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The Lada Terra rise and Quetzalpetlatl Corona: A region of long-lived mantle upwelling and recent volcanic activity on Venus

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ABSTRACT

Quetzalpetlatl Corona (~850 km in diameter) and Boala Corona (~350 km × 250 km in diameter), are both situated within the Lada Terra rise, a prominent ~2000-km-wide circular topographic feature rising ~2.5–3 km above the mean planetary radius in the southern hemisphere of Venus, south of the Lavinia Planitia lowlands. Together these features form a unique configuration that combines the characteristics of corona-dominated rises (e.g., Eistla), rifted volcanic rises (e.g., Beta Regio), and large coronae structures (such as Artemis and Heng-O). Three zones of extension converge on the central part of the rise at Boala Corona, and hundreds of extensive lava flows emerge from the summit region, stream down the sides of the rise, and flood the surrounding topographic annulus and moat. Detailed geological mapping of the region shows that Cocomama Tessera terrain was flexed, uplifted and flooded during the formation of the Lada rise. Stratigraphic relationships show that the rise formed over an extended period of time following tessera formation. Evidence for early uplift includes flexure of the tessera, formation of the Quetzalpetlatl Corona annular ridge, and the radial array of flows originating from the center of the feature (showing the presence of downhill slopes). Early Quetzalpetlatl Corona activity was focused on the formation of the annular ridge, and the outer moat continued to form throughout the extended history of the rise, deforming even after the emplacement of some of the most recent lavas. Central radial flows ponded behind the early-forming annular ridge, concentrating the load inside the ridge, perhaps adding to the evolution of the moat. Late-stage activity includes final radial flows and central shields inside Boala Corona. On the basis of gravity, topography and image data, volcanism has persisted into the most recent geological era. We compare the central Lada rise with other regions of Venus thought to be currently active on the basis of Venus Express VIRTIS emissivity data and we conclude that although the area may have been active in the very recent geological past, stratigraphic evidence favors an endogenic origin for some VIRTIS anomalies. The coaxial combination of the broad rise of Lada Terra with large coronae (Quetzalpetlatl and Boala) suggests that these two types of features are parts of a continuum related to the magnitude and history of mantle thermal upwellings. We see no evidence that the culmination of this process results in tessera formation.

1. Introduction

Lada Terra (Fig. 1a) is a broad region of midlands (0–2 km above MPR, mean planetary radius) at high southern latitudes (60–80°S; 300–90°E). Its western portion (Fig. 1a) is dominated by a large (~2000 km across) dome-shaped structure, a topographic rise, the summit of which reaches elevations 2.5–3 km above MPR (Fig. 1b). The vast lowland of Lavinia Planitia (1–1.5 km below MPR) surrounds the western portion of Lada Terra to the north (Fig. 1a and b). Before the Magellan mission, the regional geology of the Lada Terra region was known on the basis of topographic data acquired by the Pioneer-Venus altimeter (Masursky et al., 1980; Pettengill et al., 1980) and radar images received by the Arecibo telescope (Campbell et al., 1991; Senske et al., 1991). Arecibo radar images and early Magellan results showed that the Lada Terra region is the site of numerous coronae including one of the largest corona on Venus, Quetzalpetlatl Corona (Stofan et al., 1992), interconnected by belts of fractures and graben (Baer et al., 1994; Magee and Head, 1995). One of these belts, Kalaipahoa Linea (Fig. 1a), extends from the east to the west along a regional break of slope in the marginal zone between Lada Terra and Lavinia Planitia (Fig. 1a and b). In contrast to Lada, there are no coronae within Lavinia Planitia (Stofan et al., 1992; Crumpler and Aubele, 2000; Ivanov and Head, 2001) and the floor of the lowland is populated by complex patterns of deformational features in the

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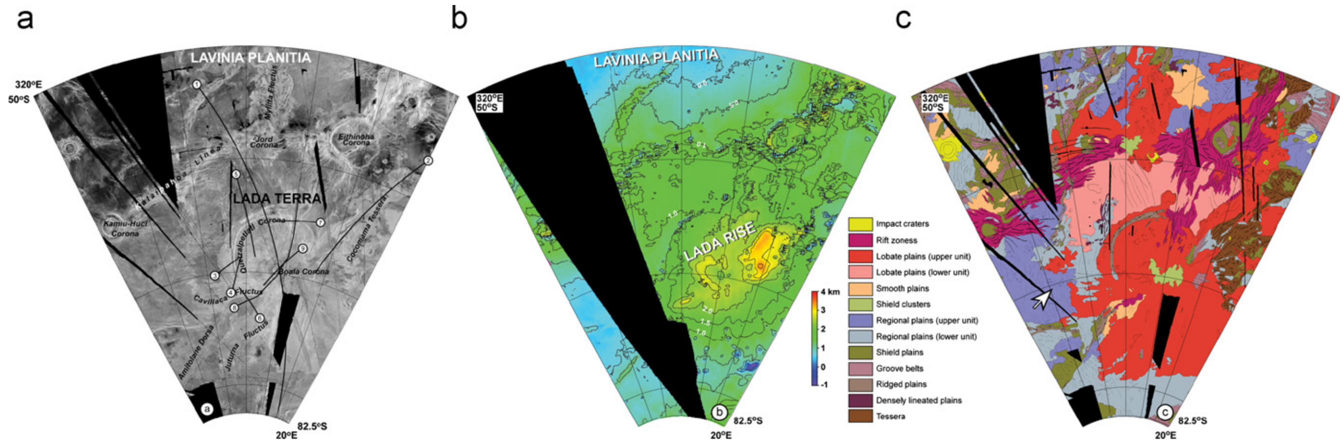

Fig. 1. (a) The area of study includes the western portion of Lada Terra dominated by Cocomama Tessera, Quetzalpetlatl and Boala Coronae, and major complexes of lava flows, Cavillaca and Juturna Fluctūs. The lowland of Lavinia Planitia borders Lada Terra in the North. A rift-like zone of Kalaipahoa Linea extends along the northern edge of Lada Terra and connects several coronae (Kamui-Huci, Jord, and Eithinoha). Jord Corona is the source of another major complex of lava flows, Mylitta Fluctus. Thick lines with numbers indicate topographic profiles. Map is in Lambert azimuthal equal-area projection. (b) Major topographic feature of the study area. The Lada rise dominates the western portion of Lada Terra and hosts Quetzalpetlatl and Boala Coronae. The rise has a dome-like shape and is outlined by the 1.0 km contour line. The rim of Boala Corona at the summit of the rise is at 2.5 km elevation. The SE portion of Cocomama Tessera forms a high peak ($\sim$3.5 km) on the eastern flank of the rise. (c) Geological map of the study area. Relatively young volcanic plains (smooth and lobate plains) cover the largest portion of Lada Terra. The summit of the Lada rise is the source of the most extensive younger volcanic units. White arrow indicates one of the areas where flow-like features of the upper unit of regional plains (rp2) flow along the regional slope on the flanks of the rise. Maps are in Lambert azimuthal equal-area projection.

form of belts of ridges and grooves (Squyres et al., 1992; Solomon et al., 1992). Among the most spectacular morphologic features of Lada Terra are large complexes of lava flows, Fluctūs. They are related to two major centers of volcanism: Jord Corona within Kalaipahoa Linea (Mylitta Fluctus) (Roberts et al., 1992) and Boala Corona at the summit of the Lada rise (Cavillaca and Juturna Fluctūs) (Fig. 1a). Fluctūs are absent within Lavinia Planitia (Ivanov and Head, 2001). Magellan gravity data (Konopliv and Sjogren, 1994; Konopliv et al., 1999) show that both the high values of vertical gravity acceleration (up to 120 mGal) and geoid height (up to 40 m) characterize the region of western Lada Terra centered at the rise. The surrounding lowlands of Lavinia Planitia are characterized by low free-air gravity values (-30 mGal) and negative geoid heights (-10 m) (Konopliv et al., 1999). Thus, the important morphologic and topographic/gravity characteristics indicate that the western Lada Terra and Lavinia Planitia represent two very distinct provinces with apparently different geodynamical histories. The gravity characteristics, topographic configuration, and pattern of deformation belts of Lavinia Planitia have been cited as the evidence for a large-scale mantle downwelling (Bindschadler et al., 1992) whereas the topographic and gravity signatures of Lada Terra are consistent with mantle upwelling there (Kiefer and Hager, 1991; Smrekar et al., 1997; Stofan and Smrekar, 2005).

The largest structure of Lada Terra is Quetzalpetlatl Corona (Fig. 1a), which is $\sim$850 km across (Stofan et al., 1992). A rim consisting of linear parallel ridges outlines the northwestern portion of the corona and mostly defines Quetzalpetlatl (Stofan et al., 1992). Topographically, the rim of Quetzalpetlatl extends at the base of the Lada rise (Fig. 1b). The intimate spatial association of the corona and the rise suggests that both features are genetically related and may represent specific stages in the evolution of a hotspot-like region. The major goals of our study were to address questions related to the evolution of the Lada rise and Quetzalpetlatl Corona in the context of regional geologic history of Lavinia Planitia and Lada Terra. When did the corona and the rise form? Do these features represent sequential phases of a continuous evolutionary process or do they correspond to different pulses of activity separated in time but coinciding in space? We addressed these questions during the geological mapping (1:5 M, quadrangles V-55, V-56, and V-61 (Ivanov and Head, 2001, 2006; Kumar and Head, 2010)). Here we focus on the geological mapping, reconstruction of the sequence of events, and correlation of units and structures with topography in a broad region that includes Lavinia Planitia and Lada Terra.

2. Regional geology: units, structures, and their stratigraphic relationships

In the geologic mapping analysis, we used traditional methods of geologic unit definition and characterization for the Earth (for example, American Commission on Stratigraphic Nomenclature, 1961) and planets (for example, Wilhelms, 1990) appropriately modified for radar data (Tanaka, 1994). We defined units and mapped key relations between them and tectonic structures using the full resolution Magellan synthetic aperture radar (SAR) image data (C1- and F-MIDR's, and F-Maps) and altimetry data and transferred these results to the base map compiled at a scale of 1:5 M. The background for our unit definition and characterization is described in several publications (e.g., Tanaka, 1994; Basilevsky and Head, 1995a, b; Basilevsky et al., 1997; Ivanov and Head, 1998).

Several different geologic processes have influenced the region of Quetzalpetlatl Corona and its surroundings and formed its geologic record (Fig. 1c). Volcanism is apparently the dominant process of crustal formation on Venus (Head et al., 1992) and in the production of the observed geologic units. Tectonic activity has modified some of these basic crustal materials (Solomon et al., 1992; Squyres et al., 1992) in a variety of modes (extension and contraction). In places deformation is so extensive (e.g., tessera, groove belts, rift-like zones) that structures become part of the definition of the material unit (see also Tanaka, 1994; Scott and Tanaka, 1986). Relative ages that were established on the basis of consistent relationships of embayment among material units are summarized in the correlation chart (Fig. 2).

