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Model of formation of Ishtar Terra, Venus

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Abstract. For more than a decade, the radar mapping of Venus' surface has revealed that it results from a complex volcanic and tectonic history, especially in the northern latitudes. Ishtar Terra (0 E–62 E) consists of a high plateau, Lakshmi Planum, surrounded by highlands, Freyja Montes to the north and Maxwell Montes to the east. The latter is the highest relief of Venus, standing more than 10 km in elevation. The high resolution of Magellan radar images (120–300 m) allows us to interpret them in terms of tectonics and propose a model of formation for the central part of Ishtar Terra. The detailed tectonic interpretations are based on detailed structural and geologic cartography. The geologic history of Ishtar Terra resulted from two distinct, opposite tectonic stages with an important, transitional volcanic activity. First, Lakshmi Planum, the oldest part of Ishtar Terra is an extensive and complexly fractured plateau that can be compared to a terrestrial craton. Then the plateau is partially covered by fluid lava flows that may be similar to Deccan traps, in India. Second, after the extensional deformation of Lakshmi Planum and its volcanic activity, Freyja and Maxwell Montes formed by WSW–ENE horizontal crustal shortening. The latter produced a series of NNW–SSE parallel, sinuous, folds and imbricated structures that overlapped Lakshmi Planum westward. So these mountain belts have the same structural characteristics as terrestrial fold-and-thrust belts. These mountain belts also display evidence of a late volcanic stage and a subsequent period of relaxation that created grabens parallel to the highland trend, especially in Maxwell Montes. Copyright © 1996 Elsevier Science Ltd

Introduction

In northern latitudes, a widespread area, Ishtar Terra is one of two predominant topographic highlands on Venus. Based on radar altimetry data obtained both by Pioneer Venus orbiter and Magellan orbiter (Masursky *et al.*, 1980; Saunders and Pettengill, 1991; Saunders *et al.*, 1992; Ford and Pettengill, 1992), Ishtar Terra consists of a high plateau, Lakshmi Planum, standing at 4 km in elevation surrounded by four highlands, e.g. Danu Montes to the southwest, Akna Montes to the northwest, Freyja Montes to the north, and Maxwell Montes to the east. The latter is the highest with an elevation reaching more than 10 km above the mean planetary radius.

The radar images obtained by radar orbiters, e.g. Venera 15–16 in 1983–1984 and Magellan, eight years later (Alexandrov *et al.*, 1985; Basilevsky *et al.*, 1986; Saunders *et al.*, 1991) display that Ishtar Terra's surface is characterized by volcanic features especially on Lakshmi Planum and areas of intensively wrinkled, complexly deformed crust located on highlands. Owing to the correlation between their high topography and the intensity of their surface deformation, the four highlands surrounding Lakshmi Planum are interpreted as mountain belts resulting from horizontal shortening of the crust and the lithosphere produced by large-scale compression (Campbell *et al.*, 1983; Barsukov *et al.*, 1986; Basilevsky, 1986; Basilevsky *et al.*, 1986; Crumpler *et al.*, 1986; Pronin, 1986; Vorder Bruegge and Head, 1989, 1991; Bindschadler and Parmentier, 1990; Grimm and Phillips, 1990; Roberts and Head, 1990; Solomon *et al.*, 1991, 1992; Kaula *et al.*, 1992; Ansan, 1993; Ansan *et al.*, 1994, 1995; Keep and Hansen, 1994).

Here, we present the detailed geologic and structural interpretations of the central part of Ishtar Terra including eastern Lakshmi Planum, Maxwell Montes and Freyja Montes (Fig. 1). This study was performed with classic methods of image interpretation, based on nine Magellan full-resolution radar images obtained during the first cycle of radar coverage (F-MIDRPs 75N332, 75N351, 70N339, 70N007, 65N342, 65N354, 65N006, 60N355 and 60N005) and Magellan altimetry. Tectonic structures, their distribution, and their superposition and/or cross-cutting relationships allow us to determine the geologic history of central Ishtar Terra (Ansan, 1993; Ansan *et al.*, 1994,

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1995). These tectonic structures result from both vertical and horizontal motions of the Venusian crust from which a kinematic model is proposed at the regional scale.

Data and method

During the first cycle of Magellan radar coverage (1990), the Venusian surface has been scanned with a radar beam oriented approximately to the east. Owing to the elliptical, nearly polar orbit of the Magellan probe, the incidence angle and the image resolution decreased with latitude (Ford *et al.*, 1989, 1993; Saunders *et al.*, 1993). At latitudes between 77°N and 60°N, the incidence angle was close to 25° and the cross-track (E–W) ground resolution was about 300 m (Saunders *et al.*, 1992). Each Magellan full-resolution radar image covers an area of approximately $500 \times 500\,\mathrm{km}^2$ and is in a sinusoidal equal area projection.

Classic methods of image interpretation are used with some precautions in respect to image type, in order to establish a geologic and structural map. Indeed, the radar image is a 2-D surface representation where the brightness is the response of the electromagnetic wave interaction with the ground. Consequently, it depends on (1) the incident wave characteristics, e.g. wavelength, polarization, (2) illumination geometry, e.g. radar beam orientation, incidence angle, and (3) the surface characteristics, e.g. topography, surface roughness in relation to wavelength, and dielectric properties of the surface materials. The predominant effect on the brightness amplitude is the topography. Areas facing the radar beam appear bright, whereas areas opposite to the radar beam appear dark. In some cases, the effect can induce great geometric distorsion on the observed features (foreshortening or layover).

With these cautions, the geometric shape of illuminated features can be correlated to geologic features based on the surface contrasts on the radar image. Furthermore, owing to the low erosion rate on Venus (Krasnopolsky and Parshev, 1983; Avduevshiy *et al.*, 1983; Zolotov and Volkov, 1992), geologic processes including impact cratering, volcanism and tectonics seem to be responsible for the morphology of the actual Venusian surface. A geologic and structural map is then established on which impact craters, volcanoes, folds, and faults are reported. Relative chronology between these different geologic units can be inferred from superposition and/or cross-cutting relationships. Then, based on the type, the orientation and the distribution of structural features, the type and the style of crustal deformation are determined. Image interpretations are supported by Magellan altimetric data, although the horizontal resolution of altimetric data is not the same as that of radar images, i.e. in global topographic map from Magellan altimetry, the pixel size is equal to $\sim 5 \times 5$ km, whereas it is equal to 75×75 m in radar images (Pettengill *et al.*, 1991; Ford *et al.*, 1993). Consequently, altimetry data provide broad topographic information of the surface but do not have high enough horizontal resolution for the determination of heights of individual tectonic structures.

Geologic and structural interpretations

With Magellan full-resolution radar images, major geologic and structural features such as volcanoes, impact craters, folds and faults can be identified and mapped at 100 m scale. Here, we report the major geologic and structural results characterizing the high plateau, Lakshmi Planum, and the surrounding highlands, Maxwell Montes and Freyja Montes.

