COMPOSITE GRABEN TECTONICS OF ALBA PATERA ON MARS

JOUKO RAITALA

Department of Astronomy, University of Oulu, Oulu, Finland

(Received 17 May, 1988)

Abstract. The Alba Patera main graben zone is radial to the Tharsis bulge, indicating the importance of the Tharsis bulge-related peripheral rift tectonics. The concentric grabens around the Alba Patera area are also partly caused by crustal bending due to the central load of the Alba Patera volcano. These two graben sets partly coincide forming composite structures. Both tectonic systems were still active after the last major volcanic lava extrusions took place. After this, the crater chain grabens, radial to the northernmost part of the Tharsis bulge were formed. These collapse craters were evidently caused by the late-tectonic forces due to the northern Tharsis and adjoining lava loads, resulting in flexural tension and activating previous faults.

1. Introduction

As a part of the major Tharsis area, Alba Patera (Figures 1, 2) represents the northernmost part of the Tharsis-related plume activity (Raitala, 1985; Raitala and Saunders, 1986). The horizontal surface dimensions of Alba Patera make it one of the largest volcanic structures on Mars (Carr *et al.*, 1977; Carr, 1980; Greeley and Spudis, 1981) although its general topographic relief is low rising only few, possibly 4 to 7 kilometers over the surrounding areas (Carr, 1976, 1980). The diameter of the central area of Alba Patera is about 500 km, but lava flows may extend 900 km from its center.

The Alba Patera volcano is located in the middle of an almost 3000 km long graben-horst zone which is approximately radial to the Tharsis bulge (Figure 2). These grabens denote, together with other similar zones, the borders of lithospheric blocks radial to the Tharsis bulge (Raitala, 1985). Some of the graben faults form slightly arcuate structures around the Alba center (Carr, 1973; Greeley and Spudis, 1981). The wide areal graben fractures, mainly oriented N-S to NE-SW, tend to bend especially on the northwestern, southwestern and eastern side of the volcano. The grabens are much more numerous on the eastern side and they tend to be oriented in a slightly complex manner (Scott and Tanaka, 1980), possibly indicating the complexity of the previous stress fields (Wise, 1976).

The motivation for this study stemmed from a need to understand and characterize the tectonic events that have taken place on Mars. The Alba Patera area consists of several volcanic and tectonic formations of different age and generation (Plescia and Saunders, 1979; Carr, 1980; Neukum and Hiller, 1981), and these complicate structures graphically display a part of the diversity of Martian tectonics. The paper is focusing primarily on descriptions of tectonic structures and the development of Alba Patera in order to understand the tectonic framework (Raitala and Saunders, 1986) of the area.

Earth, Moon, and Planets **42** (1988) 277–291.

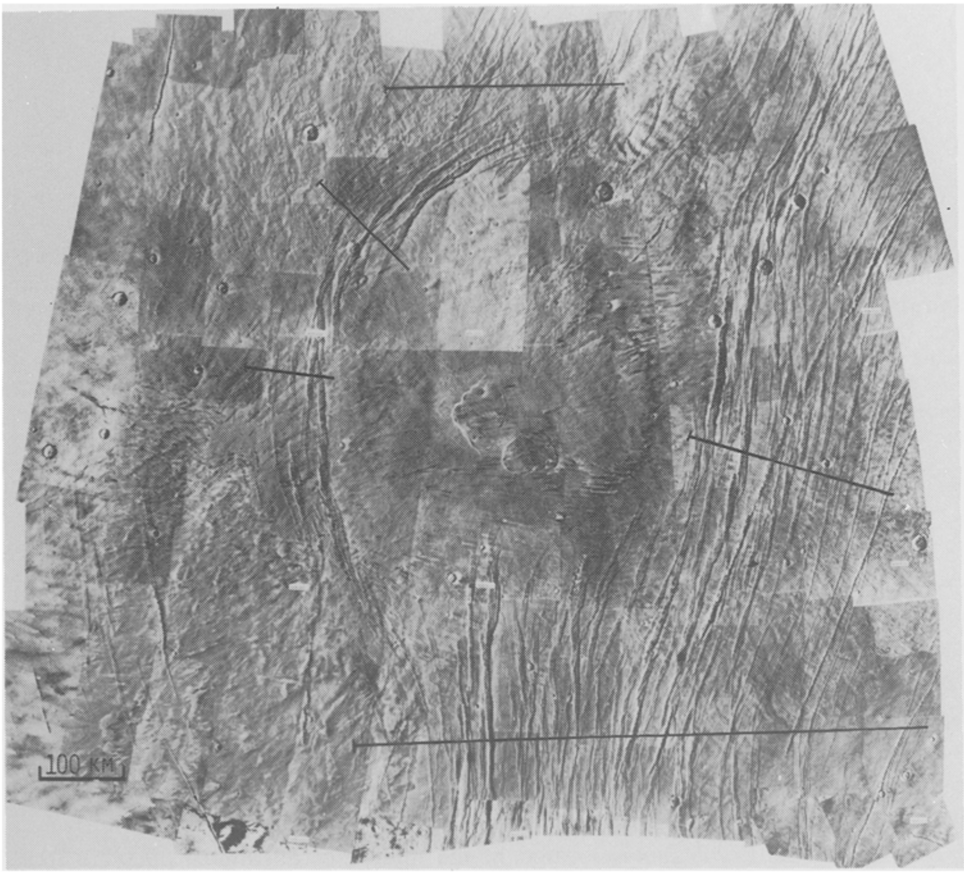

Fig. 1. Photomosaic of Alba Patera compiled by using the USGS MTM mosaics 35102, 35107, 35112, 35117, 40102, 40107, 40112, 40117, 45102, 45107, 45112 and 45117. The location of cross-sections in Figure 4 are indicated.

