

New mapping along Ishtar Terra margins: use and limits of Magellan SAR data for testing Venus crustal plateau formation models

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2 **for testing Venus crustal plateau formation models**

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12 **Key Points:**

- 13 • New detailed mapping along the margin of Ishtar Terra tests crustal plateau formation
14 models.
15 • Results reveal plains-forming volcanism after all highland tectonism and a large
16 variance in possible deformational histories.
17 • A two times higher resolution radar imagery and an order of magnitude better
18 resolution elevation map are vital to interpret the geology.

19 **Abstract**

20 The origins of crustal plateaus on Venus are poorly understood. Several formation models
21 have been proposed, including four previously explored models: downwelling, upwelling,
22 pulsating continents, and bolide impact models; as well as a waning heat-pipe model. Key
23 predictions which vary across models include surface deformation, marginal deformation,
24 and the tessera-plain onlapping relationships. Addressing this problem, we perform detailed
25 mapping of five sites along the margin of Ishtar Terra, the highland region holding Venus's
26 highest peak, focusing on identifying surface units and sets of deformation lineaments. This
27 work indicates that all tessera units and associated deformations are embayed by lava plains
28 in four out of five studied areas. Plains-forming volcanism occurs after, or outlasts, all crustal
29 plateau tectonism, which is consistent with three models: the pulsating continents, waning
30 heat-pipe, and upwelling models. At the fifth site, tessera units appear to be embayed by

31 plains, but it is also possible that this boundary is a linear fault system. Deformation
32 relationships alone are unable to test models as they show a large variance in possible
33 deformational histories given significant radar data uncertainties. A two times higher
34 resolution radar imagery (i.e., 40 meters/pixel) and an order of magnitude better resolution
35 topographic map (i.e., 450 meters/pixel) will be necessary to more rigorously test models via
36 embayment relationships and deformation patterns. Our mapping also identifies some new
37 features, including (1) embayment of tessera fractures alone on lava plains, as well as (2) 10-
38 20 km long and 2-5 km wide eye-pattern ridges, composed of (3) V-shape lineaments.

39 **Plain Language Summary**

40 Large mountains exposing complexly deformed surfaces occur on Venus. These mountains
41 have been studied for decades, but the mechanisms of their formation remain hotly debated.
42 We examine five proposed mechanisms which predict different mountain shapes and
43 deformation structures. We studied Ishtar Terra, one of the largest mountain regions on
44 Venus, to see which models can predict the observations. Specifically, we map out five
45 marginal regions of Ishtar Terra with surface radar imagery to study the landforms and
46 consider the possible evolutions of each area. Our mapping work shows that widespread lava
47 plains were emplaced after all mountain deformation, which is consistent with models
48 suggesting that the mountains are (1) analogous to Earth's continents, (2) thickened by
49 upwelling mantle plume, or (3) formed by heat-pipe tectonics induced global contraction. We
50 also find that studying the deformation structures alone is unable to test the models as it
51 shows a wide range of possible interpretations under large uncertainties in the radar imagery.
52 Future radar measurement with two times higher resolution will be required to further test the
53 models. Our mapping also identifies two new related structures – (1) eye-pattern ridges
54 composed of (2) V-shape faults, which many reflect crustal flow.

55 **1 Introduction**

56 The formation mechanisms of the crustal plateaus and tessera terrains on Venus have been a
57 controversial topic. These crustal plateaus appear to (1) feature thickened crust, evidenced by
58 small gravity anomalies with relatively shallow apparent depths of compensation
59 (Bindschadler et al., 1992; Grimm, 1994; Moore and Schubert, 1997; Simons et al., 1997;
60 Smrekar and Phillips., 1991), and (2) expose or preserve tessera terrain across about 8% of
61 the planetary surface (Brown and Grimm, 1997; Ivanov and Head, 1996). Tessera terrain is
62 defined by the complex deformation of at least two overlapping lineament sets, which

63 appears as bright backscatter regions on radar images. (Bindschadler and Head, 1991; Ivanov
64 and Head, 1996; Sukhanov, 1992). Mapping shows that lava flows mostly embay these
65 tessera fabrics, indicating that tessera is locally older than adjacent plains emplacements
66 (Basilevsky and Head, 1995, 1998; Ivanov and Head, 2011; Ivers and McGill, 1998).
67 However, the density of impact craters on both tessera terrain and volcanic plains are similar,
68 which may suggest a simultaneous formation of both units and the erasure of the impacting
69 record by surface deformation or relaxation (e.g., M. A. Ivanov and Basilevsky (1993);
70 Phillips and Hansen (1998); Romeo and Turcotte (2008)). Therefore, any viable model must
71 be able to explain the thickening of crust, the stratigraphic relationships, and the distribution
72 of impact craters.

73 The origin of the tessera highlands has been explained via a variety of hypotheses. Models
74 include: (i) mantle downwelling resulted in thickening and horizontal shortening of the crust
75 (Bindschadler and Head, 1991; Bindschadler and Parmentier, 1990; Bindschadler et al., 1992;
76 Kiefer and Hager, 1989; Roberts and Head, 1990), (ii) an upwelling plume impinged upon
77 early thin crust which leads to crustal thickening by magmatic processes (Ghent and Hansen,
78 1999; Hansen and Willis, 1998; Phillips and Hansen, 1998), (iii) buoyant crustal material that
79 contracted during an episodic global subduction event (Romeo and Turcotte, 2008), (iv)
80 regions of thickened crust forming in response to global radial lithospheric contraction driven
81 by heat-pipe volcanism that transitions to stagnant lid cooling (Moore et al., 2017), and (v)
82 the cooling of a large impact-generated lava pond where massive partial melting formed a
83 low-density residuum resulted in surface uplift of solidified lava pond (Hansen, 2006).
84 Testable model predictions include distinct highland geometries and the relative age of
85 bounding faults, tessera and marginal deformation, and volcanism.

86 Four of the above models have been previously explored to explain Ishtar Terra's formation
87 including the downwelling (Bruegge and Head, 1989; Ivanov and III, 2008; Roberts and
88 Head, 1990a), upwelling (Hansen and Willis, 1998), episodic overturn/pulsating continents
89 (Romeo and Turcotte, 2008), and bolide impact with lava pond models (Hansen, 2006).
90 Hence, we explore the margins of Ishtar Terra, a plateau-shaped highland holding Venus's
91 highest peak and located near the north pole at 70.4°N 27.5°E with the dimensions of
92 approximately 4500×2600 km. (Figure 1).

93 Tessera-plain overlapping relationships, surface deformation, and marginal deformation are
94 key features to differentiating these models. Therefore, we undertook mapping along five

Ishtar Terra marginal areas in unprecedented detail to identify tessera-plain embayment relationships and deformation structures. Mapping selected small areas in exceptional detail can carefully test the key model predictions. The five areas identified in Figure 1 have good radar and topographic data coverages and represent margins of different types. The southern margin (Figure 4) has been mapped as part of regional mapping efforts (Campbell and Campbell, 2002; Sukhanov et al., 1989) providing a comparison for our higher resolution map. The southwestern (Figure 7), northern (Figure 8), and western (Figure 9) margins are selected because previous studies suggest they host a contractional belt (Keep and Hansen, 1994), subduction zone (Ivanov and Head, 2007), and a strike-slip fault system (Marinangeli and Gilmore, 2000) respectively. The eastern margin (Figure 10) was selected as the only marginal area with both stereo-derived topographic data (Herrick et al., 2012) and radar imagery available.

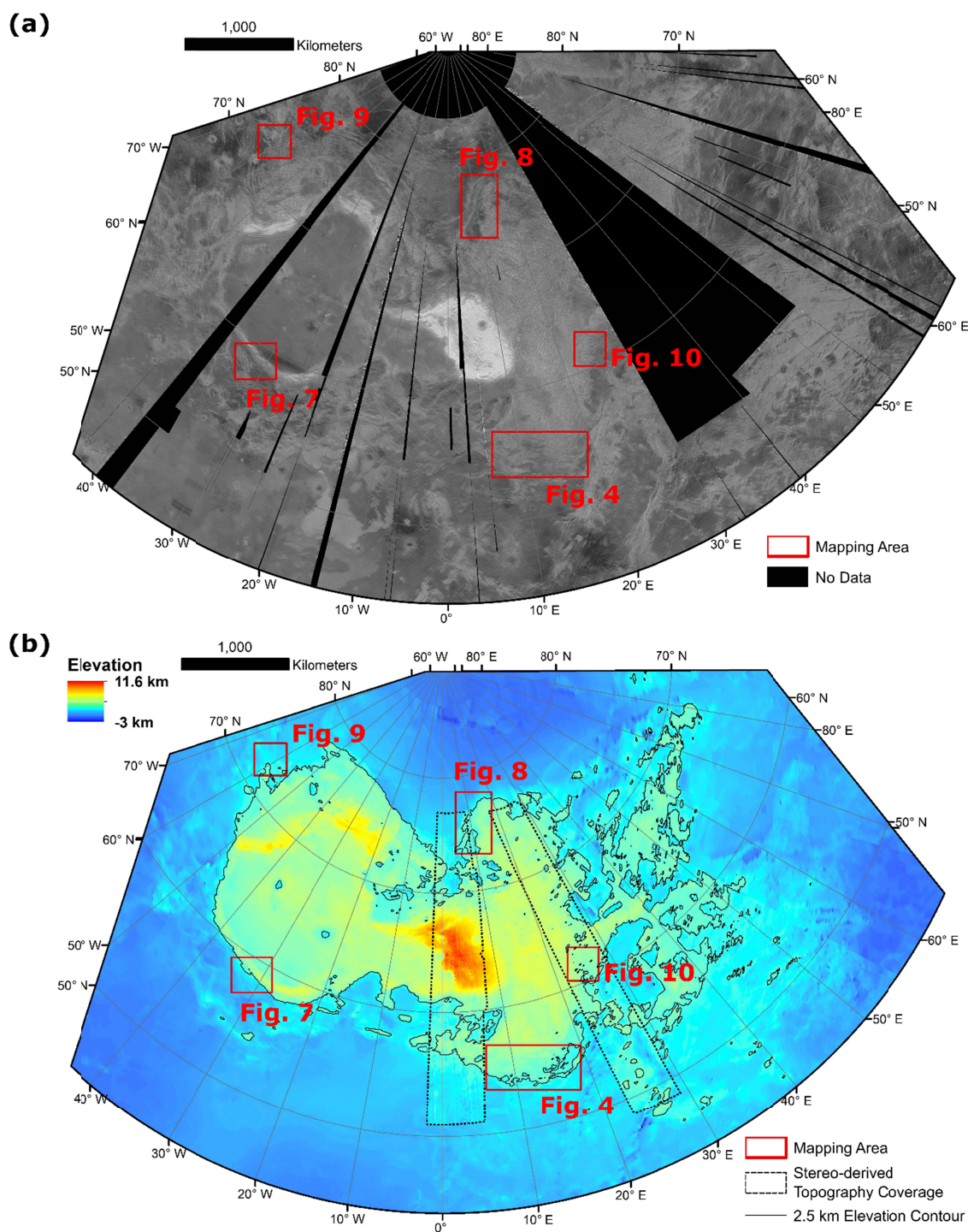


Figure. 1 Magellan SAR image (a) and topographic data (b) of Ishtar Terra. Locations of the study areas are framed in red outlines. The 2.5 km elevation contour represents the base of the highland and is outlined in thin black lines in (b). The stereo-derived topographic data (Herrick et al., 2012) is overlaying the Magellan elevation map, and its coverage is outlined in dotted-lined frames. The elevation is above the mean planetary radius, 6051 km.

In this contribution, we first outline the details of five proposed models and their testable predictions. We then present our maps of surface units and lineament sets across five Ishtar

Terra marginal areas (Figure 1). A distinction of our approach is that much prior mapping serves to establish consistency with single hypotheses, whereas our mapping seeks to bracket the range of possible structural evolutions.

2 Proposed crustal plateau formation models

The mantle downwelling/convergence model (Figure 2a - c) shows the crustal plateau as a result of crustal thickening and radial horizontal shortening (Bindschadler and Head, 1991; Bindschadler and Parmentier, 1990; Bindschadler et al., 1992; Kiefer and Hager, 1989; Roberts and Head, 1990). Such a regional long-lived mantle downwelling leads to: (i) a progressively formed symmetric broad swell (Bindschadler and Parmentier, 1990; Ghent and Hansen, 1999) growing from tessera inliers to margins; (ii) volcanism occurring throughout all stages of crustal plateau evolution (Ivanov and Head, 2008); (iii) an intense contractional history with early radial ridges and later concentric thrust-fold mountain belt deformation (Kiefer and Hager, 1989), followed by minor extensions (Bindschadler et al., 1992) (Figure 2c); (iv) progressive contraction from core to rim during the mountain building period (Ivanov and Head, 2008); and (v) possible intra-tessera volcanism due to delamination (Figure 2b) (Bindschadler and Parmentier, 1990; Hess and Head, 1990; Ivanov and III, 2008) or basal melting (Figure 2a) (Ivanov and III, 2008; Roberts and Head, 1990), which postdates some early developed folds and thrusts.

However, based on the geometry prediction tested by former workers, such as Ghent and Hansen (1999), it has been argued that this model fails to produce the observed steep-sided, flat-topped plateau topography on Venus. Nonetheless, the side steepness may be strongly dependent on the Venus crustal rheology, which remains poorly constrained. For example, the higher basal viscosity can resist the tendency of high topography to spread and result in a steep-sided plateau (Kiefer and Hager, 1991). It is also possible that this model could work for a steep-side and flat-topped plateau if a later lithospheric root removal event influences the topography. Thus, we suggest that the topography alone does not provide a sufficiently compelling test of the model.

In the upwelling model, a mantle plume impinged upon early thin crust and thickened the overlaying crust by magmatic processes (Figure 2d) (Ghent and Hansen, 1999; Hansen and Willis, 1998; Phillips and Hansen, 1998). This model is proposed to produce: (i) a steep-sided and flat-topped highland due to a later viscous relaxation after losing the thermal support (Ghent and Hansen, 1999), (ii) old highland bounding faults mostly covered by adjacent

147 plains and some potentially crosscutting surrounding lava plains, (iii) a three-phase
148 deformation (Figure 2e and f) of ribbon structures formed when the brittle-ductile transition
149 was shallow, then minor folding due to thermal subsidence, followed by graben formation
150 caused by gravitational relaxation at the late stage with a deepened brittle-ductile transition
151 (Ghent and Hansen, 1999; Hansen et al., 2000; Hansen and Willis, 1998), and (iv) surface
152 lava flow and intra-tessera volcanism (Phillips and Hansen, 1998).

153 Model of episodic overturn/pulsating continents (Figure 2g and h) interprets the tessera
154 highland as a continental crust that was not recycled in a proposed global subduction event
155 responsible for resurfacing the rest of the planet (Romeo and Turcotte, 2008). After the global
156 subduction event, the surviving continental crust was surrounded by the mantle and freshly
157 formed crust. Romeo and Turcotte (2008) stated that such hot surrounding induces
158 compression that thickens the remaining crust, forming a crustal plateau (Figure 2g).
159 Alternatively, we suggest the subduction itself can already cause the compression, much like
160 the downwelling model. The generation of a new lithosphere below the crust will cause basal
161 heating and the gravitational collapse of the plateau. During this collapse, the crust becomes
162 partially decoupled from the underlying lithospheric mantle, which facilitates delamination of
163 the lithospheric mantle to occur in the next global subduction event. The above processes
164 form a cyclic behavior of plateau growth during a global subduction event and subsequent
165 collapse before the next subduction event. This model suggests (Figure 2h): (i) a plateau
166 made of buoyant crust, (ii) highland formation and contractional deformation predate the
167 formation of the new global crust and the emplacement of plains, (iii) a highland
168 deformational history with an early concentric fold-thrust belt formed by subduction or
169 surrounding mantle heat, and later grabens due to gravitational relaxation, (iv) marginal
170 contractions on the adjacent plains formed by the highland gravitational spreading, and (v)
171 intra-tessera volcanism driven by late decompression or basal heating. These predictions are
172 basically the same with those of the downwelling model, except that the bounding terrain
173 actually subducts, rather than being part of the rigid lid.

174 Waning heat-pipe to stagnant lid tectonics (Figure 2i and j) is newly proposed for this
175 problem. Active heat-pipe tectonics have been proposed on Venus but dismissed due to
176 inadequate surface heat flux (Turcotte, 1989). Moore et al. (2017) suggested that Venus's
177 thick lithosphere, uniformly distributed impact crater record, the dominance of volcanism and
178 isostatic support of crustal plateau are evidence of waning heat-pipe volcanism with a recent
179 transition to stagnant lid. During early heat-pipe tectonics, plateaus developed under a global

180 contraction, the consequence of on-going downwards advection of lithosphere in response to
181 the ongoing evacuation of mantle materials to the surface via volcanism. The rapid surface
182 volcanism buried and advected old surface layers downwards forming a thick, cold, and
183 single-plate lithosphere. As heat-pipe cooling waned, the thickness of the lithosphere was
184 reduced due to a lower surface burial rate (Figure 1 of Moore et al. 2017). The global
185 contraction was also weakened. Later on, as heat-pipe cooling gradually transitioned into a
186 stagnant-lid regime, the thinned lithosphere began to thicken again by the establishment of a
187 conduction-dominated thermal profile with limited volcanism. (Moore et al., 2017). The
188 contraction- formed highlands are preserved within this thickened lithosphere (Figure 2i).

189 Analogous to Jupiter's moon Io, such a heat-pipe operation leads to the following predictions
190 on Venus (Figure 2j): (i) Plateaus should be elevated regions of rough surfaces with linear or
191 curved boundaries representing initiating thrust faults (Schenk et al., 2001; Turtle et al.,
192 2001). (ii) These mountains should be among the oldest features of the Venusian surface. The
193 faults/deformation systems bounding such mountains should be overprinted by later
194 deformation or overlain by younger materials, so that they are all surrounded by embayment
195 features. (iii) The global contraction formed highland lineaments of ridges and grabens
196 subparallel to the bounding marginal thrust fault system predicted from Io's mountains, such
197 as Hi'iaka Mons, and Shamshu Mons (Bunte et al., 2010). Modeling work also shows such
198 mountain systems experienced early contraction and the initiation of thrust faults in the
199 subsurface. The uplift of fault-bound blocks led to gravitational collapse and extension across
200 elevated regions. (Bland and McKinnon, 2016). (iv) the rest of Venus' surface underwent
201 resurfacing with continuously global volcanism (Moore et al., 2017; O'Reilly and Davies,
202 1981; Turcotte, 1989).

