selective deposition and erosion synchronous with emplacement and could represent the mechanism by which patches of veneer at Inari Corona form (Figure 23) (Branney & Kokelaar, 2002).

**Pyroclastic Flow Deposits.** Pyroclastic flow deposits comprise an inhomogeneous mix of volcanic particles and gas propelled by ground-hugging currents. Pyroclastic flow deposits are density-driven, can transport large volumes of volcanic debris rapidly for many kilometers, and can be emplaced in more than one event. Pyroclastic flow deposits form low profile sheets that bury or partly blanket pre-eruption topography; accumulative downslope and depletive where flow decelerates, pyroclastic flow deposits can blanket (partially obscure) topography rather than fill (Branney & Kokelaar, 2002).

Possible pyroclastic flow deposits (covering areas up to 40,000 km²) have been identified on Venus on coronae margins, appearing radar-bright with diffuse margins and displaying evidence of blanketing tectonic features (Campbell & Clark, 2006; Ghail & Wilson, 2013 Campbell et al., 2017). High atmospheric pressure and a lack of water inhibit explosive volcanism on Venus but might help enable pyroclastic flow deposits.
The huge patches of veneer at Inari Corona (potentially covering up to 150,000 km²) could potentially result from extensive pyroclastic flow deposits stemming from Inari’s center. Pyroclastic flow deposits could selectively deposit, erode, and remobilize material from Inari’s center outwards hundreds of kilometers and assimilate with flows on the outer flanks. However, positively identifying pyroclastic flow deposits at Inari Corona requires further investigation through modeling and is outside the scope of this project.

**Timing Implications.** Interpreting the temporal relationships between the suites of the features and surface veneer presents challenges. The relative timing of the formation of secondary structures is non-trivial and non-unique to interpret, partly because there is not a single unique interpretation of temporal relations between different lineament suites. For example, lineaments could be fractures, faults, dikes, graben, etc. and each might impose different geometric and mechanical constraints that would affect surface expression and temporal relations (Hansen & Willis, 1998). In addition, the cross-cutting patterns indicate potentially differing temporal relations. Troughs and trough fill are both cut by, and appear to bury, radial and concentric fractures and pit chains, indicating lineament formation occurred before, during, and/or after troughs formed and were “filled.” Some fractures likely locally evolved into pit chains, which in turn locally evolved into troughs. Radial and concentric fractures and pit chains appear to cross one another, and, locally, to connect. Radial, concentric, and neither radial, nor concentric features are visible, but faint, in areas of veneer (as if covered); elsewhere these features are clearly visible; and veneer boundaries vary in sharpness throughout the map areas. The lack of a specific sequence of feature development, although challenging to interpret, likely indicates that the troughs, fractures, pit chains, and surface veneer overlapped
through time—that is, that each of these elements occurred time-transgressively across Inari Corona. The relationships of lineaments and surface domains revealed in detailed mapping exposes the rich geologic history of the area. The evolution of lineaments and surface domains overlapped temporally and spatially—rather than a successive evolution.

CONCLUSION

In conclusion, Inari Corona is a large feature, similar to a magmatic blister on the surface, that displays an outward evolution. Geologic relations at and near Inari’s center record progressive tectonism through the formation of extensive fractures, pit chains, and troughs indicative of subsurface stoping. Inari’s center is dominated by subsurface processes (erosion via stoping). The mid-flank region records both subsurface and surface processes. Radial fractures, pit chains, and parallel troughs indicate a lack of lava flows, and evidence of subsurface processes. Characteristics of extensive surface deposits belie a lava flow origin: a lack of flow features, diffuse boundaries, and the blanketing (as opposed to burying) of preexisting structures. A local area along the southeast mid-flank records a distinctive surface layer of similar thickness along slope concentric to overall Inari. This deposit is cut by wide, periodically spaced, parallel, downslope erosional troughs; earlier formed features are visible within the trough floors. Collectively, these characteristics challenge a lava flow origin, and are consistent with a pyroclastic flow deposit synchronously depositing and eroding material during emplacement. These deposits seem to emerge from radial/concentric lineaments. Inari’s distal flank hosts extensive surface flow deposits with well-developed flow features.