2.1. Units

Tessera (t, Fig. 3a) occupies $\sim$5.3% of the mapped area and displays a unique pattern of deformation consisting of intersecting arches, ridges, and grooves that deform some precursor

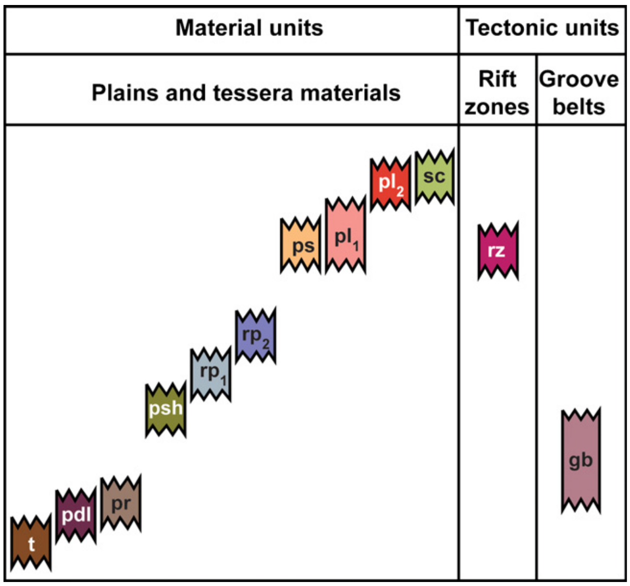

Fig. 2. Correlation chart of units mapped in the western portion of Lada Terra. (Modified from Ivanov and Head, 2006.)

terrain of unknown origin (Barsukov et al., 1986; Basilevsky et al., 1986; Bindschadler and Head, 1991; Sukhanov, 1992; Solomon et al., 1992; Ivanov and Head, 1996; Hansen and Willis, 1996; Hansen et al., 1997). There is one major massif of tessera in the study area, Cocomama Tessera, near the center of the Lada Terra (Fig. 1a and c). Less deformed materials embay tessera where it is exposed, which suggests that tessera represents one of the oldest units.

Densely packed lineaments (some of them may be fractures) cut the surface of *Densely lineated plains* (pdl, Fig. 3b). They appear to be the stratigraphically oldest plains. Occurrences of the unit are typically small (a few hundreds of km across), are embayed by younger units, and occupy only ~1.5% of the mapped area. Densely lineated plains do not occur in contact with tessera, thus, the relative timing of formation of these units cannot be established. The less complex pattern of deformation within the unit pdl suggests, however, that this unit was deformed after the major episodes of tessera-forming tectonics (Fig. 2).

Ridged plains (pr, Fig. 3c) are commonly deformed by relatively broad ridges 5–10 km wide and tens of kilometers long. The ridges are typically arranged in linear belts 100–150 km wide and hundreds of km long that predominantly occur on the floor of the basin of Lavinia Planitia. The area of ridged plains is ~2.1% of the mapped area. Temporal relationships between ridged plains and densely lineated plains are not clear because these units are not in direct contact. In places, however, the ridges similar to those of ridged plains deform unit pdl. This suggests that the deformation responsible for the final morphology of ridged plains took place after emplacement of units pdl and pr (Fig. 2). The rim of Quetzalpetlatl is indistinguishable morphologically from a typical ridge belt.

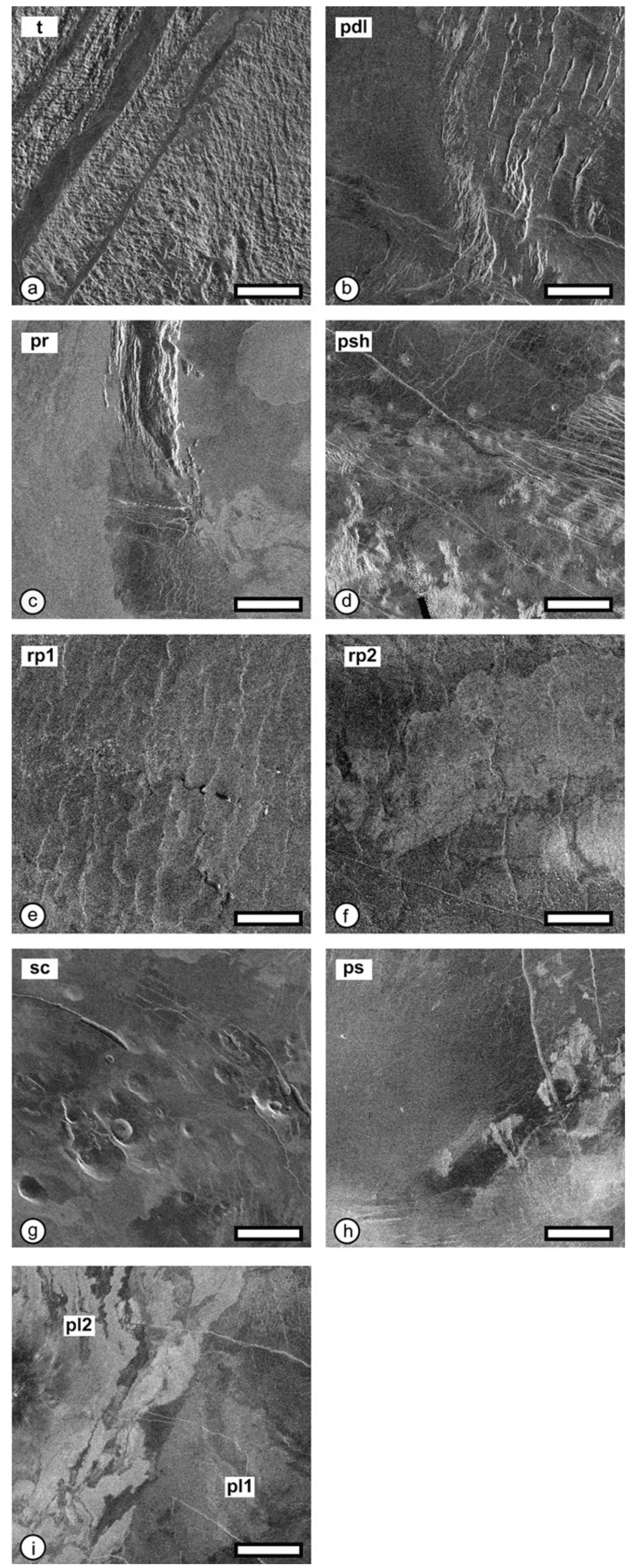

Fig. 3. Examples of units predating the youngest volcanic plains. (a) Tessera (t), fragment of C1-MIDR_60s014, center of the image is at 64.3°S, 12.4°E. (b) Densely lineated plains (pdl, right), fragment of C1-MIDR_60s347, center of the image is at 64.8°S, 345.2°E. (c) Ridged plains in the rim of Quetzalpetlatl (rp, up, center), fragment of C1-MIDR_75s338, center of the image is at 69.8°S, 347.1°E. (d) Shield plains (psh, lower half of the image), fragment of C1-MIDR_45s350, center of the image is at 48.7°S, 345.7°E. (e) Lower unit of regional plains (rp_1), fragment of C1-MIDR_75s338, center of the image is at 68.9°S, 339.2°E. (f) Upper unit of regional plains (rp_2, flow-like features correspond to the white arrow in Fig. 1c), fragment of C1-MIDR_75s338, center of the image is at 70.1°S, 333.5°E. Each scale bar is 25 km; all images are in sinusoidal projection. Examples of the youngest volcanic units. (g) Shield cluster (sc) on the floor of Boala Corona, fragment of C1-MIDR_75s023, center of the image is at 69.6°S, 2.7°E. (h) Smooth plains (ps, featureless plains in the upper left portion of the image), fragment of C1-MIDR_60s347, center of the image is at 57.2°S, 349.1°E. (i) Two units of lobate plains: the lower unit (pl_1, right) and the upper unit (pl_2, left), fragment of C1-MIDR_60s347, center of the image is at 55.8°S, 356.9°E.

Tessera, densely lineated plains, and ridged plains are strongly tectonized and embayed by all other units and appear to form the base of the regional stratigraphic column (Fig. 2).

Shield plains (psh, Fig. 3d) occupy ~4.6% of the mapped area and are characterized by abundant small shield-shaped features a few km across, many of them with summit pits. The shields occur in clusters, giving the unit a locally hilly texture, and are interpreted to be small volcanoes. The unit occurs predominantly on the northern regional slope of Lada Terra and on the floor of Lavinia Planitia where it embays occurrences of densely lineated plains and ridged plains and, since that, is younger (Fig. 2). Shield plains are absent in the interior of Lada Terra where this part of the stratigraphic section can be completely buried by vast mantles of younger plains.

Regional plains (Fig. 3e and f) are more abundant than the previous units (total area is ~15.3%) and are composed of morphologically smooth, homogeneous material of intermediate-dark to intermediate-bright radar albedo deformed by sinuous ridges. In contrast to the shield plains, the sources of regional plains are not obvious. On the basis of the typical pattern of radar backscatter, regional plains are subdivided into two units, both of which embay all previous units and are deformed by pervasive networks of wrinkle ridges. The stratigraphically lower unit (rp_1, Fig. 3e ~14.1%) with a homogeneous and relatively low radar albedo preferentially occurs on the floor of the lowlands surrounding Lada Terra (e.g., Lavinia Planitia) (Fig. 1c). The lower unit of regional plains forms a broad background around the Lada rise and occurs on the western flank of it coming almost to the NW rim of Quetzalpetlatl Corona (Fig. 1c). In one locality, plains that morphologically are similar to the unit rp_1 are seen embaying the ridges at the southern end of the corona rim (Fig. 3c). The plains in this area make up the surface of a topographic ridge that is embayed by younger plains units (Fig. 3c). These relationships suggest that the lower unit of regional plains near the edge of the rim of Quetzalpetlatl Corona occurs in a stratigraphic window, which plays an important role in the assessment of the sequence of events in evolution of the Lada rise region. The stratigraphically upper unit (rp_2, Fig. 3f, ~1.2%) occurs on the northern and western regional slopes of Lada Terra (Fig. 1b and c). The plains have higher radar albedo and sometimes are characterized by lobate boundaries and internal flow-like features that tend to outline local highs of the unit rp_1 suggesting that the unit rp_2 generally post-dates the lower member of regional plains (Fig. 2). On the western flank of the Lada rise, the flow-like features of the upper unit of regional plains extend westward along the regional slope of the rise (Ivanov and Head, 2006). Both units of regional plains consistently embay shield plains (see Fig. 3d) and are thus younger (Fig. 2). Shield plains and regional plains are distinctly less deformed than the older units (t, pdl, and pr) and appear on the basis of stratigraphic relations to form the middle stratigraphic level of the regional stratigraphic column (Fig. 2).

The units that are younger than regional plains have lobate and digitate margins, morphologically smooth surfaces, and, in places, clusters of small shield-like features similar to those of shield plains, but clearly stratigraphically younger. The younger plains clearly postdate both units of regional plains and all other units and collectively represent the uppermost regional stratigraphic sequence (Fig. 2). Four types of younger plains units are recognized (Fig. 3g–i).