203 Finally, the bolide impact with lava pond model (Figure 2k and l) suggests a large bolide
204 impact generated a highland-scale lava pond where partial melting and differentiation formed
205 a low-density residuum resulting in a surface uplift of the solidified lava pond (Figure 2k)
206 (Hansen, 2006). This model makes several predictions (Figure 2l): (i) A roughly circular
207 highland is expected. (ii) Local resurfacing was occurring with highland tectonism (Hansen,
208 2006). (iii) Magma convection in the lava pond shortened the layer and formed early fold
209 crests representing selective amplifications of instabilities in the congealed surface. Then,
210 extensional fabrics (ribbons and grabens) representing maximum principal stresses
211 overlapped early fold crests (Hansen, 2006). (iv) Subsurface magma may later leak to the
212 surface flooding local lows in structural topography and solidifies as intra-tessera plains.

213 Hence, there are three key differentiations among the predictions: the tessera-plain
214 overlapping relationship, tessera deformation, and the marginal deformation (Table 1). First,
215 most of the models agree tessera is the locally oldest unit, but the upwelling and bolide
216 impact with lava pond models suggest tessera is not in all places older than plains. Second,
217 the upwelling model also predicts an extensional highland formation with late minor
218 contraction, followed by another extension. The lava pond model predicts a plateau with
219 extensional fabrics overprinting early fold crests, whereas all other models predict
220 contractional highland formations. Third, the downwelling, episodic overturn/pulsating
221 continent, and waning heat-pipe to stagnant lid models predict significant compression along
222 the tessera block edges while the upwelling model predicts limited marginal contraction. In
223 the following sections we present mapping in 5 marginal regions of Ishtar Terra to determine
224 if these differentiating predictions can be tested.

Downwelling

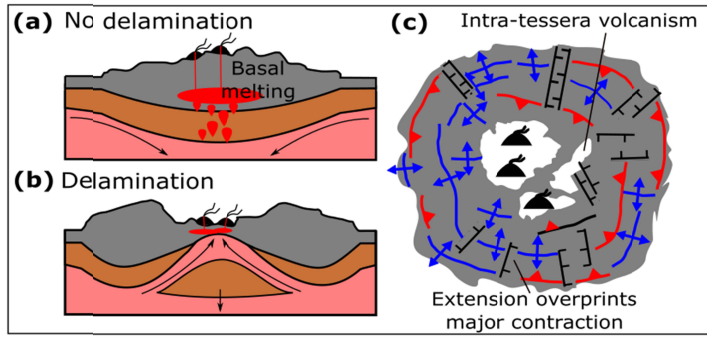
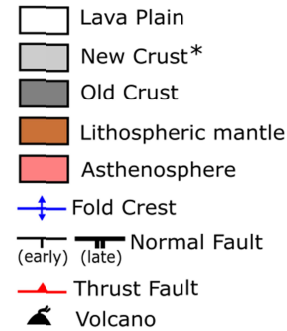
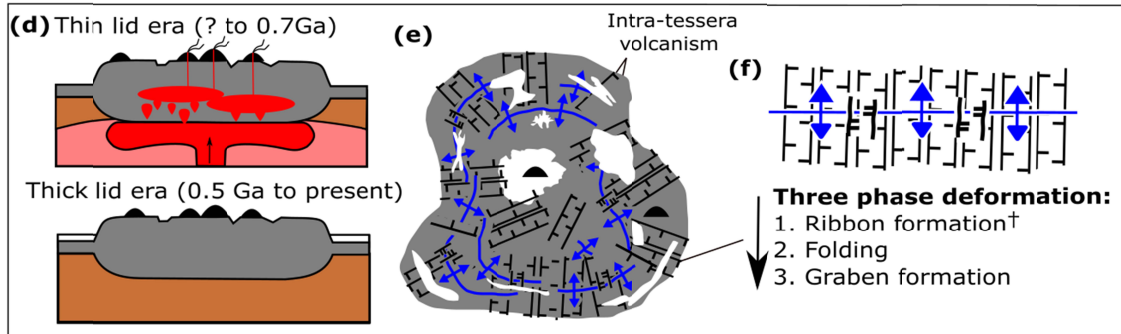


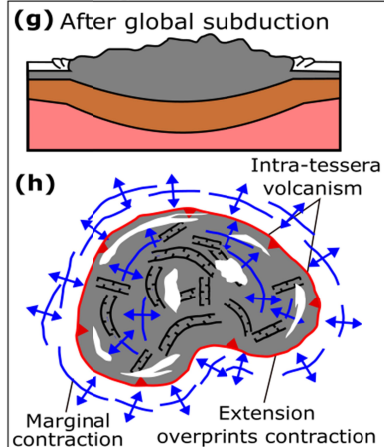
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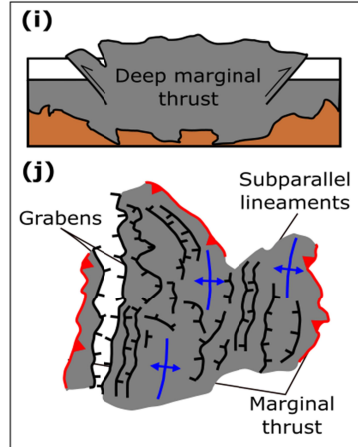
Upwelling



Episodic overturn/ Pulsating continents



Waning heat pipe to stagnant lid



Bolide impact with lava pond

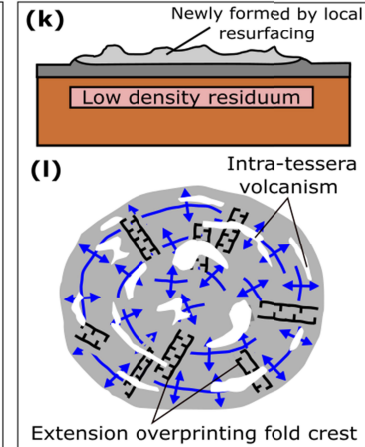


Figure. 2 The models proposed to explain the formation of the crustal plateaus exposing complexly deformed surfaces, with both evolutionary diagrams and predictive maps. Mantle downwelling model diagrams (a) (b) are modified from Roberts et al's (1990) Figure 3e, with a predictive map added (c). Mantle upwelling model diagram (d) is modified from Phillips and Hansen (1998), its predictive map (e) and three phase deformation diagram (f) are based on Ghent and Hansen (1999). Pulsating continents model diagram (g) and its predictive map (h) are modified from Romeo and Turcotte (2008). Waning heat-pipe to stagnant lid model diagram (i) is modified from the highland cross-section of Io from Ahern et al (2017) with lithospheric structure on Moore and Webb (2013), and its predictive map (j) is based on the map of West Shamsu Mons on Io from Ahern et al. (2017). Bolide impact with lava pond model diagram (k) and its predictive map (l) are modified from Hansen (2006). *New crust refers to a crust formed by local volcanic resurfacing events simultaneously with deformation in the bolide impact with lava pond model. It differs from other models for which the crust exists before tessera tectonics. †"Ribbon structure" is the opening of tension fractures in a thin, brittle layer above a ductile substrate with a near-vertical trough wall. This proposed Venus tessera structure indicates a shallower

239 *early brittle-ductile transition compare to a deeper one for graben formation. (Ghent and Hansen, 1999;*
240 *Hansen and Willis, 1998)*

Model	Bounding Fault vs. Plain-forming volcanism	Surface Deformation	Marginal Deformation
Downwelling	Associated in all stages of development	Major contraction and late extension	Concentrated compression along elevated block edge
Episodic Overturn /Pulsating Continents	Bounding fault is older than adjacent plains		
Waning heat-pipe to stagnant lid			
Upwelling	Bounding fault is mostly older than adjacent plains, but not in all places	Major extension, followed by minor contraction and late minor extension	Marginal extension
Bolide impact with lava pond	Formed simultaneously by local resurfacing	Early fold crests and late extension	Slight or none

241 *Table. 1 Central differentiations of Venusian crustal plateau formation model predictions.*

242 3 Remote Sensing data and mapping methods

243 3.1 Mapping data, software, and approach

244 Stratigraphic unit and structural mapping are conducted using synthetic aperture radar (SAR)
245 images, and topographic data collected by the Magellan spacecraft with a 12.6-centimeter
246 wavelength radar mapper (Ford and Plaut, 1993), and stereo-derived topographic data created
247 by Herrick et al. (2012). Full-resolution (FMAP) SAR images are the fundamental data set
248 for detailed Venus mapping with a 75 meters resolution (Saunders et al., 1992). FMAP
249 images are produced by the US Geological Survey Astrogeology Science Center (1994).
250 Left-looking images are used as a base map due to its higher coverage. Illumination is from
251 the west (left) at an incidence angle close to 25° in Ishtar Terra region (latitude between 60°N
252 and 77°N) (Saunders et al., 1992) (see Figure 3a and b). The relative radar brightness in the
253 image relates primarily to surface roughness at a scale comparable to the wavelength (12.6
254 cm) (Maurice et al., 1994), which dark areas represent low backscatter, implying a smooth
255 surface, and bright areas represent high backscatter, implying a rough surface.

256 Topographic data from the Magellan mission radar altimetry (Ford and Plaut, 1993; Ford and
257 Pettengill, 1992) and hillshade imagery are also used to study the crustal plateau with a much
258 lesser horizontal resolution of 4641 meters/pixel and a vertical resolution (relative height)
259 may approach 5 meters, depending on the terrain roughness, with the absolute uncertainty of
260 50 meters due to orbital uncertainties (Pettengill et al., 1991). Stereo-derived topographic
261 data is available for a small portion of Ishtar Terra margin (Figure 1b), which has a horizontal

resolution of ~1-2 km and a vertical resolution of ~100 m (Herrick et al., 2012). The construction of geological maps is conducted with the use of ArcGIS in north pole stereographic projection.

3.2 Stratigraphic unit mapping

Stratigraphic material units are primarily defined by their relative radar brightness and surface textures. Brightness contrasts and cross-cutting relations are used to map unit boundaries. Mapping units are grouped into three categories: tessera unit (t), lava plains (p), and impact crater (IC). *Tessera (t)* is distinctively radar-bright and heavily deformed by two or more intersecting tectonic elements (Bindschadler and Head, 1991). *Lava plains (p)* are smooth lava plains with a varies range of radar brightness (Hansen and Willis, 1996). Some of the lava plains are isolated patches within the tessera unit. An *impact crater (IC)* is a circular depression structure with a rim, central peak and ejects materials, formed by impacting of meteorites. This mapping aims to distinguish the marginal tessera-plains overlapping relationships.

3.3 Structural mapping

Structures are mapped based on radar contrasting lineaments and then grouped by their appearances, patterns, and trends. Loosely following Stofan et al. (1993), we classify structures in three categories: [1] fractures of indeterminate origin(s), [2] curvilinear ridges, and [3] discrete structures such as faults. Radar-bright narrow lineaments occurring in parallel sets are commonly referred to as fractures (e.g., Ansan et al. (1994); Bender et al. (2000); Gilmore and Head (2000); Gilmore et al. (1997); Hansen and Willis (1998); McGill (2000); Romeo and Capote (2011)). Individual lineaments have widths up to a few resolution-cells (Magellan SAR resolution is 75 m per pixel). Some sets of lineament features can be identified as curvilinear ridges, fault sets, or other discrete structures based on the changes in the radar brightness adjacent to the features (Figure 3). In this paper, the term “curvilinear ridge” refers to a continuous raised lineament where two sloping sides meet at a smooth crest, such that the radar-facing side appears as radar-bright and the opposite side appears as a radar-dark downslope that gradually brightens as the slope becomes less steep (Figure 3b and e). In short, this is what an uneroded fold with a subhorizontal fold axis would look like (and Venus should have almost no surface erosion (Craddock, 2011)). Faults and other distinct discrete structures are most readily identified in sets (e.g., fault sets) or where the features require multiple component slopes (e.g., lava channels) (see Figure 3). For faults,

the case of fault-bound troughs bordered by two parallel faults commonly has the two faults appearing as a pair of sharp bright and dark lineaments within regular patterns of shaded and unshaded stripes (Figure 3a, c and d).

Lineament systems can be interpreted in a range of contexts: as features within contractional (Figure 3h and i) or extensional (Figure 3f and g) systems, mixed systems such as gravity slides with break-away zones and shortening at leading edges (Figure 3k), or as lava channels (Figure 3j). Previous mapping works interpret curvilinear ridges as contractional deformations (Figure 3i) (e.g., Ansan et al. (1996); Marinangeli and Gilmore (2000); Pritchard et al. (1997)), including simple folding and fault-propagation folding (Figure 3i). This is viable; nonetheless, normal faulting may also result in similar ridge structures (Figure 3g). For example, bookshelf faulting accommodates fault rotation, such that the tilted fault blocks form parallel long ranges and basins (Figure 3g). The lack of erosion on Venus' surface should leave continuous structures with discrete morphologies without smoothing by sediment-filled basins and eroded ranges. It follows that elevated ranges look ridge-like on SAR images, and this effect is magnified at higher latitude where radar foreshortening is more intense. The lava channels (Figure 3j) commonly record downcutting and have sub-vertical sides that appear as discrete structures on the radar image (Baker et al., 1997). Another possible distinctive model for tessera fault sets is the “ribbon structure” concept (Hansen et al., 2000; Hansen and Willis, 1996; Hansen and Willis, 1998), in which opening of tension fractures in a thin, brittle layer above a ductile substrate with a near-vertical trough wall (indicating a shallow brittle-ductile transition) formed the fault sets.

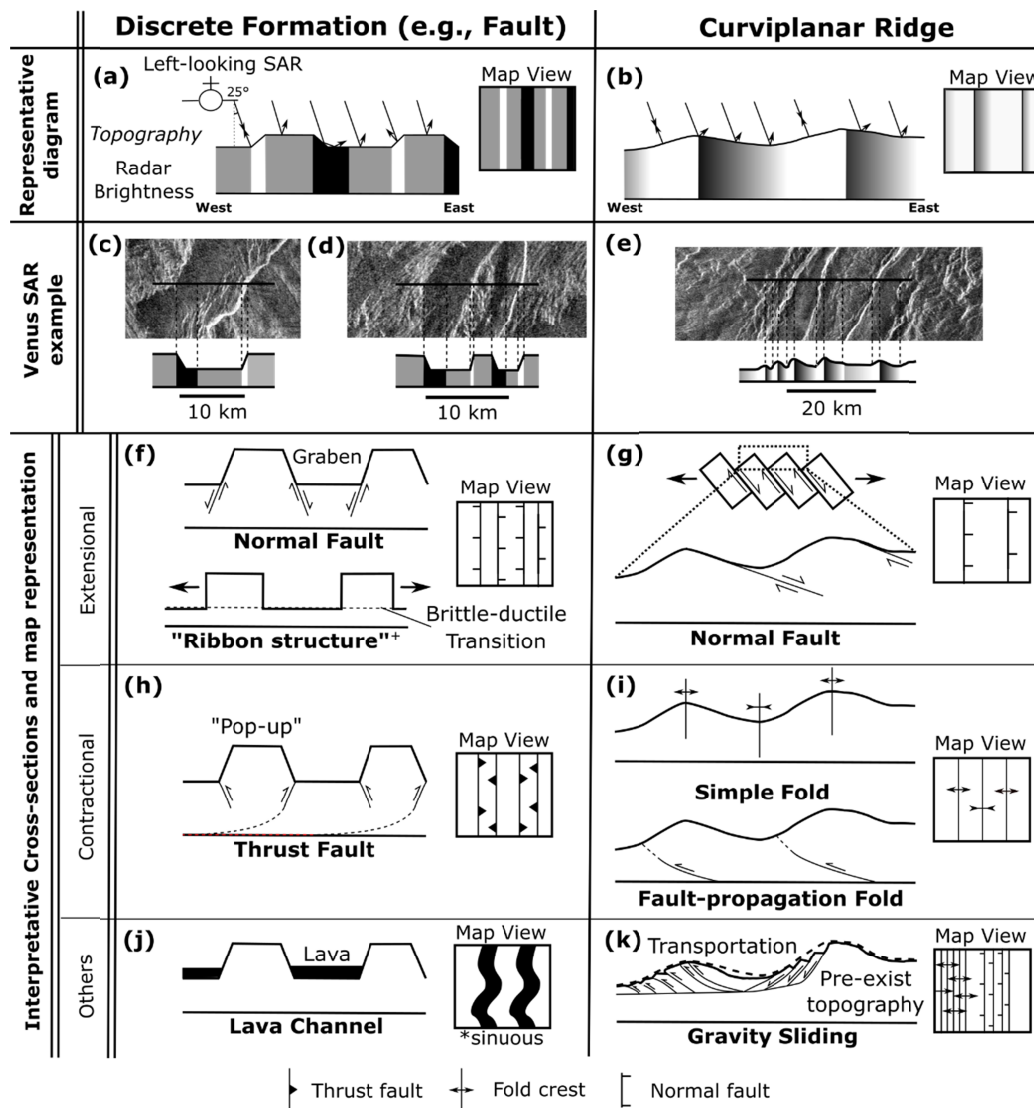


Figure. 3 Representative interpretative sketch cross-sections. Radar interactions with surface geology for both discrete formation (a) and curviplanar ridge (b) modified from Stofan et al. 1993, and their Venus SAR example (c) located at 59.147N, 31.848W, (d) located at 54.303N, 16.303E and (e) located at 71.89N, 16.839W. Interpretative cross-sections and map representation of brittle extensional (f), normal fault (g), thrust fault (h), fold (i), lava channel (j), and gravity sliding (k). * "Ribbon structure" is the opening of tension fractures in a thin, brittle layer above a ductile substrate with a near-vertical trough wall. This proposed Venus tessera structure indicates a shallower early brittle-ductile transition versus to a deeper one for graben formation. (Ghent and Hansen, 1999; Hansen and Willis, 1998)

4 Geological mapping results of Ishtar Terra

4.1 Regional characteristics of Ishtar Terra

The Ishtar Terra crustal plateau region on Venus (Figure 1) can be divided into two distinct parts: the western part dominated by Lakshmi Planum and the eastern part of Fortuna Tessera. Lakshmi Plenum is a low-lying plateau mostly covered by lava. This plateau is roughly 3.5

km above the mean planetary radius and bounded by mountains on most sides (Barsukov et al., 1986; Bruegge et al., 1990). These mountain belts include the northwestern Akna Montes and Freyja Montes, the southern Danu Montes, and on the east, the largest range being Maxwell Montes of about 11 km above the mean planetary radius. Adjoining the Maxwell Montes on the east is the Fortuna Tessera. Fortuna Tessera is a highly deformed terrain with complex trends of ridges and troughs that intersect one another, i.e., a classic tessera terrain. It extends from relatively low topography in the east to higher topography westward (Bruegge and Head, 1989). In short, Ishtar Terra displays complex morphology and tectonics, leading to series of previous mapping works (Ansan et al., 1994; Ansan et al., 1996; Bruegge and Head, 1990; Campbell and Campbell, 2002; Gaddis and Greeley, 1990; Hansen and Phillips, 1995; Hansen and Willis, 1998; Head, 1990; Ivanov and Head, 2007; Ivanov and Head, 2010; Ivanov and III, 2008; Keep and Hansen, 1994; Marinangeli and Gilmore, 2000; Pritchard et al., 1997; Roberts and Head, 1990; Sukhanov et al., 1989).