Lakshmi Planum

Lakshmi Planum is a 4 km high plateau characterized by a radar-dark surface on which several 1–2 km raised blocks are observed especially in the northern boundary of Lakshmi Planum (Fig. 1). Lakshmi Planum is 2000 km long E–W and 1500 km wide N–S. The full-resolution radar image, F-MIDRP.65N-354, located in the eastern part of Lakshmi Planum shows the different geologic units in detail (Fig. 2). Blocks, marked by abrupt brightness changes, are characterized by a mosaic of intersecting ridges and troughs. Troughs are linear, limited by a flat radar-dark floor and a pair of parallel scarps hundreds of metres high. The west facing scarps are outlined by a relatively bright line whereas the opposite scarps appear with a dark line. Owing to their geometry, scarps seem to be fault-controlled, and the formation of troughs would be due to normal faulting of these scarps. Hence, troughs are interpreted as grabens that bound rectangular horsts (Fig. 2b, box 1).

The orientation and distribution of grabens are not randomly arranged. Three networks of grabens are observed, NW–SE, NE–SW, and N–S, that are regularly arranged whatever observed blocks. Their geometry resembles that of a chocolate slab. Consequently, these blocks formed during an intense extensional deformation. Owing to their regular distribution at large scale (1000 km), this terrain could be compared to terrestrial continental regions submitted to lithospheric extension.

Grabens display a radar-dark flat floor, as if they are filled by the same material that covers Lakshmi Planum (Fig. 2a). As this material covers a relatively flat surface, its low radar backscatter would be due to surface textural characteristics. This material is then characterized by a fine-grained surface in relation to 12.6 cm radar wavelength (Saunders *et al.*, 1992). Owing to characteristics of radar backscatter, reflectivity and emissivity, and as well as geologic correlation as the presence of a great volcano, Sacajawea Patera located at 64°N–336°E, this material could be interpreted as volcanic in origin. However, this volcanic material could outcrop similarly to flood basalt flows observed in several terrestrial continental areas such as Deccan traps, in India, because it covers a widespread area of Lakshmi Planum.

The lava flows are crosscut by a network of NNW–SSE linear troughs extending over 100 km (Fig. 2, lower part). These 5 km wide troughs are bounded by two parallel lobate scarps, which suggests that they did not form by tectonic processes, but rather by dike emplacement (McKenzie *et al.*, 1992). However, the orientation of troughs had to be controlled by the basement fracturation.

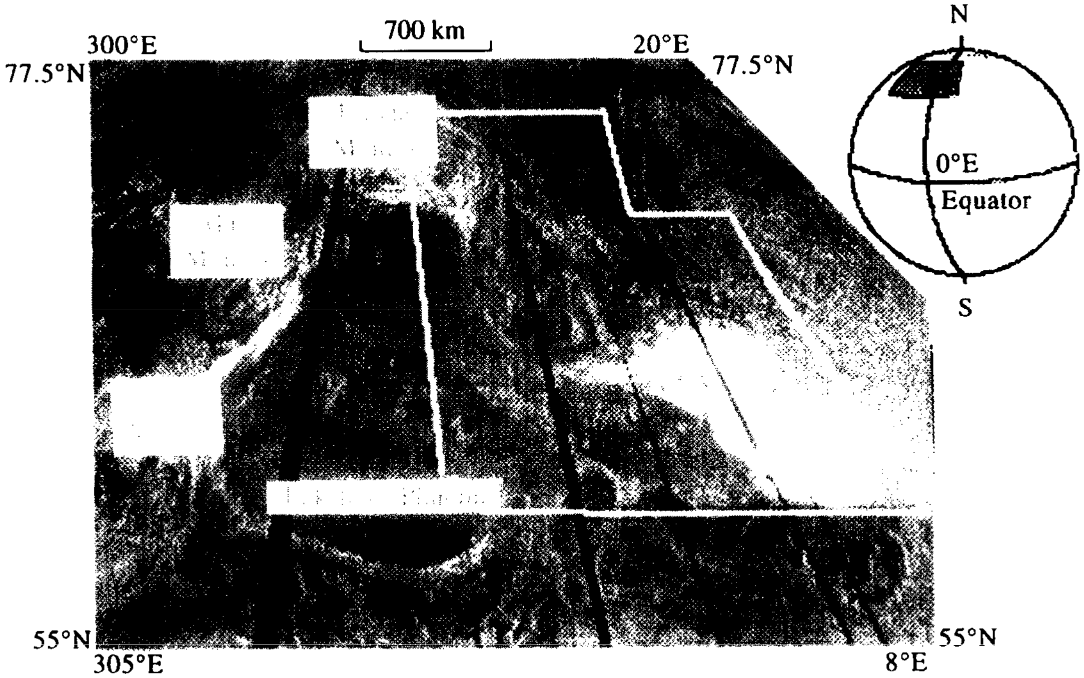


Fig. 1. Part of the Magellan radar image mosaic [C260N-333]. This image shows Central Ishtar Terra. It consists of high plateau, Lakshmi Planum, standing 4 km high, surrounded by highlands, Freyja Montes, Akna Montes, Danu Montes, and Maxwell Montes. Central Ishtar Terra is located at northern latitudes as shown on the globe. The studied area corresponds to the enclosed area

