TECTONICS OF SYRTIS MAJOR PLANUM ON MARS

J. RAITALA and K. KAUHANEN
Department of Astronomy, University of Oulu, Finland

(Received 28 June, 1989)

Abstract. Mare ridges were caused by compressional tectonics and indicate the shortening of the planum surface foiled by lavas. At least two separate tectonic phases within Syrtis Major Planum can be found. The two central calderas are located on the southwestern continuation of the Nili Fossae graben zone at the junction of the N–S and NW–SE mare ridge sets. These central calderas were formed by surface collapses into relatively shallow magma chambers. Radial and concentric mare ridges around the two calderas represent a shortened surface environment within the large compressional megacaldera. Shortening was caused by sinking of the crust due to the lava load, plumbing of the magma chambers and cooling of the interiors. The main NW–SE ridge trend parallels highland faults of the major structural zone extending from Hesperia Planum to Vastitas Borealis. These NW–SE ridges indicate the large scale areal tectonic trend along the Scopulus Oenotria – Phison Rupes fault zone and support the idea of a main SW–NE compression. The N–S directed mare ridges of the northern planum area favour a change in compressional stress direction from SW–NE in the south to E–W in the northern planum, obviously due to the buried local topography. These linear mare ridges can also be interpreted as forming a large Isidis Planitia-concentric ridge circle connecting Nili Fossae to Libya Montes. Formation of the mare ridges was the youngest of the main tectonic phases involved within the area studied.

1. Introduction

The distinct Syrtis Major Planum area is located on the eastern side of Isidis Planitia (Figure 1) just on and north of the equator between longitudes 280° and 300° (Meyer and Grolier, 1977; Schaber, 1982). This $1000 \times 1000\ \text{km}^2$ in planum is bordered by Martian cratered highlands in the north, west and south. The horizontal dimensions of the lava cover of Syrtis Major Planum make it a very large volcanic area even on Martian scale.

Most of the surrounding terrain consists of old plains and rounded hills cratered and smoothed by old impacts and aeolian activity. There are some small young plains between the cratered areas (Meyer and Grolier, 1977; Schaber, 1977). Antoniadi, Baldet and Schroeter are the largest craters in the close vicinity of Syrtis Major Planum. Remnants of the Isidis basin impact ring are found in the form of Arena Colles and Libya Montes on the NE and SE border of Syrtis Major Planum, respectively. There is no ring formation around Syrtis Major Planum.

In the east, the Syrtis Major Planum is bordered by Isidis Planitia which is covered by aeolian formations (Meyer and Grolier, 1977; Schaber, 1977). On the transformation zone between the two plains the aeolian Isidis materials mantle the lavas of Syrtis Major Planum. The east to west direction of aeolian deposits is seen in the numerous wind streaks behind the impact craters. The Syrtis Major Planum surface is covered by extensive ridge sets, while Isidis Planitia is smoother.

Earth, Moon, and Planets **46**: 243–260, 1989.

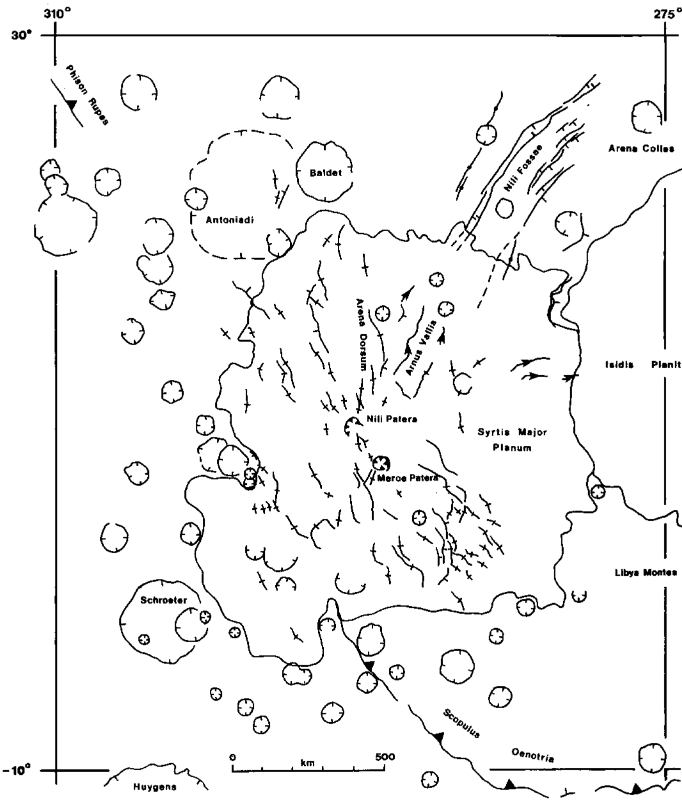

Fig. 1. The main structures of the Syrtis Major Planum area are the two central calderas (Nili Patera, Meroe Patera) and numerous prominent mare ridges (lines with barbs). Major lava channels are indicated with lines and arrows. Syrtis Major Planum is located adjacent to Isidis Planitia. Aeolian deposition direction is from the east. In the west and south the planum is bordered by highland terrain.

This indicates a main difference in their geology and reflects the effect of the thick aeolian coverage on the Isidis basin.

On the northern side of Syrtis Major Planum the cratered highland area is cut by the Nili Fossae graben zone concentric to Isidis Planitia. This graben zone is a 300 km wide and 600 km long northwestward arcuate belt which extends from the northern Syrtis Major Planum into Utopia Planitia parallel to the border of Isidis Planitia. Nili Fossae consist of one wide main graben and a few parallel small grabens with steep fault scarps. At the southwestern end this graben zone is covered by lavas. The main orientation of the grabens is N45° E. The graben system is approximately 2 km higher than the Isidis Planitia. Being topographically high and having deep arcuate fault scarps, the Nili grabens were formed in connection with a tensional force directed approximately perpendicular to the zone itself and radially to the Isidis basin. The large, rounded Isidis basin is a multi-ringed impact basin. The formation of the grabens may have been connected to the existence of a load-induced peripheral bulge around the Isidis Planitia basin and the tensional fracturing along the bulge crest (Raitala, 1987). There are not any concentric grabens around Syrtis Major Planum, however, which indicates that tensional force has not been active around it.