2. Graben Zone Structures

The graben zone of Alba Patera consists of several different parts (Figure 2). The southern unit, Ceraunius Fossae is radial to the main Tharsis bulge and divided into parts by younger lava cover (Scott and Tanaka, 1980). Ceraunius Fossae seems to consist of elevated and faulted islands which are surrounded and penetrated from the borders by lava floods. In particular, both north and south ends of the Ceraunius Fossae first merge and then gradually disappear due to lava fill near Alba Patera and Tharsis area near Ascraeus Mons (Figure 3), respectively. South of Alba Patera the graben structures are oriented mainly in a north-south direction. The Ceraunius Fossae islands are best characterized as a relatively rough ancient volcanic flow and ejecta debris material. The crater density varies with the degree of volcanic resurfacing.

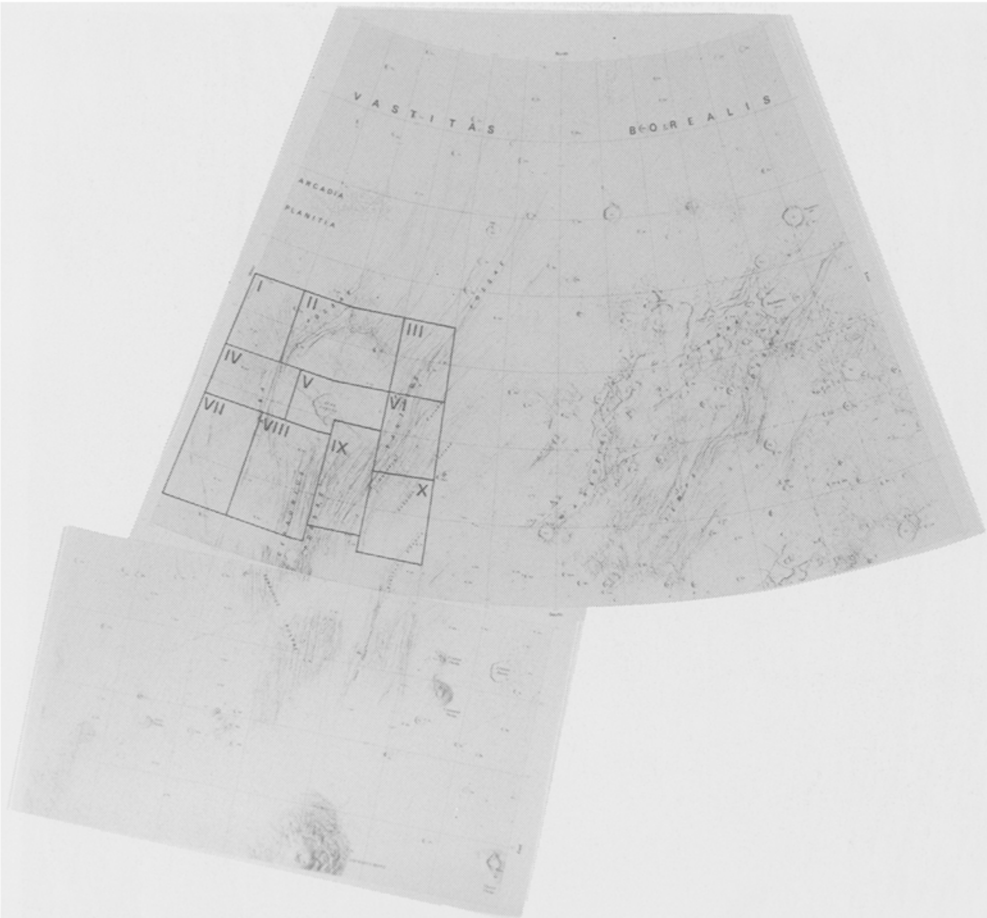

Fig. 2. Composition of USGS shaded relief maps I–926 and I–963 displaying the wider Alba Patera area together with Tempe Terra and northern Tharsis. Compare the length of the Alba Patera graben zone to the dimensions of the Alba Patera volcano. Within Tempe Fossae there is a minor volcanic centre with some surrounding arcuate grabens. Subareas for graben measurements (Figures 8, 9) are indicated by I-X.

Most of the graben structures of Ceraunius Fossae are restricted to within the relatively large blocks of older surface embayed and partly buried by various younger flows (Scott *et al.*, 1981a, b). Some small graben faults cut to some extent through nearby younger units (Figure 3) indicating the relative young age of these faults and the existence of a time sequence in the graben formation. Within the Ceraunius Fossae there are some distinct grabens with a crater chain on the bottom; they have mainly northern orientation. The longest one, called Tractus Catena, has a north-south orientation which bends to the northeast-southwest direction when crossing flow units (Scott *et al.*, 1981a, b) east of Alba Patera and north of the Ceraunius Fossae. Several similar crater chain grabens exist in the Alba Patera area (Figure 2).