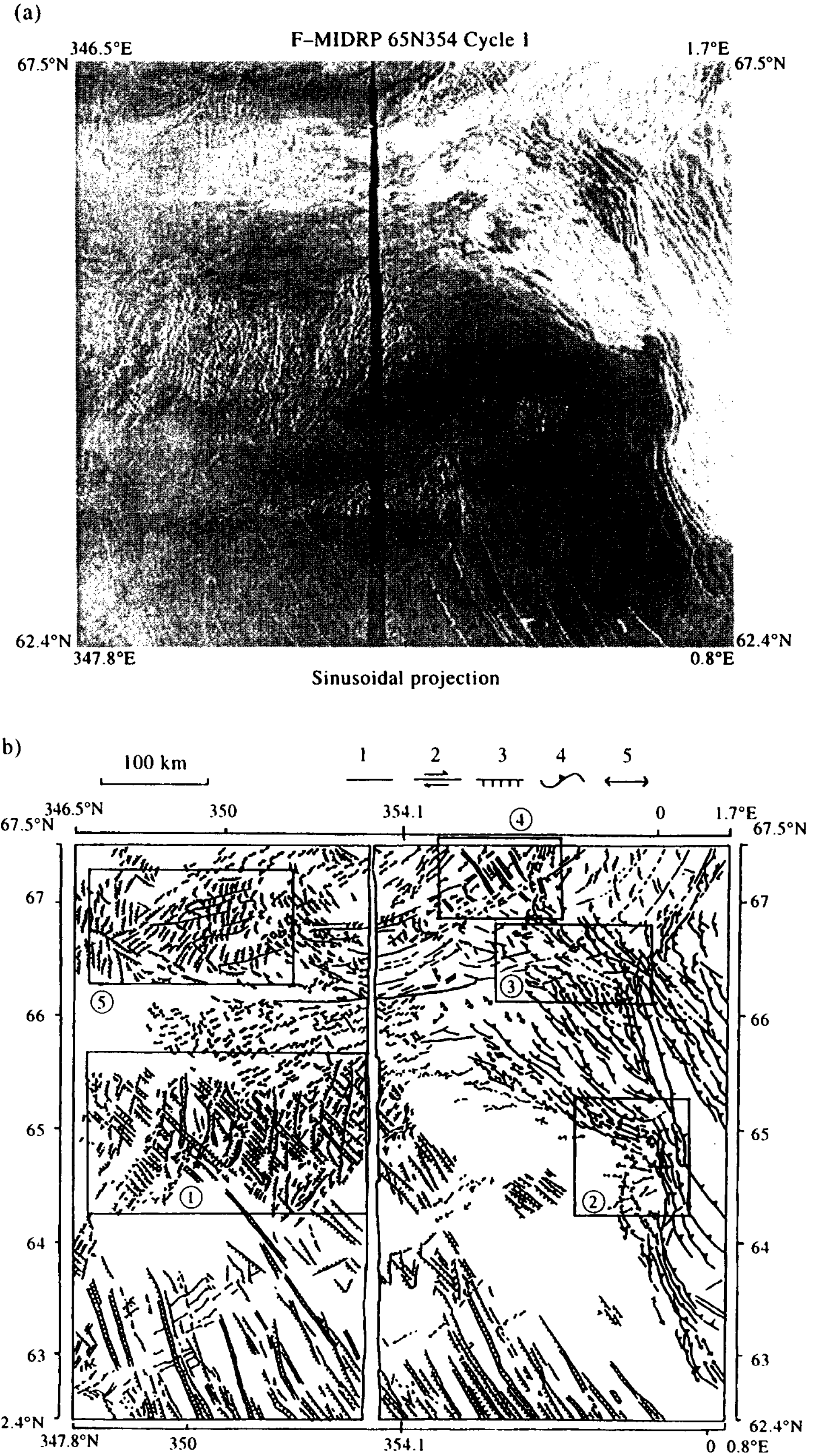


Fig. 2. (a) Magellan full-resolution radar image displays eastern Lakshmi Planum (radar dark area) bounding the highest Venusian highland Maxwell Montes (bright zone) [F-MIDRP 65N-354]. Centred at latitude 65°N and longitude 354°E, this image covers an area of approximately 500 km × 500 km. The radar beam is oriented $\sim 25°$ to the east. (b) The detailed structural map of eastern Lakshmi Planum from F-MIDRP 65N-354: 1, fault; 2, strike-slip fault; 3, normal fault; 4, thrust fault; 5, fold. Lakshmi Planum is characterized by a mosaic of extensional faults distributed in three networks. Maxwell Montes located at the eastern part of image is characterized by folds and thrust faults. The geologic and structural features of the enclosed areas are described and discussed in the text

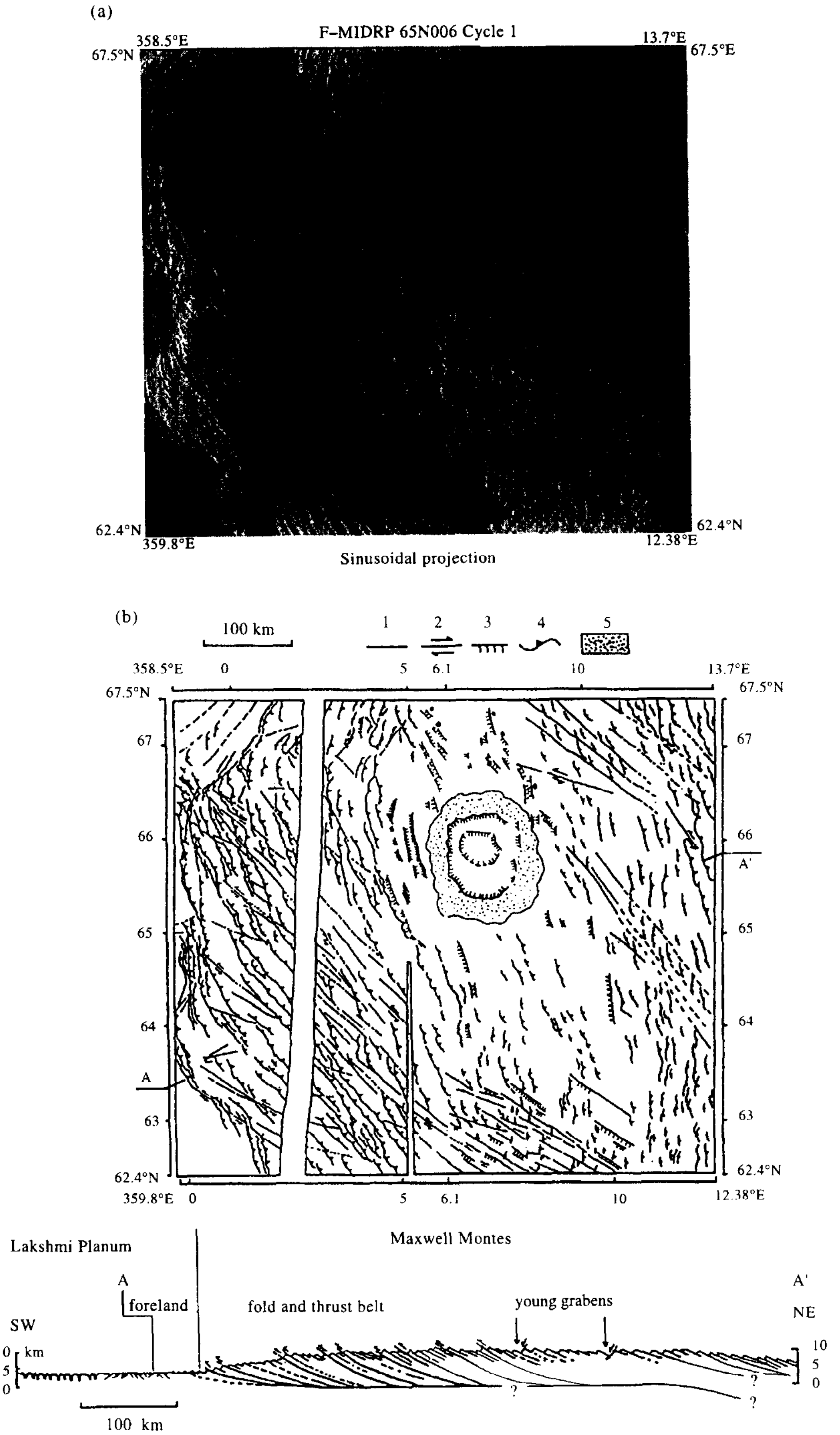


Fig. 3. (a) Magellan full-resolution radar image shows the inner part of Maxwell Montes, the highest relief of Venus [F-MIDRP 65N-006]. This image is 450 km wide and the radar beam is oriented to the east. (b) The detailed structural map of Maxwell Montes from F-MIDRP 65N-006. The pattern of NW to NNW ridges are interpreted as folds bounded by thrust faults lowly dipping eastward. The circular feature centred at 66°N of latitude and 7°E of longitude corresponds to Cleopatra double-ring impact crater: 1, fault; 2, strike-slip fault; 3, normal fault; 4, thrust fault; 5, ejecta. AA′ schematic cross-section oriented SW–NE through Maxwell Montes. It shows that Maxwell Montes would be comparable to fold-and-thrust belt lately deformed by gravitational relaxation marked by grabens on its summit. Thrust faults would connect to a shallow detachment zone