Syrtis Major Planum has an eastwardly downsloping, flood lava-type surface topography. Its western parts are 5 km higher than the areas close to Isidis Planitia. In the middle of the planum there are two major calderas and most of the planum surface is patterned by mare ridges. A prominent rille of Arnus Vallis cuts through the northern planum beside the major N–S ridges of Arena Dorsum. The diameter of the central caldera complex, or megacaldera, of Syrtis Major Planum measures approximately 280 km. The calderas seem to be relatively simple. The two calderas in the middle of Syrtis Major (Figure 1) have diameters of about 75 km for the NW caldera called Nili Patera and 50 km for the SE caldera called Meroe Patera. They are 100 km apart from each other and have distinct rims or levées. Their rim relief is low, rising only slightly above the surrounding lava surface. They are located within a large megacaldera. Recent results of terrestrial calderas were used to evaluate the caldera growth in association with the shallow magma chambers. Mare ridge structures of the planum were studied from Viking imagery in order to find the tectonic development of the area.

2. Central Calderas

The central Syrtis Major Planum is totally covered by low-viscosity lavas (Schaber, 1982) but can be interpreted as being a low-relief volcanic shield associated with a large negative Bouguer anomaly thus being mostly compensated (Scott and McDonald, 1984). Thickness estimations for lavas vary from 0.5 km to 1–2 km with a maximum of 3 km (Schaber, 1982; Wichman and Schultz, 1988). All lavas were drawn from magma chambers below the planum where magma pipes led lavas to extrusion vents. These extrusions were obviously timewise restricted and relatively young (approximately $3.1–2.6 \times 10^9$ yr old; Mutch, 1970; Soderblom *et al.*, 1974; Meyer and Grolier, 1977). Lava flows seem to have had a low viscosity and high effusion rate. The smooth, uniform lava coverage indicating the low viscosity of erupting material may be due to its high temperature, peculiar basaltic composition or high effusion rate, or in some combination of these. The composition of the lava flows may be critically indicative of the Martian internal development (Greeley and Spudis, 1981; Raitala, 1988).

The most important volcanic vents may have been connected to the two central calderas in the middle of the circular structure. Lava flows may also have covered numerous previous older vents as well as vents of their own. Some small extrusive vents can be found from within the caldera area. There are a few lava channels originating from some of the vents. A few short rilles meander near the main calderas in the centre of Syrtis Major Planum. Some lava flows may have originated from these rilles. There may also be a few central pits within the Syrtis Major Planum volcanoe. Most of them are lava-modified volcanic vents.

2.1. Nili Patera

The more northwestern and larger of the two main calderas (Figure 2) has a pear-shaped form. In the west, northwest and north the rim is at its most distinct as an arcuate horst. Outside the rim there is an arcuate fault-bounded trough or rille graben, possibly indicating the most recent tectonic activity cutting the surrounding lava planum in the west around Nili Patera (Schaber, 1982). The northeastern rim of the caldera has several rilles on the wall. These arcuate rilles suggest extension of the uppermost lava surface and can account for additional subcollapses and caldera expansion.

Inside the high rim wall there is a steep fault followed by a trough. In places the trough floor is rough and blocky. This eastward-facing horseshoe-shaped wall and its internal trough surround a slightly elevated caldera centre which opens to the southeast into the lava planum. A small hill, possibly a volcanic neck (Schaber, 1982), rises over the elevated central area and a straight NE–SW oriented graben runs through it. The central elevation gradually changes to lava planum in the southeast. The low, dome-like elevation is due to volcano-tectonic activity and may be caused by a laccolithic or sill intrusion doming its roof. The caldera does not display many albedo phenomena, but there are aeolian layers covering some small areas of the caldera bottom.

2.2. Meroe Patera

The smaller, southeastern caldera, Meroe Patera, is more circular and measures 50 km in diameter (Figure 2). The caldera has a well-defined steep inward-dipping wall on its eastern side. The rounded rim becomes slightly indistinct in the west where it has been broken by overflowing lava. The caldera bottom is flat and lower than the surrounding lava surface. There are some small impact craters and a few aeolian albedo markings within the caldera. The caldera may be relatively young as indicated by its fresh appearance and by the small amount of impact craters.

On the Meroe Patera rim there is a small lava flow. It originates from a narrow lava channel-like rille which has its beginning in a small vent crater within the outermost caldera fault. The rille is thus older than the fault. The eastern wall of the caldera is slightly step-like indicating the existence of superimposed collapse faults (Schaber, 1982).

2.3. Magma chamber depth

It is difficult to estimate the age difference between the two calderas. These calderas were formed during the major volcanic caldera collapse activity. Their intensive faulting indicates a timewise fluctuation of the caldera-forming activity. They are collapse calderas caused by the collapse of the roof into the magma

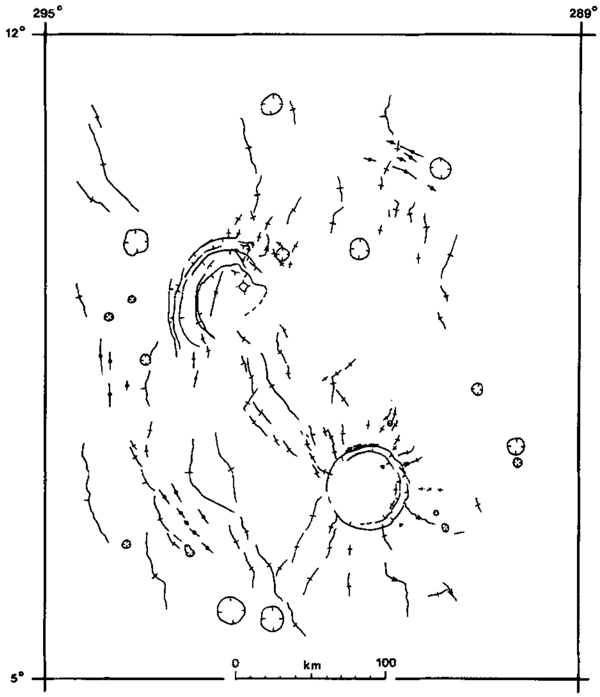

Fig. 2. The rims of the two main calderas of the central Syrtis Major Planum area are indicated by solid and broken lines with barbs downhill. Nili Patera (Figure 1) has a steep arcuate fault-like wall from the SW through NW to NE, with additional tensional arcuate rilles, while the southeastern rim is less distinct. There are a few lava channels (lines with arrows) near the calderas. Impact craters are mapped with rings with barbs inside. Mare ridges are indicated by solid lines with barbs and tensional megacaldera rilles by lines with filled circles.

chamber from which the magma has dried up or been removed. The formation of a circular normal fault has been connected to a circular tensional stress field within the caldera area. The circularity indicates that the magma chambers have been symmetrical penny-shaped lenses and during caldera growth the associated stress field has been relatively uniform. The caldera collapse took place when the magma chamber penetrated slightly higher resulting in changes in associated tensile stress fields. Collapse caldera fault planes are steep to almost vertical and the middle part of the caldera sunk along this circular-shaped ring fault. Several mare ridge-like formations radiate around both calderas indicating that the central Syrtis Major Planum caldera area has been compressional due to extrusions and lava load. The withdrawal and cooling of the magma chamber may have increased the process.