Analyses of Pioneer Venus (Grimm and Phillips, 1991; Sjogren et al., 1984) and Magellan (Hansen and Phillips, 1995; James et al., 2013; Kucinskas et al., 1996; Moore and Schubert, 1997) gravity data at Ishtar Terra show it has positive gravity anomalies consistent with apparent depths of compensation from ~ 130 to 180 km. Different mechanisms have been proposed to explain Ishtar Terra's thickened crust. Kucinskas et al. (1996) suggest that Ishtar Terra is mostly compensated (>80%) and supported by Airy compensation at the higher western Ishtar mountain belts and Fortuna Tessera (crustal thickening), with added thermal compensation at Lakshmi Planum (lithospheric thinning to -100 km). Significant delamination of a dense eclogitic lower lithosphere layer into the mantle may, therefore, be presently active in Lakshmi Planum (Kucinskas et al., 1996). Hansen and Phillips (1995) noted that Ishtar Terra is compensated at long-wavelengths (> 2500 km) from ~ 130 to 180 km, consistent with above findings, and short-wavelengths (500 – 2500 km) varying from a range of 25 – 70 km. They suggested the long-wavelength feature reflects ponding and thickening of partial melt residuum, and the short-wavelength features reflect heterogeneously deformed thickened lower crust. However, the resolution of the Venus gravity data is insufficient to conclusively test these models.

4.2 Basic mapping of Ishtar Terra margins

Here we present four detailed maps along the Ishtar Terra margin.

4.2.1 The southern margin of Ishtar Terra (Fortuna Tessera)

361 The southern margin of Ishtar Terra (Figure 4) is a gentle slope of the tessera highland. The
362 mapped tessera-plain boundaries reveal that the tessera units are completely embayed by the
363 surrounding lava plains (Figure 4 and 5), indicating that the tessera is the older unit in this
364 area. Some isolated lava plains patches within the tessera unit up to few 100s meters from the
365 margin may be formed by adjacent lava flow infilling or intra-tessera volcanism. A modified
366 impact crater is identified on the tessera unit, which is deformed by tessera fractures.

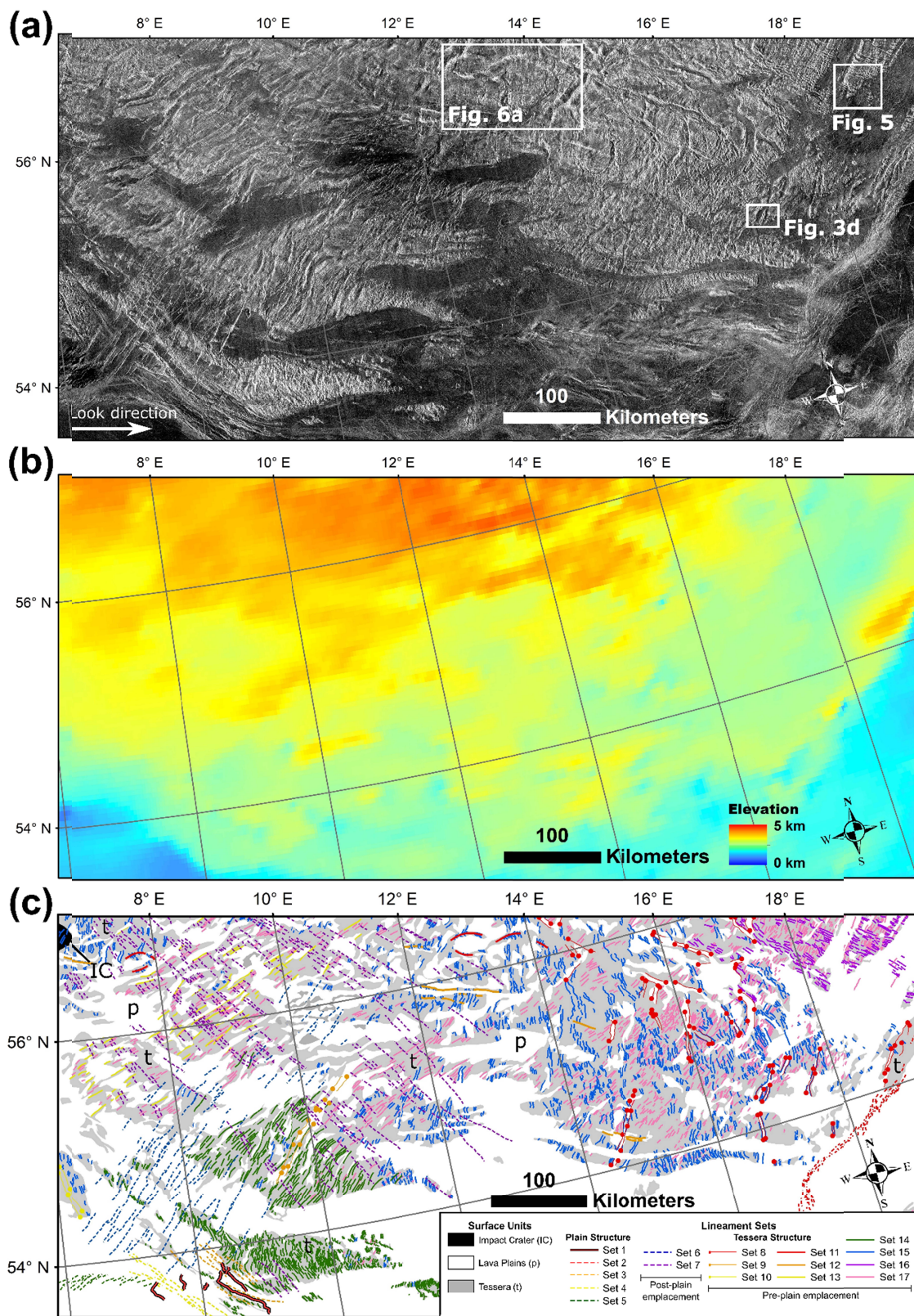


Figure 4 Left-looking SAR image (a), topographic map (b) and geological map (c) of the southern margin of Ishtar Terra. See Table 2 for the details of mapped structural set 1-17.

There are seventeen lineament sets of deformation mapped in this region. Descriptions of each set are recorded in Table 2. These lineament sets are discussed and grouped below according to the chronological order, from older to younger features, based on the cross-cutting relationship on the map: (1) tessera fractures, (2) tessera curviplanar ridges, (3) tessera faults, (3) and post plains emplacement deformations.

Set	Lineament description	Latitude N	Longitude E	n	Trend	Length km	Pattern	Interpretation
Plains Structures								
1	Sinuuous paired bright and dark lineaments	53.729	8.254	8		28.3	Sinuuous	Lava channel
2	Curvilinear bright fractures	53.524	17.294	82	NE	9.3	Subparallel	Fracture
3	Linear bright lineaments	53.729	8.254	21	SE	24.7	Parallel	Fracture
4	Linear bright lineaments	53.697	7.666	21	SE	14.6	Parallel	Fracture
5	Short bright lineaments	53.868	6.47	20	NE	10.7	Parallel	Fracture
Tessera Structures								
6	Long, straight, bright lineaments	54.56	7.786	98	NE	19.7	Parallel	Post-plain emplacement fracture
7	Long, straight, bright lineaments	55.971	9.548	36 4	SE	13.7		Post-tessera and plain fracture
8	Paired bright and dark lineaments with the mid-trough infilled by lava flow	55.024	16.794	77	SE-NE	19.2	Polygonal	Fault
9	Straight, long paired bright and dark lineaments	54.924	9.95	12	NE	16.7	Parallel	Fault
10	Long, straight, paired bright and dark lineaments	54.636	6.16	2	SSE	53.5	Parallel	Fault
11	Concentric lineaments	56.191	13.367	6		16.2	Concentric	Curviplanar Ridge
12	Symmetrical lineaments	55.787	13.393	11	ESE	19.3	Parallel	Curviplanar Ridge
13	Long, straight, bright lineaments	56.194	8.999	42	NE	13.7	Parallel	Fracture
14	Disrupted lineaments	54.38	9.727	10 7	NNE	12.1	Parallel	Fractures
15	Short, fragmentary bright lineaments	55.005	14.382	15 25	NW- NE	8.1	Parallel	Fractures
16	Fragmentary paired radar bright and dark lineaments	55.447	18.536	13 8	SE	7.6	Parallel	Fracture
17	Fragmentary bright lineaments	54.998	15.724	11 07	NE	5.8	Parallel	Fracture

Table. 2 Details of mapped structural sets 1 – 17 in Figure 4, with descriptions, locations, numbers of lineaments mapped (n), trends, mean lengths, patterns, and possible interpretations.

Set 13, 14, 15, 16 and 17 are bright fragmentary lineaments on tessera with the width of few resolution-cells sizes (Figure 4). These chaotic sets are crosscut by tessera curviplanar ridges and faults, indicating early phases of tessera deformation. These tessera fractures are mostly embayed by lava plains, whereas some scattered short fractures are exposed on the plains surface next to the embayed tessera margin (see Figure 5), indicating that these embaying fractures must be elevated above the surrounding lava plains.

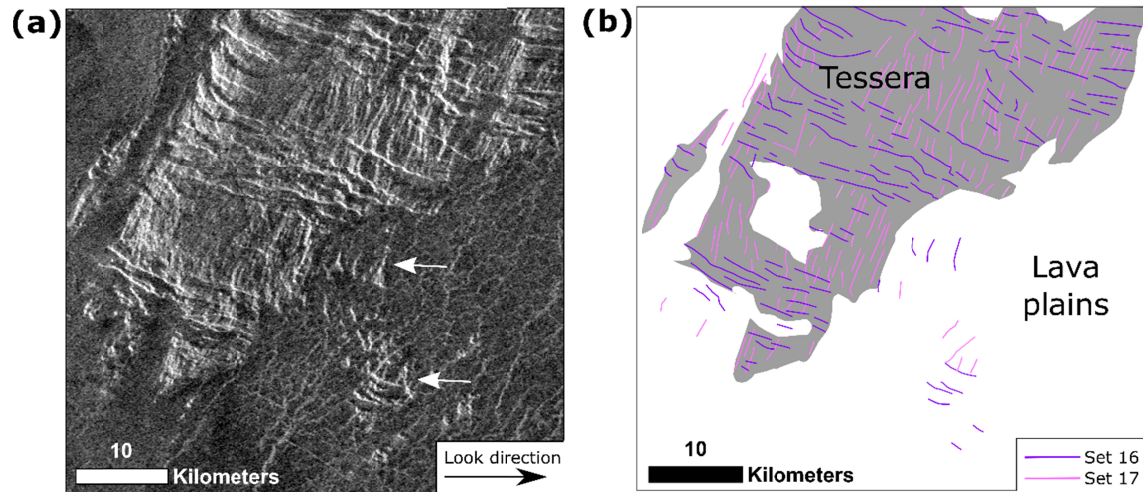


Figure. 5 A close-up image of clear lava embayed tessera and disrupted appearances of embaying fractures exposed on dark lava plains surfaces (white arrow). This area is located in the eastern part of the mapping area in Figure 4.

Sets 8, 9, and 10 are tessera faults and sets 11 and 12 are tessera curviplanar ridges (Figure 4). Set 12 is subparallel to the ESE-trending highland topographic margin (Table 2). Set 11 of “eye-pattern” concentric ridges are different from other subparallel lineament sets, as they are drastically bent. One of the ridges is found composed of recumbent V-shape fault of set 15 tilted along the ridges (Figure 6b). Interpretation of these features will be further discussed in section 5.1.1 Some of these tessera curviplanar ridges are locally cut by the discrete set of 8 (Figure 4). For faults, set 8 is paired linear and curvilinear faults deforming the eastern tessera in this area. The middle troughs bounded by the fault pairs are infilled with lava flows, dividing the marginal tessera into isolated blocks. Set 9 and 10 are two pairs of large faults on the tessera. All of the tessera curviplanar ridges and faults are cut by the lava embayment, indicating tessera deformations are earlier than the regional plains emplacement volcanism.

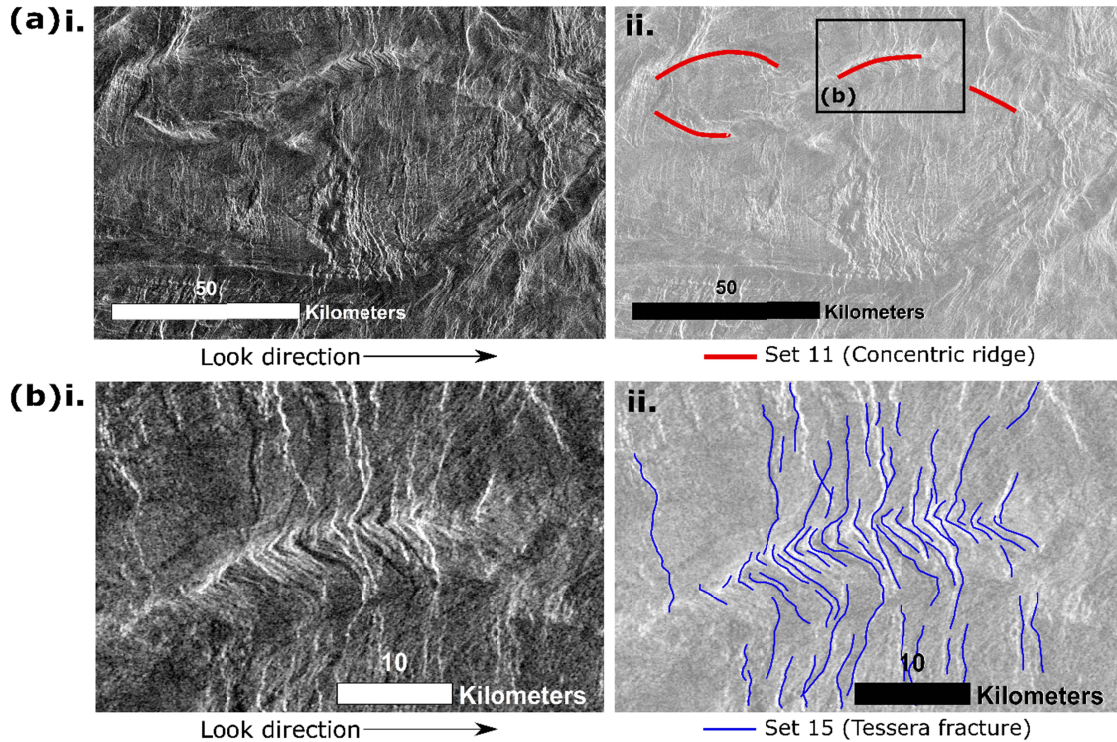


Figure. 6 SAR image (i.) and mapped image (ii.) of the “eye-shape” concentric ridge structures (a) labeled as Set 11, and the fragmentary tessera fractures (b) labeled as Set 15.

Furthermore, there are seven lineaments sets of post-plains emplacement structures. Set 6 and 7 are lineament sets across both the tessera and plains on the west side of this area. Set 2, 3, 4, and 5 are plains fractures. Set 1 is classified as lava channels due to its high sinuosity.

4.2.2 Southwestern margin of Ishtar Terra (Vesta Rupes)

The southwestern margin of Ishtar Terra (Figure 7) is a sharp topographic boundary between the tessera highland and adjacent low-lying plains. There are two major tessera blocks: the western block and the eastern elongated belt named Vesta Rupes, which is part of the mountain belts bounding the southwestern margin of Lakshmi Planum. The western low-lying tessera block is embayed by the adjacent lava plains, indicating that it is the regional oldest unit. Although the eastern tessera block appears to be embayed by plains in the mapping, it represents a rather linear feature along margins – a large fraction of Ishtar Terra’s west flank (see Figure 1). Thus, it is also possible that this boundary is a major fault system. Higher resolution data would be necessary to confirm the boundary type. This terrain has been described previously as a contractional deformation belt (Keep and Hansen, 1994).

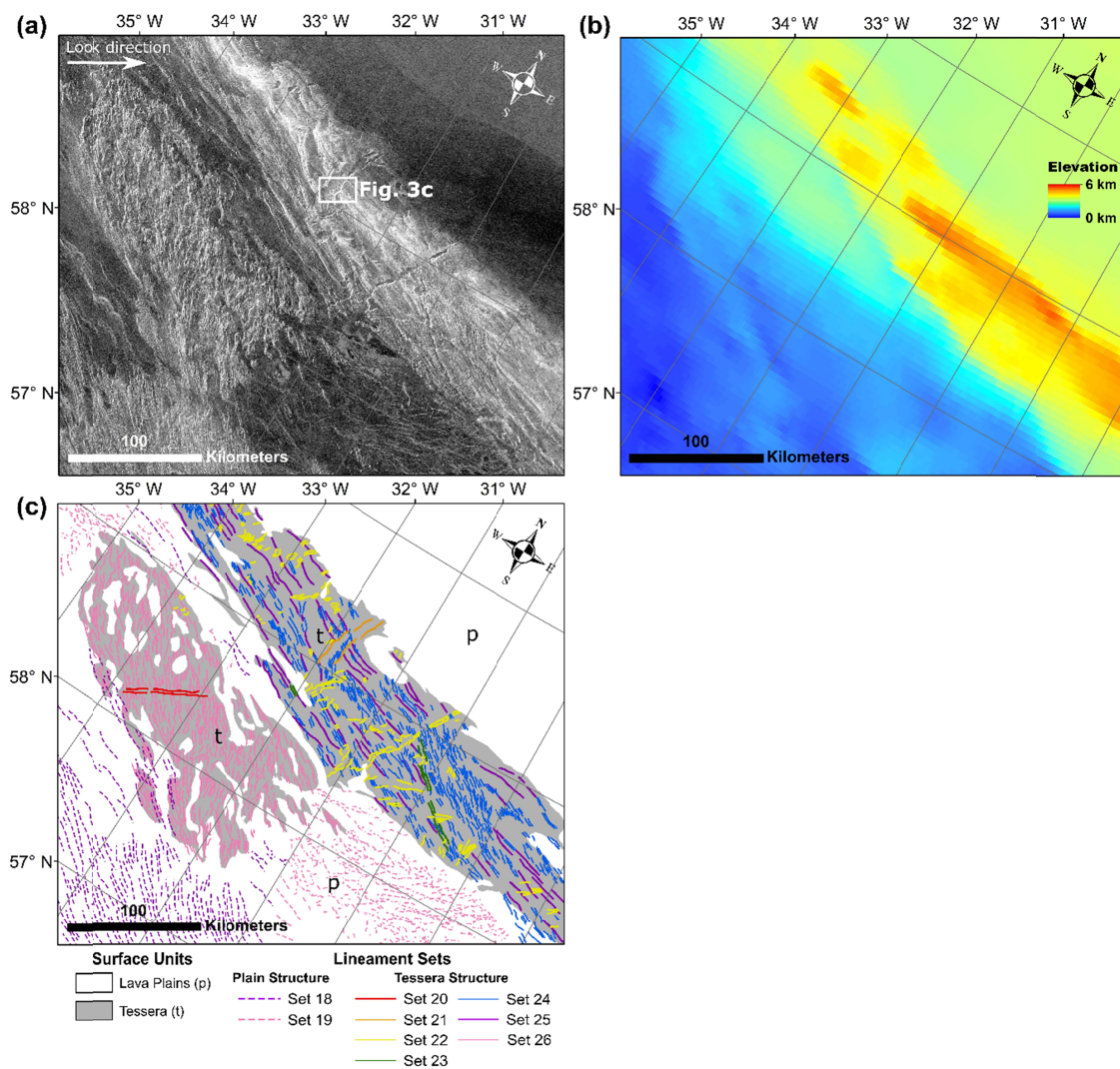


Figure. 7 Left-looking SAR image (a), topographic map (b) and geological map (c) in the southwestern margin of Ishtar Terra. There are two major tessera blocks: the western block and the eastern block, Vesta Rupes. See Table 3 for the details of mapped structural set 18-26.