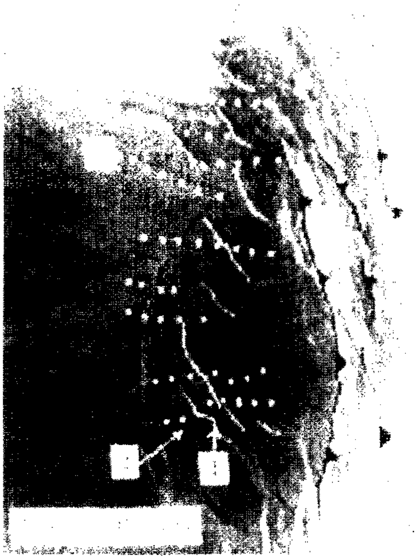


Fig. 4. A close-up view of Maxwell Montes foreland located at 64.5°N of latitude and 0°E of longitude. This image covering an area of 120 km, E–W, by 150 km, N–S, corresponds to box 2 in Fig. 2b. The radar beam is oriented to the east. Lava flows of Lakshmi Planum (radar dark area) are deformed by two oblique to orthogonal networks of ridges interpreted as folds. As NNW–SSE folds (underlined by white broken lines) were deformed by WNW–ESE folds (underlined by white dotted lines), the latter postdated NNW–SSE folds parallel to the main thrust front of Maxwell Montes (marked by black lines with triangular symbols)

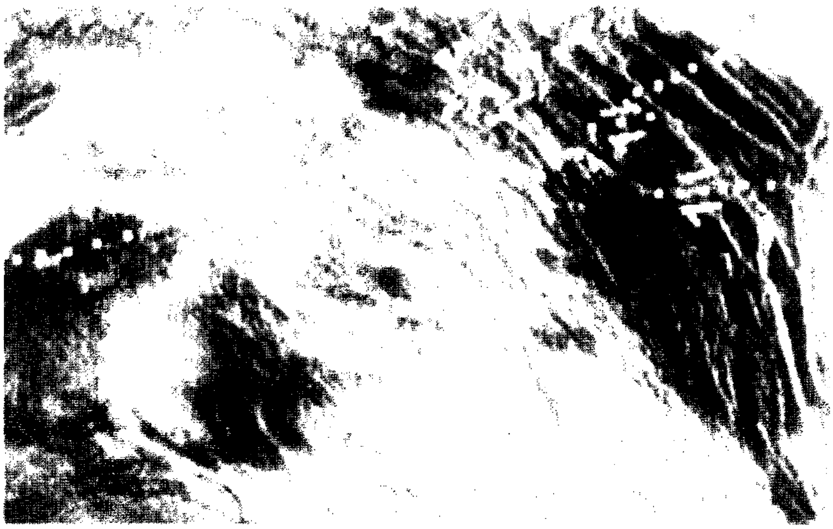


Fig. 5. This close-up view extracted from F-MIDRP 65N-354 corresponds to box 3 in Fig. 2b. Image covers an area of 186 km, EW, by 115 km, NS, and is located at the inner part of NW Maxwell Montes arm. The radar beam is oriented to the east. Ridges oriented NW–SE, outlined by a radar-bright western contour, are interpreted as folds and overturned folds. Locally, they show right-lateral offsets due to their accommodation along right-lateral tear faults underlined by white dotted lines

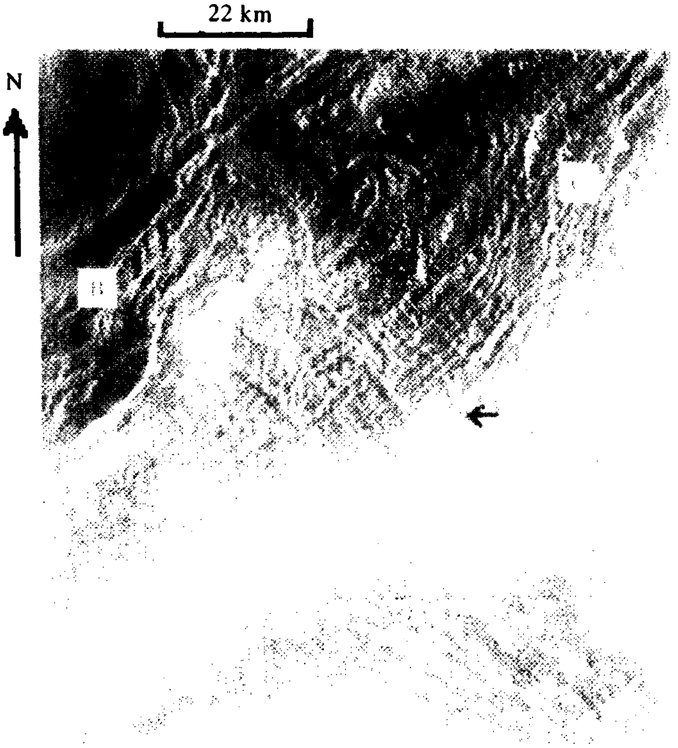
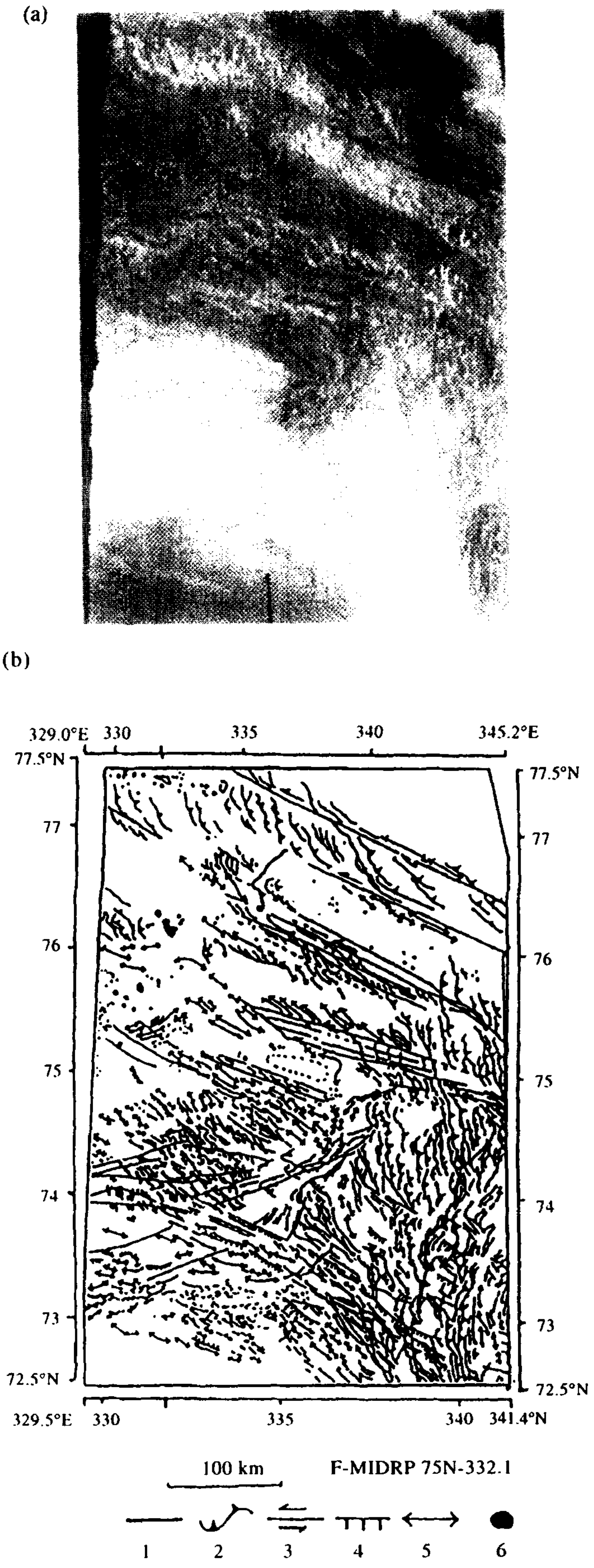