The depth and dimensions of the magma chamber are the most important in caldera formation. The caldera diameter is indicative of the horizontal dimensions of the magma chambers. The volume of the caldera relates to the dimensions of the dried up magma volume which left space for the collapse, to magmatic pressure against the magma chamber roof and its subsequent withdrawal, and to the lava-lake formation on the top of an extruding magma column. Maximum normal faulting indicates places where maximum tensional stresses existed. This helps us to estimate the depth of a magma chamber responsible for a particular caldera collapse. The caldera wall fault was most probably generated above the highest margin of the magma chamber. The caldera wall faults were not able to develop within areas with too deep magma chambers.

When magmatic activity below Syrtis Major Planum broke the magma chamber roof and initiated the caldera fault fracture opening and caldera collapse, the magmatic pressure was high enough. The chamber diameter/roof depth ratio was high, possibly ≈5.0 (Gudmundsson, 1988), allowing tensional stresses to have been located along the margins of the chamber to break the roof for the caldera formation.

Before the caldera collapse phase in the development of Syrtis Major Planum the two magma chambers increased laterally and vertically until the diameter/depth ratios in these two cases reached values sufficient for caldera collapse. This collapse along the ring fault occurred as effectively in both cases. In the case of Meroe Patera of Syrtis Major Planum a symmetric penny-shaped magma chamber existed and the roof suffered a piston-like collapse into the chamber (Figure 3). This caldera collapse was more symmetric than the northwestern one, indicating the high symmetry of the chamber shape.

The 75 km diameter of Nili Patera and a diameter/roof depth ratio of 5.0 give an estimate of 15 km for the caldera roof thickness. This may be a good preliminary estimate for the depth of the major magma chamber. The actual depth of the NW

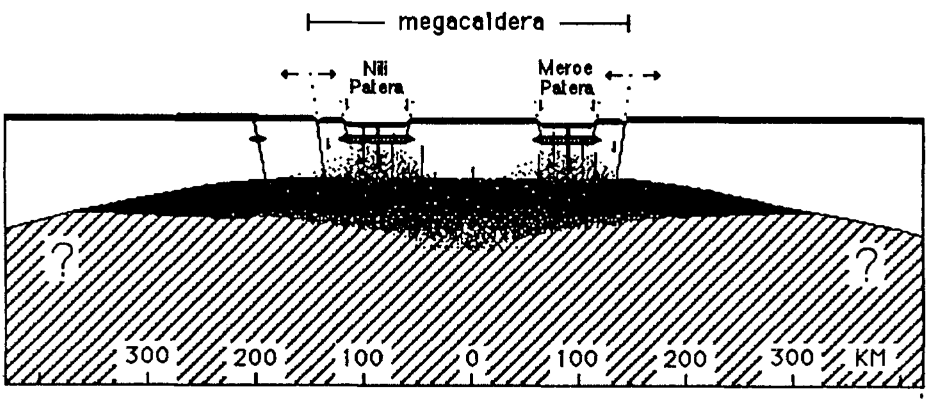

Fig. 3. Schematic representation of the magma chamber activity in the formation of the calderas of Syrtis Major Planum. Nili and Meroe Paterae are connected to the relative high-level, penny-shaped crustal magma chambers while the megacaldera development was controlled by a deeper magmatic layer, possibly more directly connected to endothermic asthenosphere processes. Deep Martian interiors are, however, rather unknown and this is indicated by question marks and adjoining lines.

magma chamber could have been slightly less. If the intrusive activity within the central elevation is taken into account, the magma chamber roof depth could have been closer to 10 km.

In the case of Meroe Patera, a diameter of 50 km and the diameter/depth ratio of 5.0 give 10 km for the initial magma chamber roof depth. Because of the intense lava lake-like appearance of the caldera interiors the final magma chamber depth may have been slightly less than 10 km. A reasonable magma chamber depth value could have been 8–10 km.

2.4. The magma source depth

The most obvious way to obtain low viscous lavas would have been a deep primary magma reservoir. The original mantle melt may have been less viscous than magmas with a more complex history. This favours an original mantle-related composition of the Syrtis Major Planum lavas and their fast eruption to the surface. A high effusion rate would also have allowed lavas to flow long distances and build dimensional lava lobes. The wide lava coverage of Syrtis Major Planum could thus have originated relatively directly from a primary magma source with a minimum stay in the magma chambers.

The formation of tensional concentric grabens took place around central calderas. Using a diameter value of 280 km for the faint circumcaldera graben ring (Figure 1 in Schaber, 1982) and adopting the diameter/roof depth ratio of 5.0 (Gudmundsson, 1988) a main magma reservoir, or lithosphere depth of about 56 km (or slightly more because no total collapse existed) can be estimated. The lithosphere was thick and robust and did not allow the volcanic load of central Syrtis Major Planum to sink very much as a whole. Only a slightly tensional near-surface environment was acquired resulting in the formation of small tensional grabens. The central area of Syrtis Major Planum has considered to have been sunken relatively little due to the volcanic load, drying up of the magmatic materials in the lower lithosphere and magma cooling-induced contraction. A volume decrease due to the cooling of the interiors may also have contributed slightly to the central collapsional environment. One part of the central compression is explained by collapsional processes below the surface.

3. Mare Ridges

The whole lava planum area is covered by extensive sets of reticulate mare ridges (Saunders *et al.*, 1981) which resemble the mare ridges on the Moon. The ridges are mostly linear and have only a slightly arcuate positive-relief topography (Figure 4a). A few major mare ridge arrangements can be interpreted. Some ridges seem to be radial to central calderas while concentric or tangential ones are also to be found. A set of linear ridges connects the two calderas. Ridges of the planum area may have some connection to the structures of the surrounding terrain. The possibility that there are also ridges somehow connected to the Isidis basin must a