There are nine sets of deformations mapped in the area. Descriptions of each set are recorded in Table 3. These lineament sets are discussed below according to the chronological order, from older to younger features, based on the cross-cutting relationship on the map: (1) tessera fractures and curviplanar ridges, (3) tessera faults, and (4) plains fractures.

Set	Lineament description	Latitude N	Longitude E	n	Trend	Length km	Pattern	Interpretation
Plains Structures								
18	Bright lineaments	57.056	-32.375	176	SE	18.7	Parallel	Fracture
19	Short, disrupted bright lineaments, networking in polygon-shapes	57.969	-29.54	423		6.1	Polygonal	Fracture
Tessera Structures								
20	Long, straight, paried	58.308	-33.421	8	NE	13.6	Parallel	Fault

	bright and dark lineaments							
21	Paired bright and dark lineaments	59.23	-31.288	4		24.2	Parallel	Fault
22	Paired of bright and dark lineaments	58.902	-30.533	166	NNE	5.6	Parallel	Fault
23	Long, straight, paired bright and dark lineaments	58.649	-29.931	11	SE	12.4	Parallel	Fault
24	Disrupted, short, paired bright and dark lineaments	58.911	-31.102	544	E	6.4	Parallel	Fault
25	Symmetrical lineaments	58.911	-31.102	119	E	19.8	Parallel	Curviplanar Ridge
26	Disrupted symmetrical lineaments	58.902	-30.533	499	SE	8.2	Subparallel	Fracture

Table. 3 Details of mapped structural sets 18 – 26 in Figure 7, with descriptions, locations, numbers of lineaments mapped (n), trends, mean lengths, patterns, and possible interpretations.

The earliest deformation in this area is set 26 and 25. Set 26 are fragmentary fractures deforming the southwestern tessera block in this area. Set 25 are curviplanar ridges along the elongated Vesta Rupes in the northeast. Above two sets of deformation are crosscut by three sets of faults. Set 20 is a pair of long faults on the southwestern tessera terrain, overlapping the fragmentary fractures of set 26. On the eastern elongated tessera block (Vesta Rupes), faults of set 24 are parallel to tessera margin and crosscutting the tessera curviplanar ridges of set 25. Set 23 is a pair of long fault oblique to the Vesta Rupes, cross-cutting set 24 and 25. Set 21 and 22 are faults crosscutting both set 23, 24 and 25, and oriented normal to the tessera margin. These fault sets are interpreted as grabens that formed in a later extensional collapse event by Keep and Hansen (1994). All of the above tessera fractures, curviplanar ridges and faults are cut by the embayment of lava plains, indicating tessera deformation predate the regional plains emplacement volcanism.

There are two sets of plains fractures. Set 18 are densely packed of parallel bright lineament located in the southwestern region on lava plains and crosscutting the marginal areas of the adjacent tessera. This set trends southeast, parallel to the topographic margin and tessera fracture of set 26. Set 21 is short, disrupted bright lineaments, obliquely networking in small polygon-shapes with a width of 3 – 10 km. These polygonal fractures are locally crosscut by the bright lineament of set 18.

4.2.3 The northern margin of Ishtar Terra (Semuni Dorsa)

The northern margin of Ishtar Terra (Figure 8) is also a sharp tessera highland boundary, adjacent to a marginal ridge belt on plains, Semuni Dorsa. Consistent with the description in Ivanov and Head (2007), all tessera units are embayed by surrounding lava plains and their edges do not display any preferred orientation. An impact crater is identified on the eastern part of the area at the tessera margin.

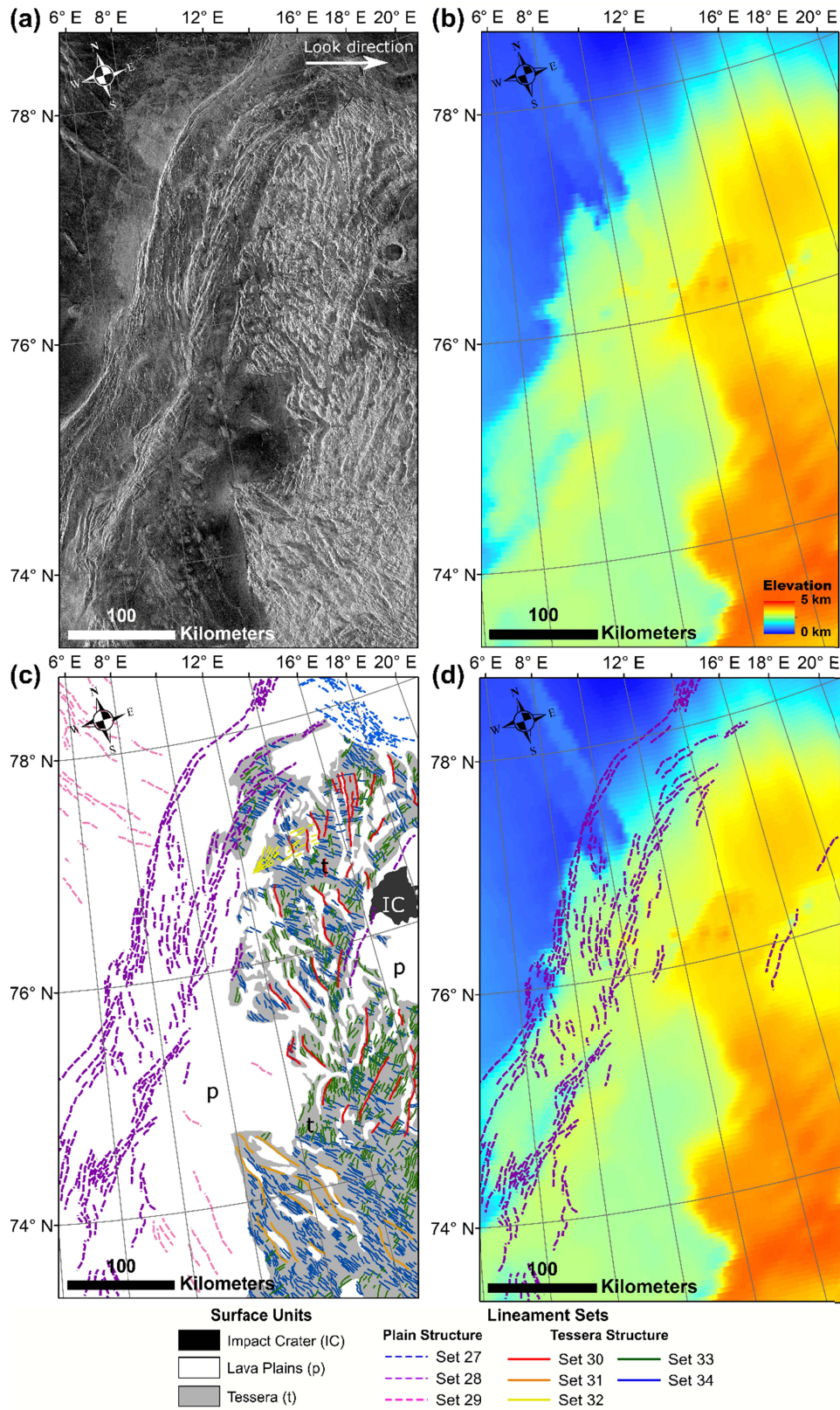


Figure. 8 Left-looking SAR image (a), topographic map (b) and geological map (c) of Semuni Dorsa in the northern margin of Ishtar Terra. Set 28 overlaid on the topographic map to show the marginal deformation (d). See Table 4 for the details of mapped structural set 27-34.

This area is mapped with eight sets of deformations, and detailed descriptions of each set are recorded in Table 4. These lineament sets are discussed below according to the chronological order, from older to younger features, based on the cross-cutting relationship on the map: (1) tessera fractures, (2) tessera curviplanar ridges, (3) wrinkle ridges, (4) marginal ridge belt – Semuni Dorsa, and (5) plains fractures.

Set	Lineament description	Latitude N	Longitude E	n	Trend	Length km	Pattern	Interpretation
Plains Structures								
27	Bright lineaments	77.777	18.163	62	SE	11.2	Subparallel	Fracture
28	Curvilinear of asymmetrical lineaments (Semuni Dorsa)	76.516	8.903	210	NNE	22.6	Subparallel	Curviplanar Ridge
29	Wrinkled symmetrical dark and bright lineaments	75.681	6.729	41	SE	2.4	Subparallel	Wrinkle ridge
Tessera Structures								
30	Symmetrical lineaments	75.619	14.602	39	NNE	26.7	Subparallel	Curviplanar Ridge
31	Symmetrical lineaments	73.876	11.741	14	SE	39.8	Parallel	Curviplanar Ridge
32	Bright lineaments	76.867	13.449	23	NE	10.1	Subparallel	Fracture
33	Fragmentary bright lineaments	74.883	14.984	502	NE	8.7	Subparallel	Fracture
34	Fragmentary bright lineaments	74.883	14.984	833	SE	8.6	Subparallel	Fracture

Table. 4 Details of mapped structural sets 27 – 34 in Figure 7, with descriptions, locations, numbers of lineaments mapped (n), trends, mean lengths, patterns, and possible interpretations

Set 32, 33 and 34 are fragmentary bright lineaments on tessera with a width of few resolution-cells sizes (Figure 8). These chaotic sets are crosscut by tessera curviplanar ridges of set 31 and 30. Set 31 in the southern part of the mapped tessera is SE-trending and set 30 in the northern part is NNE trending, which their distributions and orientations differentiate the two sets (Figure 8). These tessera curviplanar ridges are previously defined by Ivanov and Head (2007) as chaotically oriented linear ridges and troughs cut by the angular tessera edge. All these tessera fractures and curviplanar ridges are cut by the embayment of lava plains (Figure 8), indicating tessera deformations are earlier than the regional plains emplacement volcanism.

Wrinkle ridges on the regional lava plains are mapped as set 29, which extend from northwest to southeast and cut by a ridge belt of set 28 along the highland margin (Figure 8). The marginal ridge belt, Semuni Dorsa, is mapped as set 28. This belt elevated adjacent plains along the tessera edge to 3 km above the low-lying plains (Figure 8d). This feature has been studied previously as a linear belt of contractional structures in contact with tessera region and proposed as a possible extinct zone of convergence, underthrusting and subduction on Venus (Ivanov and Head, 2007). Plains fractures of set 27 are mapped at the northeast part of this area, which cut the ridge belt of set 28.

4.2.4 The western margin of Ishtar Terra (Atropos Tessera)

This mapping area is the western margin of Ishtar Terra (Figure 9), which is a gentle slope of the tessera highland, Atropos Tessera. Such terrain edge has been mapped previously as part of the Akan Montes-Atropos Tessera geological map in Marinangeli and Gilmore (2000), and the tessera was defined as linearly deformed terrains. Consistent with the previous mapping, the tessera units are completely embayed by the surrounding lava plains, appearing as the locally oldest units.

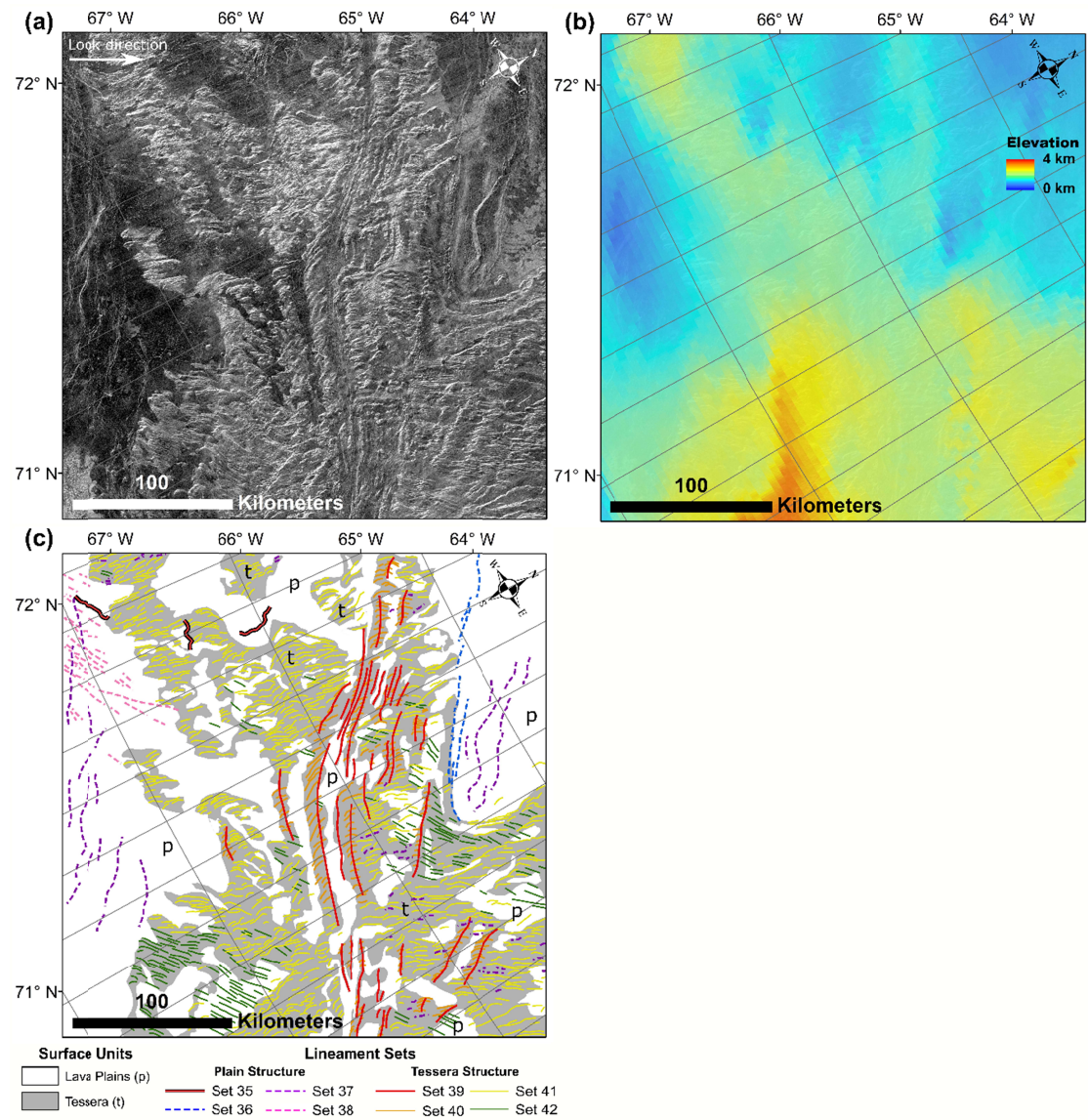


Figure. 9 Left-looking SAR image (a), topographic map (b) and geological map (c) of Atropos Tessera in the western margin of Ishtar Terra. See Table 5 for the details of mapped structural set 35-42.

This area is mapped with eight sets of deformations, and detailed descriptions of each set are recorded in Table 5. These lineament sets are discussed below according to the chronological order, from older to younger features, based on the cross-cutting relationship on the map: (1) tessera fractures, (2) curviplanar ridges, and (3) plains fractures and lava channels.

Set	Lineament description	Latitude N	Longitude E	n	Trend	Length km	Pattern	Interpretation
Plains Structures								
35	Sinuuous paired bright and dark lineaments	72.617	-65.076	3		26.1	Sinuuous	Lava Channel
36	Symmetrical lineaments along the tessera margin	73.742	-61.217	13	SE	15.8	Parallel	Curviplanar Ridge
37	Curved symmetrical lineaments	73.797	-60.285	21	SE	25.2	Subparallel	Curviplanar Ridge
38	Bright lineaments	72.169	-64.596	31	E	9.9	Parallel	Fracture
Tessera Structures								
39	Long symmetrical lineaments	73.362	-60.851	36	SE	28.6	Subparallel	Curviplanar Ridge
40	Short, fragmentary symmetrical lineaments	73.362	-60.851	232	N	5.4	Subparallel	Fracture/Small fold
41	Disrupted bright lineaments	72.984	-59.611	677	NE	8.4	Subparallel	Fracture
42	Fragmentary bright lineaments	71.652	-59.338	169	NE	8.6	Subparallel	Fractures

Table. 5 Details of mapped structural sets 35 – 42 in Figure 8, with descriptions, locations, numbers of lineaments mapped (n), trends, mean lengths, patterns, and possible interpretations.