Shield clusters (sc, Fig. 3g) are morphologically similar to shield plains (psh) but display distinct small lava flows superimposed on nearby lava plains. There are two small occurrences of this unit (each a few hundreds of km across) that occupy less that 1% of the mapped area. One is inside and near Jord Corona and another is within Boala Corona at the summit of the Lada rise (Fig. 1c). The surface of *smooth plains* (ps, Fig. 3h, ~6.4%) is not deformed tectonically and characterized by uniform and preferentially low albedo. Patches of this unit mostly occur near major volcanic centers and sometimes in close spatial association with some impact craters (Fig. 1c).

Lobate plains (units pl_1 and pl_2, Fig. 3i) make up the largest portion of the studied region (about 2,357,000 km^2, ~41.5%). Lobate plains have internal elements arranged in parallel to sinuous to lobate radar bright and dark strips and patches, and unit boundaries are typically lobate. The internal elements and flow-like features of the upper unit of lobate plains, pl_2, are more prominent and superposed on features of the lower unit of the plains, pl_1 (Fig. 3i). There is no compelling evidence, however, to establish the relative timing of the lower unit of lobate plains with smooth plains. Lobate plains predominantly occupy the central portion of the western Lada Terra on the slopes of the rise (Fig. 1c) but also occur around some distinct centers such as coronae along the transition zone from Lada Terra to Lavinia Planitia (Fig. 1c). Lobate plains are absent on the floor of Lavinia Planitia. Sometimes, lobate plains display very large (~1000 km across) complexes of overlapping lava flows, Fluctūs. Two of them, Cavillaca and Juturna Fluctūs, are sourced from Boala Corona, which is inside Quetzalpetlatl Corona and on top of the Lada rise (Fig. 1a), and the third, Mylitta Fluctus, is sourced by Jord Corona within the deformational zone of Kalaipahoa Linea near the northern edge of Lada Terra (Fig. 1a). The flows of the fluctūs extend down the regional topography and appear to be the youngest volcanic features. They form a significant portion of the upper unit of lobate plains (Fig. 1c). Within Boala Corona, flows of this unit both embay and are embayed by shields of a shield cluster (unit sc).

2.2. Structures

A variety of extensional and contractional tectonic structures, individual and collected into belts and zones is observed and mapped in the studied region.

2.2.1. Contractional structures

Two types, scales, and ages of contractional features are observed. The older are ridges and arches (Fig. 3c) that deform ridged plains (unit pr) and dominate the floor and southern edges of the lowland of Lavinia Planitia (Fig. 1c), where the ridges are collected into belts and embayed by shield and regional plains. The younger contractional features are wrinkle ridges (Fig. 3e and f) that are sinuous and narrow (a few km wide) structures tens of kilometers long. Wrinkle ridges do not produce belts and deform regional plains and older units and are embayed by smooth and lobate plains.

The most prominent tectonic structure of Quetzalpetlatl Corona is its northern rim that represents a belt 40–50 km wide consisting of broad (5–10 km) ridges (Figs. 1a and 3c). Near the southern end of the rim, the lower unit of regional plains is exposed in a stratigraphic window and embays ridges of the rim (Fig. 3c). Thus, both stratigraphically and morphologically, the rim resembles the ridge belts elsewhere. In contrast to the other occurrences of ridge belts that are typically linear or slightly sinuous features, the rim of Quetzalpetlatl is a distinct 120°-arc (Fig. 1a and c) that mostly defines the corona (Stofan et al., 1992). Some coronae on Venus display ridged rims (Pronin and Stofan, 1990; Stofan et al., 1992), although the majority of coronae are characterized by rims consisting of extensional structures (Stofan et al., 1992, 1997; Squyres et al., 1992). The specific planimetric shape of the rim of Quetzalpetlatl Corona suggests that this structure is related to the evolution of the corona rather than representing a portion of regionally developed ridge belts. Inside the corona there are isolated and heavily flooded fragments of ridges that morphologically resemble ridges of the rim. These fragments indicate that initially the rim was broader and extended inside the corona for ~100–120 km. The flooded ridges are seen near the northwestern and northern segments of the rim and are absent near its western segment where either the rim was narrower or the thickness of the flooding lavas was greater or both. There are no exposures of flooded ridges outside the rim of the corona.

2.2.2. *Extensional structures*

Extensional structures in the studied region form either widely or tightly spaced swarms of graben and fractures. Long linear fractures and graben of Enyo Fossae originate at Jord Corona and run southward toward Quetzalpetlatl Corona (Figs. 1a and 4). At the hypsometrically higher Jord Corona, the graben begins in elongated depressions with rounded edges (Fig. 4a) and at the lower topographic level near Quetzalpetlatl there is evidence for lava flows emanating from the graben (Fig. 4b). The spatial association with the magmatic center of Jord Corona, extension from the higher to lower elevation, and the presence of lava flows at the lower ends of the graben all suggest that the graben of Enyo Fossae may represent the surface manifestations of dikes radiating away from the Jord (Ernst et al., 1995; Grosfils and Head, 1995, 1996). Cross-cutting relationships of the graben imply that the graben swarm of Enyo Fossae formed late in the geologic history, synchronously with emplacement of the upper unit of lobate plains.

Kalaipahoa Linea represents a zone of densely packed broad (several km wide) fractures and graben which sometimes form an anastomosing pattern. The zone runs in the ENE direction for about 2200 km along the crest area of a broad and low topographic ridge in the transitional zone between Lada Terra and Lavinia Planitia (Fig. 1). At Eithinoha Corona (~57.0°S, 7.5°E) the zone of graben and fractures turns to the NE and continues to follow the edge of Lada Terra (Baer et al., 1994). Structures of the Kalaipahoa rift zone cut the lower unit of lobate plains (unit pl_1) and appear to be embayed by the upper unit of the plains (unit pl_2).

Three more zones of extensional structures converge at the center of the Lada rise (Fig. 5). The arrangement of these zones around the rise resembles a triple junction of rifts, as seen in Beta and Atla Regiones (Stofan et al., 1989; Senske et al., 1991; Basilevsky, 2008), and suggests that the zones probably relate to the formation of the rise. The southwestern zone (SW in Fig. 5) is within a stratigraphic window embayed by the upper unit of lobate plains (Cavillaca and Juturna Fluctūs). Relatively old smooth plains are exposed within the window and are cut by the structures of the rift zone. To the east of the SW zone within the lava flows of Juturna Fluctus, there is a swarm of narrow fractures that cuts the flows, are parallel to the structures of the

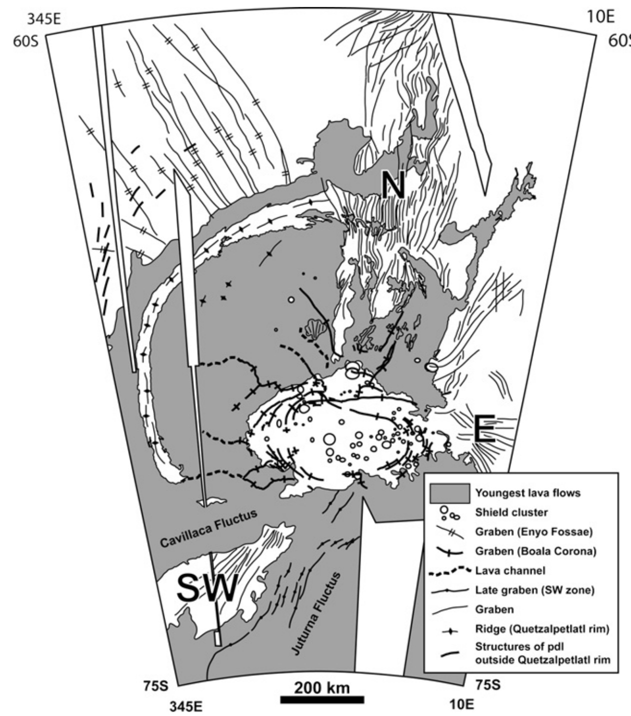

Fig. 5. Sketch map of the major structures and structural zones around the Lada rise. The two most prominent zones of extension dominate the southwestern (SW zone) and northern (N zone) flanks of the rise and converge to its center. There is perhaps an additional zone of extension to the east of the summit of the rise (E zone) but it is largely covered by young volcanic plains. Contractional structures (ridges) form the rim of Quetzalpetlatl along the northwestern base of the Lada rise. Map is in Lambert azimuthal equal-area projection.

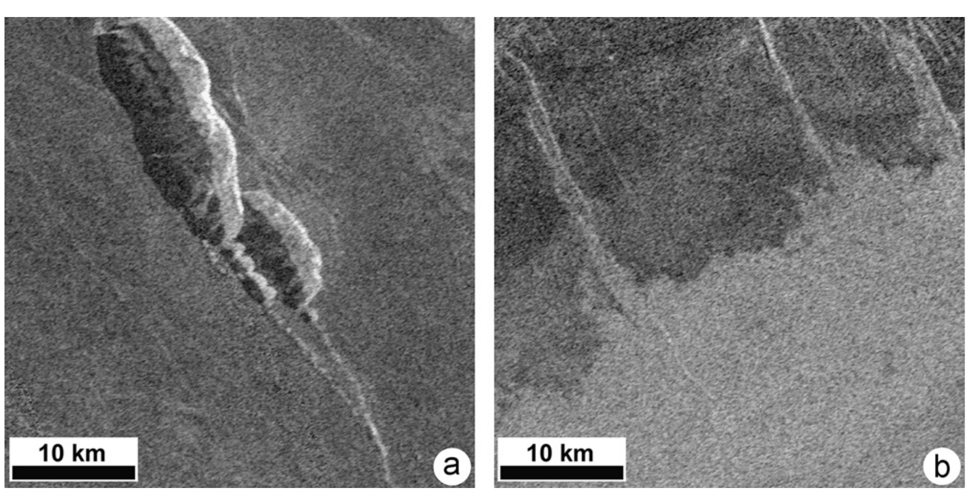

Fig. 4. (a) The topographically upper end of Enyo Fossae is often represented by elongated, flat-floored, and steep-sided depressions with scalloped edges. The topographically lower parts of the depressions are usually narrower and are connected with narrow graben. Chains of rimless pits often occur in the transition from the depression to graben, fragment of F-MIDR_60s355, center of the image is at 60.5°S, 351.6°E. (b) The topographically lower end of Enyo Fossae: where the graben approach the moat of Quetzalpetlatl Corona, radar-bright flows appear to emanate from the graben, extend down slope, and spread out onto the floor of the moat, fragment of F-MIDR_65s354, center of the image is at 62.5°S, 353.7°E.