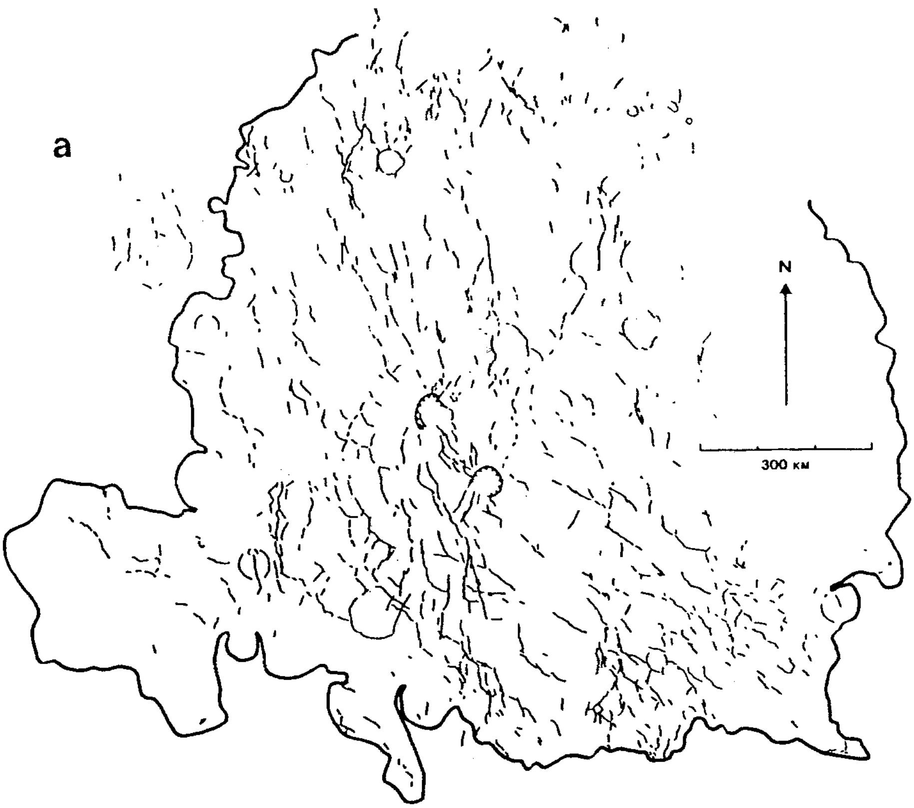

Fig. 4(a).

be taken into account. There are two possible explanations for the origin of mare ridges. Tensional explanations would involve mainly dyke protrusions into tensionally opened fractures (Fielder, 1965) while compressional ones emphasize thrust faulting of the subsurface layers (Raitala, 1982; Golombek, 1985) with additional deformation of the uppermost surface (Watters, 1988).

In order to study these mare ridges closer the Syrtis Major Planum area was divided into several subareas (Figure 4b). The mare ridges of these subareas were measured separately and presented in histograms for further analysis. In the orientation histogram of all mare ridges there is only one main peak indicating the symmetric orientation of these ridges in respect to N15° W (Figure 4c). The lack of NEE–SWW ridges is evident indicating the lack of conjugate mare ridges on the planum area. Thus, ridge formation may have been an areally, rather than globally, controlled process.

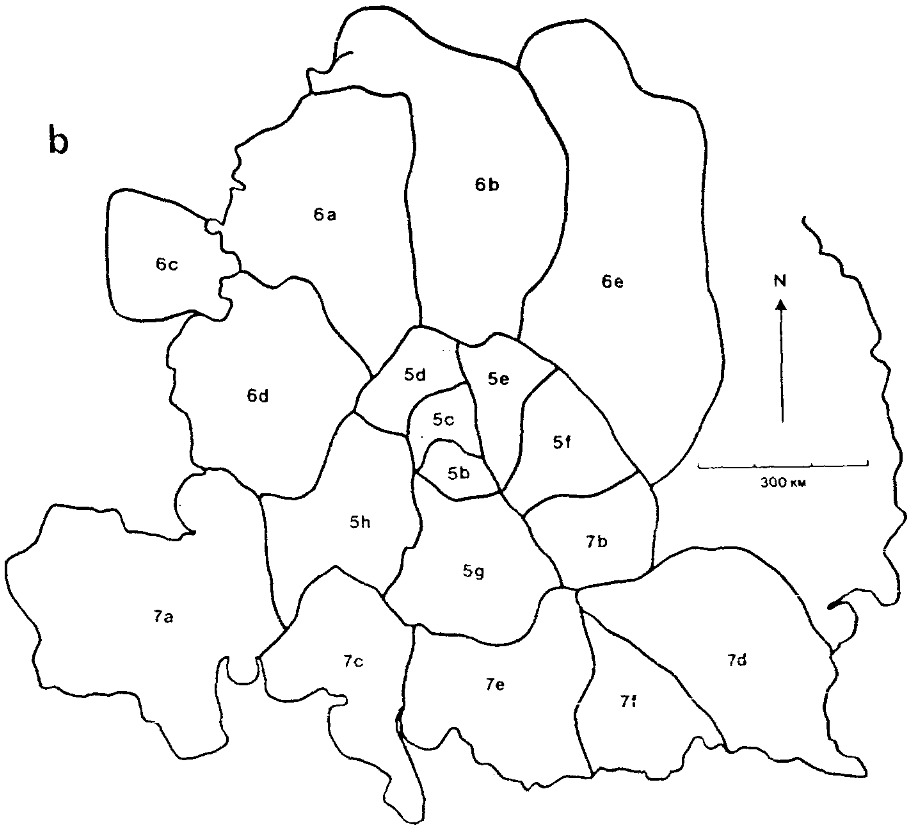

Fig. 4(b).

3.1. RIDGES CONNECTED TO CALDERAS

In the sum graph of mare ridge orientations within the central Syrtis Major Planum around the two calderas there is only one main peak indicating the symmetric N30° W to N30° W orientation of these ridges (Figure 5a). The lack of NEE–SWW ridges outside the main peak direction is even more obvious than in the total graph (Figure 4c).

Mare ridges between the calderas of Syrtis Major Planum are linear and slightly arcuate structures connecting the two collapsed areas together. The main distribution peaks for their orientation (Figure 5b) are at N10°–20° W and N30°–40° W. These ridges set between the two calderas are slightly curved like the field lines between two adjacent magnetic poles (Figures 4a, 5b). Although these mare ridges