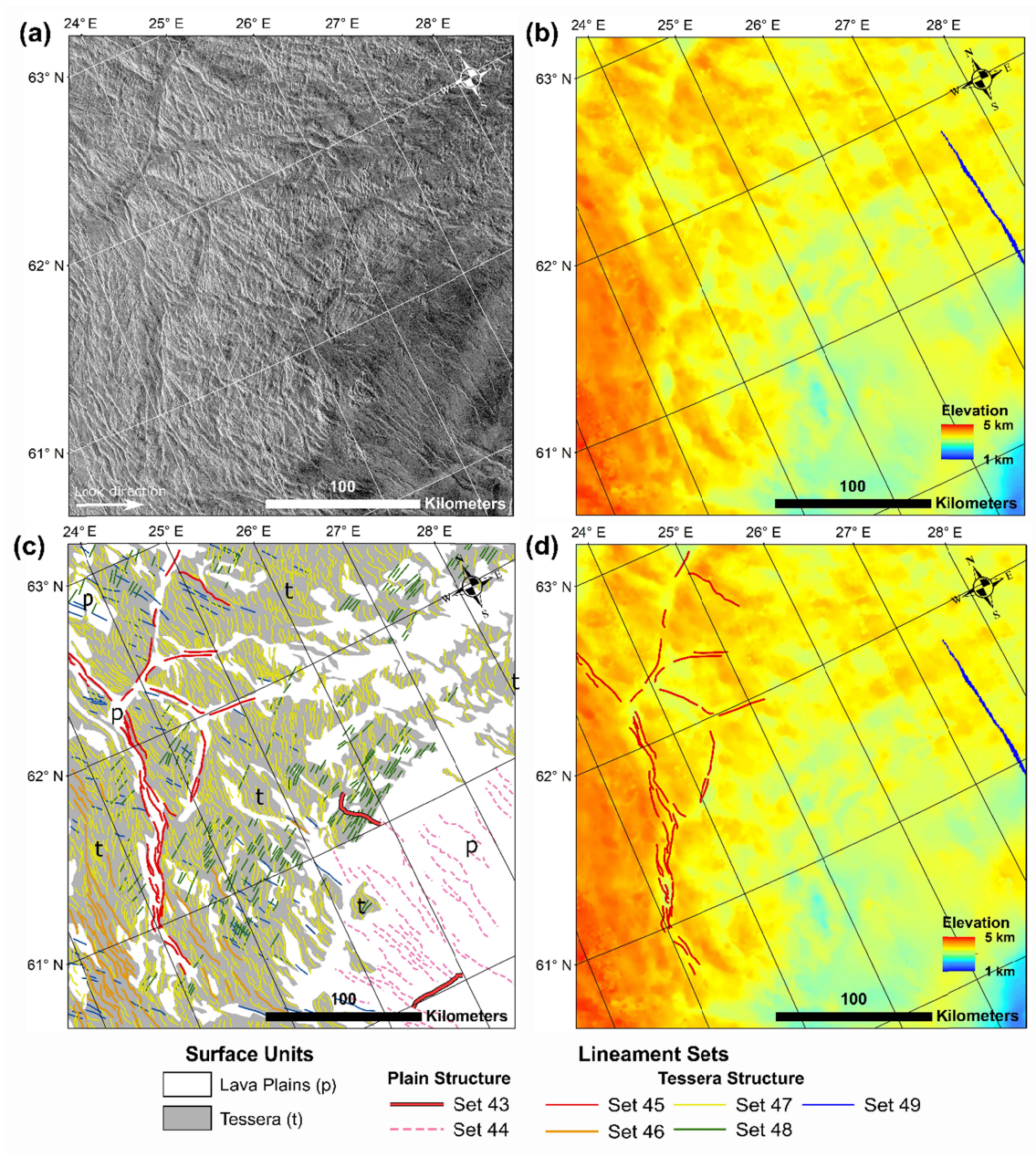
There are three sets of fragmentary fracture on tessera: set 40, 41, and 42. Set 41 is subparallel fractures across the entire tessera terrain, trending from northeast to southwest (Figure 9). Set 40 is also subparallel tessera fractures but tilted due north along major curviplanar ridges of set 39, and thus, mapped separately from set 41 to show the distinction. Besides, set 42 exposed locally on the tessera terrain and isolated plains patches, postdating plains emplacement on tessera basin. All these tessera fractures are cut by the embayment of tessera adjacent lava plains, indicating tessera deformations earlier than the regional plains emplacement volcanism.

Tessera ridge of set 39, tessera marginal curviplanar ridges of set 36 and plains curviplanar ridges of set 37 all trend to the southeast, indicating a northeast-southwest compression or extension (Figure 9).

There are two more sets of lineaments mapped on plains: set 35 is sinuous lava channels and set 38 is plains fractures (Figure 9).

4.2.5 The eastern margin of Ishtar Terra (Fortuna Tessera)

507 The last mapping area is the eastern margin of Ishtar Terra (Figure 10), which is a gentle
 508 slope of the tessera highland, Fortuna Tessera. It is the only mapping area in this study with
 509 available stereo-derived topographic data. The fine resolution data clearly shows that the
 510 marginal tessera blocks stand high surrounded by low-lying plains. All the tessera units are
 511 completely embayed by the surrounding lava plains, appearing as the locally oldest units.



512

513 **Figure. 10** Left-looking SAR image (a), topographic map (b) and geological map (c) of the eastern margin of
 514 Fortuna Tessera in Ishtar Terra. Set 45 overlaid on the topographic map to show the lineament along with
 515 toughs separating tessera block along the margin (d). See Table 5 for the details of mapped structural set 43-49.

This area is mapped with seven sets of deformations, and detailed descriptions of each set are recorded in Table 6. These lineament sets are discussed below according to the chronological order, from older to younger features, based on the cross-cutting relationship on the map: (1) tessera fractures, (2) tessera curviplanar ridges, and (3) wrinkle ridge and lava channels.

Set	Lineament description	Latitude N	Longitude E	n	Trend	Length km	Pattern	Interpretation
Plains Structures								
43	Sinuuous paired bright and dark lineaments	61.094	25.668	2		39.1	Sinuuous	Lava Channel
44	Symmetrical lineaments along the tessera margin	60.388	26.047	59	SE	19.5	Parallel	Wrinkle Ridge
Tessera Structures								
45	Curvilinear, long symmetrical lineaments	61.661	23.594	39		28.6	Polygonal	Curviplanar Ridge
46	Long symmetrical lineaments	60.94	22.366	54	N-NE	18.6	Subparallel	Curviplanar Ridge
47	Disrupted, short bright lineaments	61.076	25.881	1432	NE	7.4	Subparallel	Fracture
48	Fragmentary bright lineaments	61.582	25.125	258	NE	7.7	Parallel	Fracture
49	Fragmentary bright lineaments	62.724	24.449	115	SE	8.6	Subparallel	Fracture

Table. 6 Details of mapped structural sets 43 – 49 in Figure 8, with descriptions, locations, numbers of lineaments mapped (n), trends, mean lengths, patterns, and possible interpretations.

There are three sets of fragmentary fractures on tessera: set 47, 48, and 49. Set 49 are scattered SE-trending linear bright fractures (Figure 10). Set 48 are NE-trending linear bright fractures, which are densely exposed at the eastern tessera margin in this area. Set 47 are widespread fragmented, short tessera fractures, which crosscut both fractures of set 47 and set 48.

There are two sets of curviplanar ridges crosscutting all the above tessera fractures (Figure 10). Set 46 are subparallel, N- to NE- trending, long curviplanar ridges at the southwestern part of the mapped tessera. Besides, set 45 are curvilinear ridges crosscut the subparallel curviplanar ridges of set 46. These curviplanar ridges form at high angles to one another, forming polygonal-shapes and isolating tessera blocks (30-100 km in diameter) along the topographic margin. The elevated tessera blocks are separated by lava-filled troughs (2-12 km in width) and set 45 is aligned with the troughs (Figure 10d) exposed on tessera block edges and lava plains. Similar curvilinear structures of ridges and troughs isolating tessera blocks are also observed in Ovda Regio by Romeo and Capote (2011) and Tellus Regio by Gilmore and Head (2018).

Finally, there are two more sets of lineaments observed on plains: set 43 is sinuous lava channels and set 44 is SE-trending wrinkle ridges (Figure 10).

4.3 Interpretive maps for Ishtar Terra margins

Our mapping documents the complex deformation along Ishtar Terra margins (Figure 4, 7-10). There are two key findings: (1) All tessera unit and structures mapped are embayed by lava plains, showing plains-forming volcanism occurred after the tessera tectonism. (2) We observe 49 lineament sets. 25 out of 49 are classified as plains or tessera fractures, which are unable to interpret due to the limit of data resolution. The tessera fractures are the oldest deformation features and are crosscut by tessera curvilinear ridges and faults in all mapping areas. The tessera fractures do not show patterns of orientations that might be associated with potential plateau-bounding structures via such common fault system patterns as parallelism (synthetic and antithetic structures), shear fractures (R, R', P), Andersonian fault conjugates, en echelon fracturing, etc. (Ramsay, 1967; Twiss and Moores, 2007) Therefore, the pervasive tessera fractures appear to record early processes unrelated to plateau margin development. We can identify the remaining 24 lineament sets as faults, lava channels or curvilinear ridges for structural interpretations (Figure 3).

Here we present different interpretive maps of the mapped areas. Lacking clear distinguishing information, we allow that all sets of curvilinear ridges and faults may have formed within either contractional or extensional systems. Such interpretations of lineament sets may be considered as “end-members,” because any set may contain lineaments formed in multiple stages, perhaps variably by compression and extension. The “end-member” set interpretations are the most parsimonious options, in that the lineaments in the same set would be formed in single stages.

4.3.1 The southern margin of Ishtar Terra

In the southern margin of Ishtar Terra (Figure 4), we map three sets of tessera faults (set 8, 9 and 10), two sets of tessera curvilinear ridges (set 11 and 12), and one set of lava channels (set 1). The ESE-trending tessera curvilinear ridges are generally subparallel to the topographic margin whereas the faults are generally normal to the margin. Although some faults cut curvilinear ridges locally, the regional relative age relationship is unclear. These curvilinear ridges and faults are interpreted separately as contractional and/or extensional deformations, resulting in four different cases (Figure 11).

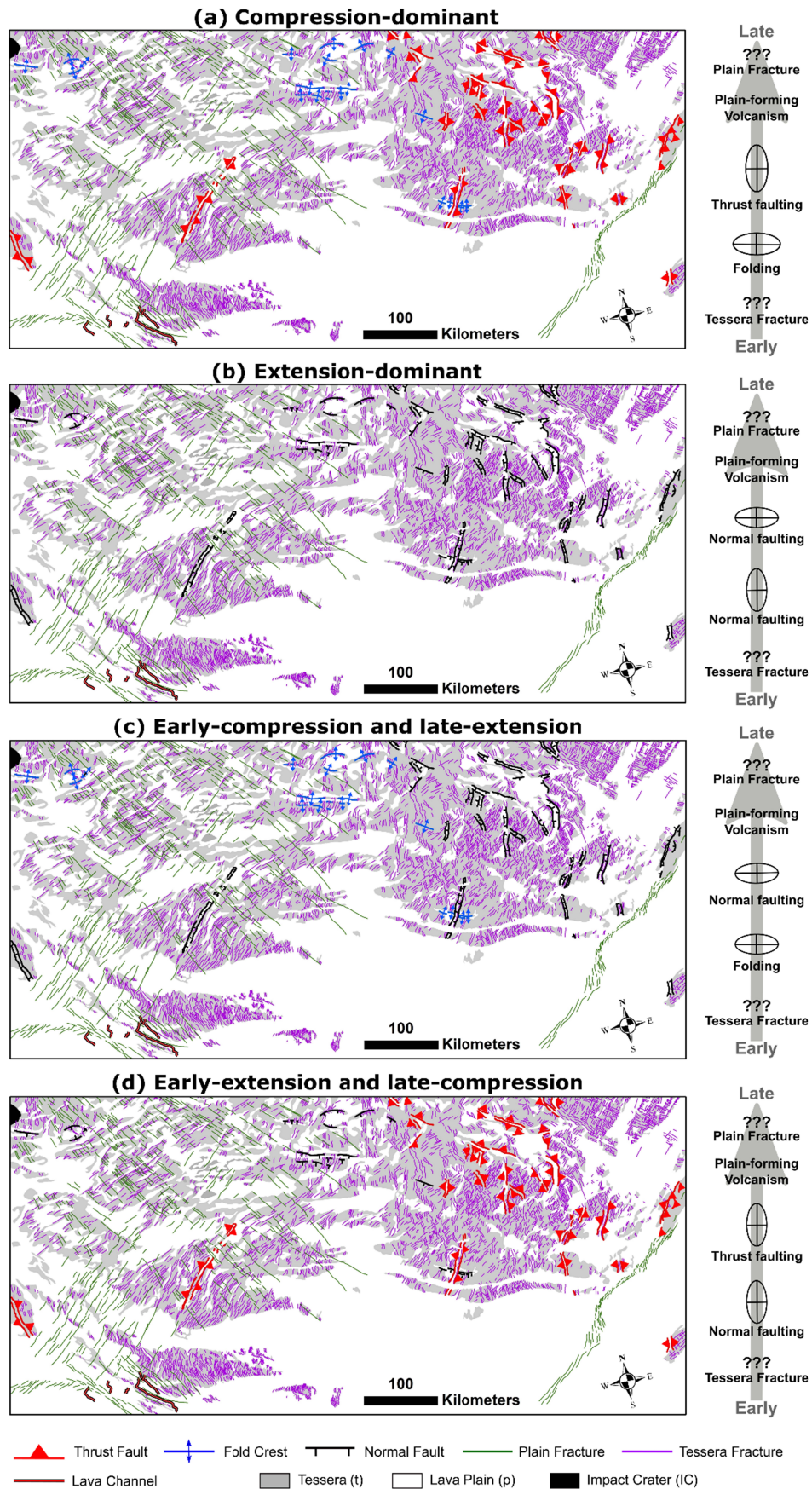


Figure. 11 Interpretative maps and their possible evolutionary path with regional strain evolution of the southern margin basic geological map in Figure. 4, including compression-dominant (a), extension-dominant (b), early-compression and late-extension (c), and early-extension and late-compression (d) cases.

“Compression- dominant” (Figure 11a) and “extension-dominant” (Figure 11b) evolutions are shaped dominantly by either contractional (folds and thrust faults) or extensional (normal faults) features respectively. The tessera curvilinear ridges could be folds while the faults can be normal faults, resulting in an “early-compression and late-extension” case (Figure 11c). Alternatively, the curvilinear ridges can be formed by normal faulting when the faults are thrust faults, resulting in an “early-extension and late-compression” case (Figure 11d).

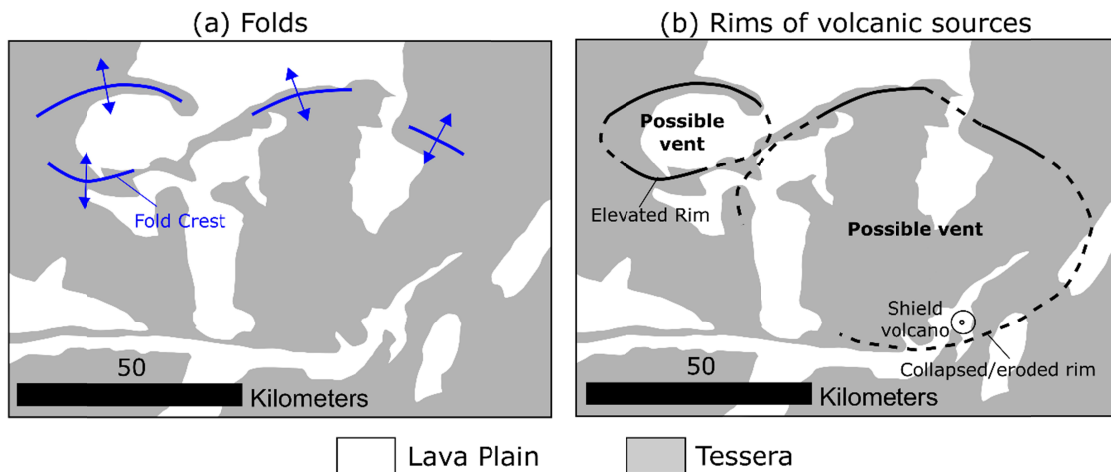


Figure. 12 The possible interpretations of mapped concentric curvilinear ridges of set 10 in Figure 5a, which includes folds (a) and rims of volcanic sources(b).

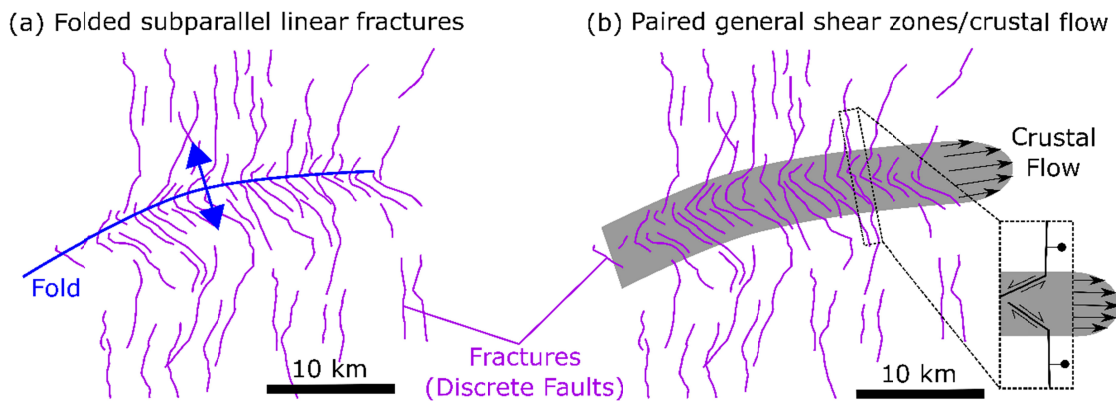


Figure. 13 The possible interpretations of mapped “V-shape” fractures of set 8 in Figure 5b, which includes ridged subparallel linear faults (a) and paired general shear zones (b).

We identify two new related structures: (1) eye-pattern ridges composed of (2) V-shape faults. The “eye-pattern” concentric ridges (Figure 5a) can be formed by chaotic folding appearing like an “eye-pattern” or subcircular rims of volcanic sources (Figure 12a), which part of it is

587 collapsed and associated with surrounding lava fills and the shield volcanoes (Figure 12b).
588 Similar structures have been mapped in Ovda Regio by Romeo and Capote (2011) and
589 interpreted as chaotic folds and thrusts. While we zoomed in to one of the ridges presented in
590 Figure 6b, the ridge is composed of recumbent V-shape faults along with it. These V-shape
591 structures may be formed when subparallel linear fractures of the surface were deformed by a
592 fold (i.e., compatible with the folds interpretation for concentric curvilinear ridges in Figure
593 5a) and appear as tilted along the fold crest viewing from a side-looking radar or caused by
594 radar layover (Figure 13a). Another possibility is that the V-shape faults are paired general
595 shear zones (Figure 13b), which are formed by two parallel adjoining shear zones that have
596 opposing senses of shear. Such a crustal flow feature may suggest minor crustal flows
597 beneath the upper crust, or subsurface flows, such a lava tube of around 2-5 km wide. This
598 interpretation is incompatible with the above two “eye-pattern” concentric ridges
599 interpretation (folds and rims of volcanic sources) (Figure 5), as it predicts a rather flat
600 morphology; the possible relationship with the larger eye-shaped structures remains unclear.

601 **4.3.2 Southwestern margin of Ishtar Terra (Vesta Rupes)**

602 In the southwestern margin of Ishtar Terra (Figure 7), we map one set of tessera curvilinear
603 ridges (set 25), and five sets of tessera faults (set 20, 21, 22, 23 and 24). The faults are
604 observed to crosscut the curvilinear ridges in all places on the tessera highland. These
605 curvilinear ridges and faults are interpreted separately as contractional and/or extensional
606 deformations, resulting in four different cases (Figure 14).