Fig. 6. Part of the radar image F-MIDRP 65N-354 corresponds to box 5 in Fig. 2b. This image covers an area of 100 km wide and 80 km high. The radar beam is oriented to the east. The regional topographic slope dips to NW. On the NW slope, a mosaic of orthogonal troughs bounded by two parallel scarps developed (A) and they are interpreted as grabens. Owing to the slope, this mosaic of horsts and grabens is not stable, and gravitational sliding occurs above a detachment zone leading to tilting of old grabens and forming gravity thrusts at the bottom (B). To the east, the mosaic of horsts and grabens are disturbed by oblique tectonic thrusts (C) resulting from the regional E–W crustal shortening of Maxwell Montes. However, their distribution is closely controlled by pre-existing fracturation, especially by NW–SE grabens (black arrow) because overturned folds stop orthogonally to them


(a)
(b)
329.0°E
330
335
340
345.2°E
77.5°N
77
76
75
74
73
72.5°N
77.5°N
77
76
75
74
73
72.5°N
329.5°E
330
335
340
341.4°N
100 km
F-MIDRP 75N-332.1
1
2
3
4
5
6

In conclusion, the basement of Lakshmi Planum has been the site of crustal extensional deformation. The three networks of grabens formed during this tectonic stage. A volcanic activity occurred then, and lava flows blanketed partially Lakshmi Planum.

Maxwell Montes

Maxwell Montes is the highest Venusian highland standing 10 km in elevation. It is located on the eastern boundary of Lakshmi Planum. It is characterized by its radar brightness that may be due to the high dielectric constant of metallic compounds present in materials at this elevation (Pettengill *et al.*, 1988; Klose *et al.*, 1992; Ford *et al.*, 1993). At the image resolution scale, Maxwell Montes displays a variation of radar brightness interpreted as due to local topographic changes (Fig. 3a). Owing to the radar illumination, the radar brightness variations are associated to positive relief as ridges. These ridges are tens to hundreds of kilometres long, hundreds of metres high, and typically spaced at intervals of 10 km. They display a sinuous, asymmetric profile with a narrow, western, bright side, and a wide, eastern gentle tilted side. Despite the geometric distortion induced by radar acquisition, these characteristics suggest that ridges would correspond to folds, overturned folds and imbricated structures bounded by low eastward-dipping thrusts (Fig. 3b, AA′ cross-section) (Ansan *et al.*, 1994, 1995). These compressive structures are arranged in a NNW–SSE parallel network, which is indicative of a regional WSW–ENE trending crustal shortening. Furthermore, these folded and imbricated structures are associated with NW–SE, narrow, long, linear troughs along which left-lateral displacement is observed (Fig. 3b). Their formation would be synchronous with that of folds, owing to their orientation and their kinematics.

The summit of Maxwell Montes, a 300 km wide plateau, shows a 105 km in diameter circular feature, named Cleopatra (Fig. 3). It consists of two concentric depressions characterized by a flat, radar-dark ground. These concentric depressions are surrounded by an irregular ring of bright, rough surface material corresponding to ejecta. Because of the presence of ejecta surrounding concentric depressions, Cleopatra is interpreted as a double-ring impact crater (Basilevsky and Ivanov, 1990; Ivanov *et al.*, 1992; Schaber *et al.*, 1992). Moreover, this double-ring impact crater kept its original circular shape. Consequently, it postdated the compressive formation of Maxwell Montes.

Maxwell Montes shows evidence of late extension and volcanism. To the north and the south of Cleopatra, some grabens, 10 km wide, parallel to the mountain trend are bounded by small volcanoes (Fig. 3). Their orientation and their location on the mountain summit seems to indicate that these grabens would result from gravitational relaxation (Froidevaux and Ricard, 1987; England and Houseman, 1989; Solomon *et al.*, 1992; Ansan *et al.*, 1994, 1995). Although no direct cross-cutting relationships are observed between grabens and Cleopatra impact crater, their formation would be simultaneous or immediately after the impact crater formation.

On the eastern part of Maxwell Montes (Fig. 3), folded or imbricated structures are spaced by valleys characterized by a radar-dark floor. With its dark radar characteristics, the valley floor would be volcanic in origin. Some lava flows emanate from the Cleopatra impact crater, which seems to indicate that lava flows would result from impact melt and/or volcanism triggerred thermal–chemical changes in rocks after the impact.

On the western side of Maxwell Montes (Fig. 2 and Fig. 2b, box 2), lava flows covering Lakshmi Planum shows a series of NNW–SSE, parallel, sinuous ridges. As ridges deformed lava flows, they postdated volcanic deposits. These ridges are arrranged in three half-circles that cross-cut each other at their tips, and are parallel to the sinuous, NNW–SSE boundary of Maxwell Montes extending over more than a thousand kilometres. The geometry of the western boundary of Maxwell Montes is characteristic of a thrust front associated with a folded foreland (series of ridges) in the western part. All the structural interpretations show that Maxwell Montes is similar to a terrestrial fold-and-thrust belt. It formed under a WSW–ENE crustal shortening and overlapped Lakshmi Planum westward (Fig. 3, cross-section) (Solomon *et al.*, 1992; Kaula *et al.*, 1992; Ansan *et al.*, 1994, 1995).

At 64 N of longitude and 0 E of latitude, a series of sinuous, flat-topped, WNW–ESE to W–E trending ridges interpreted as folds developed obliquely to the main NNW–SSE thrust front of Maxwell Montes (Fig. 2b, box 2). They intersected and deformed the NNW–SSE folds parallel to the main thrust previously described, which implies that the WNW–ESE folds are younger than NNW–SSE ones (Fig. 4) (Ansan, 1993; Ansan *et al.*, 1994, 1995).

To the north, the ridge orientation changes progressively, from WNW–ESE to NW–SE (Fig. 2b, box 3 and Fig. 5). In addition, their geometry becomes asymmetric. Ridges display a northeastern lowly tilted limb and lobate

Fig. 7. (a) Magellan full-resolution radar image centred on central Freyja Montes [F-MIDRP 75N-332]. This image is approximately 350 km wide. The radar beam is oriented to the east. The dark area located to the south is the northern boundary of Lakshmi Planum. The bright area corresponds to Freyja Montes standing at 6 km in elevation. To the north, the WNW–ESE banded terrain corresponds to Itzpapalotl Tessera (76°N–335°E). (b) The detailed structural map of central Freyja Montes as interpreted from F-MIDRP 75N-332: 1, fault; 2, thrust fault; 3, strike-slip fault; 4, normal fault; 5, fold; 6, volcano. Freyja Montes is characterized by a compressive deformation marked by N–S to NW–SE folds associated with network of conjugate strike-slip faults. Folds on Lakshmi Planum indicate that Freyja Montes formation postdated that of Lakshmi Planum

southwestern outline, indicating they could correspond to southwestern facing overturned folds (Fig. 5). These overturned folds are bounded by a network of parallel, narrow, discontinuous troughs. Locally, folds show a visible right-lateral offset along these troughs without local tip flexion. Therefore, these troughs would correspond to right-lateral tear faults. They would be the response of cover deformation that moves southward at an unequal rate above a horizontal detachment zone (Ansan *et al.*, 1995).