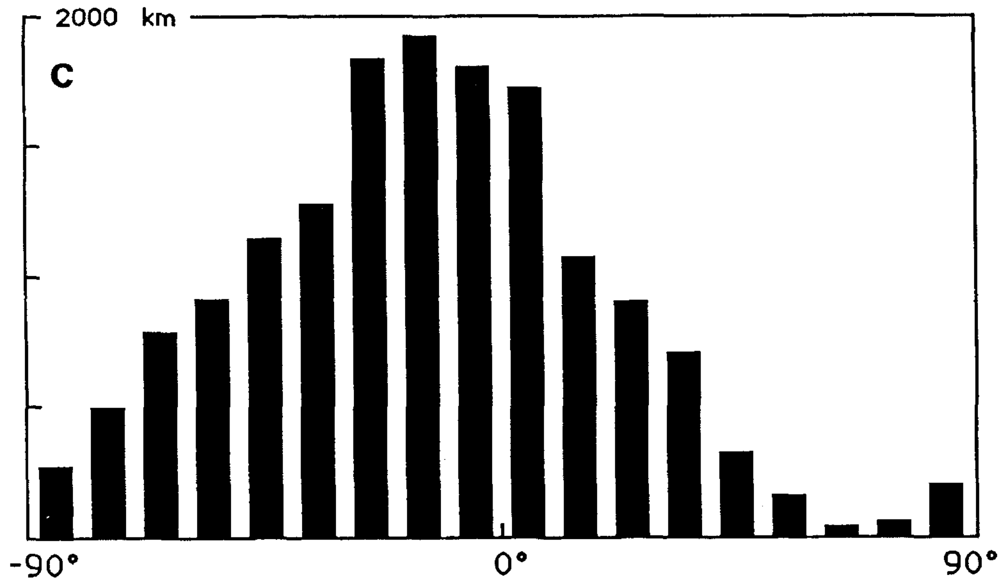

Fig. 4. The distribution of all mare ridge formations of Syrtis Major Planum (a; lines) are measured in several subareas (b; for subarea definitions refer to Figures 5, 6, 7) in order to obtain their combined total strike histogram (c).

can most probably be interpreted as tectonic structures rather than protrusion dykes, a caldera-related volcanic force has affected their development. Their tectonic control may have been connected to volcanic activity from within the calderas and the magma chambers below the uppermost surface. The ridges oriented between N10°–40° W indicate an even, radial compressional co-influence of the two volcanic pipes in the ridge formation.

There are also other mare ridges radial to both of the two calderas. The area just north of Nili Patera (Figures 4a, b, 5c) has linear radial ridges with a northeastern orientation peak at N10°–20° E while the northwestern area has radial ridge distribution peaks at N10° W and N40°–50° W (Figures 4a, 5c). Ridges northeast of Meroe Patera (Figures 4a, 5e) are mostly radial to Meroe Patera but the main peak is in the N–S direction. A certain share of ridges seems to belong to the radial mare ridge group also in areas east, south and west of Meroe Patera (Figures 5f, g, h, respectively).

Within the planum areas close to the calderas the radial ridge distribution peaks seem to be rather important. Ridge formation may have been affected by stress fields connected to calderas up to one hundred kilometres away (cf. the faint circumcaldera graben ring with the diameter value of 280 km). Ridges have also formed tangential or concentric systems which may have been controlled by caldera-connected forces. Concentric ridges are more abundant on the western side of the two calderas than in the east.

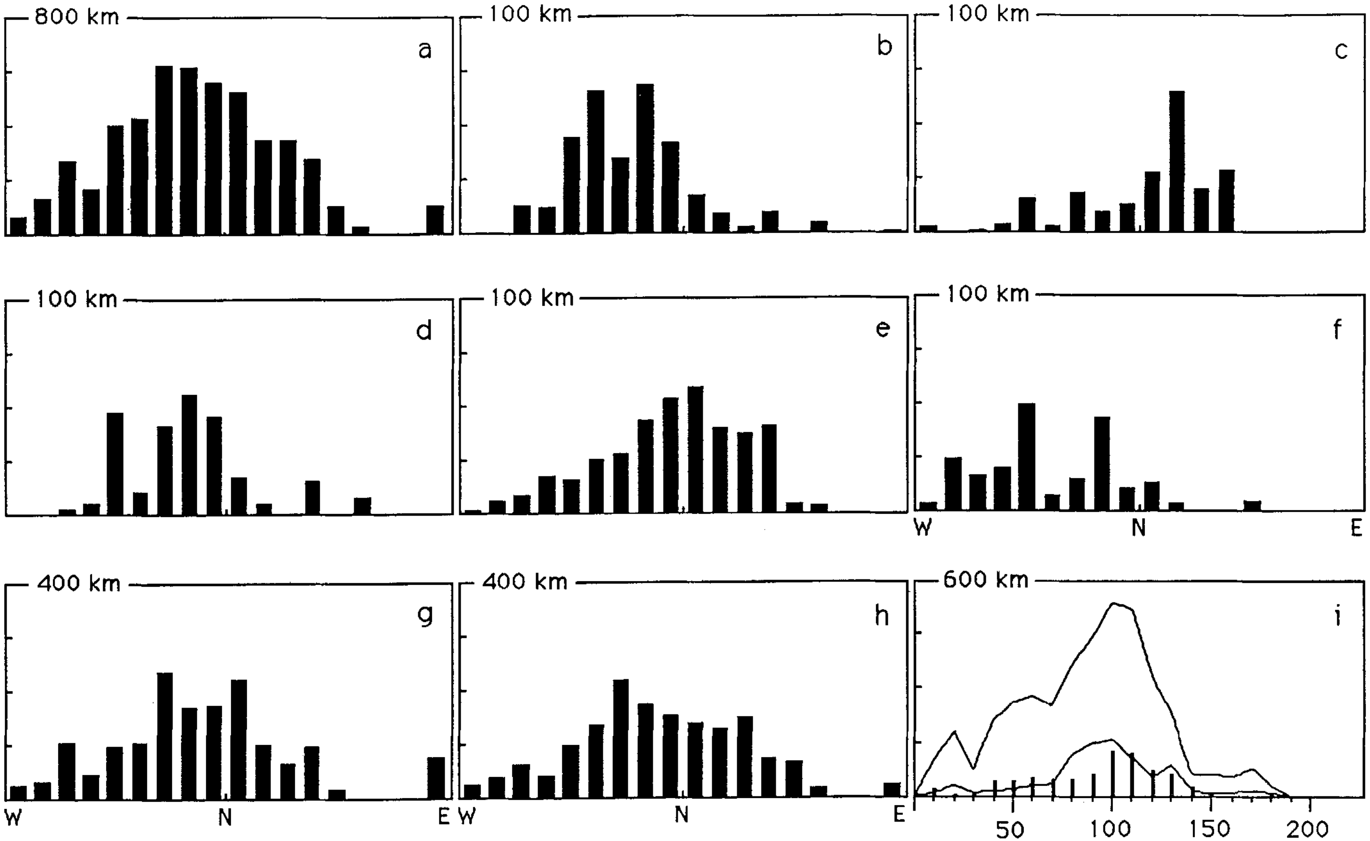

Fig. 5. The orientation of all central mare ridges (a) and that of the different subareas of central Syrtis Major Planum (b–h, cf. Figure 4b) around the two calderas are presented by histograms. The vertical cumulative ridge length scale varies and is indicated in the upper left corner of each histogram. Mare ridges related to the two central calderas are indicated by the diagram (i) which represents the distribution of all (the uppermost line) mare ridges around the calderas. Mare ridges radial (lower line) and concentric (bars) to the central caldera area seem to be most abundant approximately 100 km away from the reference point in the middle of the two calderas.