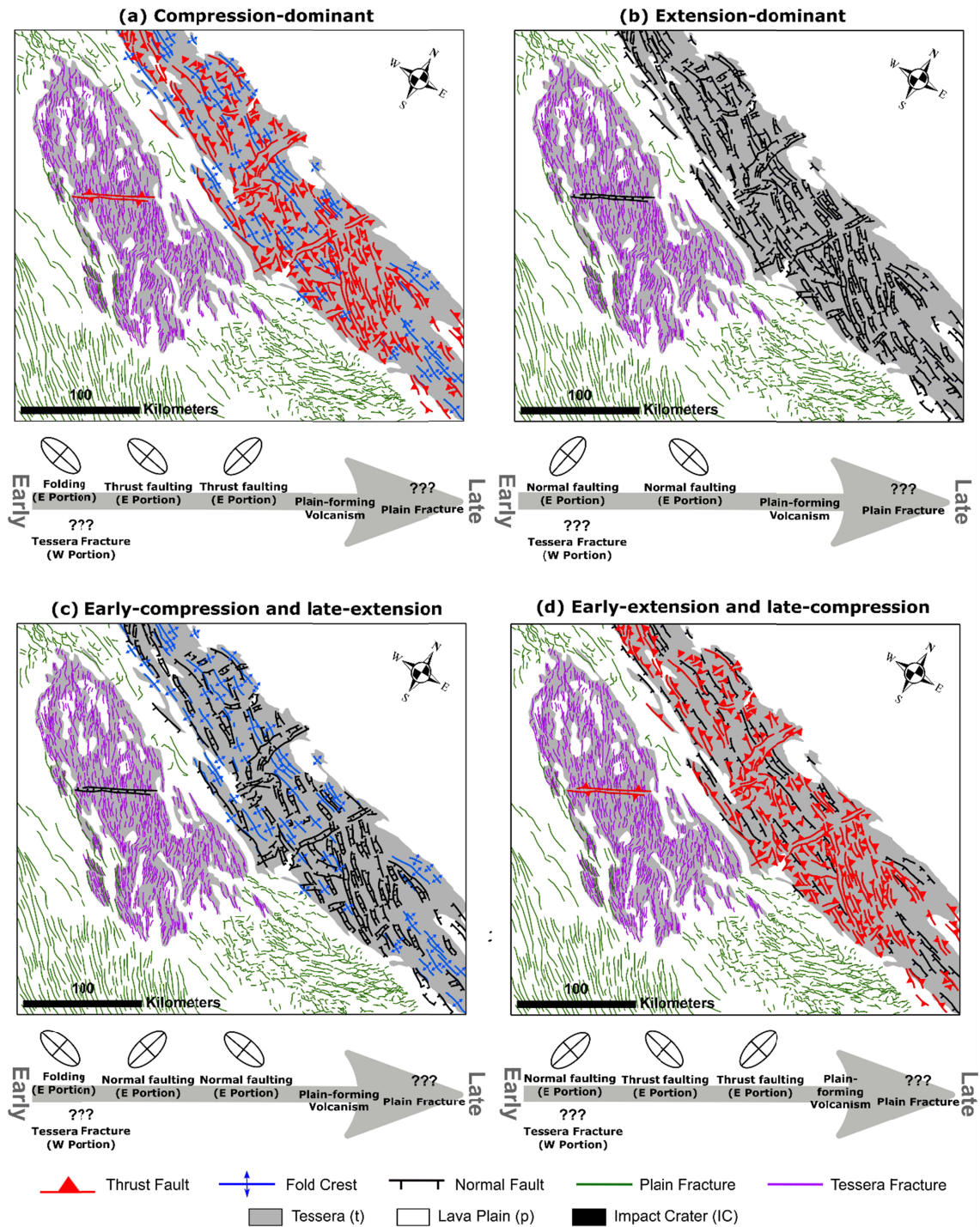


Figure. 14 Interpretative maps and their possible evolutionary path with regional strain evolution of the southwestern margin (Vesta Rupes) basic geological map in Figure 6, including compression-dominant (a), extension-dominant (b), early compression and late extension (c), and early extension and late compression (d) cases.

“Compression- dominant” (Figure 14a) and “extension-dominant” (Figure 14b) evolutions are possible that the entire area is shaped by either contractional (folds and thrust faults) or

extensional (normal faults) features respectively. Besides, the curvilinear ridges can be folds formed under compression, and the faults may be normal faults formed under tension, producing an “early compression and late extension” case (Figure 14c). This case was previously proposed by Keep and Hansen (1994): they suggested early folding under N-S compression built or deformed the tessera mountain belt (Vesta Rupes), then extensive grabens formed during extensional collapse. On the other hand, the case of “early extension and late extension” (Figure 14d) is also possible if the curvilinear ridges are normal faults and faults are thrust faults.

4.3.3 The northern margin of Ishtar Terra (Semuni Dorsa)

Along the northern margin of Ishtar Terra (Figure 8), we map two sets of tessera curvilinear ridges (set 30 and 31), and one set of marginal ridges named Semuni Dorsa (set 28). The tessera curvilinear ridges are cut by lava plains embayment, indicating a deformation earlier than the regional plains emplacement volcanism. In contrast, Semuni Dorsa is deforming the adjacent lava plains, indicating a deformation after the regional plains volcanism. The tessera and margin curvilinear ridges are interpreted separately as contractional and/or extensional deformations, resulting in four cases (Figure 15).

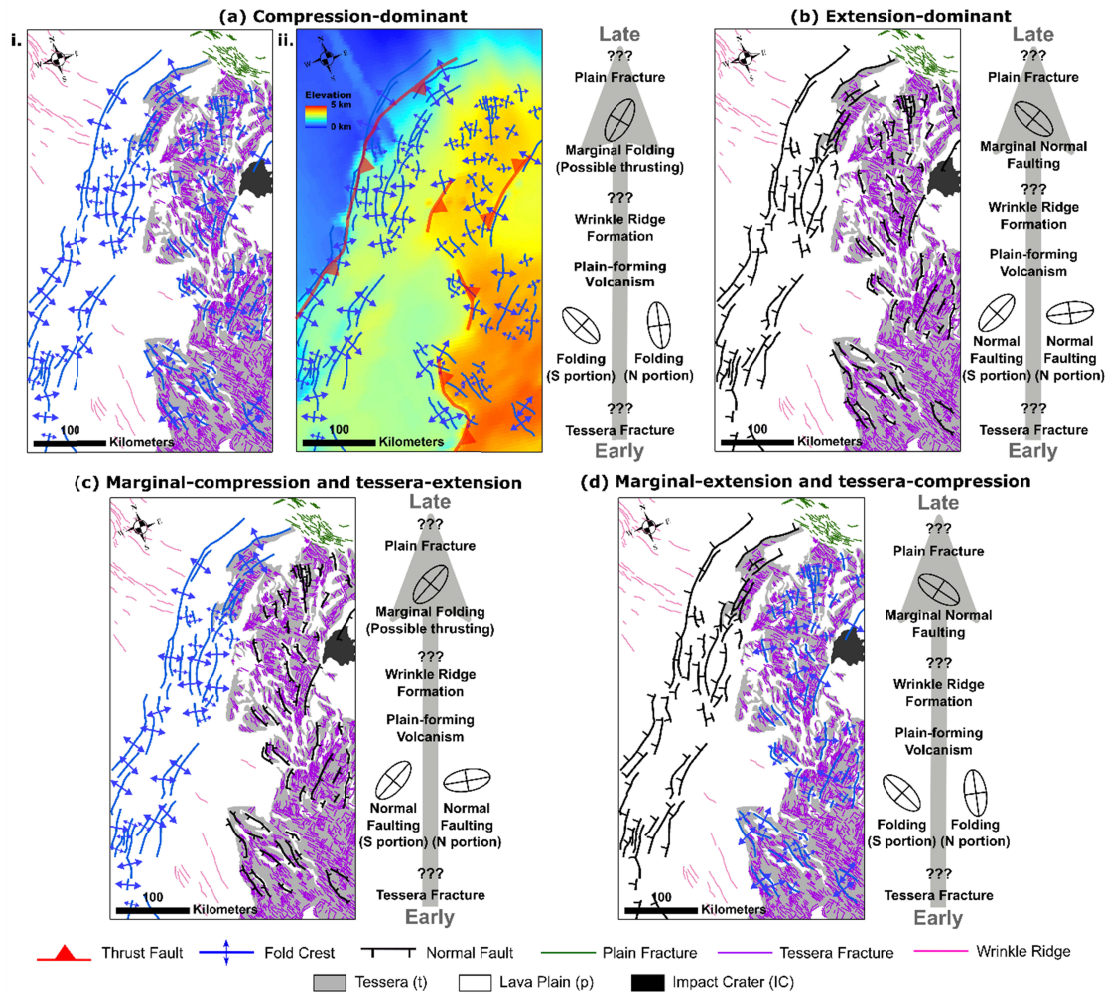


Figure. 15 Interpretative maps and their possible evolutionary path with regional strain evolution of the northern margin basic geological map in Figure. 7, including compression-dominant (a) with inferred possible marginal thrusts onlapping on the interpretative map (i) and topographic data (ii), extension-dominant (b), marginal-compression and tessera-extension (c), and marginal-extension and tessera-compression (d) cases.

In the “compression-dominant” case (Figure 15a), we interpret possible major thrusts bounding the highland based on the sharp topography presented in Figure 15a (ii). Then, we overlay the inferred thrusts on the interpretative map on Figure 15a (i) and find that the thrusts are aligning with the tessera and marginal folds, which may indicate possible highland bounding faults later covered by lava flows. On the other hand, a “extensional-dominant” (Figure 15b) case is also viable. The marginal curviplanar ridges belt can be formed under compression or extension, whereas the tessera ridge can be formed under opposition modes, resulting in “marginal-compression and tessera-extension” (Figure 15c), and “marginal-extension and tessera-compression” (Figure 15d) cases.

Ivanov and Head (2007) interpreted Semuni Dorsa as a contractional deformation belt. They proposed it may be an extinct subduction zone on Venus. The “compression-dominant” (Figure 15a) and “marginal-compression and tessera-extension” (Figure 15c) cases can accommodate this hypothesis.

4.3.4 The western margin of Ishtar Terra (Atropos Tessera)

We map three sets of southeast trending curvilinear ridges on tessera and plains (Set 36, 37 and 39) in the western margin of Ishtar Terra (Figure 9). These curvilinear ridges are all trending southeast and subparallel to each other. We interpret these curvilinear ridges into three types of deformations: contractional, extensional, and transpressional deformations (Figure 16).

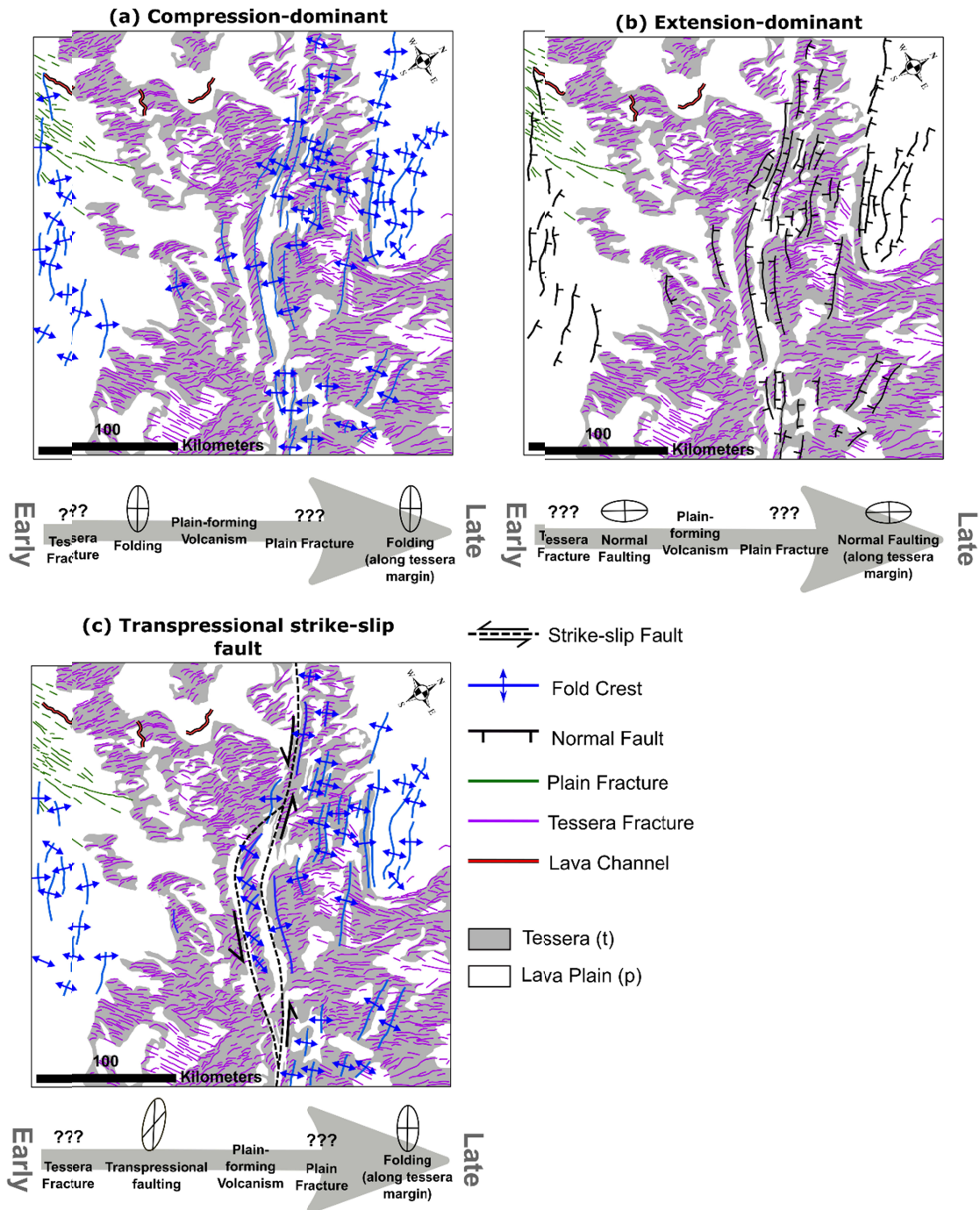


Figure. 16 Interpretative maps and their possible evolutionary path with regional strain evolution of the western margin basic geological map in Figure. 8, including compression-dominant (a), extension-dominant (b), and transpressional strike-slip faulting (c) cases.

The curviplanar ridges can be formed solely under SW-NE compression (Figure 16a) or extension (Figure 16b). Another possibility is that the curviplanar ridges are formed by transpressional strike-slip faulting (Figure 16c). In this case, the fragmentary fractures of set 40 may be the small fold formed by horizontal shortening under the strike-slip motion along

662 the major tessera curvilinear ridges of set 39. Such horizontal strike-slip movement was
663 proposed previously by Marinangeli and Gilmore (2000) and articulated in their Akan
664 Montes-Atropos Tessera geological map.

665 **4.3.5 The eastern margin of Ishtar Terra (Fortuna Tessera)**

666 We map two sets of tessera curvilinear ridges (Set 45 and 46) in the eastern margin of Ishtar
667 Terra (Figure 10). Set 46 are subparallel, N- to NE- trending curvilinear ridges at the
668 southwestern part, crosscutting curvilinear ridges of set 45, which separate the tessera into
669 isolated cores. We interpret these two sets of curvilinear ridges into contractional folds and
670 extensional normal faults (Figure 17).

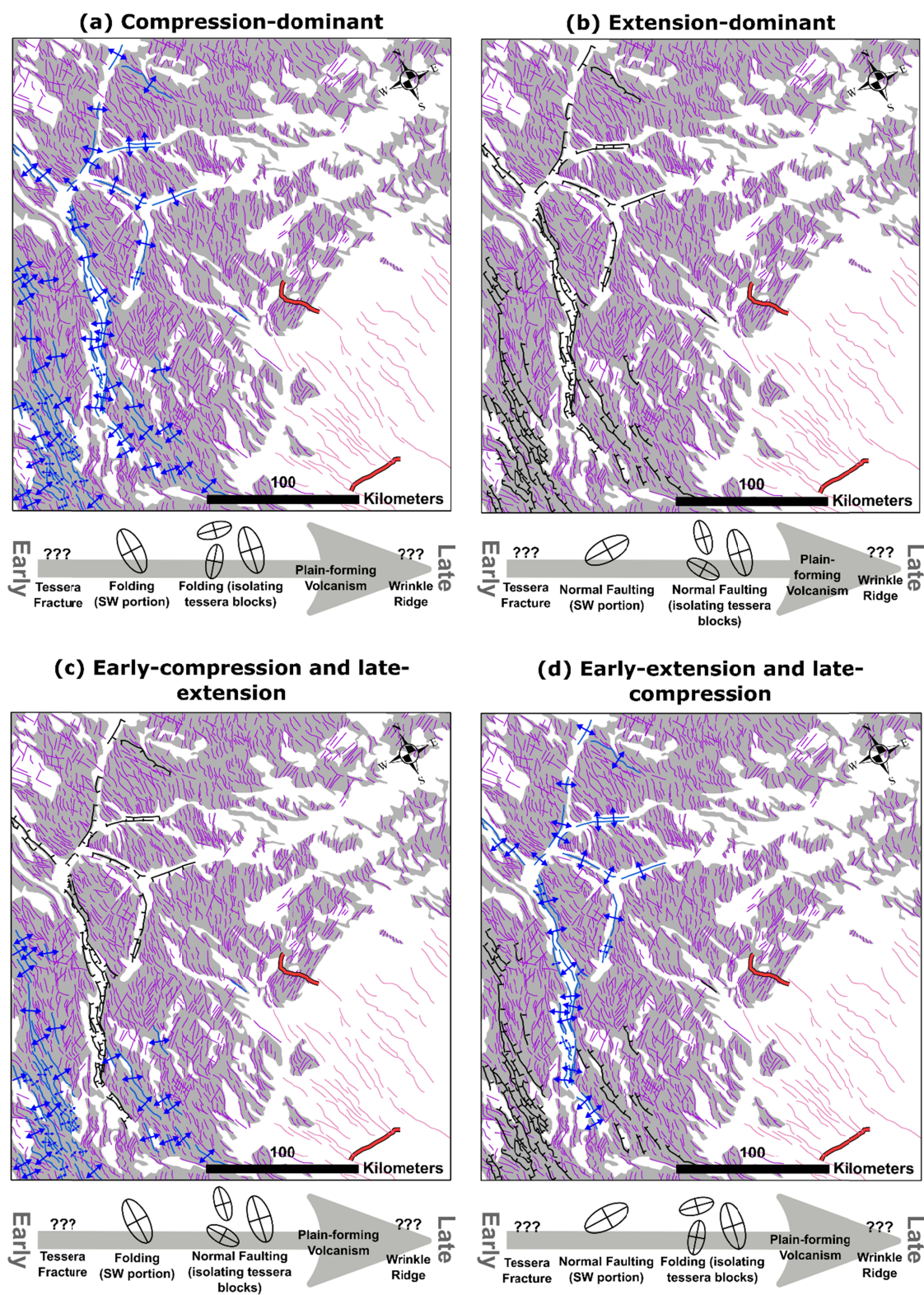


Figure. 17 Interpretative maps and their possible evolutionary path with regional strain evolution of the eastern margin basic geological map in Figure. 10, including compression-dominant (a), extension-dominant (b), early-compression and late-extension (c), and early-extension and late-compression (d) cases.