When approaching northward closer to the volcanic center of Alba Patera, the

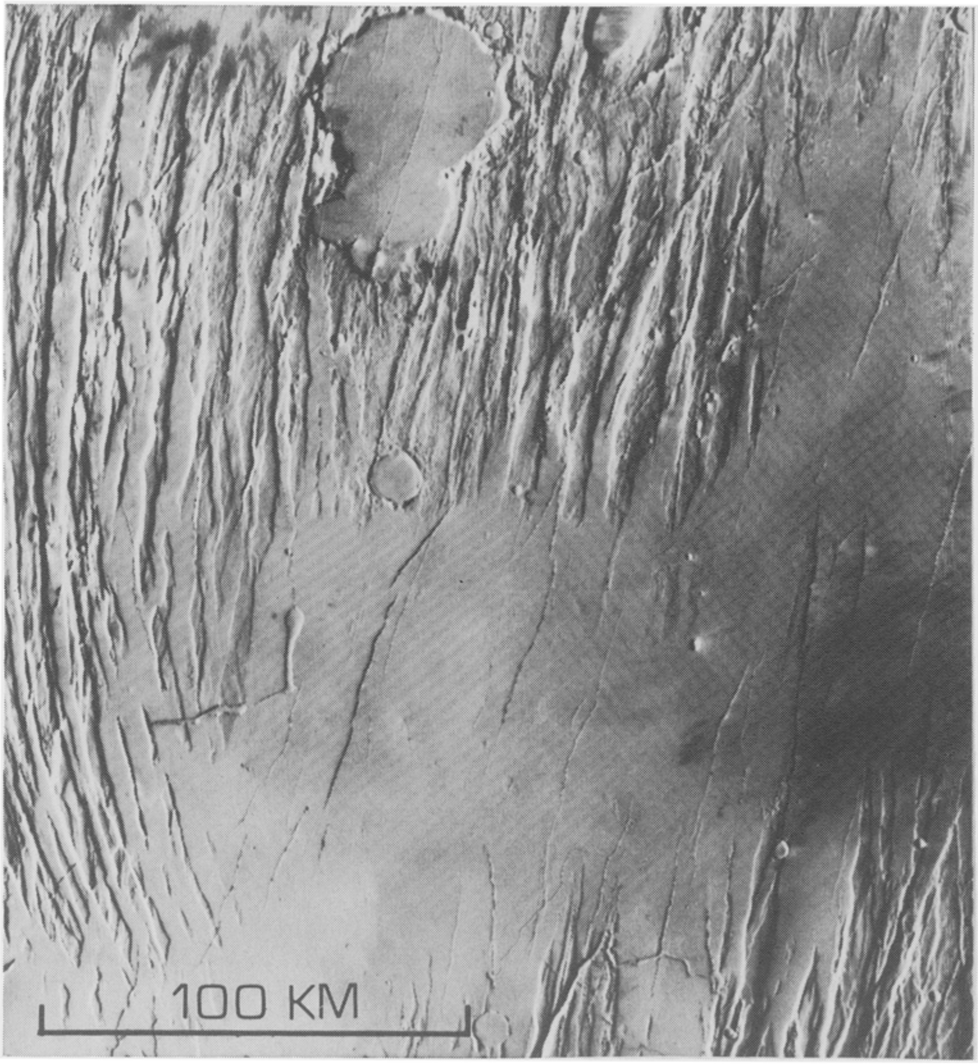

Fig. 3. Relatively young lava plains cover low areas of Ceraunius Fossae partially filling its old graben structures which belong to the main Alba Patera graben zone. Young grabens on the lava plain may belong to the late Tharsis-load-induced flexural tensional tectonics described by Banerdt *et al.* (1982). NASA/Viking 516A10.

graben rilles divide into three. The middle graben faults with almost north-south trend tend to continue straight through the Alba Patera summit area. At a distance of about 60 km south of the main summit caldera even the most extensive graben structures become filled. Just south of the summit caldera there are only a few faint hints of grabens buried by extrusives (Figure 1).

This middle graben zone continues further on the northeastern side of Alba Patera, having there a NE-SW direction. It has, however, been buried much more extensively on the northern side of the Alba Patera volcano (Cattermole, 1986). The faults of this middle graben section first appear about 175 km northeast of the main summit caldera. The direction of the grabens in this northeastern middle section is radial to the Alba Patera center as is the case of the grabens of the southern middle section (Figure 1).

The western set of graben structures, Alba Fossae, tends to form a beautiful double-bow system of arcuate fault-bounded graben depressions. These arc sets begin with NNW-SSE oriented graben structures southwest from Alba Patera and west of the northern Ceraunius Fossae (Figure 1). There are a small number of grabens in the outer arc at a distance of approximately 350 to 500 km from the central caldera. The bottoms of some of these grabens are marked by crater chains with an orientation of about N15°–20° W. The course of this outer arc is best defined in the southwestern part but there is also a well-preserved N-W crater chain graben northwest of Alba Patera. The outermost western arcuate graben set cuts several relatively freshlooking lava flow tongues but it has also been buried by volcanic material within the area just west of the Alba Patera summit (Figure 1).

The inner western graben arc, Alba Fossae, consist of a set of more continuous graben depressions. Southwest of Alba Patera this innermost graben arc begins with a deflection of the westernmost Ceraunius Fossae graben to make a detour past the central area of Alba Patera. In places, this western inner graben set consists of graben segments which interconnect to form large arcuate grabens. There are only a few graben fault cross-cuttings in the southern area. The cross-cuttings are more frequent north of Alba Patera where the western inner arc tends to take on an almost NEE-SWW direction across the near-Alba-Patera-end of the NE-SW oriented grabens of the middle graben zone. The graben depressions just west of the summit of Alba Patera (Figure 1) have been at least partially covered by lava flows, similar to the lava coverage over the graben in the outer arc. After extrusion of lava, graben faulting was repeated causing new faults through the lava flows, especially along the graben nearest Alba Patera. The episode of main graben formation also postdates the extensive lave flows in the northwestern and southwestern part of the Alba Patera (Figure 1).

The eastern set of graben structures, Tantalus Fossae, consists of two parts. One tends to be concentric to Alba Patera resembling the western inner arc system. The majority of grabens in Tantalus Fossae is oriented in a NNE-SSW direction similar to the graben structures of the northern middle set and the orientation of the crater-chain-bottomed grabens of northern Tractus Catena. The concentric and NNE-SSW trends of the graben structures do, however, intermingle. Within the southwestern area they have approximately the same course. Their directions differ only east and northeast of Alba Patera, while farther north most grabens again trend along the middle set.

The northeastern course of grabens is essential to the Alba Patera graben system. Both the northern graben zone and the northern Tractus Catena have approximately similar northeastern orientation and there are also two more crater-chain-bottomed graben structures between them: the N25°–35°E oriented Phlegethon Catena and the N30°E oriented Acheron Catena. Both of these crater-chain-graben structures penetrate from northeast through the parts of Tantalus Fossae concentric to Alba Patera. There are also several parallel shorter graben structures with crater chains. The extreme northeastern ends of Tractus Catena, Acheron Catena, Phlegethon Catena and Tantalus Fossae are approximately parallel to Tempe and Mareotis Fossae.