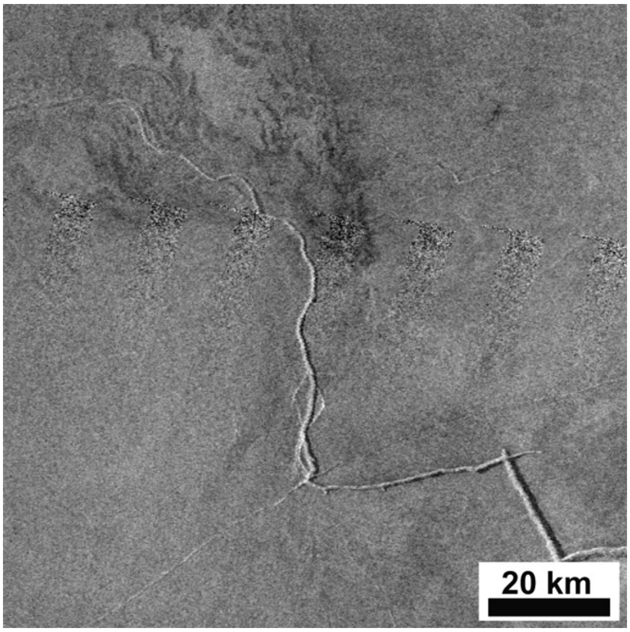

Fig. 6. An example of a lava channel emanating from a linear graben on the NW slope of the rim of Boala Corona. The channel cuts the youngest lava plains and flows that make up flanks of the Lada rise, fragment of C1-MIDR_75s338, center of the image is at 68.2°S, 353.5°E.

SW swarm, and appear to continue its trend (Fig. 5). The graben within the younger plains are much less abundant and may provide evidence that the peak of tectonic activity within the SW zone predated emplacement of the youngest material units. The northern zone (N in Fig. 5) appears as a branch of the Kalaipahoa rift that connects Quetzalpetlatl and Eithinoha Coronae. Structures of the northern zone cut the lower unit of lobate plains (pl_1) and are embayed by the upper unit of the plains (pl_2). The eastern zone (E in Fig. 5) is much less prominent and shorter than the other two because it is largely embayed by flows of the upper unit of lobate plains. Structures of the eastern zone appear to cut materials of smooth plains that are exposed eastward of Boala Corona. Thus the stratigraphic position of the eastern zone of graben seems to be similar to the position of the SW zone.

A set of several arc-like and arcuate graben encircles Boala Corona (Fig. 5). The graben are wide (up to several km) and produce a concentric pattern around the center of Boala. Less frequently, graben are radial and lava channels begin at the distal ends of some of them (Fig. 6) suggesting an association with subsurface dikes (Grosfils and Head, 1995, 1996; Ernst and Buchan, 1997). The concentric and radial graben and the channels are among the youngest structures and postdate the flows of Cavillaca and Juturna Fluctūs (unit pl_2).

3. Correlation of stratigraphy and topography in the western Lada Terra

The data on the global altimetry collected during Pioneer-Venus and Magellan missions (Pettengill et al., 1980; Ford and Pettengill, 1992) show that three principal topographic provinces characterize the surface of the planet (Masursky et al., 1980). Lowlands (below 0 km) make up ~11% of the surface and form equidimensional basins and elongated depressions thousands of kilometers across. Midlands, which is the most widespread province constitute about 80% of the surface of Venus, occur at elevations between 0 and 2 km, and host the richest variety of terrains, units, and structures. Highlands are above 2 km and comprise ~9% of the surface. They include two distinct classes of features that are thousands of kilometers across: (1) relatively steep-sided and plateau-like regions, the surface of which is typically made up of tessera (e.g., Ovda Regio and Fortuna Tessera) and (2) dome-shaped rises (Sjogren et al., 1983; Smrekar et al., 1997). Some of the rises are rifted and topped by large volcanoes (e.g., Atla Regio, western Eistla Regio) while others show little evidence for rifting and have large coronae associated with them (e.g., Eistla Regio, Fig. 7). The rises appear to be compensated at deep levels, hundreds of kilometers, suggesting their dynamical support by active mantle upwelling (e.g., Smrekar, 1994; Stofan and Smrekar, 2005). In Smrekar and Stofan (1999) it is suggested that the rifted and volcano-dominated rises (such as Beta Regio, for example) are related to deep mantle plumes rising from the core–mantle boundary. The corona-dominated rises, in contrast, may have been formed due to a series of smaller and shallower upwellings rising from the upper/lower mantle discontinuity.

3.1. *The Lada rise*

The major portion of Lada Terra belongs to the midlands and is surrounded from the north by the broad lowland of Lavinia Planitia (Fig. 1b). The most prominent topographic feature of Lada

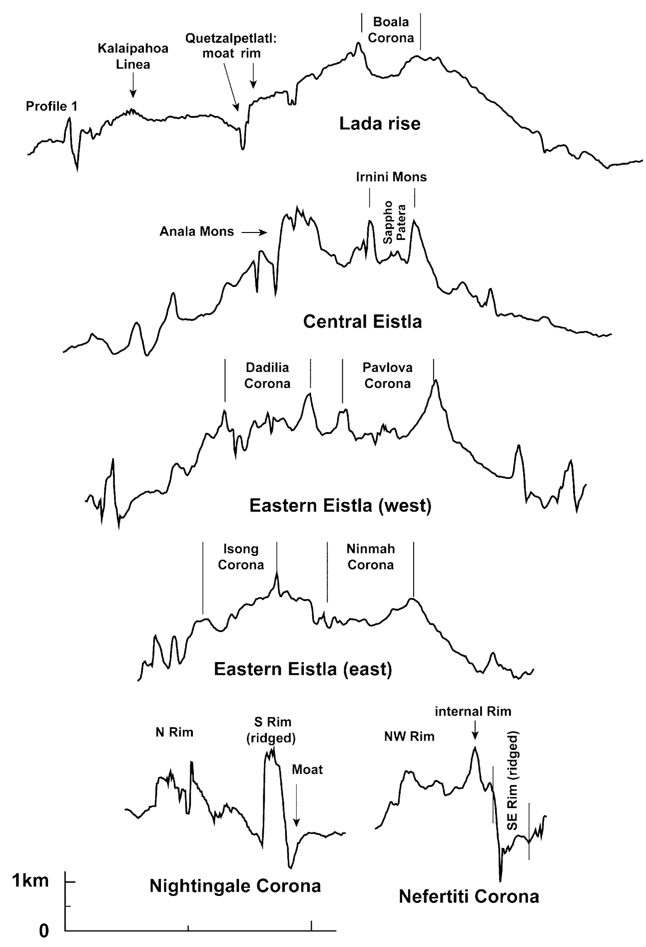

Fig. 7. A series of topographic profiles illustrating the major topographic characteristics of the Lada rise in comparison with the other corona-dominated rises on Venus and two large coronae (Nightingale and Nefertiti Coronae). The coronae, like Quetzalpetlatl Corona, display a prominent rim and a moat. See Fig. 1a for the position of profile 1. Here and for all other profiles, the topographical data are from the gridded Magellan topography with the resolution ~4.6 km/px.

Terra is a large (~1500 km across) dome-shaped rise, the summit of which reaches an elevation of ~2.5–3 km. By its dimensions and the overall topographic configuration, the Lada rise clearly falls into the category of the corona-dominated rises (Stofan et al., 1995; Smrekar et al., 1997; Smrekar and Stofan, 1999) (Fig. 7). In contrast, the Lada rise displays the presence of both rift-like zones (SW and N zones, Fig. 5) and nested coronae (Quetzalpetlatl and Boala), which makes it somewhat unique among the other corona-dominated rises. The overall topography of the rise is illustrated by a regional topographic profile that crosses the northern edge of Lavinia and the central portion of Lada from the N to the S (Fig. 7). In this profile, the rise appears as a broad asymmetric feature (gentle dome) ~1900 km wide with a steeper southern flank (~0.16°) and shallower northern flank (~0.10°). The maximum height of the rise is ~2.8 km. The overall aspect ratio of the low-frequency topography (wavelength corresponds to the dimension of the rises) for the Lada rise (~0.88, the ratio is multiplied by 1000) is in the range of these values typical of the other rises (from ~0.82 for the central portion of Eistla to ~0.94 for the western portion of eastern Eistla). The aspect ratios of the rises are significantly smaller than those characterizing large volcanoes on top or near the domes (e.g., ~4 for Anala Mons on top of eastern Eistla). The large volcanoes are clearly short-wavelength structures the relative steepness of which may be because they are mostly volcanic constructs.

3.2. *Cocomama tessera*

Cocomama Tessera (Fig. 1a) is a medium-sized elongated tessera massif (Ivanov and Head, 1996) to the northeast of the Lada rise that is heavily embayed by all types of lava plains including the relatively old shield plains (Fig. 1c). About half of the tessera (its northern portion) lie within relatively flat midlands of Lada Terra while the southern half of Cocomama is within the Lada rise (compare Figs. 1b and c).

The topographic profile along Cocomama Tessera displays two different portions of the tessera (Fig. 8). To the north of ~62°S (corresponds to ~800 km in the profile), Cocomama is represented by plateau-like, steep-sided massifs with very rough topography embayed by relatively old units such as regional plains and shield plains. Median elevations of these massifs are clustered around a value ~1.2 km (Fig. 8). We used a median estimate of the elevation instead of the mean because the median is much less sensitive to large short wave topographic variations that characterize tessera. These variations also may be related to likely errors in the radar topography data within topographically rough terrain such as tessera. This median value for the tessera is ~0.4 km larger than the median elevation of the plains embaying the northern half of the tessera (Fig. 8). To the south of ~62°S (within the Lada rise) the tessera is heavily embayed by lobate plains (units pl_1 and pl_2) and distinctly tilted (~0.2° at ~400 km baseline), appears much smoother, and has no steep bounding scarps such as those that characterize the rest of Cocomama outside the rise. The smoothness of the surface (the absence of deep troughs) and lack of the scarps are most likely due to flooding of the tessera by lobate plains.

The stratigraphic position and topographic configuration of Cocomama Tessera provides the possibility to estimate both the amplitude of uplift of the Lada rise and the thickness of the youngest lava material on slopes of the rise. Under the assumption that initially the surface of the tessera was approximately horizontal (as is observed in the northern segment of the tessera) the uplift magnitude is estimated to be ~2 km (Fig. 8) The absence of a topographic difference between the tessera surface and the embaying lava flows for the tilted segment of the tessera suggests that the minimum thickness of flooding lavas on the flanks of the rise is about 0.4 km (the difference between the median elevations of the tessera and plains surface outside the rise).

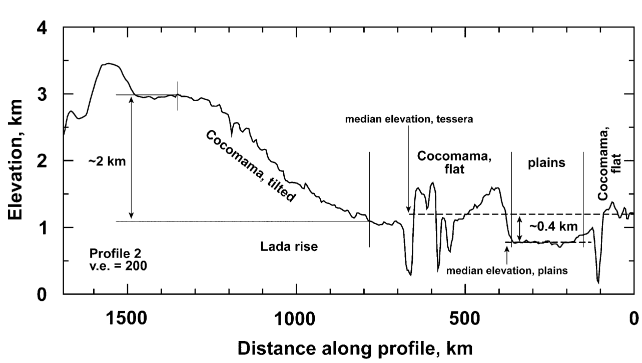

Fig. 8. A topographic profile along the Cocomama Tessera shows that the tessera consists of two parts. The northern part (from the beginning of the profile to ~800 km) is horizontal with large variations of relief. The difference between the median elevations of the tessera and the surrounding plains is ~400 m. The southern part of the tessera is tilted toward the summit of the Lada rise. This portion of the tessera demonstrates much smaller variations of relief. See Fig. 1a for the position of the profile.