The stress field in the vicinity of the two calderas may also have been controlled by pre-existing zones of weakness. Major crustal stresses may have been guided by the processes in the magma reservoirs in large scale and thus also in the caldera collapses. The direct control of the mare ridge formation by developing calderas has been strongest between the two calderas and in the closest vicinity of the caldera area within distances related to the distance between calderas.

3.2. Main ridge orientations

In the middle northern part of the Syrtis Major Planum (Figure 4a, b) the ridges tend to be almost in the N–S direction (Figures 6a, b), giving an impression that they were radial to the calderas. This may, however, indicate an overall N–S trend of the northern Syrtis Major Planum ridges (Figures 6c, d, e). Close to the Isidis basin area the ridges are in the N–S direction (Figure 6e). Their orientation peak

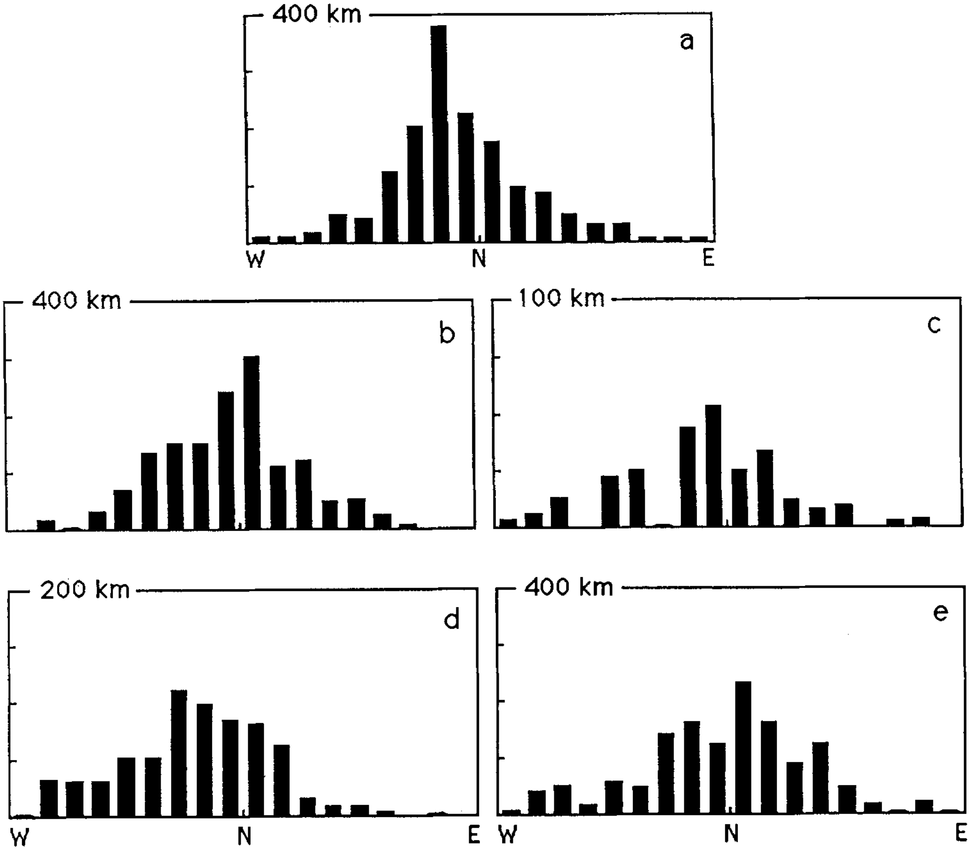

Fig. 6. The strike distribution of mare ridges in different areas on northern Syrtis Major Planum are presented by histograms (a–e, cf. Figure 4b). The vertical cumulative ridge length scale is indicated in the upper left corner of each histogram.

is at N5° E while the main distribution peak of all ridges is centered at N15° W (Figure 4c). Ridges are generally oriented as being part of the concentric Isidis Basin ring or large regional structures rather than having any connection to the calderas. This N–S direction is common throughout the whole northern Syrtis Major Planum (Figure 6b). Even within the cratered highland area west of Syrtis Major Planum the same N–S mare ridge orientation can be found (Figure 6c) indicating that this trend may have been caused by a wide regional force common over the whole northern planum. The mare ridge orientation within the northwestern planum is slightly more western with peaks at N10°–20° W (Figures 5d, 6a). The western area with the main ridge distribution peak at N20°–30° W has both of these trends (Figure 6d).

A N–S trend is also present in the southern Syrtis Major Planum (Figures 5g, h, 7a, b, e, f) although most ridges belong to the major NW–SE ridge group (Figures 5g, h, 7a, b, c, d, e, f). The histograms of all southern ridge groups

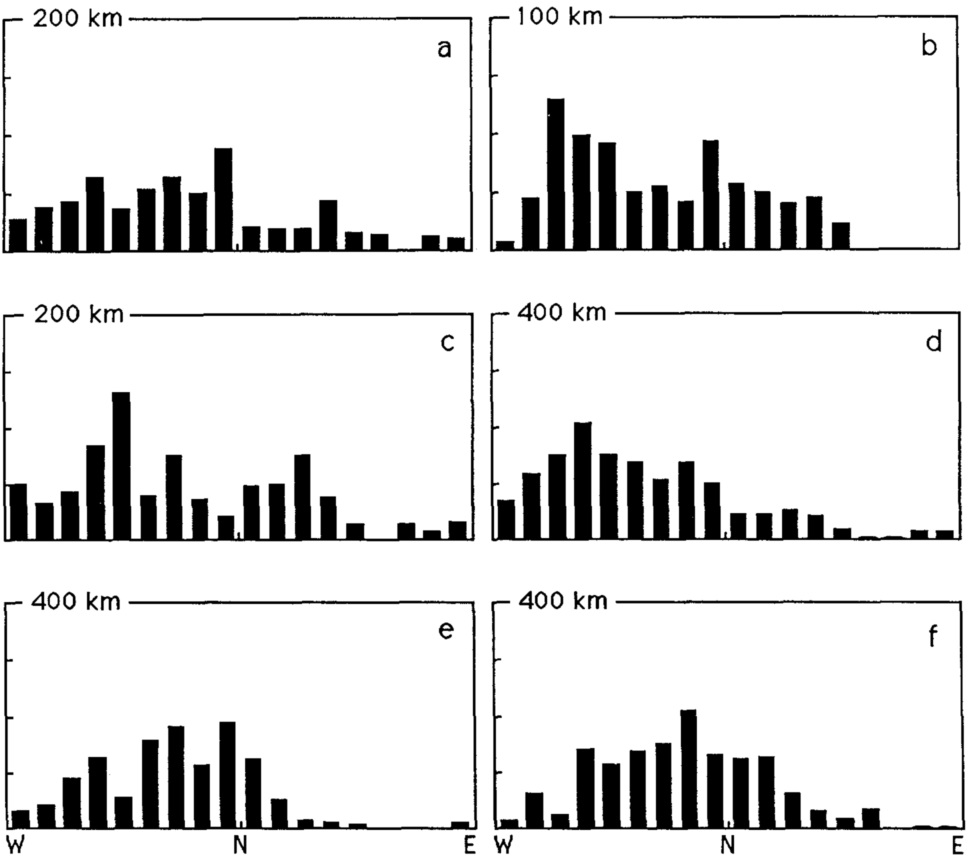

Fig. 7. The orientation distribution of mare ridges in different areas on southern Syrtis Major Planum are presented by histograms (a–f, cf. Figure 4b). The vertical cumulative ridge scale length varies as indicated in the upper left corner of each histogram.