The evolution of Inari Corona that emerges via geologic and structural element mapping varies in space and time, with operative magmatic processes related to
evolution, magma buoyancy, and the thermal and mechanical evolution of the crust (Figure 24). Radial fracturing occurs through time via dikes in the subsurface; some dikes can further evolve to pit chains, and further evolve to troughs by thermal erosion via stoping of material. With time and resulting heat transfer, the temperature difference between the subsurface mantle and surface lithosphere would decrease; thus, dikes could reach shallower crustal levels, and ultimately stoping occurs. These subsurface processes dominate the highest elevations of Inari’s center and mid-flank domain; whereas surface flows (lava?) are mainly limited to the distal flanks. At intermediate elevation, magma might continue to rise due to low density from dissolved gasses which upon reaching the surface could form density-driven pyroclastic flows blanketing downslope regions.

Inari Corona’s huge circular footprint represents the surface expression of a magmatic diapir. Heat transfer via conduction and advection dominate lithosphere heat transfer processes, occurring at depth and exposed as surface features. With time, some fractures evolve to pit chains and/or troughs, and new fractures continue to form. Inari Corona preserves a more accessible record of its evolution due to its domical character, resulting in the development of lineaments at high elevations, and thus the prevalence of subsurface processes versus surface processes. The evolution of structures and surface topography at Inari Corona reveal its dynamic evolution through space and time. Inari is likely a long-lived tectonomagmatic feature and records contemporary heat transfer processes on Venus.

REFERENCES
Abelson, M., Baer, G., Shtivelman, V., Wachs, D., Rax, E., Crouvi, O., Kurzon, I., and Yechiel, Y., 2003, Collapse-sinkholes and radar interferometry reveal neotectonics concealed within the Dead Sea basin. Geophysics Research Letters,


Figure 1. Mollweide projections of Venus. (a) Altimetry (topography): highlands, red; mesolands, yellow; lowlands, blue. Aphrodite Terra and Ishtar Terra are dominated by highland features including ancient crustal plateaus (blue circles) and contemporary volcanic rises (red circles); Phoebe Regio (dashed) maintains some thermal support, and Artemis and Ishtar Terra are unique features (green ovals). ‘P.’ indicates planitiae, ‘C.’ chasmata. Topographic profiles of Ovda Regio, 90°E and Beta Regio, 23.6°E (~6 km vertical, 3500 km horizontal). (b) Global distribution of fracture zone terrain and ribbon-tessera terrain and Artemis (green) and the Artemis superstructure radial structures (gray lines) and concentric wrinkle ridges (light red lines). Labels as in (a). The blue star marks the location of Inari Corona (from Hansen, 2018).
Figure 2. Hypsometric curves of Venus and Earth. (a) Hypsometric curve data for Venus (top) and Earth (bottom), with 300 m elevation bin. Venus’ distribution is very similar to Earth’s oceanic crust. Earth’s bathymetry data has been corrected for the ocean weight. (b) Cumulative global hypsometric curve data for Venus (top) and Earth (bottom), with 200 m elevation bin. Venus and Earth both have a region where the elevation is directly proportional to the square root of the cumulative area percentage. The straight line (black) represents the best fit linear regression line defining the limits of the proportional relationship. On Venus, about 70% of the surface follows the linear relationship. On Earth, the oceanic crust exhibits this relationship and makes up 60% of the surface. The green line represents the MPR (mean planetary radius) on the plots for Venus, and the general boundary between continental and oceanic lithosphere on plots for Earth (modified from Rosenblatt et al., 1993).
Figure 3. Mercator projection of part of Aphrodite Terra. A geologic map of structural elements including coronae (stars), local radial fractures, local concentric fractures, chasmata, steep scarps, fracture zone terrain, and ribbon-tessera terrain. Black box designates 2,860,000 km² Inari Corona (In) map area. (from Hansen & Lopez, 2018).
Figure 4. Mercator projection geologic structural element map of Inari Corona. Rectangles A-G designate detailed map areas. Black star on Venus globe represents the relative location of Inari Corona. ‘NRNC’ on key stands for ‘neither radial, nor concentric’ to Inari Corona.
Table 1. Summary of physical characteristics of Venus vs. Earth.