The parts of the Tantalus Fossae concentric to Alba Patera consist of several parallel arcuate grabens forming a zone with a width of slightly less than 200 km. The grabens closer to the Alba Patera center are slightly more concentric and deeper or wider than more distant grabens which tend to follow the approximate courses of Acheron Catena and Phlegethon Catena and, likely, have smaller measured depth and width. The grabens closest to the Alba Patera are, however, not so distinct due either to partial filling or to less intensive faulting. The eastern graben structures closest to the Alba Patera summit are about 100 km east of the summit caldera. The distance between the caldera and the deepest or widest concentric graben is less than 200 km. The set of concentric arcuate grabens northeast of Alba Patera tends to bend again to follow the NE-SW course of the northern middle graben zone.

There are intense, cross-cutting graben faults in two areas within the Tantalus Fossae–Tractus Catena area: (1) just east of Alba Patera where the concentric graben pattern crosses the Acheron-Phlegethon Catena graben pattern, and (2) to the SSW of Alba Patera where the faults of both eastern concentric and straight patterns penetrate into the northeastern Ceraunius Fossae. The complicated pattern of graben faults allows very few conclusive interpretations of the fault slip directions to be made.

Both the NE-SW-oriented and concentric graben faults cut through the youngest lava flow tongues, particularly within the southeastern part of the eastern graben zone (Figure 1). Graben depressions do not seem to have deflected any major lava tongue from the assumed, approximately radial downslope flow. The relatively weak appearance of the grabens nearest the Alba Patera center may, to the contrary, be the result of either partial filling or less extensive faulting, or both.

The Ceraunius-Alba-Tantalus graben system is at least 3000 km long and up to 900–1000 km wide depending upon whether or not Tractus Catena is included. The volcanic edifice of Alba Patera is located approximately in the middle of the graben system. The diameter of the innermost concentric graben is 450 km. The surface area influenced by Alba Patera lava flows is at least 1500 km wide.

The huge dimensions of the graben system with respect to the main Alba Patera area, and the fact that only part of the graben structures appears to have been locally deflected from the main course to form the concentric pattern around the central Alba Patera suggests that the graben system is a primary tensional linear structure, like a rift on which the Alba Patera volcano is locally imposed indicating the effectiveness of Martian endogeneous forces. The dimensions of the graben system indicate the existence of mantle-related activity over a wide area, while Alba Patera denotes the importance of more local mantle-induced volcanic activity in the crest of the graben zone.

3. Graben Measurements

Graben depths and widths were measured along certain lines across the graben zones (Figure 1, 4). The cross-section was chosen through the Ceraunius Fossae just south of Alba Patera approximately along the 35th northern latitude. Two more measurement lines were chosen across the inner western graben arc west and northwest of Alba Patera. A fourth cross-section was measured through the eastern-southeastern graben complex. We also intended to measure a line across the northern main graben zone but poor resolution over the northeastern Alba Patera region, caused possibly by clouds or haze, made measurements too inaccurate for more than partial coverage across this zone. All measurements were performed from the U.S. Geological Survey's photographic MTM-mosaics in the scale 1:502 000.

Besides the determination of the location of graben-connected faults and the width of the grabens, the widths of the sun and shadow areas caused by the sun-facing and shadow-lying slopes were measured to estimate the depths of grabens.

The determination of rim locations and widths of grabens is straightforward except for the uncertainty caused by unidentifiable details in areas of too bright sunlight or too dark shadow. Monoclinal faults and the asymmetry of grabens may also cause minor variations in interpretations. In spite of that, Figure 4b effectively illustrates the distribution of numerous multiple grabens along the measured cross-sections.

Figure 4a illustrates the distribution of the largest and widest grabens of Ceraunius Fossae immediately south of Alba Pateral, an area with numerous multiple, overlapping faults. A few of the grabens have either a large width or depth, or both. The majority of the grabens seem, on the other hand, to be relatively similar in size often consisting of segments parallel to one of the main grabens.

Other cross-sections reveal a different situation (Figure 4 (NW, W, SE)). Here with widest and deepest grabens are in the middle of the measured zones. Widths and depths decrease more abruptly near the Alba Patera end of the cross-sections and more gradually with increasing radial distance from area of the most extensive grabens. In the case of arcuate rilles, the most extensive graben formation has taken place relatively near the Alba Patera central massif. This is particularly apparent within the southeastern line. The western inner graben arc is, however, quite narrow. The lack of grabens further away Alba Patera may indicate the same phenomenon. The slightly asymmetric western location of Alba Patera on the main graben zone and the evident importance of the NE-SW direction of grabens on the eastern Tantalus Fossae areal, as indicated by faults parallel to Phelegethon, Acheron and Tractus Catena, may have caused the more extensive and wider appearance of the graben zone and its more gradual disappearance on the eastern side of Alba Patera. Part of the asymmetry may be explained by more extensive volcanic coverage within the western area. This does not account for the major difference between areas because the majority of graben formation seems to have taken place after most of the volcanic activity.

In Figure 4 the influence of graben faults on surface topography is illustrated by