3.3. *Quetzalpetlatl corona*

3.3.1. *Ridged rim and moat*

The rim and the moat are paired topographic features that form a large arc and define the most prominent western and northern portions of Quetzalpetlatl Corona. The rim of the corona encircles the northwestern third of the base of the Lada rise (Fig. 1a and b). Although prominent morphologically, the rim systematically has little topographic signature from the inside of the corona where it is heavily flooded by material of unit pl_2. From the outside, the rim in places is about several hundred meters high (up to 800 m) and its surface is tilted toward the moat (Fig. 9). Such a topographic asymmetry of the rim may be explained by the preferential flooding of the rim by young lava flows inside the corona. If the rim of Quetzalpetlatl Corona was initially a symmetric structure as it is suggested by the topographic configuration of rims of the other coronae (Fig. 7), then the thickness of lavas inside the corona near the topographic barrier of the rim should be many hundreds of meters. The stratigraphic window, in which the lower unit of regional plains (rp_1) embays the rim, represents a gentle topographic ridge ~300 m high and 150 km across (Fig. 9) that continues the trend of the ridged rim to the south.

The moat is a broad (100–150 km between the major breaks of slopes on both sides) and relatively shallow depression (~350–400 m for the most of it) that displays an additional narrower (a few tens of km) and deeper trench (Fig. 9). The moat begins at the western side of Quetzalpetlatl near the stratigraphic window and continues as a broad arc along the outer edge of the entire ridged rim to the area where the northern zone of extensional structures crosses the corona. The lower unit of regional plains (rp_1) makes up broad areas on flanks of the Lada rise to the west of the moat. To the east of it, regional plains are seen within the stratigraphic window at the edge of Quetzalpetlatl Corona (Figs. 3c and 9). This pattern of the exposures of the plains suggests that the moat did not control the distribution of the lower unit of regional plains.

The surface of the lower unit of lobate plains (pl_1) outside of the moat is almost horizontal but it is tilted downward within the moat (Fig. 10). The upper unit of lobate plains (pl_2) covers the majority of the surface within the moat and the internal trench

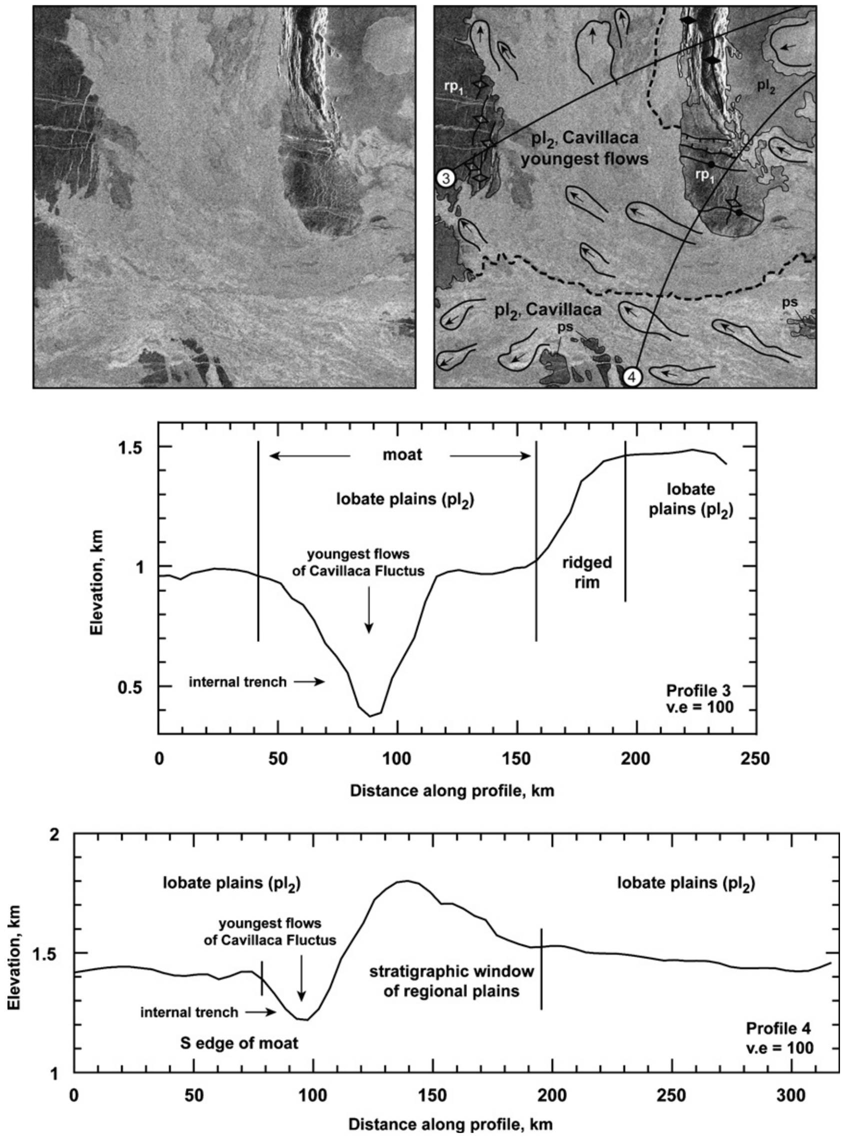

Fig. 9. The distribution of the youngest lava flows and the topographic configuration of the southern portion of the rim and moat of Quetzalpetlatl Corona. The rim (upper portion of the map) is a prominent morphologic feature but it has little topographic expression and its surface is tilted toward the rim (profile 3). The narrower and deeper internal trench within the moat controls the distribution of the youngest flows of Cavillaca Fluctus (map, profiles 3 and 4). The exposure of the lower unit of regional plains (rp_1) within a stratigraphic window at the southern edge of the rim (map) represents a prominent topographic ridge several hundred meters high (profile 4). Map: fragment of C1-MIDR_75s338, center of the image is at 70.3°S, 345.8°E. See Fig. 1a for the position of the profile.

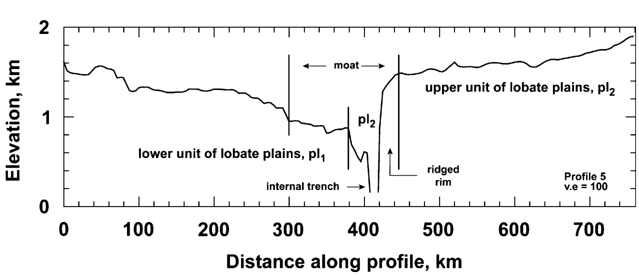

Fig. 10. A topographic profile across the moat of Quetzalpetlatl Corona. The surface of the lower unit of lobate plains (pl_1) outside of the moat is roughly horizontal and it is tilted downward within the moat. The upper unit of lobate plains (pl_2) fills the internal trench within the moat. See Fig. 1a for the position of the profile.

clearly controlled the distribution of the youngest lava flows of the unit pl_2 (Figs. 9 and 10). The topographic position and pattern of the spatial distribution of lobate plains (pl_1 and pl_2) suggest that the current topographic configuration of the moat began (or continued) to form subsequent to the emplacement of the lower unit of lobate plains.

3.3.2. *Radial zones of extensional structures*

Three radial zones of fractures and graben converge at the center of the Lada rise (Fig. 5). The southwestern and northern zones are the most prominent both morphologically and topographically and appear to form a large continuous belt of extensional structures that crosses the center of Quetzalpetlatl Corona and the Lada rise.

The southwestern zone is within a stratigraphic window where relatively old units such as smooth plains (ps) that predate emplacement of lobate plains are exposed (Fig. 1c). The surface of the window forms a broad (~200 km across) and relatively high (~900 m) ridge (Fig. 11a) and represents a kipuka heavily embayed by the younger flows of Cavillaca and Juturna Fluctūs. The northern zone represents a heavily deformed terrain that consists of numerous extensional structures that cut the ridged

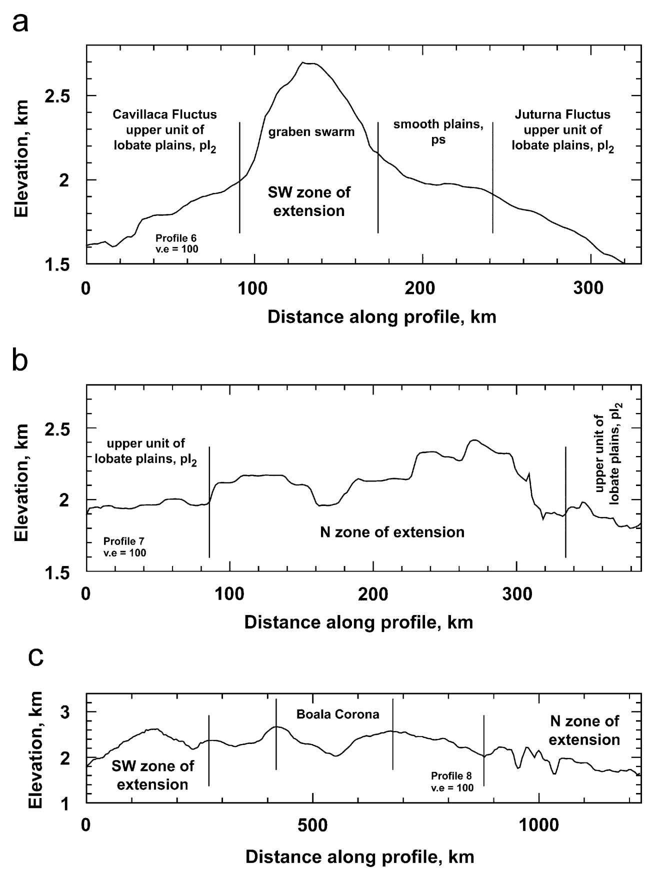

Fig. 11. A series of topographic profiles across (a, b) and along (c) the zones of extension at the SW and N flanks of the Lada rise. (a) The SW zone (profile 6) has a significant relief probably inherited from the older ridge belt on which the zone is superposed. (b) The northern zone (profile 7) displays more subdued topography and consists of flat-topped ridges and box-shaped troughs. (c) Both zones follow the general shape of the Lada rise but the SW zone peaks almost as high as the rim of Boala Corona on top of the rise. See Fig. 1a for the position of the profiles.

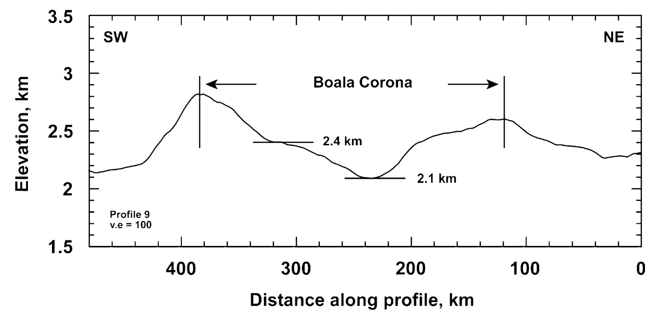

Fig. 12. A topographic profile across Boala Corona. The corona is a shallow depression surrounded by a gentle rim. The break in slope at the SW internal slope of the rim (~2.4 km) corresponds to the elevation at which the upper group of lava channels occurs at the outer slopes of the corona. The floor of Boala (~2.1 km) is at about the same level as the lower group of channels on the outer slopes of the corona. See Fig. 1a for the position of the profile.

rim of Quetzalpetlatl and deposits of the lower unit of lobate plains (unit pl_1) outside the corona. The younger lava flows (unit pl_2) embay structures of the northern zone inside and outside of the corona. In contrast to the southwestern zone, the northern zone is not prominent topographically and consists of flat-topped ridges and box-shaped troughs distributed within a broad (200–250 km) zone of deformation (Fig. 11b).