To the north (67°N–356°E), the pattern of folds and tear faults vanishes and another pattern of ridges and troughs is observed (Fig. 2b, box 4 and Fig. 6). Two orthogonal networks of troughs bounding rectangular, flat-topped, steep-sided ridges oriented NE–SW are observed on the lower left corner (Fig. 6). This arrangement is similar to that observed on Lakshmi Planum blocks (Fig. 2b, box 1). Hence, these ridges and troughs would correspond respectively to horsts and grabens. However, their distribution is disturbed northward. Ridges display a NW–SE asymmetric profile associated with a northward lobate contour, which is characteristic of overturned folds. In reference to Magellan altimetric data, this pattern of horsts and grabens is located on a NW dipping slope. Consequently, this association of structures along a slope is characteristic of a deformation by gravity sliding (Smrekar and Phillips, 1988; Smrekar and Solomon, 1992; Ansan *et al.*, 1995).

To the east (Fig. 6), the ridge orientation changes progressively, from NE–SW to N–S. Furthermore, their geometry becomes more and more asymmetric associated with a western lobate outline. Because of their geometry, orientation and distribution, ridges are interpreted as overturned folds or imbricated structures overlapping the north polar plain to the west (Ansan *et al.*, 1995). However, their distribution is controlled by the pre-existing fracturation, especially by NW–SE grabens because folds stop along NW–SE normal faults. This suggests that the deformation results from the reactivation in compression of old basement of Lakshmi Planum characterized by a mosaic of horsts and grabens, during the WSW–ENE crustal shortening of Maxwell Montes.

The northwesternmost part of Maxwell Montes is characterized topographically by a gentle northward slope on which tear faults vanished to the west of 353°E of longitude (Fig. 2, box 5). To the west, a network of radial and concentric troughs bounded by a pair of parallel scarps developed. They are interpreted as grabens (Ansan *et al.*, 1995). Locally, grabens are deformed by folds indicating the compressive deformation associated to crustal shortening of Maxwell Montes postdates the graben formation. In this area, the manifestation of compressive deformation would be both folds and vertical motions.

In conclusion, Maxwell Montes resulted from a WSW–ENE crustal shortening. The deformation of central Maxwell Montes has characteristics of a fold-and-thrust belt associated with a folded foreland (Fig. 3, cross-section). In the northwestern part of Maxwell Montes, the deformation is rather characterized by a cover deformation where the intensity and the distribution of the compressive deformation are closely controlled by topography and the pre-existing fracturation of basement.

Freyja Montes

Freyja Montes is the highland standing at 6 km in elevation along the northern boundary of Lakshmi Planum and located to the northwest of Maxwell Montes (Fig. 1). This highland consists of two distinct structural areas (Fig. 7). Its eastern part is characterized by a series of long, sinuous, N–S asymmetric ridges spaced at intervals of 20 km. They are interpreted as overturned folds overlapping Lakshmi Planum westward (Ansan *et al.*, 1994). Owing to their orientation, they are formed under a E–W crustal shortening. These overturned folds display a network of WNW–ESE, narrow, discontinuous troughs. They are bounded by two parallel, rectilinear scarps spaced at 5 km, interpreted as normal-fault scarps. Consequently, troughs would correspond to grabens. These grabens are arranged en echelon with a visible right-lateral offset induced by the late westward propagation of overturned folds (Ansan *et al.*, 1994).

The western part of Freyja Montes is the most intensively deformed and is oriented orthogonally to the other one. Ridges oriented NNW–SSE to NW–SE are disrupted by a network of conjugate shear zones. Along the WNW–ESE shear zones a relative left-lateral offset is observed, whereas the displacement is right-lateral along the ENE–WSW shear zones. The kinematics observed along these shear zones is consistent with a E–W crustal shortening (Fig. 7).

To the north, the compressive deformation is controlled by a network of long, narrow, WNW–ESE troughs that limit the banded-terrain of Itzpapalotl Tessera (Fig. 7b). The surface of banded-terrain shows a network of NW–SE ridges interpreted as folds. Folds are deformed near the long, narrow, WNW–ESE troughs, showing a systematic left-lateral offset. Owing to the fold offset along the regional "Z sigmoidal"-shaped troughs, the latter are interpreted as left-lateral strike-slip faults (Kaula *et al.*, 1992; Ansan, 1993; Ansan *et al.*, 1994).

All the structures indicate that Freyja Montes results from a complex polyphased tectonics (extension and compression). The last main tectonic phase corresponds to an E–W crustal shortening. In the northern part of Freyja Montes, the shortening is controlled by old, WNW–ESE tectonic structures that were reactivated into left-lateral strike-slip faults. Furthermore, this mountain belt is associated with a foreland located on Lakshmi Planum, where lava flows are deformed by folds (Fig. 7). Therefore, this is indicative of the late period of Freyja Montes deformation in relation to that of Lakshmi Planum. Following this crustal shortening, a volcanic activity occurred in Freyja Montes, marked by widely distributed volcanoes (Fig. 7b).

Discussion

The major structural features of central Ishtar Terra are reported on a regional structural map (Fig. 8). The previous study shows that central Ishtar Terra is characterized by two distinct structural and temporal units: the high plateau, Lakshmi Planum, and the surrounding