The curvilinear ridges can be formed solely compression (Figure 17a) or extension (Figure 17b). Another possibility is that the subparallel curvilinear ridges are first formed by E-W compression, and then the tessera unit is separated by a potentially sequential extension (Figure 17c). On the other hand, the subparallel curvilinear ridges may be normal faults formed by E-W extension, and the tessera unit is later deformed by multi-directional compression (Figure 17d).

5 Discussion

This work seeks to test Venus crustal plateau formation models via mapping of tessera - plain overlapping relationships and structural features across key $\sim 10^5$ - 10^6 km² regions along the margins of Ishtar Terra. All mapped tessera units and concomitant deformations along these margins appear embayed by lava plains, although non-embayment map patterns are likewise viable for the southwestern region (Figure 7). Structural mapping identifies 49 total sets of deformation lineaments in the mapped areas (ranging from 8 to 18 sets per area). Twenty-five sets are tessera fracture sets representing tessera fabric development which appears to pre-date plateau margin formation. The remaining twenty-four sets are interpreted as folds, faults, and lava channels. The sets interpreted as tectonic features permit a large range of possible deformational histories, because it is generally not possible to determine whether most develop in contractional or extensional contexts. In the following section, we discuss the implications of these findings for crustal plateau formation models.

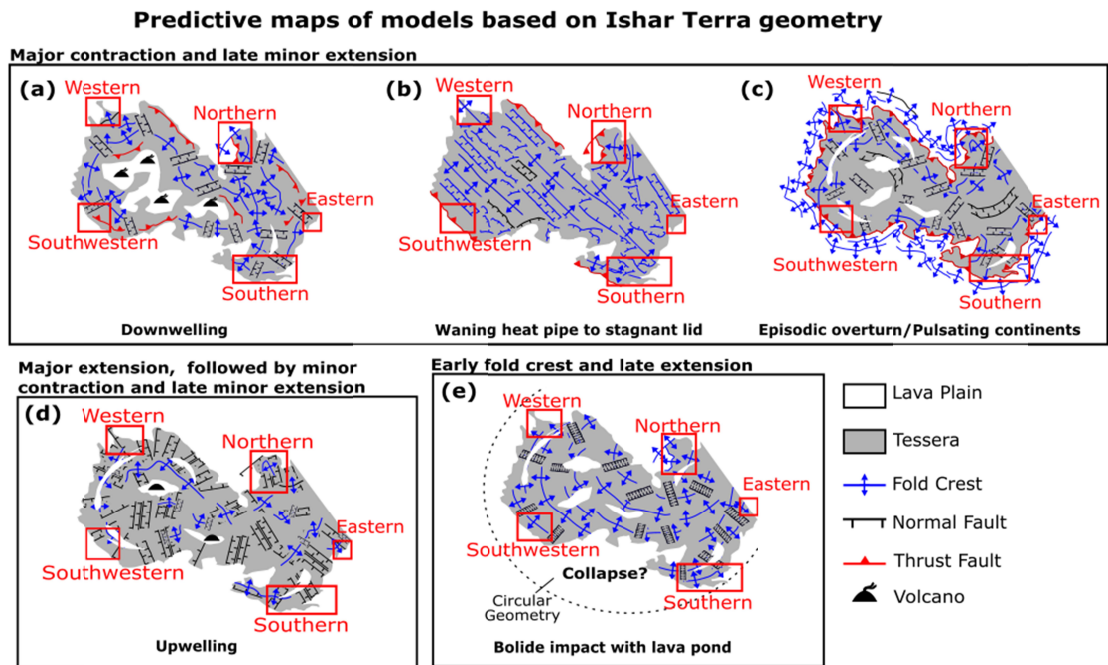
Our mapping also identifies two new structures – (1) eye-pattern ridges of 10-20 km long and 2-5 km wide (Figure 6a), composed of (2) V-shape faults (Figure 6b). The former may be folds (Figure 12a) or rims of volcanic craters (Figure 12b), and the latter may be ridged linear faults (Figure 13a) or paired general shear zones (Figure 13b), which may reflect crustal flow within and perhaps extending beneath the upper crust. Another discovery of interest is that some tessera fractures are exposed on adjacent lava plains (Figure 5), which indicates that these fractures must be elevated above the plains and underlying tessera.

5.1 Implications for Venusian crustal plateau formation models

Cross-cutting relationships of tessera and lava plains indicate that plains-forming volcanism occurred after the tessera tectonism, which is consistent with the episodic overturn/pulsating continents, waning heat-pipe to stagnant lid, and upwelling models (Table 1). Downwelling and lava pond with bolide impact models predict plains-forming volcanism with the

706 simultaneous deformations of tessera highland. The southwestern margin (Figure 7) may
 707 alternatively represent a portion of a major linear fault system.

708 Models predict different crustal plateau deformations and our mapping shows a large
 709 variance in possible deformation interpretations. We present predictive diagrams of Ishtar
 710 Terra with proposed highland and marginal deformation, which these predictions (Table 1)
 711 contradistinguish the five models into three groups (Figure 18): (1) Downwelling, waning
 712 heat-pipe to stagnant lid, and episodic overturn/pulsating continents models predicting major
 713 contraction and late minor extension, (2) Upwelling model predicting major extension,
 714 followed contraction and late minor extension, and (3) Bolide impact with lava pond model
 715 predicting early fold crest formation and late extension. Hence, we group the different
 716 interpretive maps of Ishtar Terra margins from section 4.3 with the models that have
 717 predictions consistent with the map interpretations (Figure 19).

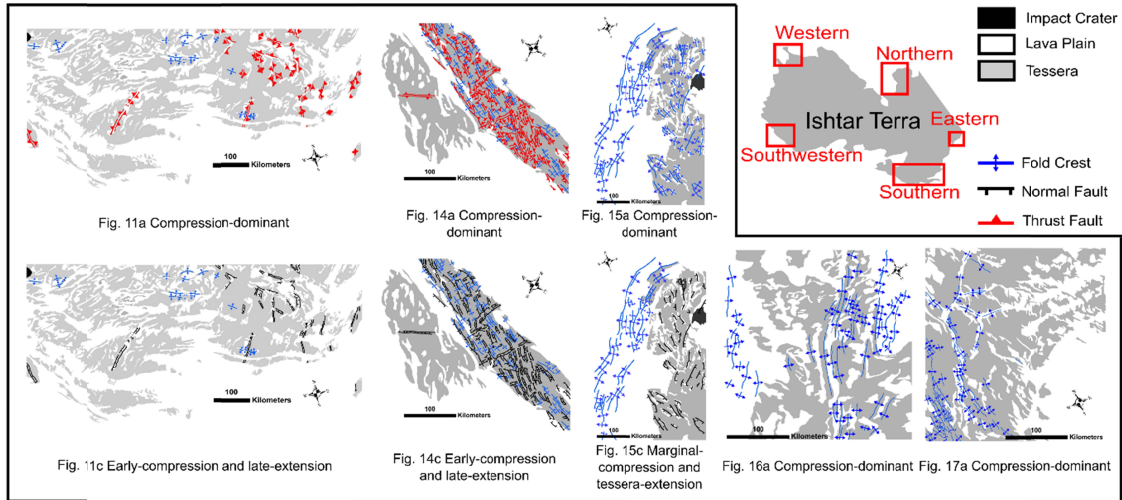


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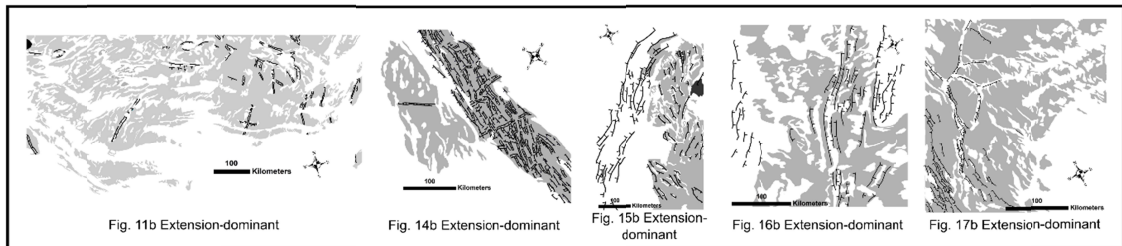
719 **Figure. 18** Predictive maps of models based on Ishtar Terra geometry, including the downwelling (a), waning
 720 heat-pipe to the stagnant lid (b), pulsating continents (c), upwelling (d) and bolide impact with lava pond (e)
 721 models, modified from Figure 2. The models are grouped based on similar deformation prediction.

Interpretative map of Ishtar Terra marginal areas

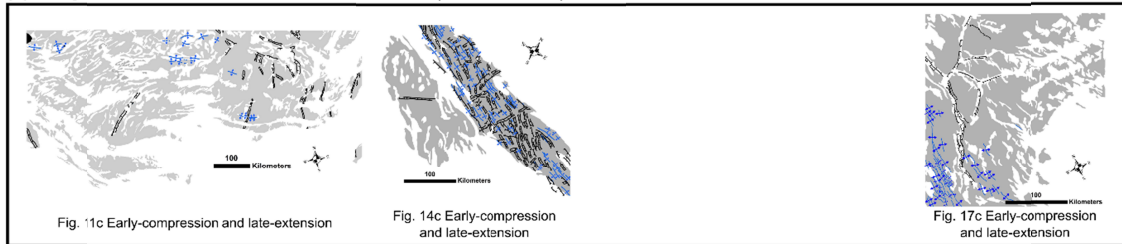
(a) Major contraction and late minor extension: Downwelling, waning heat pipe to stagnant lid, and episodic overturn/pulsating continents models



(b) Major extension, followed by minor contraction and late minor extension: Upwelling model



(c) Early fold crest and late extension: Bolide impact with lava pond model



Southern margin (Fig. 11) Southwestern margin (Fig. 14) Northern margin (Fig. 15) Western margin (Fig. 16) Eastern margin (Fig. 17)

Figure. 19 Interpretative maps of southern (Fig. 11), southwestern (Fig. 14), northern (Fig. 15), western (Fig. 16), and eastern (Fig. 17) margins are listed with the agreeing model predictions.

“Compression-dominant” (Figure 11a, 14a, 15a, 16a and 17a), “early compression and late extension” (Figure 11c, 14c), and “marginal-compression and tessera-extension” (Figure 15c) cases are consistent with downwelling, waning heat-pipe to stagnant lid and episodic overturn/pulsating continents models, which predict contractional highland and marginal deformations (Figure 18a).

Alternatively, all “extension-dominant” cases (Figure 11b, 14b, 15b, 16b and 17b) fit the upwelling model prediction of a significant extension during the crustal plateau formation

(Figure 18b). However, the cases of “early extension and late compression” (Figure 11d, 14d, and 17d) and “marginal-extension and tessera-compression” (Figure 15d) are not consistent with the upwelling model. Although these cases predict early and marginal extensions followed by late compression, the upwelling model has difficulties in producing such compression without accompanying massive extensions, which is not observed in the mapping.

Furthermore, the “early compression and late extension” cases in the southern and southwestern margin (Figure 11c and 14c) fits the bolide impact with lava pond predicting early marginal parallel fold crest overprinting by perpendicular grabens (Figure 18c). Although there is no fitting case for northern and western margins, this model may be viable ranging between the “end-members” interpretations which part of the curvilinear ridges and faults may be formed under compression and the other part formed under extension.

Also, there are some interpretative cases unexplained by the proposed models. For example, the cases for “early-extension and late-compression” (Figure 11d and 14d) and “marginal-extension and tessera-compression” (Figure 15d) are discussed above for unfitting the upwelling model. Also, the case for “transpressional strike-slip faulting” (Figure 16c) in the western marginal area is also unexplained. Although the possible offset of the proposed strike-slip fault is unknown from the mapping, strike-slip faulting in such scale (inferred fault up to 100s of kilometers) may require plate tectonics-like models to explain, which is not considered in any of the proposed models.

In short, we sought to test models by interpreting deformations to see which predictions are robust, but thus far, the structural mapping cannot independently falsify an existing model. The type of deformation (compressional vs. extensional) of features such as tessera, margin faults, and curvilinear ridges is a critical issue for testing crustal plateau formation models. As shown, the current radar resolution does not allow us to clarify deformation to this extent. Failed tests of the downwelling and bolide impact models are based on tessera-plain embayment relationships rather than interpretation of deformation.

5.2 Necessary future data to test the models

We illuminate a mountainous region on Earth to explore the required resolution of radar imagery and topographic data to test the crustal plateau formation models on Venus. All mapped tessera margins appear embayed by lava plains, although non-embayment map patterns such as a major fault system are likewise viable for the southwestern region. Possible

764 faults of this size are not clear on available radar imagery, and similarly available elevation
765 data cannot resolve such features. To illustrate the required future data resolution which could
766 reveal faults of this scale, we use an Earth-based example: the active left-slip Altyn Tagh
767 fault. This fault marks the northern edge of the Tibetan plateau and has restraining bends
768 marked by topographic highs above the surrounding area due to local transpression and
769 uplifting (E. Cowgill et al., 2004). These topographic highs display complexly deformed
770 surfaces surrounded by low-lying flat plains, and thus display surface patterns not entirely
771 unlike those of the Ishtar Terra margins.

772 We present the TerraSAR-X ScanSAR imagery and ASTER Global Digital Elevation map
773 (DEM) of a portion of the Altyn Tagh fault with the Magellan data resolution in Figure 20a (i)
774 and b (i), which are 75 meters/pixel for radar imagery, 4650 meters/pixel for Magellan
775 topographic data and 1200 meters/pixels for stereo-derived topographic data. We conduct
776 mapping with this data and present it in Figure 20c (iii). The elevated complexly deformed
777 surfaces appear to be embayed by the low-lying plains, and marginal faults are too narrow to
778 show up in the elevation data.

779 The radar imagery and DEM by progressively improving their resolution (see supplementary).
780 When the radar imagery is two times better (Figure 20a (ii)), and DEM is an order of
781 magnitude better (Figure 20b (ii)) in resolution, the active highland bounding faults are
782 observed. A strike-slip fault of about 100 km and thrust faults of around 10 to 20 km can be
783 mapped (Figure 20c (ii)). Thus, improving radar resolution could help us identify uncovered
784 highland marginal faults post-dating lava plain formation.

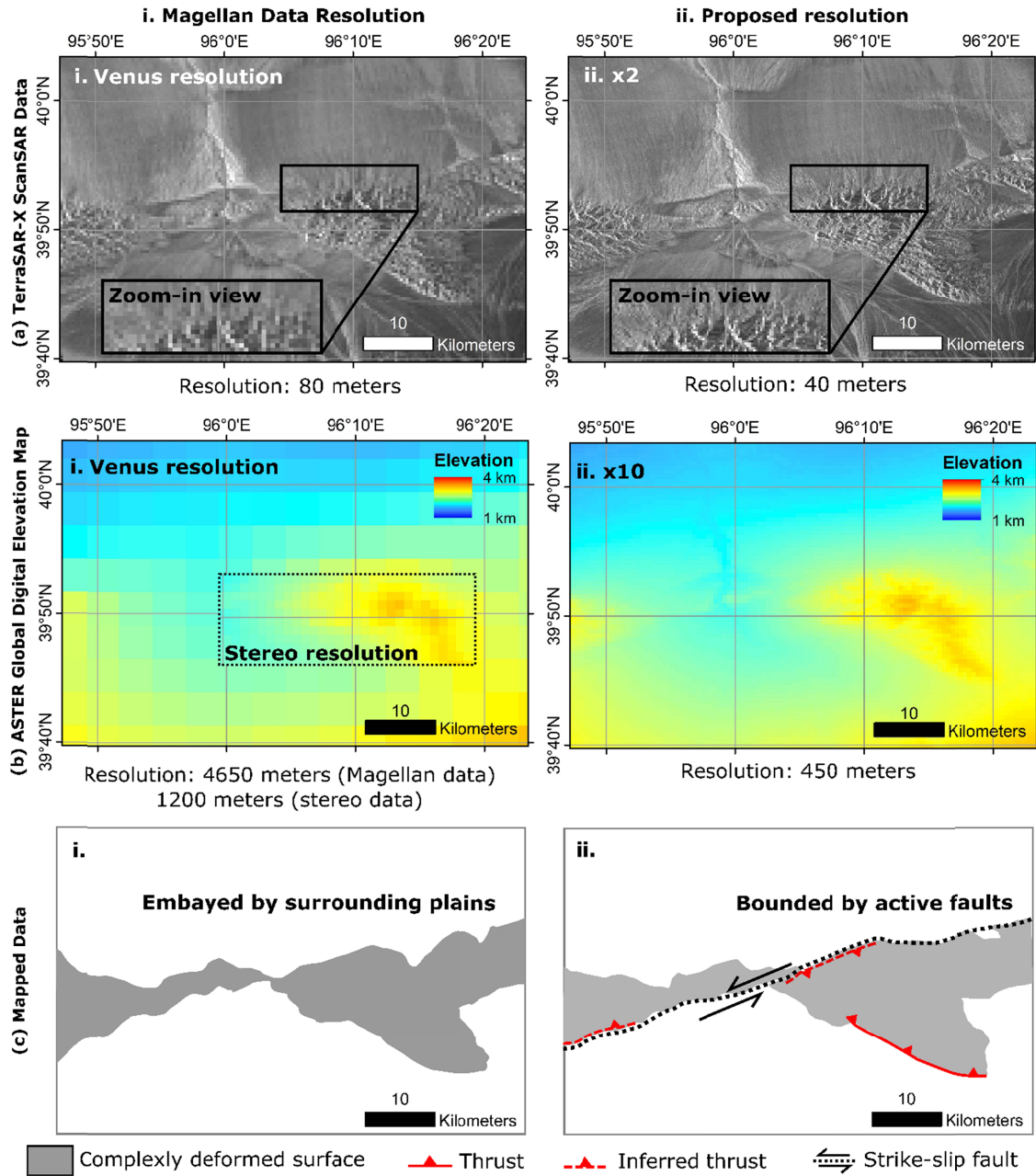


Figure. 20 TerraSAR-X ScanSAR data acquired on June 19, 2010, (a) and ASTER Global Digital Elevation Map (b) of the Altyn Tagh fault region on Earth are presented in Magellan data resolution (i) and proposed resolution (ii). Mapped data (c) resulted from these two resolutions (i) (ii) are presented.