In the longitudinal profile along the trend of both zones (Fig. 11c), the southwestern zone represents a tall topographic ridge that displays significant relief peaking almost at the same elevation as the rim of Boala Corona on top of the Lada rise. The heavily disrupted northern zone is significantly lower and coincides with the general topographic trend of the flanks of the Lada Terra rise. The southwestern zone of extensional structures is complicated by the presence of an older ridge belt (Amitolane Dorsa, Fig. 1a), the formation of which predated emplacement of the lower unit of regional plains. Contractional structures of the belt form a prominent topographic ridge ~100 km wide and ~300 m high oriented in NE direction. The elongated window of smooth plains deformed by extensional structures of the SW zone continues the strike of the ridge belt of Amitolane Dorsa toward the center of the Lada rise. The ridges of the belt are not seen within the window (they are probably flooded). The presence of the topographic anomaly of the ridge belt suggests that the topography of the SW zone may have been inherited from the older ridge belt and enhanced during formation of structures of the zone, which could explain the noticeable topographic difference between the southwestern and northern zones of extensional deformation (Fig. 11c).

3.3.3. *Boala corona*

Boala Corona crowns the summit of the Lada rise and represents an elongated depression ~350 × 250 km across. In contrast to many other coronae on Venus (Stofan et al., 1992; Crumpler and Aubele, 2000), Boala does not display a morphologically distinct rim. Three types of morphologic features indicate the presence of Boala Corona. The first is numerous lava flows (Cavillaca and Juturna Fluctūs are among them) that radiate away from the corona, which is apparently the source of the flows. The second is a cluster of small shields that occupy the corona floor. The third and the most prominent is the set of narrow (<1 km wide) and arcuate concentric and radial graben-like features that outline the floor of the corona (Fig. 5). Topographically, Boala is a shallow (~600–700 m deep) and asymmetric rimmed depression (Fig. 12). The prominent topographic rim outlines the western half of the corona and is absent on its eastern side (Fig. 1b). The rim has almost no morphologic expression (except for the arcuate graben) and topographically is a gentle feature ~0.5 km high and ~70–75 km wide bounded by distinct breaks in slope from the outside and inside of the corona. Around the rimmed side of Boala there are five radial graben (Fig. 5) at the distal end of which lava channels begin (Fig. 6). This suggests that the graben are the surface manifestation of dikes (Ernst et al., 1995; Grosfils and Head, 1995, 1996) (see also Fig. 4a and b). Two channels to the north of the corona begin at an elevation of ~2.5 km, which corresponds to the level of the rim base of Boala (Fig. 12). Three other channels to the west of Boala start at an elevation of ~2 km, which corresponds to the level of the deepest portion of the corona floor (Fig. 12).

4. Discussion: evolution of the central Lada Terra region

The Lada Terra rise, Quetzalpetlatl Corona, and Boala Corona represent the three main features of the western Lada region. They appear as coaxial structures, which is not typical for the corona-dominated rises on Venus (Stofan et al., 1995; Smrekar et al., 1997; Smrekar and Stofan, 1999; Jurdy and Stoddard, 2007). The coronae and the rise may represent a specific class of genetically related features or be the result of superposition of different processes. Consistent age relationships of units and structures and their specific topographic position allow reconstruction of both the general sequence of events and the major episodes in evolution of the principal structures in the region of central Lada Terra. The following questions can be addressed in our study. What appears to be the lower stratigraphic limit of the evolution of Quetzalpetlatl and Boala Coronae and the rise? Are the coronae and the rise close not only in space but also in time and do they represent sequential phases of evolution of a hotspot? Are these large-scale features independent of each other and do they display different and unrelated volcano-tectonic regimes? Did formation of the rise superpose on structural elements of Quetzalpetlatl Corona and reactivate them?

4.1. *Quetzalpetlatl corona*

The apparently oldest unit in the region, tessera, displays no features that may be interpreted as the evidence of the presence of Quetzalpetlatl before the tessera or during its formation (Fig. 13). The topographic characteristics of Cocomama Tessera (Fig. 8) are likely due to involvement of tessera terrain, which is the oldest unit in the region of our study, into formation of the Lada Terra rise. Small fragments of the next unit, densely lineated plains (pdl), occur mostly outside of Quetzalpetlatl and some of them appear to be arranged concentrically to the corona rim (Fig. 5). This may indicate that formation of Quetzalpetlatl affected the distribution of fragments of pdl and that the corona probably began to form either before or during emplacement of material of the unit pdl (Fig. 13).

The most prominent feature of Quetzalpetlatl Corona, the rim, is morphologically similar to ridge belts on the floor of Lavinia Planitia and to the southwest of the corona where the belts are embayed by shield plains and regional plains. The morphologically similar plains (the lower unit of regional plains, rp_1) occur in vast areas around the Lada rise and are also seen in stratigraphic windows adjacent to the outer edge of the rim that surrounds the NW sector of Quetzalpetlatl Corona. The morphological similarity and pattern of the regional and local areal distribution of the unit rp_1 suggests that the plains within the window also represent the lower unit of regional plains. If it is indeed the case, the ridged rim of Quetzalpetlatl formed as a morphological feature before emplacement of the unit rp_1. The plains in the window, however, make a prominent topographic ridge (Fig. 9) and probably were warped up after emplacement. This may be due to continuation of the development of the rim as a topographic feature that formed a broad arch. Emplacement of the unit rp_1 corresponds then to the waning stages of development of the rim of Quetzalpetlatl Corona (Fig. 13).

The moat is in close spatial association with the rim and forms with it a pair of structures that is a common feature of some coronae on Venus (Pronin and Stofan, 1990; Stofan and Head, 1990; Sandwell and Schubert, 1992; Smrekar and Stofan, 1997) (Fig. 7). This suggests that the moat at Quetzalpetlatl can also be a feature related to the formation of the corona. Exposures of the lower unit of regional plains (rp_1) are seen on both sides of the moat. To the west of it, the plains form background on flanks of the Lada rise and come to the outer edges of the moat. To the east of the moat, plains that we interpret as the lower unit of regional plains are exposed within the stratigraphic window at the continuation of the rim of Quetzalpetlatl. This pattern of the exposures of the plains suggests that the moat did not control their distribution near the corona and may not have existed at this time. Thus, the unit rp_1 may represent the lower stratigraphic limit of development of the moat and its formation was delayed relative to the rim.

The pattern of areal distribution of the units of lobate plains puts additional constraints on the history of the moat. The surface of the older unit of lobate plains (pl_1) outside of the moat is almost horizontal but it is tilted downward within the moat (Fig. 10). The upper unit of lobate plains (pl_2) covers the majority of the surface within the broader moat but the narrower internal trench clearly controls the distribution of the youngest lava flows of the unit pl_2 (Figs. 9 and 10). The topographic position and pattern of the spatial distribution of the younger volcanic plains (pl_1 and pl_2) suggest that the current topographic configuration of the moat began to form after emplacement of the lower unit of lobate plains and underwent more of its flexure (the internal trench) prior and may be during emplacement of the youngest lava flows of Cavillaca Fluctus.

4.2. *Evolution of the Lada rise*

The areal distribution and topographic configuration of units of different relative ages put constraints on the evolution of the Lada rise. The tilted portion of Cocomama Tessera strongly suggests that the rise formed after the tessera deformation. The geological mapping in the V-61 quadrangle (Ivanov and Head, 2006) showed that lava flows of the upper unit of regional plains (rp_2) are consistently oriented away from the elevated portions of the rise (Fig. 1a). This suggests that a broad topographic feature already existed there by the time of emplacement of this unit (Fig. 13). There is no evidence in the preserved stratigraphic record that can indicate more precisely when the rise began to form.

On the northern and southwestern flanks of the rise there are prominent zones of extensional structures (fractures and graben) that make a continuous belt passing through the center of the rise (Fig. 5). Association of zones of extensional structures with some large dome-shaped highlands is typical on Venus (Stofan et al.,

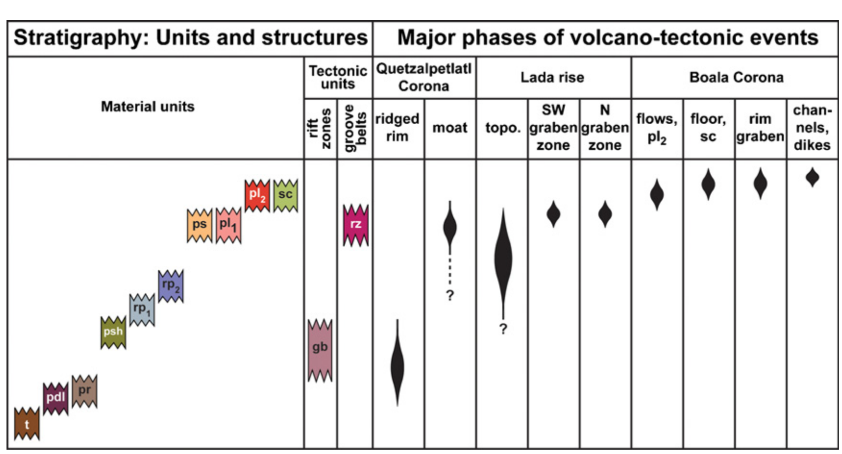

Fig. 13. Correlation chart of units and major volcanic and tectonic events for the Lada rise and its surroundings. See text for details.

1995; Stofan and Smrekar, 2005) and occurs on Earth (Baker et al., 1972; Rosendahl, 1987; Ebinger et al., 1997; Chorowicz, 2005). These zones are usually considered to be the result of the growth of the highlands (McGill et al., 1981; Senske et al., 1992; Stofan et al., 1995). The radial arrangement of the extensional zones relative to the center of the Lada rise suggests that these zones, as in other instances on Venus and Earth, are also related to the formation of the rise.

The southwestern zone is seen within a large stratigraphic window (Figs. 1c and 5) where smooth plains are exposed. Material of smooth plains embays wrinkle ridges and, thus, post-dates emplacement of both units of regional plains. The structures of the southwestern zone form a prominent belt and appear to form partly contemporaneously with smooth plains because they both cut and are embayed by the plains. These relationships indicate that the main episode of deformation on the south-western flank of the Lada rise began during emplacement of smooth plains (Fig. 13) and, thus, after emplacement of the upper unit of regional plains (rp_2). Because the distribution of flows of the unit rp_2 suggests the presence of the Lada rise at the time of emplacement of the unit, the deformation at its SW flank either started or began to override volcanic activity at relatively late stages in the evolution of the rise (Fig. 13).