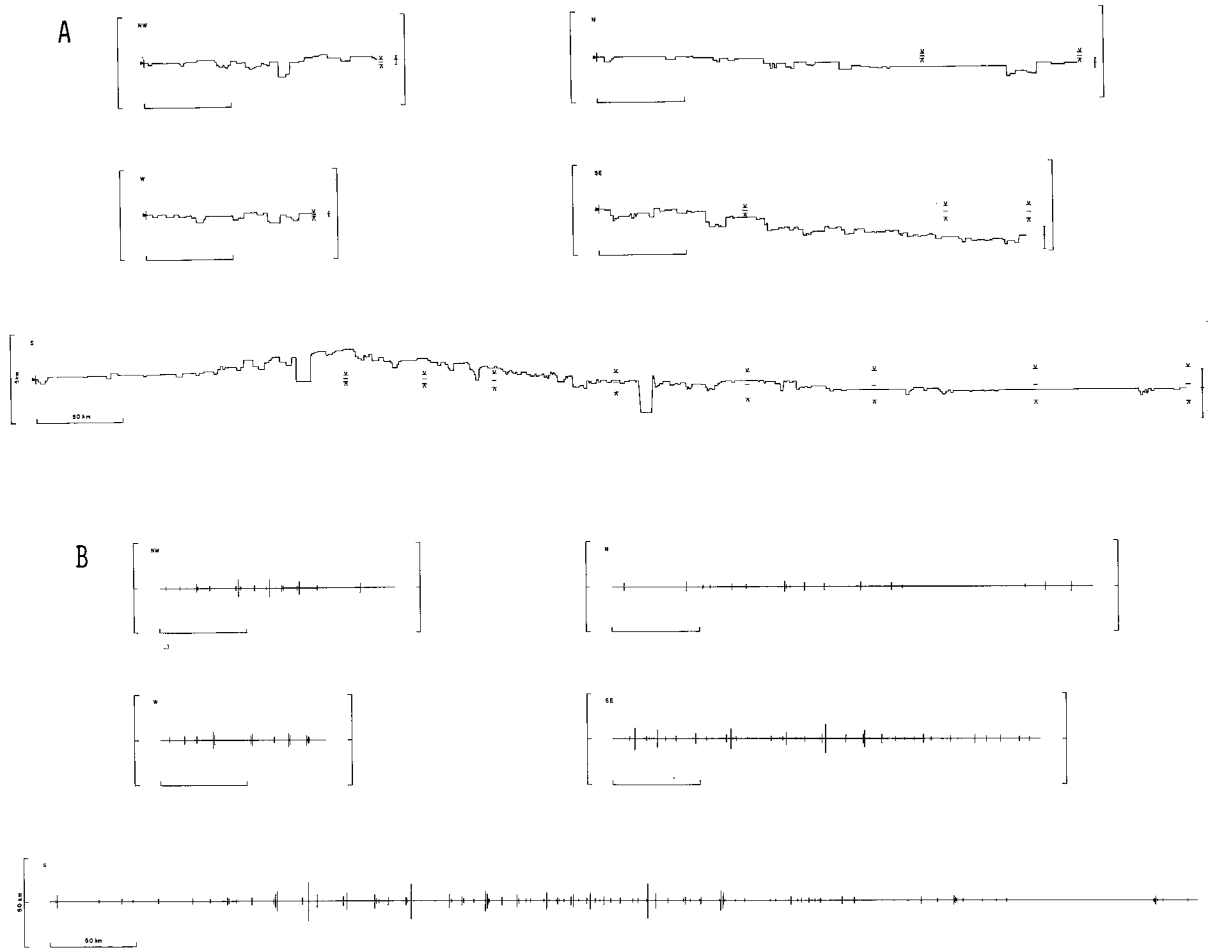

Fig. 4. Cross-section across the graben system of Alba Patera determined by the means of shadow and bright side measurements. NW, N, W, SE, and S indicate the cross-sections across northwestern, northern, western, southeastern, and southern grabens, respectively (see Figure 1). Because of the additive nature of the cross-sections, the level accuracy decreases from left to right. Three reference levels indicated by the barbs were adopted by assuming that there are two points on the same level along cross-section S. This assumption does not affect the existence of a dome-like bulge in the middle of cross-section S within the area with most extensive graben formation, but only its dimensions to the east. The cumulative error bar for the height measurements at the eastern end of each cross-section is given on the right beside the 5 km scale. b) The width of grabens along the same cross-sections is given by crosslines located at the centres of grabens; these indicate the locations of the most prominent grabens which are sometimes difficult to interpret because of the existence of multiple graben faults in the same area.

drawing the height obtained by measuring bright and dark slopes to produce a cumulative curve from the left (west) to the right (east). This kind of presentation should, in principle, reveal how the surface topography is influenced by graben formation, or how surface topography and graben formation are affected by some process of internal origin.

There are, however, difficulties when trying to display the effects of graben formation with the aid of fault height measurements: (1) if the faults are step-like, the measured width of the bright slope tends to become too large; (2) the widths of both shadow and bright slopes are difficult to measure exactly. The width of the shadow depends on the contrast between the shadow and the bottom and crest areas and on the ability to determine the edges of the shadow. Measurements of the width of bright slopes depend on the slope angle, erosional rounding of the fault crest, width and angle of talus formation, uniformity of the slope angle both across one fault and across all faults, and on the ability to determine precise locations of edges of slopes through all measurements. When compiling this kind of information, all other surface slopes must be omitted. Furthermore, it must be assumed that the reference levels on the bottoms of grabens and on surfaces of horsts are horizontal. Because all surfaces except the measured faults are assumed to be level, the graph obtained does not indicate the real surface but only the influence of graben faulting on the relative surface levels. Fault heights, obtained by measuring the width of the shadow, depend on the accuracy of the measurement, and on the height of the sun in the sky. Both these have been taken into account as well as the fact that the sun angle varies.

The main problem with these measurements is lack of knowledge of the fault angle, leading to uncertainties in bright side height values. A fault angle of 60° appears to be reasonable (Wise, 1976; Golombek, 1979). This assumed degree value does, however, not influence the shape of the measured cross-section but only decreases or increases the relative topography. The errors caused by uncertainties in the height values in measuring widths of bright and shadow regions are diminished somewhat in the southern transsection by assuming that, two points in different parts of the cross-section are on the same level. Because the existing topographic data do not allow a specific point to be chosen, three different comparison levels were chosen for display of the relative topographic differences induced by faulting. The same reference levels were used to calibrate measurements through other cross-sections.