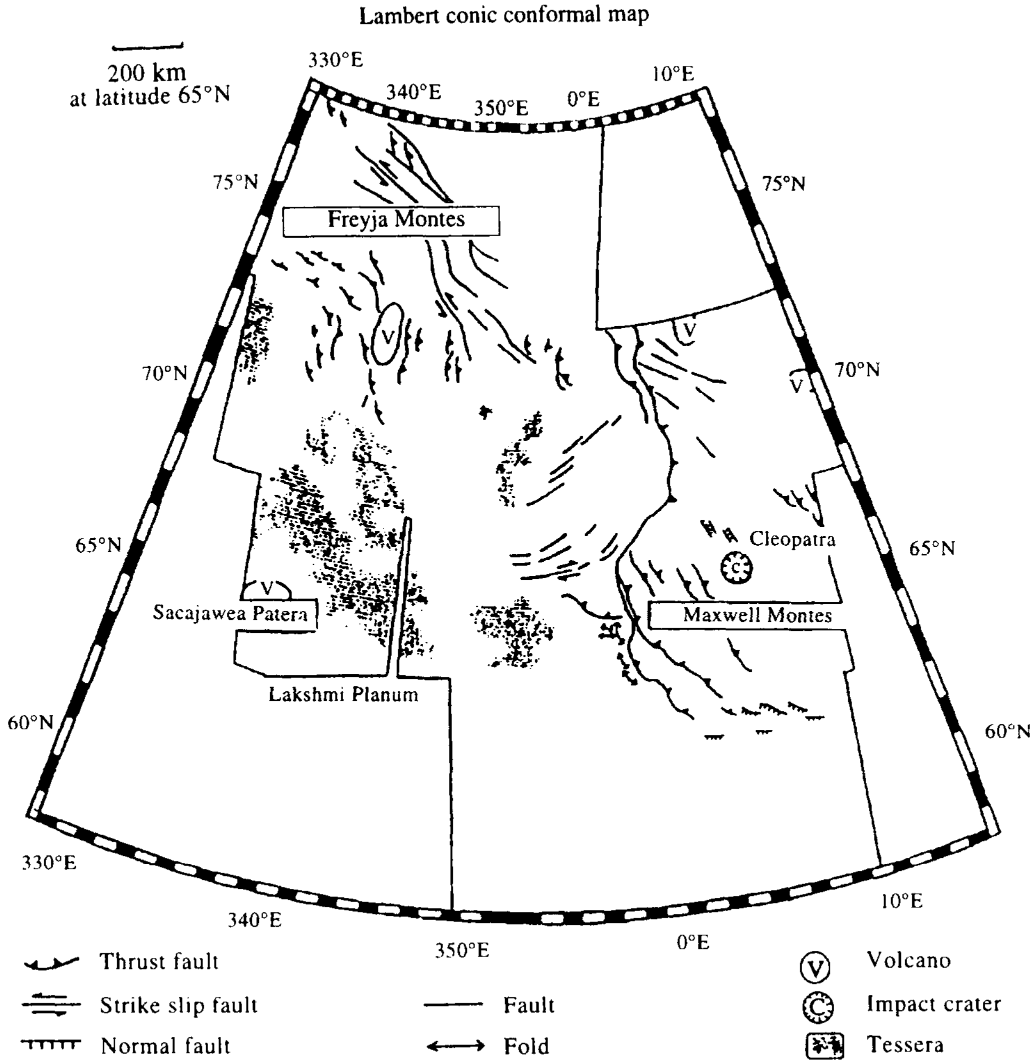


Fig. 8. Regional structural map of central Ishtar Terra. Main tectonic structures are reported on this Lambert conic conformal projection map. It covers an area of 2000 km in longitude and 2400 km in latitude. Lakshmi Planum is characterized by tessera, mosaic of horsts and grabens, distributed broadly along the northern boundary of high plateau, and a great volcano, Sacajawea Patera. Freyja Montes and Maxwell Montes are characterized by folds, overturned folds, and thrust faults, associated locally with network of strike-slip faults. Their orientation and their distribution indicate that these mountain belts resulted from a main tectonic phase: WSW–ENE crustal shortening

mountain belts, Maxwell Montes and Freyja Montes. On the basis of tectonic study and cross-cutting and/or superposition relationships of tectonic structures, we propose a model for the regional tectonic history of central Ishtar Terra. Lakshmi Planum basement is the oldest structural area. It is characterized by an intense, regularly fractured terrain in which three networks of grabens developed. They result from a lithospheric extension (Fig. 2, box 1). After the tectonic phase, a volcanic activity occurs and lava flows cover partially Lakshmi Planum (Fig. 2a, radar dark area). Because of the compressive deformation of lava flows covering Lakshmi Planum in front of highlands, Freyja Montes and Maxwell Montes, the formation of the two mountain belts postdates the formation of Lakshmi Planum (Kaula *et al*., 1992; Ansan, 1993; Ansan *et al*., 1994, 1995). Mountain belts are thus the youngest structural units of Ishtar Terra. Although their deformation is complex and polyphased especially in Freyja Montes, the mountain belts are formed during a main tectonic phase: WSW–ENE crustal shortening. Then, they show evidence of a late volcanic activity.

From the kinematic point of view, all the structural units show evidence of vertical and horizontal crustal movements. As we saw previously, Maxwell Montes and Freyja Montes have characteristics of terrestrial fold-and-thrust belts. They consist of a series of regularly arranged NW–SE to NNW–SSE folds and imbricated structures bounded by 30° to 40° dipping eastward thrust faults, especially in Maxwell Montes (Fig. 3b and cross-section for Maxwell Montes). These folded structures are associated with networks of left-lateral strike-slip faults oriented NW–SE to WNW–ESE, and ENE–WSW trending right-lateral strike-slip faults (Figs 3 and 7). In Freyja Montes, the deformation is polyphased but the last main tectonic event is the formation of NNW–SSE folds associated to the reactivation of old regional NW–SE faults in left-