6 Conclusion

This contribution offers new mapping data along the margin of Ishtar Terra. We identify 49 sets of structural lineaments in five mapping areas and provide different structural interpretations of each region. This work seeks to examine the viability of models for the Venusian crustal plateau formation. All mapped tessera units and concomitant deformations

along these margins appear embayed by lava plains, although non-embayment map patterns are likewise viable for the southwestern region. Plains-forming volcanism occurs after, or outlasts, all crustal plateau tectonism. This embayment relationship is consistent with three models: the episodic overturn/pulsating continents, waning heat-pipe to stagnant lid, and upwelling models. Tessera units appear to be embayed by plains in the southwestern margin, but is also possible that this boundary is a linear fault system. Lineament sets may reflect a variety of processes including compression, extension, and lava channels, resulting in a large variance in possible deformational histories. Thus, studying deformation relationships alone is unable to test models as they show a large variance in possible deformational histories under significant radar data uncertainties. We can only falsify the downwelling and bolide impact with lava pond models based on tessera-plain embayment relationships. Comparable studies of other tessera plateaus may help to determine more possibilities and develop more dependable constraints for the local and global tessera highland formation. We propose that a two times higher resolution radar imagery of 40 meters/pixel and an order of magnitude better resolution topographic map of 450 meters/pixel will be necessary to successfully test these models via geological mapping. The result indicates the presence of potential active bounding faults ranging from 10s to 100s of kilometers can be observed under the proposed data resolution.

Our mapping also identifies some new features, including (1) embayment of tessera fractures alone on lava plains, with the remaining components of tessera fabric buried by flows, which indicates that these fractures must be elevated, as well as (2) 10-20 km long and 2-5 km wide eye-pattern ridges, composed of (3) V-shape lineaments, which may reflect fault patterns revealing narrow crustal flows within and perhaps extending beneath the upper crust.

Acknowledgments

Maps, figures, tables and supporting documents are available at the online data repository Figshare, <https://doi.org/10.6084/m9.figshare.8798852>.

References

- Ahern, A. A., Radebaugh, J., Christiansen, E. H., Harris, R. A., and Tass, E. S., 2017, Lineations and structural mapping of Io's paterae and mountains: Implications for internal stresses: *Icarus*, v. 297, p. 14-32.
- Ansan, V., Vergely, P., and Masson, P., 1994, Tectonic interpretations of central Ishtar Terra (Venus) from Venera 1516 and Magellan full-resolution radar images: *Planetary and Space Science*, v. 42, no. 3, p. 239-261.

827 Ansan, V., Vergely, P., and Masson, P., 1996, Model of formation of Ishtar Terra, Venus: Planetary
 828 and Space Science, v. 44, no. 8, p. 817-831.
 829 Baker, V. R., Komatsu, G., Parker, T. J., Gulick, V. C., Kargel, J. S., and Lewis, J. S., 1997, Channels and
 830 valleys, in Venus II (eds. S. W. Bougher et al.): University of Arizona Press, p. 757-777.
 831 Barsukov, V. L., Basilevsky, A. T., Burba, G. A., Bobinna, N. N., Kryuchkov, V. P., Kuzmin, R. O.,
 832 Nikolaeva, O. V., Pronin, A. A., Ronca, L. B., Chernaya, I. M., Shashkina, V. P., Garanin, A. V.,
 833 Kushky, E. R., Markov, M. S., Sukhanov, A. L., Kotelnikov, V. A., Rzhiga, O. N., Petrov, G. M.,
 834 Alexandrov, Y. N., Sidorenko, A. I., Bogomolov, A. F., Skrypnik, G. I., Bergman, M. Y., Kudrin, L.
 835 V., Bokshtein, I. M., Kronrod, M. A., Chochia, P. A., Tyufin, Y. S., Kadnichansky, S. A., and
 836 Akim, E. L., 1986, The geology and geomorphology of the Venus surface as revealed by the
 837 radar images obtained by Veneras 15 and 16: Journal of Geophysical Research: Solid Earth, v.
 838 91, no. B4, p. 378-398.
 839 Basilevsky, A. T., and Head, J. W., 1995, Regional and global stratigraphy of Venus: a preliminary
 840 assessment and implications for the geological history of Venus.: Planetary and Space
 841 Science, v. 43, no. 12, p. 1523-1553.
 842 -, 1998, The geologic history of Venus: A stratigraphic view.: Journal of Geophysical Research:
 843 Planets, v. 103, no. E4, p. 8531-8544.
 844 Bender, K. C., Williams, K. K., and Homan, K. S., 2000, Tectonic evaluation of Alpha Regio highland
 845 and environs, Venus: Icarus, v. 148, no. 1, p. 153-159.
 846 Bindschadler, D., and Head, J., 1991, Tessera Terrain, Venus: Characterization and Models for Origin
 847 and Evolution: Journal of Geophysical Research, v. 96, no. B4, p. 5889-5907.
 848 Bindschadler, D., and Parmentier, E., 1990, Mantle flow tectonics: The influence of a ductile lower
 849 crust and implications for the formation of topographic uplands on Venus: Journal of
 850 Geophysical Research: Solid Earth, v. 95, no. B13 p. 21329-21344.
 851 Bindschadler, D. L., Schubert, G., and Kaula, W. M., 1992, Coldspots and hotspots: Global tectonics
 852 and mantle dynamics of Venus: Journal of Geophysical Research: Planets, v. 97, no. E8, p.
 853 13495-13532.
 854 Bland, M. T., and McKinnon, W. B., 2016, Mountain building on Io driven by deep faulting: Nature
 855 Geoscience, v. 9, no. 6, p. 429.
 856 Brown, C. D., and Grimm, R. E., 1997, Tessera deformation and the contemporaneous thermal state
 857 of the plateau highlands, Venus.: Earth and planetary science letters, v. 147, no. 1-4 p. 1-10.
 858 Bruegge, R. W., Head, J. W., and Campbell, D. B., 1990, Orogeny and large-scale strike-slip faulting
 859 on Venus: Tectonic evolution of Maxwell Montes: Journal of Geophysical Research: Solid
 860 Earth, v. 95, no. B6, p. 8357-8381.
 861 Bruegge, R. W. V., and Head, J. W., 1989, Fortuna Tessera, Venus: Evidence of horizontal
 862 convergence and crustal thickening: Geophysical Research Letters, v. 16, no. 7, p. 699-702.
 863 -, 1990, Tectonic evolution of eastern ishtar terra, venus: Earth, Moon, and Planets, v. 50, no. 1, p.
 864 251-304.
 865 Bunte, M., Williams, D., Greeley, R., and Jaeger, W., 2010, Geologic mapping of the Hi'iaka and
 866 Shamshu regions of Io: Icarus, v. 207, no. 2, p. 868-886.
 867 Campbell, B. A., and Campbell, P. G., 2002, Geologic map of the Bell Regio Quadrangle (V-9).
 868 Center, U. A. S., 1994, Venus Magellan SAR FMAP Left Look Global Mosaic 75m v1: USGS
 869 Astrogeology Science Center.
 870 Craddock, R. A., 2011, Aeolian processes on the terrestrial planets: Recent observations and future
 871 focus: Progress in Physical Geography, v. 36, no. 1, p. 110-124.
 872 E. Cowgill, E., Yin, A., Arrowsmith, J. R., Xiao-Feng, W., and Shuanhong, Z., 2004, The Akato Tagh
 873 bend along the Altyn Tagh fault, northwest Tibet 1: Smoothing by vertical-axis rotation and
 874 the effect of topographic stresses on bend-flanking faults: Geological Society of America
 875 Bulletin, v. 116, no. 11-12, p. 1423-1442.
 876 Ford, J. P., and Plaut, J. J., 1993, Magellan image data." Guide to Magellan image interpretation.

877 Ford, P. G., and Pettengill, G. H., 1992, Venus topography and kilometer-scale slopes.: *Journal of*
878 *Geophysical Research: Planets*, v. 97, no. E8, p. 13103-13114.

879 Gaddis, L. R., and Greeley, R., 1990, Volcanism in Northwest Ishtar Terra, Venus: *Icarus*, v. 87, no. 2,
880 p. 327-338.

881 Ghent, R., and Hansen, V., 1999, Structural and kinematic analysis of eastern Ovda Regio, Venus:
882 Implications for crustal plateau formation: *Icarus*, v. 139, no. 1, p. 116-136.

883 Gilmore, M. S., and Head, J. W., 2000, Sequential deformation of plains at the margins of Alpha
884 Regio, Venus: Implications for tessera formation: *Meteoritics & Planetary Science*, v. 35, no.
885 4, p. 667-687.

886 -, 2018, Morphology and deformational history of Tellus Regio, Venus: Evidence for assembly and
887 collision: *Planetary and Space Science*, v. 154, p. 5-20.

888 Gilmore, M. S., Ivanov, M. A., Head, J. W., and Basilevsky, A. T., 1997, Duration of tessera
889 deformation on Venus.: *Journal of Geophysical Research: Planets*, v. 102, no. E6, p. 13357-
890 13368.

891 Grimm, R. E., 1994, The deep structure of Venusian plateau highlands.: *Icarus*, v. 112, no. 1, p. 89-
892 103.

893 Grimm, R. E., and Phillips, R. J., 1991, Gravity anomalies, compensation mechanisms, and the
894 geodynamics of western Ishtar Terra, Venus: *Journal of Geophysical Research: Solid Earth*, v.
895 96, no. B5, p. 8305-8324.

896 Hansen, V. L., 2006, Geologic constraints on crustal plateau surface histories, Venus: The lava pond
897 and bolide impact hypotheses: *Journal of Geophysical Research: Planets*, v. 111, no. E11.

898 Hansen, V. L., and Phillips, R. J., 1995, Formation of Ishtar Terra, Venus: Surface and gravity
899 constraints: *Geology*, v. 23, no. 4, p. 292-296.

900 Hansen, V. L., Phillips, R. J., Willis, J. J., and Ghent, R. R., 2000, Structures in tessera terrain, Venus:
901 Issues and answers: *Journal of Geophysical Research: Planets* v. 105, no. E2, p. 4135-4152.

902 Hansen, V. L., and Willis, J. A., 1996, Structural Analysis of a Sampling of Tesserae: Implications for
903 Venus Geodynamics: *Icarus*, v. 123, no. 2, p. 296-312.

904 Hansen, V. L., and Willis, J. J., 1998, Ribbon Terrain Formation, Southwestern Fortuna Tessera, Venus:
905 Implications for Lithosphere Evolution: *Icarus*, v. 132, no. 2, p. 321-343.

906 Head, J. W., 1990, Formation of mountain belts on Venus: Evidence for large-scale convergence,
907 underthrusting, and crustal imbrication in Freyja Montes, Ishtar Terra: *Geology*, v. 18, no. 2,
908 p. 99-102.

909 Herrick, R. R., Stahlke, D. L., and Sharpton, V. L., 2012, Fine-scale Venusian topography from
910 Magellan stereo data: *EOS, Transaction, American Geophysical Union*, v. 93, no. No. 12, p.
911 125-126.

912 Hess, P., and Head, J., 1990, Derivation of primary magmas and melting of crustal materials on Venus:
913 Some preliminary petrogenetic considerations: *Earth, Moon, and Planets*, v. 50, no. 1, p. 57-
914 80.

915 Ivanov, M., and Head, J., 1996, Tessera terrain on Venus: A survey of the global distribution,
916 characteristics, and relation to surrounding units from Magellan data: *Journal of Geophysical*
917 *Research: Planets*, v. 101, no. E6, p. 14861-14908.

918 -, 2008, Formation and evolution of Lakshmi Planum, Venus: assessment of models using
919 observations from geological mapping: *Planetary and Space Science*, v. 56, no. 15, p. 1949-
920 1966.

921 Ivanov, M. A., and Head, J. W., 2007, Semuni Dorsa: An Extinct Zone of Convergence, Underthrusting
922 and Subduction on Venus?: *Lunar and Planetary Science Conference*, v. 38, p. 1031.

923 Ivanov, M. A., and Head, J. W., 2010, Geologic Map of the Lakshmi Planum Quadrangle (V-7), Venus:
924 USGS.

925 -, 2011, Global geological map of Venus.: *Planetary and Space Science*, v. 59, no. 13, p. 1559-1600.

926 Ivanov, M. A., and III, J. W. H., 2008, Formation and evolution of Lakshmi Planum, Venus: assessment
 927 of models using observations from geological mapping: *Planetary and Space Science*, v. 56,
 928 no. 15, p. 1949-1966.

929 Ivers, C., and McGill, G., 1998, Kinematics of a Tessera Block in the Vellamo Planitia Quadrangle:
 930 *Lunar and Planetary Science Conference*, v. 29.

931 James, P. B., Zuber, M. T., and Phillips, R. J., 2013, Crustal thickness and support of topography on
 932 Venus: *Journal of Geophysical Research: Planets*, v. 118, no. 4, p. 859-875.

933 Keep, M., and Hansen, V. L., 1994, Structural evolution of Danu Montes, Venus: Deformation around
 934 a curved boundary.: *Lunar and Planetary Science Conference*, v. 25, p. 681.

935 Kiefer, W., and Hager, B., 1989, The role of mantle convection in the formation of highland regions
 936 on Venus: *Lunar and Planetary Science Conference*, v. 20.

937 Kiefer, W. S., and Hager, B. H., 1991, Mantle downwelling and crustal convergence: A model for
 938 Ishtar Terra, Venus: *Journal of Geophysical Research: Planets*, v. 96, no. E4, p. 20967-20980.

939 Kucinskas, A. B., Turcotte, D. L., and Arkani-Hamed, J., 1996, Isostatic Compensation of Ishtar Terra,
 940 Venus: *Journal of Geophysical Research: Planets*, v. 101, no. E2, p. 4725-4736.

941 M. A. Ivanov, M. A., and Basilevsky, A. T., 1993, Density and morphology of impact craters on tessera
 942 terrain, Venus.: *Geophysical research letters*, v. 20, no. 23, p. 2579-2582.

943 Marinangeli, L., and Gilmore, M. S., 2000, Geologic evolution of the Akna Montes-Atropos Tessera
 944 region, Venus: *Journal of Geophysical Research: Planets*, v. 105, no. E5, p. 12053-12075.

945 Maurice, K. E., Leberl, F. W., Norikane, L., and Hensley, S., 1994, Venus surface roughness and
 946 Magellan stereo data.

947 McGill, G. E., 2000, Geologic map of the Sappho Patera quadrangle (V-20), Venus: US Department of
 948 the Interior, US Geological Survey.

949 Moore, W. B., and Schubert, G., 1997, Venusian crustal and lithospheric properties from nonlinear
 950 regressions of highland geoid and topography: *Icarus*, v. 128, no. 2, p. 415-428.

951 Moore, W. B., Simon, J. I., and Webb, A. A. G., 2017, Heat-pipe planets: *Earth and Planetary Science*
 952 *Letters*, v. 474, p. 13-19.

953 O'Reilly, T. C., and Davies, G. F., 1981, Magma transport of heat on Io: A mechanism allowing a thick
 954 lithosphere: *Geophysical Research Letters*, v. 8, no. 4, p. 313-316.

955 Pettengill, G. H., Ford, P. G., Johnson, W. T., Raney, R. K., and Soderblom, L. A., 1991, Magellan:
 956 Radar performance and data products: *Science*, v. 252, no. 5003, p. 260-265.

957 Phillips, R. J., and Hansen, V. L., 1998, Geological evolution of Venus: Rises, plains, plumes, and
 958 plateaus: *Science*, v. 279, no. 5356, p. 1492-1497.

959 Pritchard, M. E., Hansen, V. L., and Willis, J. J., 1997, Structural evolution of western Fortuna Tessera,
 960 Venus: *Geophysical Research Letters*, v. 24, no. 18, p. 2339-2342.

961 Ramsay, J. G., 1967, *Folding and Fracturing of Rocks*: McGraw-Hill, New York.

962 Roberts, K. M., and Head, J. W., 1990, Western Ishtar Terra and Lakshmi Planum, Venus: Models of
 963 formation and evolution: *Geophysical Research Letters*, v. 17, no. 9, p. 1341-1344.

964 Romeo, I., and Capote, R., 2011, Tectonic evolution of Ovda Regio: An example of highly deformed
 965 continental crust on Venus?. *Planetary and Space Science*, v. 59, no. 13, p. 1428-1445.

966 Romeo, I., and Turcotte, D. L., 2008, Pulsating continents on Venus: An explanation for crustal
 967 plateaus and tessera terrains: *Earth and Planetary Science Letters* v. 276, no. 1-2, p. 85-97.

968 Saunders, R. S., Spear, A. J., Allin, P. C., Austin, R. S., Berman, A. L., Chandler, R. C., Clark, J.,
 969 Decharon, A. V., Jong, E. M. D., Griffith, D. G., Gunn, J. M., Hensley, S., Johnson, W. T. K.,
 970 Kirby, C. E., Leung, K. S., Lyons, D. T., Michaels, G. A., Miller, J., Morris, R. B., Morrison, A. D.,
 971 Piereson, R. G., Scott, J. F., Shaffer, S. J., Slonski, J. P., Stofan, E. R., Thompson, T. W., and
 972 Wall, S. D., 1992, Magellan mission summary: *Journal of Geophysical Research: Planets*, v. 97,
 973 no. E8, p. 13067-13090.

974 Schenk, P., Hargitai, H., Wilson, R., McEwen, A., and Thomas, P., 2001, The mountains of Io: Global
 975 and geological perspectives from Voyager and Galileo: *Journal of Geophysical Research:*
 976 *Planets*, v. 106, no. E12, p. 33201-33222.

977 Simons, M., Solomon, S. C., and Hager., B. H., 1997, Localization of gravity and topography:
 978 Constraints on the tectonics and mantle dynamics of Venus: *Geophysical Journal*
 979 *International* v. 131, no. 1, p. 24-44.
 980 Sjogren, W. L., Bills, B. G., and Mottinger, N. A., 1984, Venus: Ishtar gravity anomaly: *Geophysical*
 981 *research letters*, v. 11, no. 5, p. 489-491.
 982 Smrekar, S. E., and Phillips., R. J., 1991, Venusian highlands: Geoid to topography ratios and their
 983 implications.: *Earth and Planetary Science Letters*, v. 107, no. 3-4, p. 582-597.
 984 Sukhanov, A. L., 1992, Tesserae: Venus Geology, Geochemistry, and Geophysics-Research results
 985 from the USSR, p. 82-95.
 986 Sukhanov, A. L., Pronin, A. A., Burba, G. A., Nikishin, A. M., Kryuchkov, V. P., Basilevsky, A. T., Markov,
 987 M. S., Kuzmin, R. O., Bobina, N. N., Shashkina, V. P., and Iyuta, E. N., 1989,
 988 Geomorphic/geologic map of part of the northern hemisphere of Venus., v. 2059.
 989 Turcotte, D. L., 1989, A heat pipe mechanism for volcanism and tectonics on Venus.: *Journal of*
 990 *Geophysical Research: Solid Earth*, v. 94, no. B3, p. 2779-2785.
 991 Turtle, E. P., Jaeger, W. L., Keszthelyi, L. P., McEwen, A. S., Milazzo, M., Moore, J., Phillips, C. B.,
 992 Radebaugh, J., Simonelli, D., Chuang, F., and Schuster, P., 2001, Mountains on Io: High-
 993 resolution Galileo observations, initial interpretations, and formation models: *Journal of*
 994 *Geophysical Research: Planets*, v. 106, no. E12, p. 33175-33199.
 995 Twiss, R. J., and Moores, E. M., 2007, *Structural Geology (Second Edition)*: W. H. Freeman and
 996 Company.

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