The choice of the first reference level was based on the assumption that the western end of the southern cross-section and a symmetrical eastern point across the main Ceraunius Fossae should be on the same level with respect to the fault heights. The middle reference level assumes that the point at which the density of grabens tends to decline would be on the same level as the western end of the line. The lowest calibration level assumes that there is a point at the same level much further to the east. This assumption does not imply the existence of positive or negative topography, but only offers a few reference surfaces for comparison of the effects of measured fault heights. Because the complication of the fault height curve is made cumulatively from the left (west) to the right (east), the possible measurement errors also accumulate towards the eastern end as indicated by the error bars in each graph.

The southern cross-section has a bulge in the middle according to the fault height measurements. The existence of the bulge indicated by the fault-height measurements does not depend on the calibration level chosen nor does it disappear within error bars. Only the width of the bulge is uncertain because estimations of the level of the easternmost part are strongly influenced by the calibration level which has been chosen and disturbed by the big error bars. This bulge displays only the fault height induced effects on the surface topography. If there are any other sloping surfaces besides the graben faults, they also affect the existing topography in a way that has not been taken into account in this survey. Investigation of such more gentle slopes that do not cause shadows or bright reflections should be done using photometric or photoclinometric studies. In this situation, these techniques are also complicated by the variety of surface materials and the existence of numerous fault-related slopes.

Close inspection of the other measured and similarly calibrated cross-sections reveals the existence of a relatively steep fault-induced eastward facing slope along the southeastern line. This slope remains valid even after involving all three calibration planes and the error bar. The two cross-sections on the western side of Alba Patera are, on an average, level in spite of the graben zone. This is quite reasonable since those cross-sections are short, and comparable to the western end of the southeastern cross-section which also indicates only minor sloping due to the graben-fault-heights. The northern cross-section is almost level with a small depression below the calibration planes. This line does not, however, extend far enough over the northern graben zone to allow any conclusions to be made.

4. Statistics of Graben Patterns

The graben pattern of the studied area consists of four main parts. The southern longitudinal grabens stretch from the Tharsis area into the central Alba Patera area to only a few tens of kilometers south of the central calderas. The arcuate grabens tend to form a discontinuous and partially buried circle at a distance of 200–500 km around the central calderas. The third set of northeastern linear grabens extends from northern to northeastern Alba Patera to Vastitas Borealis. The fourth set of grabens is defined with crater chains in the bottom (Figures 1, 5). These crater chain grabens are approximately radial to an area in northern Tharsis and they exist on both western and eastern side of and within the main fossae zone. The eastern crater chain grabens are longer and much more extensive than the western ones. The most notable crater chain grabens are situated on the southeastern side of Alba Patera where the space between these NE-SW oriented grabens is approximately 200 km. All four sets interact with each other.

In order to obtain statistical information on the graben faults around Alba Patera measurements were made over different subareas (Figures, 2, 5, 6).

Within the northwestern subarea I there are only a few graben faults, all of them with north-northeastern orientation. In area II the main fault direction is N40°–50°E. This is caused by the northwestern faults of Alba Patera where both circular and

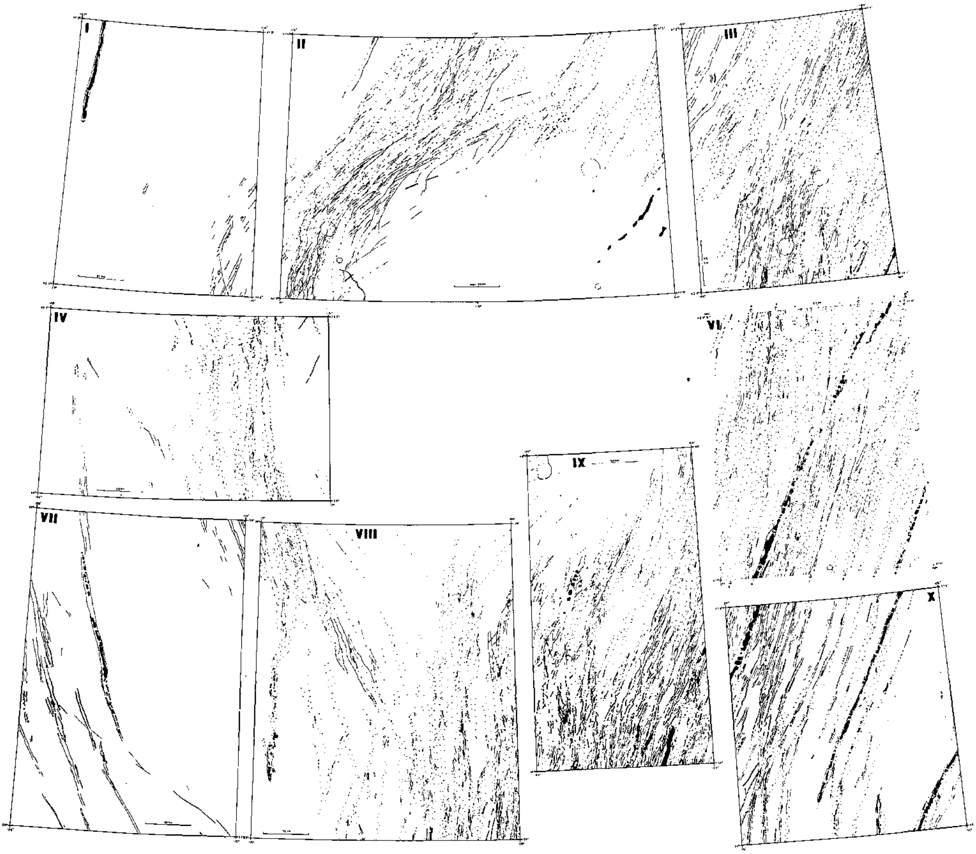

Fig. 5. Graben faults of Alba Patera interpreted from USGS MTM mosaics 1:502000. Faults of the Alba Patera area surround the main volcanic centre. Crater-chain craters present in some grabens are indicated in black. For location of each area see with Figure 2.

straight northeastern grabens have approximately this orientation. There is a lack of NW-SE faults. In area III the main fault orientation is N20°–30°E with only a few arcuate grabens concentric to Alba Patera. This is the area where the northernmost of the eastern arcuate grabens tend to interfere with the northeastern main trend to produce eastward concave graben structures.