display a common occurrence of NW–SE oriented ridges, the important peak of which is at N40°–70° W (Figures 7a–f). Mare ridges in the southwestern central areas (Figure 5g, h) have minor subpeaks at the same place, indicating a minor effect of the NW–SE ridges close to the calderas. The force related to radial and N–S ridges has been more effective in central areas. In the southern planum area the force effective in controlling the NW–SE orientation of mare ridges has been the most prominent. The N–S oriented ridges are, however, present in some areas (Figure 7a, b, e, f). The mare ridge orientation is very complex in the areas south to southwest of the two calderas and several competing trends exist there.

The appearances of mare ridges within Syrtis Major Planum seem to have been controlled by forces which favour the development of N–S and NW–SE ridges. The southern NW–SE trend may be connected to the similar tectonic trend extending from Hesperia Planum into the scarp-like Scopulus Oenotria on the cratered highland between the two plana and to the Phison Rupes scarp northwest of Syrtis Major Planum. In the middle of Syrtis Major Planum this major mare ridge orientation trend interferes with the N–S trend. In the close vicinity of the two calderas the mare ridge orientation has been more strictly controlled by caldera-connected forces. Within some subareas all these major trends tend to interfere, resulting in complex mare ridge patterns.

3.3. Compressional environment

Locating on the volcanic planum mare ridges seem to date from the late volcanic period of Syrtis Major Planum. Even if the possibility of their formation as dyke protrusions through tension gashes must be taken into account (Fielder, 1965), a more plausible explanation involves the compressional fault-like formation over tectonic zones (Raitala, 1982; Golombek, 1985) possibly also involving some folding of the surface strata over fault-induced bedrock (Watters, 1988). Late subsequent magma intrusions into zones of weakness may also have been obvious as a result but not as a reason for mare ridges.

The N–S ridges of the northern Syrtis Major Planum parallel the border against Isidis Planitia possibly indicating some influence of the Isidis Planitia basin. The most probable effect of the Isidis lava load has, however, been the concentric extensional fracturing of the peripheral areas as indicated by Nili Fossae. The existence of compressional mare ridges and the lack of major tensional structures between Isidis Planitia and Syrtis Major Planum may indicate that these two loads interacted as a single load. A continuous, uniform upper asthenosphere yielded as a whole under the load. This question of lacking tensional Isidis effect against the Syrtis Major Planum can be avoided if the lithosphere is considered to have been too thick and robust to yield under the surface lava load. This alternative explanation may slightly underestimate the influence of the Martian endogenic energy on the lithosphere. The effect of Isidis load in the concentric extensional fracturing of the Nili Fossae area indicates the importance of the relatively thin lithosphere in Isidis-related tectonics. A similar thin lithosphere condition may also have applied to the Syrtis Major Planum which has been affected by compressional tectonics.

4. Ridge Sets: Discussion

Syrtis Major Planum is not an impact basin but a large, low-profile shield volcano with an eastward facing slope and lacking a surrounding mountain ring. The origin of the slope is unknown but it may reflect the ancient topography. Low viscous magma intruded from the mantle resulted in the formation of magma chambers below Syrtis Major Planum and in adjoining frequent extrusions.

Mare ridge units indicate the deformation of the uppermost planum unit which was foiled by the lava flows. The pattern of N–S and NW–SE oriented mare ridge formations cross-cut each other and have been originally controlled by the same or related compressional forces (Figure 8). These crossing ridge sets indicate the existence of a compressional sum force in the NNE–SSW direction or radially to the Isidis basin. Syrtis Major Planum has been pushed from the east and west (N–S ridges) and from the northeast and southwest (NW–SE ridges). In the northern planum the N–S mare ridge pattern is approximately along the topographic contour lines. These N–S oriented mare ridges indicate E–W stresses perpendicular to the topographic contours. Within the southern planum the ridges have a NW–SE orientation along the contours and the evident stress direction has been NE–SW. These two trends cross-cut each other in the middle of the Syrtis Major Planum where mare ridges radial and concentric to the central calderas are also scattered within the megacaldera area around Nili and Meroe Paterae (Figures 2, 4a). The radial and concentric mare ridge arrangements favour the importance of compressional caldera events in the middle of the planum. In places the middle planum is heavily patterned by the superposed ridge sets which makes the resulting mare ridge pattern very complex.

The NE–SW compression which caused the NW–SE oriented mare ridges was the most important tectonic phase within the southern planum. These ridges may be concentric to the Isidis Planitia basin. The southern ridges are also located on the northeastern side of the large regional major fault zone extending from Hesperia Planum up to Vastitas Borealis. The southeastern ridges parallel this Scopulus Oenotria – Phison Rupes fault. This zone consists of distinct mare ridges and additional highland lineaments and scarps. The NE–SW compression connected to this fault zone may have resulted in the formation of the NW–SE ridges of the southern planum area. The activation of the fault zone could have increased the NE–SW compression over southern Syrtis Major Planum. The NW–SE lineament trend is strictly connected to Scopulus Oenotria in the south and to Phison Rupes in the northwest. In the middle part of Syrtis Major Planum, mare ridges tend to deflect to the NNW–SSE direction and become mixed with central caldera-related ridges. In the north the compression turned to a more E–W direction, possibly due to the local topography. This E–W compression then resulted in the northern