<table>
<thead>
<tr>
<th>Physical Characteristics</th>
<th>Venus</th>
<th>Earth</th>
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<tr>
<td>Mass (kg)</td>
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<td>$5.98 \times 10^{24}$</td>
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<tr>
<td>Equatorial Radius (km)</td>
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<td>Equatorial Surface Gravity (m/sec²)</td>
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<tr>
<td>Mean Surface Temperature (°C)</td>
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</tr>
<tr>
<td>Atmospheric Pressure (bars)</td>
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<td>1</td>
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<tr>
<td>Atmospheric Composition</td>
<td>96% CO₂</td>
<td>78% N</td>
</tr>
<tr>
<td></td>
<td>3% N</td>
<td>21% O₂</td>
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</table>
Figure 5. SAR data collection geometry. The look angle is the radar orientation and the radar swath represents the data collection window. The incidence angle is measured from vertical and may be affected by planetary curvature. Local incidence angle is dependent on the local topography (from Farr, 1993).
Figure 6. A typical trough cross section and associated radar interactions. (a) The low local incidence angle on the slope facing the receiver causes a strong return resulting in a bright and foreshortened image. The high local incidence angle on the slope facing away from the receiver causes less return resulting in a dark image. When the upper limit for local incidence angle is exceeded, the slope facing away from the receiver is shadowed, and no data is collected. (b) SAR image and interpretative cross section of the rift valley, Guor Linea (18.8°N,0.3°E). The dark and bright areas are interpolated to show surface variations (from Stofan, 1993).
Figure 7. SAR images of pit crater chains oriented at a high angle to radar look direction. (a) Left-look SAR, incidence angle 38 degrees; (b) right-look SAR, incidence angle 25 degrees; (c) stereo image suitable for viewing with 3D glasses; (d) right-look inverted SAR. Arrows indicate look direction.
Figure 8. SAR images of pit crater chains oriented at a low angle to radar look direction. (a) Left-look SAR, incidence angle 39 degrees; (b) right-look SAR, incidence angle 25 degrees; (c) stereo anaglyph suitable for viewing with 3D glasses. Arrows indicate look direction.
Figure 9. Different lineament types at Inari Corona, Venus. (a) Circular chains of articulated pits (pit crater chains); (b) chain of circular pits with some merging (indicated by arrow); (c) connected, branching depressions or troughs; (d) fairly straight lineaments; (e) sinuous lineaments; (f) widely spaced lineaments; (g) densely packed lineaments; (h) alternating troughs and ridges similar in appearance to erosional features on Earth. Images are all right-look SAR.
Figure 10. Mercator projection stereo image of Inari Corona, Venus. Inari Corona’s defined diameter (300 km) is shown by the dashed line (USGS, 1995). Boxes A-G represent detailed map areas discussed later.
Figure 11. Examples of map units at Inari Corona. (a) Contemporary fracture zone terrain; (b) ancient ribbon-tessera terrain; (c) Artemis domain; and (d) veneer. All images are left-looking inverted SAR.
Figure 12. Examples of primary structures at Inari Corona. (a) Chain of circular, articulated pits (pit crater chain); (b) flow channels; (c) extensive lobate flows and terminations. Images are all right-look inverted SAR.
Figure 13. Mercator projection inverted SAR image of Inari Corona, Venus with detailed map areas A-G. The left half of image (115.6E to 122.9E) is right-look inverted SAR and the right half (122.9E to 125.4E) is left-look inverted SAR.
Figure 14. SAR and geologic map panels for map area A. (a) Inverted right-look SAR image; (b) troughs; (c) radial fractures and pit chains; (d) concentric fractures and pit chains; (e) surface veneer; (f) map of all geologic elements.
Figure 15. SAR and geologic map panels for map area B. a) Inverted right-look SAR image; b) troughs; c) radial fractures and pit chains; d) concentric fractures and pit chains; e) NRNC (neither radial, nor concentric) fractures and pit chains; f) surface veneer; g) map of all geologic elements.
Figure 16. SAR and geologic map panels for map area C. (a) Inverted right-look SAR image; (b) troughs; (c) radial fractures and pit chains; (d) concentric fractures and pit chains; (e) NRNC (neither radial, nor concentric) fractures and pit chains; (f) surface veneer; (g) map of all geologic elements.
Figure 17. SAR and geologic map panels for map area D. (a) Inverted right-look SAR image; (b) troughs; (c) radial fractures; (d) concentric fractures and pit chains; (e) NRNC (neither radial, nor concentric) fractures; (f) surface veneer; (g) map of all geologic elements.
Figure Map 18. SAR and geologic map panels for map area E. (a) Inverted right-look SAR image; (b) troughs; (c) radial fractures and pit chains; (d) concentric fractures; (e) NRNC (neither radial, nor concentric) fractures; (f) surface veneer; (g) map of all geologic elements.
Figure 19. SAR and geologic map panels for map area F. (a) Inverted right-look SAR image; (b) troughs; (c) radial fractures and pit chains; (d) surface veneer; (e) map of all geologic elements.
Figure 20. SAR and geologic map panels for map area G. (a) Inverted left-look SAR image; (b) troughs; (c) radial fractures and pit chains; (d) concentric fractures; (e) N-S trending lineaments; (f) surface veneer; (g) map of all geologic elements.
Table 2. Summary of trough, radial, concentric, and other features, and veneer characteristics in detailed map areas A-G at Inari Corona.