In the western subarea IV the arcuate graben faults concentric to Alba Patera are oriented predominantly in a N-S direction with a maximum peak at N0°–10°W. Grabens in this area are not well developed and they may have been partly buried by lava flows thus allowing only the youngest ones to be measured. The graben faults of the eastern subarea VI are, on the contrary, much more extensive, displaying both concentric and northeastern trends. To get a more graphic picture of these two graben sets both western and eastern faults of the subarea VI were presented separately. The most prominent fault direction is the same, N20°–30°E in both rose diagrams, but the western diagram shows the dominance of the almost northerly

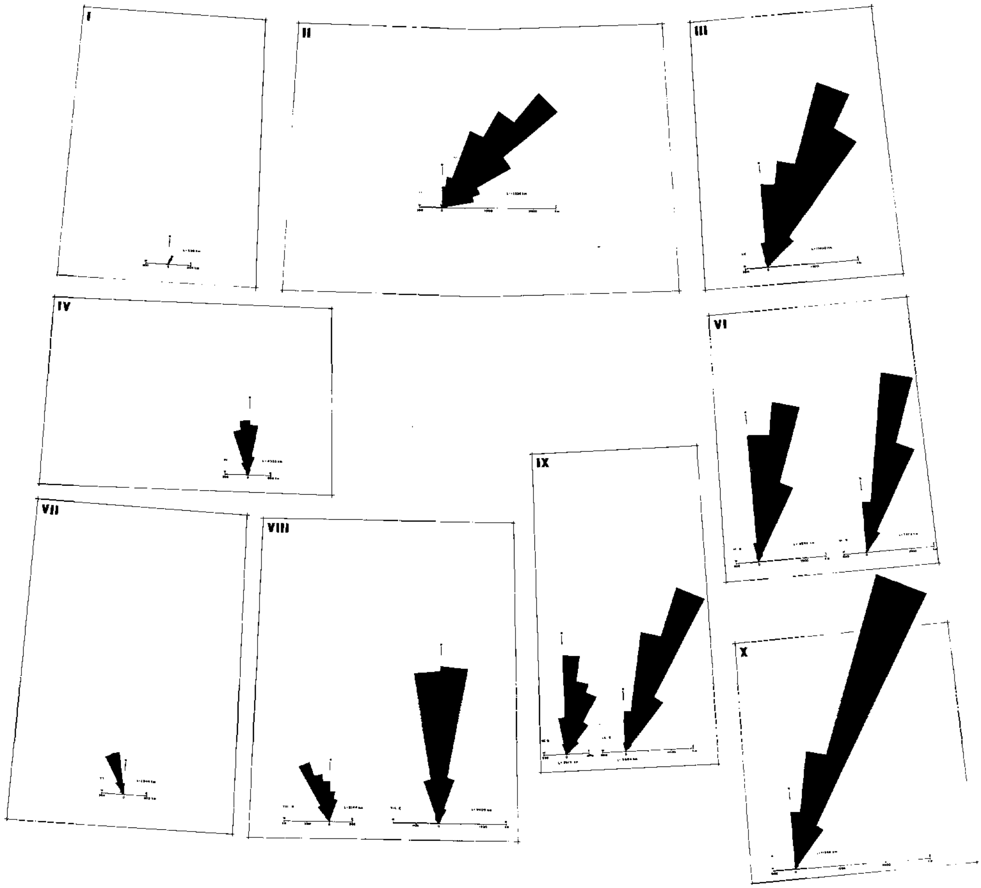

Fig. 6. The directions of graben faults of nine subareas around Alba Patera (cf. Figure 2 and 9) are represented by rose diagrams. L is the total length of faults considered in each diagram.

oriented concentric faults and the eastern diagram indicates the existence of the more easterly oriented main graben fault set.

The rose diagrams of subareas VII to X illustrate the dominance of various graben fault sets in different parts of the study area. The few westernmost graben faults of subarea VII belong to the graben set radial to the northern Tharsis bulge with a main strike of N10°–30°W. These grabens are also approximately concentric to Alba Patera although they are much farther from it (800–900 km) than the main concentric grabens. The western faults at subarea VIII are mostly deflected in the northwestern direction, forming an arcuate circular pattern with a diagram peak at N20°–30°W. The eastern graben faults of this subarea have a general N–S orientation similar to southern Alba Patera graben set.

The subarea IX offers a graphic example of how different graben sets can interfere within a narrow zone. The western part of this subarea is dominated by N-S faults with a peak at N0°–10°E. In addition, there are numerous faults with a more eastern orientation. These faults become dominant in the eastern part of subarea IX with the

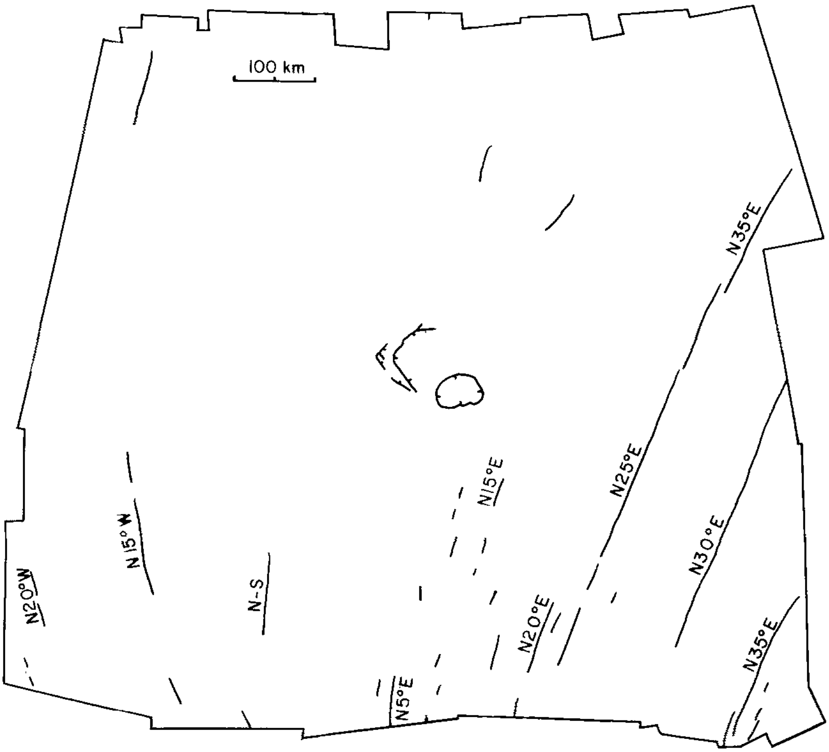

Fig. 7. Fan-like pattern of the crater-chain grabens radial to the northern Tharsis bulge. Compare with Figures 1, 2, 4 and 8.