The flows of the upper unit of lobate plains (pl_2) embay the graben of the SW zone, which means that the formation of extensional structures there waned by the time of emplacement of the unit pl_2. Within the flows of Juturna Fluctus on the southeastern and southern portions of the Lada rise, there is, however, a faint swarm of fractures within the flows of Juturna Fluctus that is parallel to the trend of the much more prominent SW zone (Fig. 5). The presence of the faint post-Juturna extensional structures near the southwestern zone implies that in the evolution of the Lada rise there was a later (and weaker, or diminishing) episode of fracturing at its SW flank.

The embayment and cross-cutting relationships strongly suggest that the northern extensional zone formed after emplacement of the lower unit of lobate plains (pl_1) and before deposition of materials of the upper unit of lobate plains (pl_2). There is little (if any) evidence that may help to establish the relative ages of smooth plains (ps) and the lower unit of lobate plains (pl_1). These two units postdate regional plains that are deformed by wrinkle ridges but can be broadly contemporaneous with each other and even represent different facies of the same volcanic episodes. Thus, the northern zone of extensional structures as well as its southwestern counterpart began either to form or dominate during the relatively late stages of evolution of the Lada rise but did not continue through the apparently latest stages of the evolution related to the emplacement of volcanic flows of the unit pl_2 (Fig. 13). Although the northern zone seems to be mostly tectonic by its nature, some of its graben appear as sources of lava flows and, thus, may be related to dikes propagating northward from the center of the Lada rise. The flows emanating from the graben embay structures of the northern zone and partly fill the internal trench inside the moat at the northwestern side of Quetzalpetlatl Corona. These relationships suggest that the interpreted dikes are related to the latest episodes of volcanism at the Lada rise.

The Lada rise is a major source of young lavas that almost completely buried many previous volcanic and tectonic features. The youngest lava flows of the upper unit of lobate plains (pl_2) form two major flow complexes of Cavillaca and Juturna Fluctūs. The flows of Juturna Fluctus cover the southern flank of the Lada Terra rise (Fig. 5) and the flows of Cavillaca Fluctus are concentrated between the SW zone of extensional structures and the rim of Quetzalpetlatl Corona (Figs. 1a and 5). These flows fill the moat and the internal trench within the moat controls the distribution of apparently the youngest flows of Cavillaca (Fig. 9). The flows of the Fluctūs extend along the actual topographic gradient on flanks of the Lada rise. This topographic distribution of the youngest flows implies that the major portion of the topography of the Lada rise was formed before emplacement of the youngest volcanic materials (Fig. 13). Thus, the main interval of the rise growth was probably confined in time between the lower unit of regional plains (rp_1) and the upper unit of lobate plains (pl_2) (Fig. 13) and largely postdated the formation of the ridged rim of Quetzalpetlatl Corona.

Morphologically, the flows of Cavillaca and Juturna Fluctūs appear to be almost identical (Fig. 14). There are no major observed differences between them in the recent Arecibo data (Kratter et al., 2007). In the area where the SW zone of extension separates the Fluctūs (Figs. 14 and 15a), however, the flows of Cavillaca are more prominent and appear to be superposed on the flows of Juturna. The southern portion of the Lada rise corresponds to the region where surface brightness anomalies were detected in the VIRTIS (Visible and Infrared Thermal Imaging Spectrometer on the ESA Venus Express spacecraft) data (Helbert et al., 2008). Three of the four anomalies described by Helbert et al. (2008) are shown in Fig. 15b. Cocomama Tessera displays

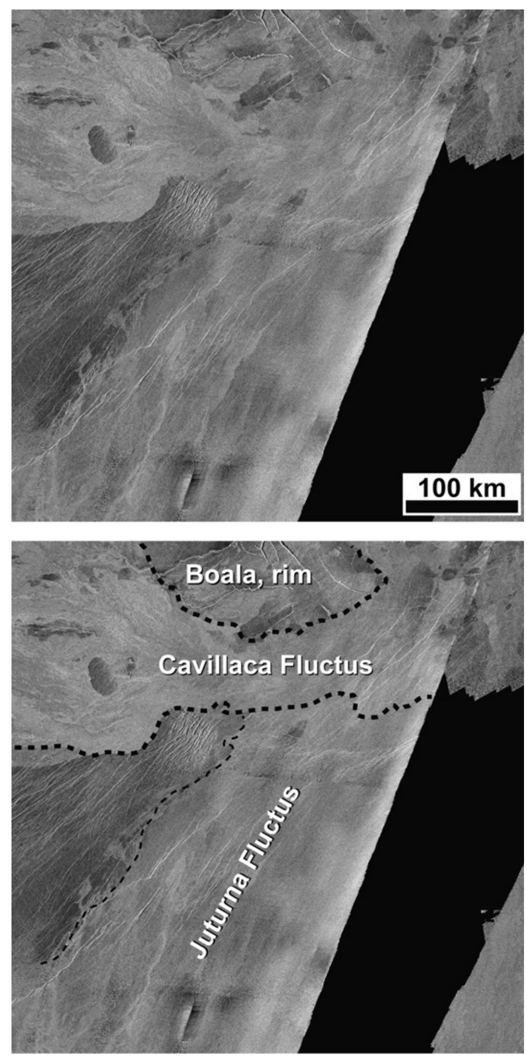

Fig. 14. The SW portion of the flank of the Lada rise where one of the VIRTIS anomalies associated with the Lada rise (Helbert et al., 2008) is located. The anomaly is in the southern portion of the image, within relatively old Juturna Fluctus. The younger flows of Cavillaca Fluctus do not show a VIRTIS anomaly. See Fig. 15 for details.

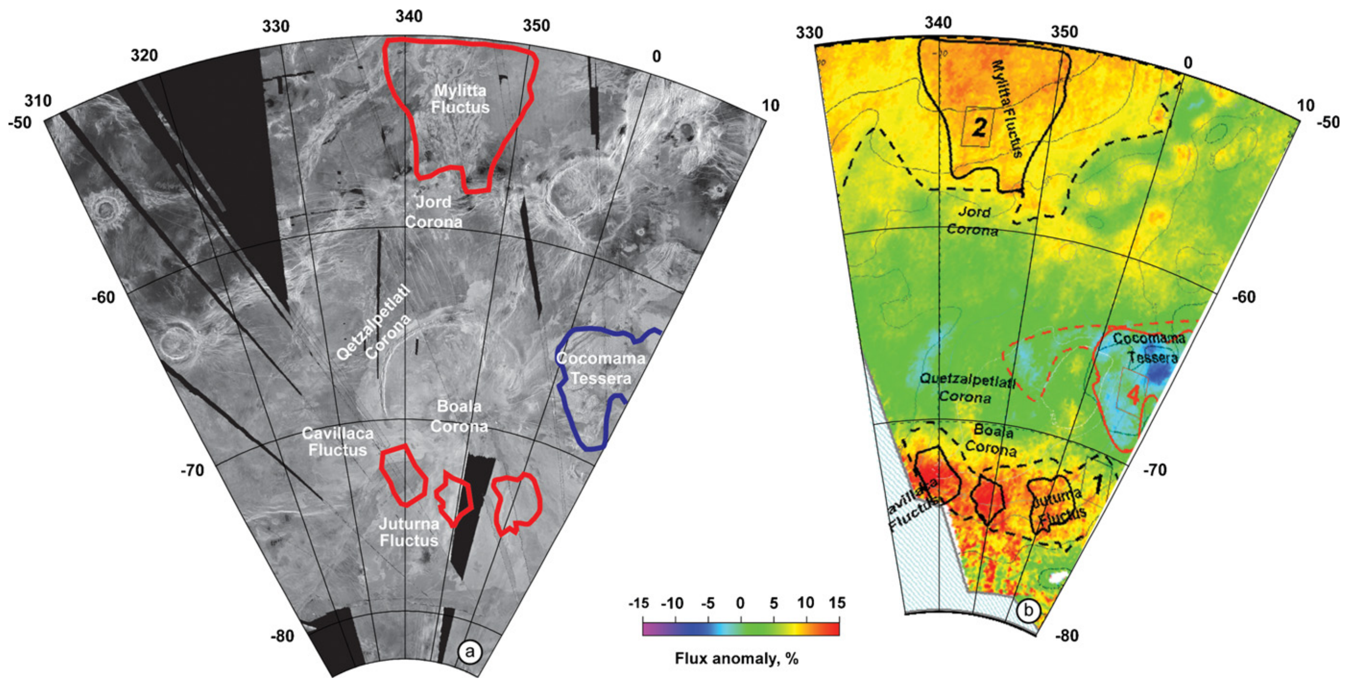

Fig. 15. Lada Terra/Quetzalpetlatl Corona area showing the location of the major geological features (a) and the variations in surface brightness in the 1.02 μm atmospheric window as observed by VIRTIS on the Venus Express mission. Outlined are three of the four areas identified by Helbert et al. (2008) as anomalous. Note that in Area 1, the left-hand high anomaly spans stratigraphic units of several different ages (compare to Figs. 1 and 14). Note that Juturna Fluctus in (b) is mis-located to the east in Helbert et al. (2008) based on current nomenclature usage [see (a) and Fig. 14 for current location]. Base map in (a) is the Magellan global mosaic, and the map in (b) is after Helbert et al. (2008), translated to the projection in (a) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

low values (4; blue in Fig. 15b), Quetzalpetlatl Corona displays intermediate values (green in Fig. 15b), Lavinia Planitia (surrounding Mylitta Fluctus, 2) displays intermediate to high values (yellow in Fig. 15b), Mylitta Fluctus itself displays somewhat higher values than its Lavinia Planitia surroundings (yellow-red in Fig. 15b), and the southern rim of Quetzalpetlatl Corona (1; orange to red in Fig. 15b) shows the highest values (three specific spots, including Cavillaca and Juturna Fluctūs); note that the feature called Juturna Fluctus in Fig. 15b is displaced to the east in the Helbert et al. (2008) paper, from its true location; compare Figs. 1a, 14, 15a and b. Helbert et al. (2008) proposed two different models to explain the anomalies: (1) an endogenic interpretation "considers that the brightness anomalies observed by VIRTIS are related to material of different composition deposited on the surface." (2) an exogenic interpretation relies on surface alteration by the Venus environment (chemical and/or mechanical weathering) to modify the surfaces of different units to a background average value; in this hypothesis, the younger (most recently emplaced) units would have had the least amount of time to undergo alteration and would thus be characterized by anomalously high surface brightness. Helbert et al. (2008) pointed to the distinctive properties of the different terrain types, ranging from tessera to several different types of flow units, and concluded that the endogenic hypothesis, in which brightness differences are linked to different surface compositions, was the more likely of the two. They pointed out, however, that with available data, both hypotheses could be supported.

In a recent paper, Smrekar et al. (2010) used variations in thermal emissivity of the surface of Venus measured by the VIRTIS on the ESA Venus Express spacecraft to identify and interpret high emissivity anomalies. These variations in emissivity are interpreted to be due to differences in "material compositions in the top few microns depth due to either primary compositional variation or alterations by surface weathering" (Smrekar et al., 2010). In their analysis, Smrekar et al. (2010) focused on areas of anomalously high emissivity associated with coronae, and volcanoes at nine hot spots associated with broad topographic rises between 65°N and S latitude, as discussed by Stofan et al. (1995); of the nine recognized hot spots, only three (Imdr, Themis and Dione) were imaged by VIRTIS, and at these hot spots the stratigraphically youngest flows have anomalously high emissivities.