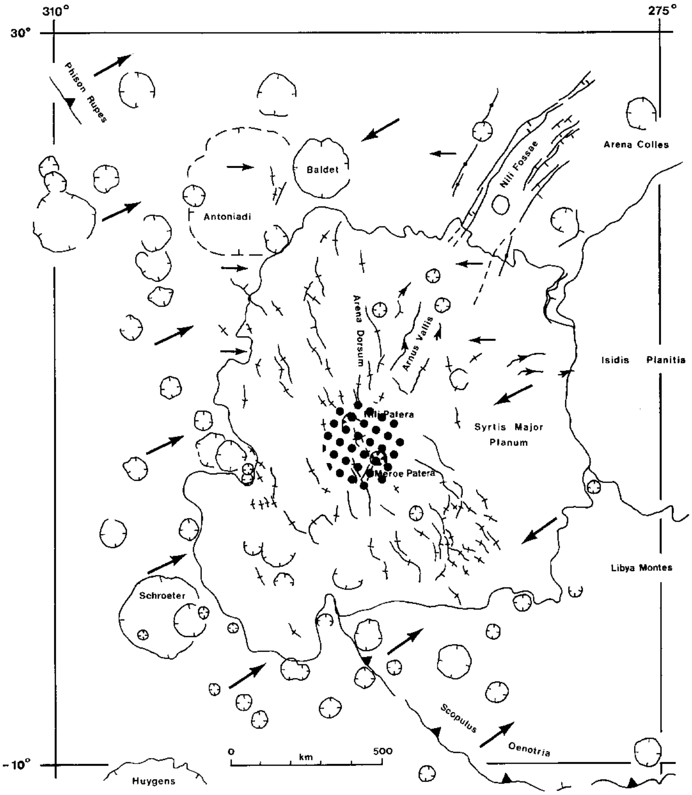

Fig. 8. Simplified tectonic sketch of the area studied showing main stresses and tectonic phases of Syrtis Major Planum. Endogenic activity resulted in formation of shallow magma chambers below Syrtis Major Planum. When these magma chambers continued to grow they reached such dimensions and thin roofs which resulted in the caldera collapses. The caldera activity had deep roots below the uppermost crust where endogenic energy from the mantle decreased lithosphere thickness and increased igneous activity until this prolonged activity resulted in megacaldera formation (dotted area). The lava load, ceased support of the decreasing endogenic activity, and the cooling and contraction of the hot interiors thus resulted in sinking of the central Syrtis Major Planum megacaldera and in formation of extra compression within its interiors. The caldera-related deformation within the central caldera area was then superposed on compressional forces supporting the idea of the main NW–SE compressional mare ridge structures parallel to the Scopulus Oenotria – Phison Rupes fault zone (large arrows). The local buried and slope topography may have influenced the stresses within the northern planum area (small arrows).

N–S mare ridge formation parallel to the topographic contours. These mare ridges may also represent a topographic subsurface trend concentric to the Isidis Planitia basin.

Located along an Isidis-centered ring (Schultz, 1984) in the junction of the mare ridge zones and in the centre of Syrtis Major Planum the calderas can be seen as part of the volcano-tectonic development of the whole area. The most important signs of tensional tectonics outside the local grabens on caldera walls form a faint

280 diameter circle around the calderas. Mare ridges of the middle Syrtis Major Planum area have a partly NNW–SSE orientation (Figures 5a, b, g, h), but all near-caldera areas display the importance of radial and concentric mare ridge patterns. The slightly arcuate occurrence of mare ridges between the two calderas makes them resemble magnetic field lines on the planum surface. The rooves of the two shallow magma chambers collapsed in connection to pressurized volcanic activity from these near-surface magma chambers. These two collapses were followed by a collapse of the whole central area resulting in the central megacaldera formation. The formation of radial and concentric mare ridges took place when these central lava-loaded areas of Syrtis Major Planum were shortened and compressed due to caldera activities and collapses. The central area has sunken in connection to its lava load and internal magmatic development. In the centre of Syrtis Major Planum surface collapses connected to pressurized volcanic activity from near-surface magma chambers resulted in two caldera collapses. Radial and concentric mare ridges of the middle planum area manifest the existence of radial force around the calderas and the dynamic development of the Syrtis Major megacaldera.

Major endogenic processes and activity can be established when considering the development of Syrtis Major Planum. Thermal roots, the cooling and drying up of magma chambers and isostatic compensation must be taken into account before a model of the development of calderas and mare ridges of Syrtis Major Planum can be acquired. The dynamic support of the upper asthenosphere decreased with the decreasing endogenic activity. Planum defined a compressional crustal unit over the cooling and drying asthenosphere. Mare ridges parallel to the contours support the idea of a main SW–NE compression phase. The local slope direction within the northern area changed the stress field to an E–W direction. The volcano-related deformation around the two calderas is superposed on this compression. Thrust faulting of the bedrock below the regolithic interlayer and the uppermost lava surface was involved. Even though some extrusions and bending of the near-surface layers may have taken place (Watters, 1988) compressional faulting has been the most effective factor in the mare ridge formation, leaving folding and dyke protrusions to play a minor role.

Acknowledgements

The Viking photographs were provided by NASA. The work was supported financially by a grant from the Finnish Cultural Foundation.

References

Fielder, G.: 1965, *Lunar Geology*, Lutterworth Press, London.
Golombek, M. P.: 1985, NASA **TM-87563**, 485–487.
Greeley, R. and Spudis, P. D.: 1981, *Rev. Geophys. Space Phys.* **19**, 13–14.
Gudmundsson, A.: 1988, *Geology* **16**, 808–810.

Meyer, J. D. and Grolier, M. J.: 1977, *Geologic Map of the Syrtis Major Quadrangle of Mars*, USGS Map I-995.
Mutch, T. A.: 1970, *Geology of the Moon: A Stratigraphic View*, Princeton University Press, Princeton, New Jersey.
Raitala, J.: 1982, *Tectonics of the Lunar Oceanus Procellarum Area.* Acta Universitatis Ouluensis, University of Oulu, Finland
Raitala, J.: 1987, *Earth, Moon, and Planets* **38**, 137–147.
Raitala, J.: 1988, *COSPAR 27th Plenary Meeting, Espoo, Finland, Abstracts* p. 280.
Saunders, R. S., Bills, T. G., and Johansen, L.: 1981, *Lunar Planet. Sci.* **XII**, 924–923.
Schaber, G. G.: 1977, *Geologic Map of the Iapygia Quadrangle of Mars*, USGS Map I-1020.
Schaber, G. G.: 1982, *J. Geol. Res.* **87**, 9852–9866.
Schultz, P.: 1984, *Lunar Planet. Sci.* **XV**, 728–729
Scott, D. H. and McDonald, T. F.: 1984, *Lunar Planet. Sci.* **XV**, 738–739.
Soderblom, L. A., West, R. A., Herman, B. M., Kreidler, T. J., and Condit, C. D.: 1974, *Icarus* **22**, 239–263.
Watters, T. R.: 1988, *J. Geophys. Res.* **93**, 10236–10254.
Wichman, R. and Schultz, P. H.: 1988, *Lunar Planet. Sci.* **XIX**, 1266–1267.