<table>
<thead>
<tr>
<th>Feature Characteristics</th>
<th>Area A</th>
<th>Area B</th>
<th>Area C</th>
<th>Area D</th>
<th>Area E</th>
<th>Area F</th>
<th>Area G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trough Lengths (km)</td>
<td>5 to &gt;100</td>
<td>2 to 200</td>
<td>5 to 200</td>
<td>8 to 20</td>
<td>30 to 100</td>
<td>5 to 100</td>
<td>10 to 75</td>
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<td>up to 30</td>
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<td>2 to 8</td>
<td>2 to 5</td>
<td>2 to 10</td>
<td>2 to 8</td>
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<td>intersecting</td>
<td>curved</td>
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<td>radial, concentric</td>
<td>radial, concentric</td>
<td>radial</td>
<td>radial, concentric</td>
<td>concentric band</td>
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<tr>
<td>Trough Bottoms</td>
<td>RS*</td>
<td>RS</td>
<td>RS</td>
<td>RS</td>
<td>RS</td>
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<td>RS</td>
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<tr>
<td>Trough Interactions</td>
<td>cuts and cut by radial &amp; concentric features</td>
<td>cuts and cut by radial, concentric, &amp; NRNC features</td>
<td>cuts and cut by radial, concentric, &amp; NRNC features</td>
<td>cuts and cut by radial, concentric, &amp; NRNC features</td>
<td>cuts and cut by radial, concentric, &amp; NRNC features</td>
<td>cut by radial features &amp; N-S lineaments</td>
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<tr>
<td>Radial Features</td>
<td>fractures, pit chains</td>
<td>fractures, pit chains</td>
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<tr>
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<td>5 to &gt;100</td>
<td>5 to 100</td>
<td>5 to 100</td>
<td>5 to 60</td>
<td>5 to &gt;100</td>
<td>5 to 150</td>
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<tr>
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<td>1 to 5</td>
<td>1 to 5</td>
<td>N/A</td>
<td>2 to 5</td>
<td>1 to 3</td>
<td>1 to 3</td>
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<tr>
<td>Radial Feature Trends</td>
<td>varies (truly radial)</td>
<td>NW-SE</td>
<td>N-S</td>
<td>E-W suite, N-S suite</td>
<td>WNW suite, WNW suite</td>
<td>WNW suite, WNW suite</td>
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<tr>
<td>Radial Feature Spacing</td>
<td>100's of m</td>
<td>TCSTD**</td>
<td>TCSTD</td>
<td>100's of m</td>
<td>TCSTD</td>
<td>TCSTD</td>
<td>TCSTD</td>
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<td>troughs, concentric features, &amp; veneer</td>
<td>troughs, concentric features, &amp; veneer</td>
<td>troughs, concentric features, &amp; NRNC features</td>
<td>troughs, concentric features, &amp; veneer</td>
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<tr>
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<td>fractures, pit chains</td>
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<td>5 to &gt;100</td>
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<td>4 to 10</td>
<td>N/A</td>
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<td>2 to 5</td>
<td>1 to 5</td>
<td>1 to 5</td>
<td>1 to 3</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>Concentric Feature Trends</td>
<td>varies (truly concentric)</td>
<td>E-W</td>
<td>E-W suite, NW-SE suite</td>
<td>NW-SE suite, NE-SW suite</td>
<td>N-S</td>
<td>N/A</td>
<td>E-W</td>
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<td>Concentric Feature Spacing</td>
<td>100's of m</td>
<td>100's of m</td>
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<td>100's of m</td>
<td>100's of m</td>
<td>N/A</td>
<td>100's of m</td>
</tr>
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<td>Concentric Feature Interactions</td>
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<td>troughs, radial features, &amp; veneer</td>
<td>troughs, radial features, &amp; veneer</td>
<td>troughs, radial &amp; NRNC features, &amp; veneer</td>
<td>troughs, radial features, &amp; veneer</td>
<td>N/A</td>
<td>troughs, radial features, &amp; veneer</td>
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Table 2. Summary of trough, radial, concentric, and other features, and veneer characteristics in detailed map areas A-G at Inari Corona. continued.