Smrekar et al. (2010) discussed weathering processes of fresh surfaces on Venus and concluded that laboratory experiments on basalts under Venus conditions "point to very rapid weathering", leading to a pronounced decrease in emissivity, even flows with diverse elemental abundances, such as unusually high primary compositions of Ti, Fe or Mg. Smrekar et al. (2010) conclude that "All plausible interpretations of the high emissivity anomalies point to relatively recent volcanism." Thus, Smrekar et al. (2010) interpreted the high emissivity anomalies as indicating a lack of surface weathering, and therefore to represent deposits that were youthful in age, suggesting that the flows analyzed were "younger than 2.5 million years, and probably much younger, likely 250,000 years or less…" Thus, while Smrekar et al. (2010) favor the exogenic interpretation for the equatorial and mid-latitude anomalies, Helbert et al. (2008) favor the endogenic model for the southern high-latitude Lada/Quetzalpetlatl area anomalies.

Our analysis of the sequence of deposits in the Lada Terra Rise and Quetzalpetlatl Corona study area provide additional insight into endogenic and exogenic sources for VIRTIS anomalies. Lada Terra/Quetzalpetlatl is too far south to have been included in the Stofan et al. (1995) analysis of volcanoes at nine hot spots associated with broad topographic rises between 65°N and S latitude. Our new mapping permits us to reassess the analysis and interpretations of Helbert et al. (2008) and Smrekar et al. (2010). Returning to Fig. 15b, we see that within area 1 on the southern rim of Quetzalpetlatl Corona, the western area of highest surface brightness is made up of several units distributed throughout the stratigraphic column (Fig. 1c), including smooth plains, rifted materials and the upper unit of lobate plains. Furthermore, examination of Fig. 14 shows that the anomaly differs little as one crosses from materials of the rift zone and smooth plains into the older part of the upper unit of lobate plains (Juturna Fluctus) and then to the younger part of the upper unit of lobate plains (Cavillaca Fluctus). In summary, regional stratigraphic relationships strongly support different relative ages for these different units, despite the fact that the values of VIRTIS anomalies in the area are high for units occurring in different parts of the stratigraphic column. Indeed, unlike the examples cited in the Smrekar et al. (2010) analysis, the stratigraphically youngest of the units (Fig. 14) associated with this anomaly (Cavillaca Fluctus) lies on the margin of the anomaly, and at least part (to the north) of it is characterized by intermediate values. These data are interpreted to favor the endogenic model, consistent with the earlier interpretation of Helbert et al. (2008), rather than the exogenic model, in which the highest values are related to very young volcanism that has not had sufficient time to equilibrate with Venus atmospheric effects (Smrekar et al., 2010).

The very approximate estimates of the thickness of the upper member of lobate plains on flanks of the rise (e.g., around Cocomama Tessera) give a value of ~0.4–0.5 km. Assuming that the thickness of the unit pl_2 reaches its maximum on flanks of the rise and is pinched out toward its summit, we estimated the volume of this unit to be $\sim 0.3–0.4 \times 10^6$ km^3. Taking into account the large uncertainties in the determination of the thickness, this value represents an approximate estimate, the upper bound of which is the volume of the rise itself, $\sim 1 \times 10^6$ km^3. Thus, the volume of volcanic materials released during the final episodes of the rise formation is about three to four times smaller than the volume of the Columbia River basalts province (1.3×10^6 km^3) (Catchings and Mooney, 1988; Tolan et al., 1989; Coffin and Eldholm, 1994) and about two orders of magnitude smaller that the volume of the largest terrestrial igneous provinces such as Ontong Java ($36–76 \times 10^6$ km^3) (Coffin and Eldholm, 1994). Thus, the late volcanism at the Lada rise appears to be modest by terrestrial flood basalt standards (even if one assumes that the entire rise is a volcanic construct).

The latest episodes of volcanism (emplacement of the flows of Cavillaca and Juturna Fluctūs) were concentrated near the summit of the Lada rise and related to formation of Boala Corona. Boala Corona appears to be the source of the flows and a cluster of small shields (unit sc) populates the floor of the Corona (Fig. 3g). Small flow-like features emanate from the shields and there is no evidence for unit pl_2 on the floor. The shields may have formed due to the latest episodes of volcanic activity that was concentrated at the summit of the Lada rise and postdated emplacement of lobate plains on the flanks of the rise. Alternatively, both units, sc and pl_2, may have formed broadly contemporaneously, but at different sites (Fig. 13). In any case, emplacement of the small shields on the floor reflects a distinctly different style of volcanism that may be related to the depletion of the magma reservoir due to formation of lobate plains and a significant drop in the rate of magma supply.

The lava channels on the upper flanks of the Lada rise around Boala Corona postdate most of the youngest lava flows and appear to be sourced by graben radiating away from the corona. There appear to be two levels where the channels begin, ~2.4 and ~2.1 km elevation. The higher level corresponds to the inner base of the Boala rim and the lower level corresponds to the deepest portion of the floor of Boala (Fig. 12). The channels and their source graben may reflect variations in the depth of the reservoir and evolution of the neutral buoyancy zone (Head and Wilson, 1992; Wilson et al., 1992). They are among the youngest features of the Lada rise, small in scale, and rare. These features appear to be manifestations of the final stages of evolution of the rise (Fig. 13).

5. Conclusions

In summary, on the basis of geological mapping and stratigraphic relationships, the sequence of major events during the evolution of the western portion of Lada Terra is interpreted to be as follows:

(1) Formation of the ridged rim of Quetzalpetlatl Corona after tessera (Cocomama) and emplacement and deformation of material of densely lineated plains. The rim of Quetzalpetlatl is the most definitive feature of the corona (Stofan et al., 1992) and apparently formed near the beginning of the observable geologic history of western Lada Terra. Both the morphologic studies of coronae (Pronin and Stofan, 1990; Stofan et al., 1991, 1992) (see also Fig. 7) and a variety of models of coronae formation and evolution (Janes et al., 1992; Sandwell and Schubert, 1992; Squyres et al., 1992; Koch and Manga, 1996; Smrekar and Stofan, 1997) suggest that outer moats of coronae form in association with the rim. There is no evidence in the actual geological record of western Lada Terra suggesting the presence of the moat during evolution of Quetzalpetlatl Corona. In contrast to the rim, the moat, as a negative topographic feature, should be much more sensitive to filling by subsequent volcanism and, for example, could be filled during emplacement of regional plains. There is no evidence in the geological record for the presence of the Lada rise at the time of formation of the rim of Quetzalpetlatl.

(2) The lower unit of regional plains (rp_1) embays the rim of Quetzalpetlatl and indicates the end of formation of the short-wavelength ridges composing the rim. It, however, continued to develop as a broader topographic feature. At the southern end of the rim the rp_1 unit is seen as a broad (60–70 km wide, several hundred meters high) arch (Fig. 9).

(3) The extension of the flow-like features of the upper unit of regional plains (rp_2) away from the center of the Lada rise down the regional slope on the western flank of the rise suggests that there was a broad (probably dome-shaped) topographic feature at the time of emplacement of the unit rp_2. A regional network of pervasive wrinkle ridges deforms both units of regional plains.
Formation of Quetzalpetlatl Corona (~800 km in diameter) and the Lada rise (~2000 km in diameter) are separated in time and clearly have different sizes. The center of the rise (Boala Corona) is also offset 200–300 km southeast of the approximate center of Quetzalpetlatl. This suggests that Quetzalpetlatl Corona and the rise represent different phases and scales of evolution of a site of mantle upwelling.

(4) Both smooth plains (ps) and the lower unit of lobate plains (pl_1) lack structures of wrinkle ridges and, thus, postdate emplacement and deformation of regional plains.

(5) The radial zones of extension to the SE, NE (and maybe to the E) of the center of the Lada rise cut the units ps and pl_1. Formation of the extensional zones is interpreted to be a manifestation of the continued growth of the rise.

(6) The lower unit of lobate plains (pl_1) that is near horizontal outside of the moat is tilted down slope toward the Quetzalpetlatl rim inside of it. The moat also controls the distribution of the latest lava flows (Fig. 9). In the interior of Quetzalpetlatl, the ridged rim has little topographic expression (Figs. 9 and 10). This suggests that the younger volcanic materials inside the corona were ponded against the rim and their thickness there may be several hundred meters. The load of these lavas near the northwestern edge of Quetzalpetlatl may have caused additional flexure (reactivation) of the moat

(e.g., Sandwell and Schubert, 1992) that deflected the surface of the lower unit of lobate plains and controlled the distribution of the youngest lava flows.

(7) Emplacement of the upper unit of lobate plains (pl_2) on the flanks of the almost completed Lada rise (the most important flow complexes are Cavillaca and Juturna Fluctūs). The flows of the unit follow the actual topographic gradients on all flanks of the rise (Kratter et al., 2007). The very approximate estimates of the volume of the lavas of the upper unit of lobate plains is $\sim 0.3\text{–}0.4 \times 10^6$ km^3 and the upper limit for the amount of volcanic materials in the Lada rise is the volume of the rise itself, $\sim 1 \times 10^6$ km^3. The late volcanism at the Lada rise appears to be modest by terrestrial flood basalt standards even if the entire rise is a volcanic construct (Columbia River: 1.3×10^6 km^3; Ontong Java: $36\text{–}76 \times 10^6$ km^3 (e.g., Coffin and Eldholm, 1994)).
Helbert et al. (2008) proposed two interpretations for the brightness anomalies seen by VIRTIS: (1) An endogenic interpretation, in which the anomalies are related to material of different composition deposited on the surface and (2) an exogenic interpretation in which the anomalies are due to a lesser degree of chemical or mechanical weathering of younger surface materials. Helbert et al. (2008) favored the first interpretation. Our data show that the high values in this area span a range of units of different stratigraphic age. This favors the endogenic model in which differences in the compositions of the units are the primary factor in the formation of the VIRTISy anomalies (Helbert et al., 2008); in contrast, Smrekar et al. (2010) interpreted VIRTIS anomalies found at other volcanic rises to be due to exogenic factors and to represent extremely young volcanism.

(8) Boala Corona formed at the very summit of the Lada rise but is offset from the center of Quetzalpetlatl Corona. Boala seems to be the source of the flows of the upper unit of lobate plains and on the basis of its topographic configuration resembles a sagging caldera. Formation of Boala is a manifestation of the latest episodes of evolution of the Lada rise (emplacement of a cluster of shields on the floor of Boala and formation of sparse concentric and radial graben at the rim of the corona).

The combination of features associated with the Lada rise (large coronae and broad rise) and their age relationships suggest that the western Lada Terra represents a site of long lasted mantle thermal upwellings. The signs of their activity can be traced from recent geological times almost back to the beginning of the visible geologic history of Venus. We see no evidence that the culmination of this process results in tessera formation. Rather, Cocomama Tessera predates the rise and was tilted and deformed during its formation.

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