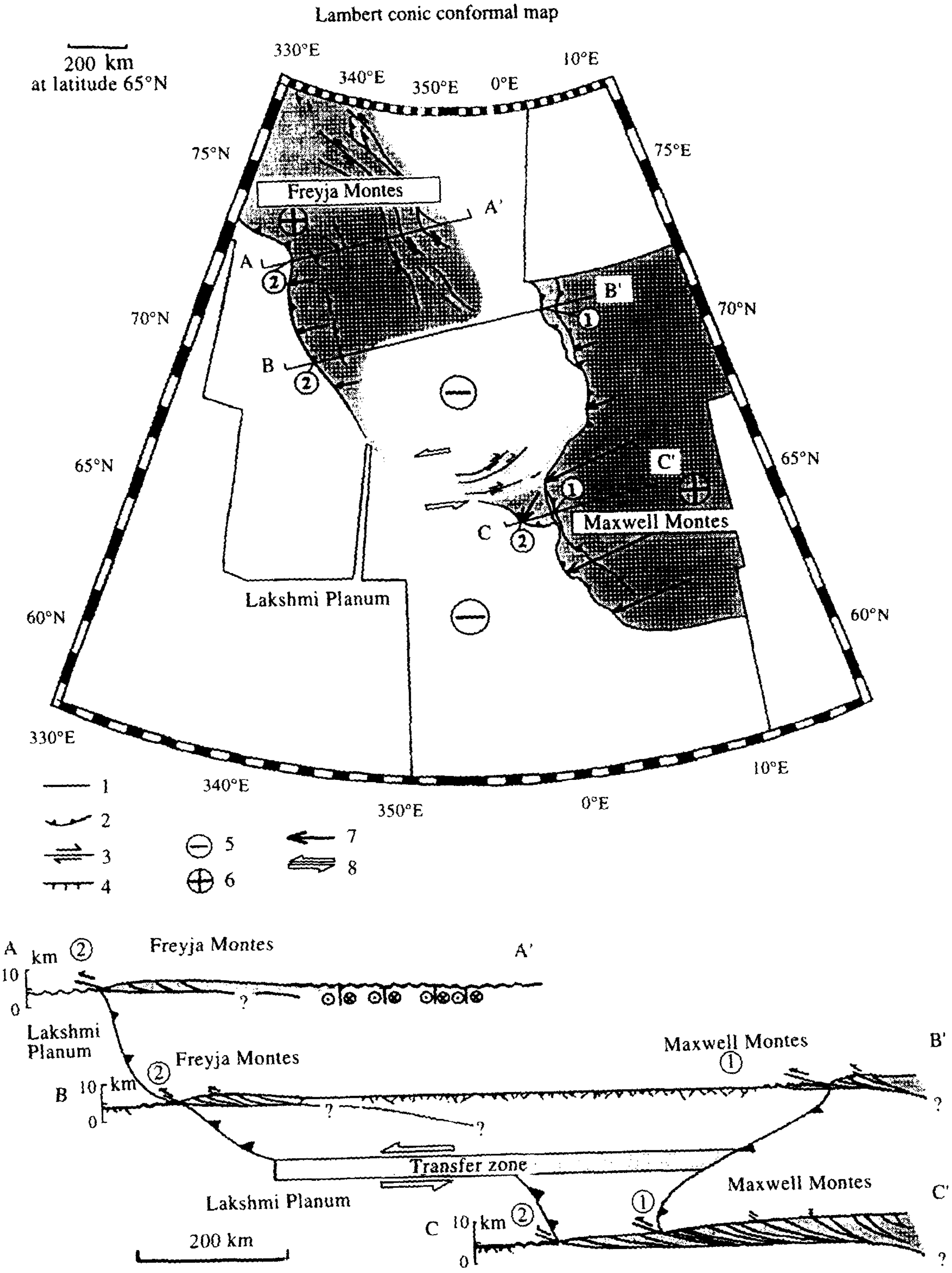


Fig. 9. Regional kinematic model of central Ishtar Terra, based on the type and the distribution of tectonic structures: 1, fault; 2, thrust fault; 3, strike-slip fault; 4, normal fault; 5, negative vertical crustal motion relative to mountain belts; 6, positive vertical crustal motion relative to Lakshmi Planum; 7, direction of qualitative horizontal crustal motion; 8, shear zone. The deformation of mountain belts led to formation of a high topography. These mountain belts show evidence of regional westward horizontal crustal motion leading to overlapping of Lakshmi Planum. Based on the distribution of compressive deformation and especially thrust fronts, it appears that deformation was partitioned and transferred from the east to the west via a wide, left-lateral shear zone. In Freyja Montes, the compressive deformation was accommodated both by folds and along strike-slip faults (AA′ cross-section). To the south, the compressive deformation was partitioned and translated from Maxwell Montes thrust front to Freyja Montes thrust front (BB′ cross-section). Further to the south, the compressive deformation was translated to the west by the main thrust front of Maxwell Montes (CC′ cross-section). The wide transfer zone characterized by a regional left-lateral motion would have allowed to accommodate the compressive deformation between the two mountain belts

lateral strike-slip. All the structures resulted from a regional WSW–ENE crustal shortening related to crustal thickening (Vorder Bruegge and Head, 1989; Ansan *et al.*, 1994, 1995). Moreover, they are indicative of a large-scale westward crustal translation: Maxwell Montes and Freyja Montes are bounded on their western side by thrust front associated with a foreland that overlapped and deformed Lakshmi Planum (Vorder Bruegge and Head, 1989; Kaula *et al.*, 1992; Solomon *et al.*, 1992; Keep and Hansen, 1994; Ansan *et al.*, 1994, 1995). The formation and the westward translation of thrusts involved the presence of a regional detachment zone to which the thrusts are connected. This detachment zone would be located at shallow depth (10 km) and correspond to a weak zone that separates the strong, upper crust to the strong, lower crust (Zuber, 1987; Banerdt and Golombeck, 1988; Phillips, 1990; Arkani-Hamed, 1993; Keep and Hansen, 1994). The great difference between Maxwell Montes and Freyja Montes is the geometry of their thrust front overlapping Lakshmi Planum westward. The Maxwell Montes thrust front is continuous, sinuous, extending over thousands of kilometres from 60°N to 72°N of latitude. However, it presents a regional curvature at 66°N–1°E (Figs 8 and 9). To the south of this inflexion point, the main thrust front propagated 200 km to the west, with an intense compressive deformation (Fig. 8). In contrast, the Freyja Montes thrust front consists of several, small, overturned folds oriented N–S to NW–SE. It extends along 340°E from 68°N to 72°N (Fig. 8). Furthermore, the intensity of deformation is relatively low because a part of deformation was accommodated by the network of WNW–ESE "Z-sigmoidal"-shaped left-lateral strike-slip faults located at the northern part of Freyja Montes (Fig. 8).

Figure 9 shows the relative crustal motions of different geographic units based on previous structural interpretations. If we consider Lakshmi Planum as the reference altimetry zone, the relative vertical motions in mountain belts result in the formation of high topography, with 11 km for Maxwell Montes and 6 km for Freyja Montes. However, the most important conclusion of structural interpretations is the relative horizontal crustal motions in mountain belts. Eastern Freyja Montes and Maxwell Montes are fold-and-thrust belts that overlap Lakshmi Planum westward. If we assume that the deformation ratio was constant in the whole central Ishtar Terra, the distribution and geometry of thrust fronts would be indicative of deformation partitioning between Maxwell Montes and Freyja Montes via a left-lateral transfer zone located along the 66°N parallel. In Freyja Montes (Fig. 9, cross-section AA′), the compressive deformation was accommodated by both folds in western Freyja Montes and left-lateral strike-slip faults in eastern Freyja Montes. To the south (Fig. 9, cross-section BB′), the compressive deformation was divided into two areas: to the east, Maxwell Montes overlapped the polar plain westward, and the compressive deformation was taken "in relay" to the west in Freyja Montes by a second thrust front. In Maxwell Montes (Fig. 9, cross-section CC′), the compressive deformation is distributed broadly and the main thrust front propagated 200 km westward. A local oblique thrust front developed in the northwestern part of Maxwell Montes. Parallel to 66°N, a 100 km wide zone (Fig. 9, grey zone) is characterized by a complex, gradual deformation: from east to west, folds and overturned folds associated with right-lateral tear faults (Fig. 2b, boxes 3 and 4, Figs 4 and 5) and old horsts and grabens reactivated by vertical motions (Fig. 2b, box 5). This zone connects geographically Maxwell Montes to Freyja Montes. It would correspond to a pre-existing crustal vertical shear zone along which the compressive deformation would be transferred from Maxwell Montes to Freyja Montes with a regional left-lateral movement, during the crustal shortening stage of Ishtar Terra (Fig. 9).

To date, it is commonly accepted that the crustal deformation is related to mantle convective strengths. Different dynamical models tend to explain the formation of tectonic structures observed in this area. Until 1991, the model of a mantle upwelling localized beneath Lakshmi Planum allowed the presence of volcanic features on Lakshmi Planum to be explained, but the formation of mountain belts remained without explanation (Pronin, 1986; Basilevsky, 1986; Grimm and Phillips, 1991). Thus, a model of a cylindrical mantle downwelling was proposed to explain the formation of Ishtar Terra by compression and lithospheric thickening (Bindschadler and Parmentier, 1990; Bindschadler *et al.*, 1990, 1992; Head, 1990; Phillips, 1990; Kiefer and Hager, 1991). Although these models take into account the high topography, gravity data and the surface deformation, they require large-scale motions of lithospheric plate. This is not in accordance with observation since Venus lacks plate tectonics (Solomon *et al.*, 1992). How does one explain the horizontal surface crustal motions observed in Ishtar Terra? As we saw previously, the deformation is characteristic of cover deformation with regional westward crustal motions of highlands on Lakshmi Planum. These two mountain belts would be compared to the terrestrial foreland thrust belt. In order to take into account this characteristic and the different isostatic compensation depths related to the observed feature scale (130 km at depth beneath Ishtar Terra and 25–70 km under different mountain belts), Hansen and Phillips (1995) propose a translation of lower crust inward—toward Lakshmi Planum. In response to this translation, the upper decoupled crust deformed by regular, parallel folds and overturned folds at the 1000 km scale. Although this model is in good accordance with observation in central Ishtar Terra, it implies the presence of an opposite "vergence" zone with a trench, a foreland and westward dipping thrusts in the eastern Maxwell Montes region, which has not been observed.

In conclusion, the previous geologic and structural interpretations of Magellan full-resolution radar images centred on central Ishtar Terra leads to define the geologic characteristics and geologic history of this area. Owing to the style and the distribution of geologic features present in this area, it appears that the Venus crustal deformation is characteristic of a cover deformation. Furthermore, the deformation resulted from both vertical and horizontal crustal movements, at least in this area. Lakshmi Planum, the oldest area, formed during a lithospheric extension leading to the basement fracturation associated with a late volcanic activity. Then, peripherical fold-and-thrust belts, Freyja Montes and Maxwell Montes, formed under an approximately E–W crustal shortening. These mountain belts give evidence of a regional crustal motion westward. Furthermore, the compressive deformation seems to be distributed in a wide area via a transfer zone.

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