<table>
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<tr>
<th>NRNC Features</th>
<th>N/A</th>
<th>fractures, pit chains</th>
<th>fractures, pit chains</th>
<th>fractures</th>
<th>N/A</th>
<th>N-S lineaments</th>
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<td>NRNC Feature Lengths (km)</td>
<td>N/A</td>
<td>10 to 100</td>
<td>5 to 100</td>
<td>2 to 50</td>
<td>3 to 100</td>
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<td>1 to 5</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>NRNC Feature Trends</td>
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<td>NW-SE</td>
<td>WNW</td>
<td>NW-SE</td>
<td>WNW</td>
<td>N/A</td>
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<td>N/A</td>
<td>100's of m</td>
<td>100's of m</td>
<td>100's of m</td>
<td>100's of m</td>
<td>N/A</td>
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<td>troughs, radial and concentric features, &amp; veneer</td>
<td>troughs, radial fan and concentric features, &amp; veneer</td>
<td>troughs, radial features, &amp; veneer</td>
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</tr>
<tr>
<td>Relative Veneer Locations</td>
<td>SW, NE, SE, center</td>
<td>NW, SW, NE, E</td>
<td>center, SW, NE</td>
<td>south-center, NE SW, NW</td>
<td>center, E NE, SW</td>
<td>NE, center S</td>
</tr>
<tr>
<td>Sharp Veneer Boundaries</td>
<td>SW (W boundary), NW (W boundary), &amp; SW, center</td>
<td>SW (W boundary), NW (W boundary), &amp; SW, center</td>
<td>south-center, center, E NE, SW</td>
<td>NE, center south-center, SE</td>
<td></td>
<td></td>
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<tr>
<td>Diffuse Veneer Boundaries</td>
<td>SW (E boundary), NE</td>
<td>SW (E boundary)</td>
<td>center, (S &amp; E boundaries)</td>
<td>NW NE, SW S</td>
<td>north-center</td>
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<td>Veneer Interactions</td>
<td>troughs, radial &amp; concentric features</td>
<td>troughs, radial, concentric, &amp; NRNC features</td>
<td>troughs, radial, concentric, &amp; NRNC features</td>
<td>troughs, radial, concentric, &amp; NRNC features</td>
<td>troughs, radial &amp; concentric features, &amp; N-S lineaments</td>
<td></td>
</tr>
</tbody>
</table>

*RS stand for radar-smooth.
**TCSTD stands for "too closely spaced to determine" width between features.
**NRNC stands for "neither radial, nor concentric" features relative to Inari Corona.
Figure 21. Block diagram of magmatic pit chain evolution. Pit chains begin as lineaments marking topographic lows; subsurface structures are fractures with dikes at depth. Individual pits within pit chains merge together to form troughs with rounded terminations. Individual troughs merge together over time (unpublished, Hansen).

Figure 22. Block diagram of stoping in magmatic pit chains. Pit chain formation can include collapse above a dike where fallen material can be transported away at depth (from Cushing et al., 2015).
Figure 23. Particle segregation in a pyroclastic density current (from Branney & Kokelaar, 2002).
Figure 24. Conceptual cartoon of Inari Corona topography, lithosphere thickness, and heat transfer via extensive fracturing (dikes at depth) and pit chain development (radial and concentric). Dikes cut thin lithosphere (with lithosphere thickness related to elevation) and stope material into the subsurface, which can be carried away at depth and emerge as surface flows at lower elevation. Mantle heat transfer occurs via convection, and lithospheric heat transfer by way of advection and conduction.