distribution peak at N20°–30°E. Within this subarea this main direction denotes graben faults both concentric to Alba Patera and belonging to NE-SW trending northwestern main zone. Within subarea X, these graben faults within subareas VI, IX, and X, the role of the arcuate concentric graben pattern close to Alba Patera on the eastern side becomes evident in contrast to the more eastern orientation of the main northeastern graben set mainly indicated by the prominent crater-chain grabens of this area (Figure 1, 5, 6).

To get a better idea of the tectonic development of the Alba Patera grabens, we must inspect its different graben sets: the location and orientation of the main graben zone radial to the Tharsis bulge (Figure 2), the rift-like occurrence of this main graben zone (Figure 4), deflected and concentric graben sets around the Alba Patera main volcanic center (Figure 6), and the crater-chain graben set radial to the northern Tharsis bulge (Figure 7), and the small grabens on the lava surface (Figure 3).

5. Concluding Remark

The composite tectonics of Alba Patera graben structures was caused by superposition. It is possible to distinguish geometrically some structural phases, to estimate

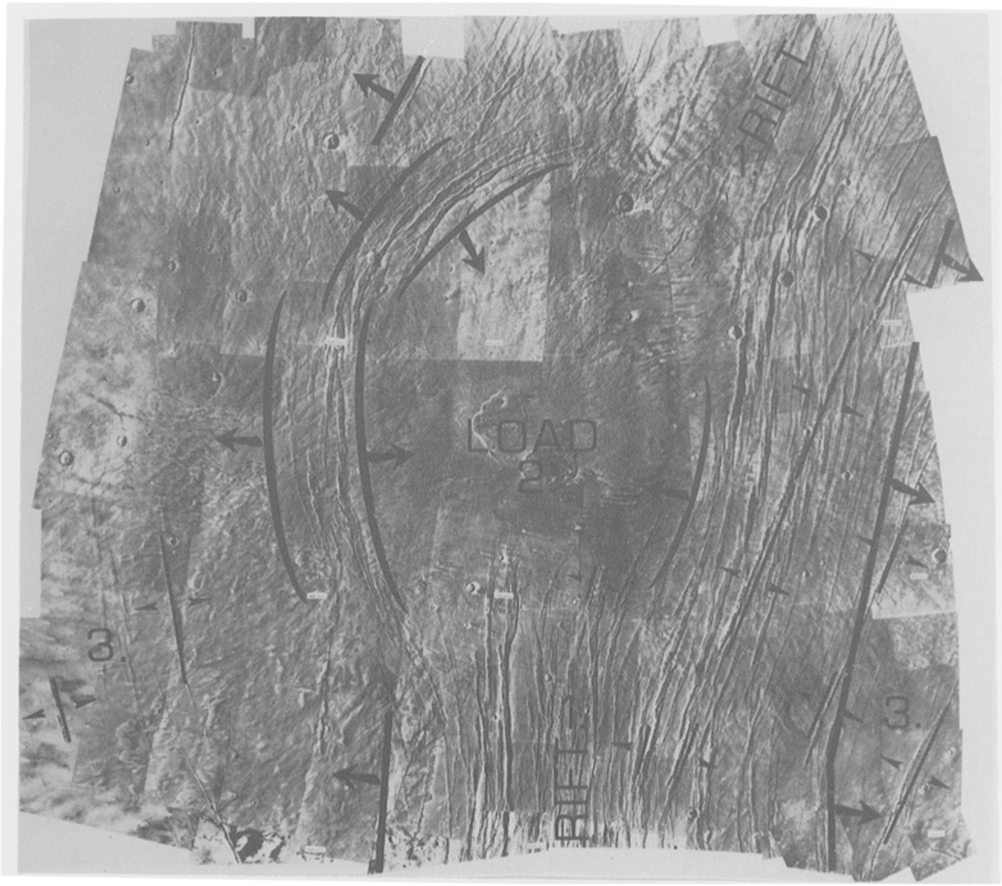

Fig. 8. Sketch of the tectonics of the Alba Patera area with (1) the tensional rift zone, (2) load-induced tensional arcuate grabens around the Alba Patera centre, and (3) additional tensional crater chains in some grabens. In addition to the load, cooling of the interior and withdrawal of magma may have contributed to the sinking of the central area and the formation of surrounding arcuate grabens.

their relative significance in different areas, and to identify the main tectonic sequence (Figure 8). It remains, however, impossible to uncover the actual age difference between grabens. The hypothesis acquired is that the domed linear Alba Patera rift-like zone, radial to the Tharsis bulge, is the oldest of the structures. Its grabens were later deflected by the thick lava layers of the central Alba Patera. The circular graben structures around the Alba Patera volcano are younger and more local and they were partly caused by the Alba Patera load and partly by rift tectonics. The crater-chain grabens then represent the youngest tectonic phase together with the small grabens on the adjoining lava plains. These late-tectonic grabens are possible to connect with the last load-induced tensional tectonics (Banerdt *et al.*, 1982).

References

Banerdt, W. B., Phillips, R. J., Sleep, N. H., and Saunders, R. S.: 1982, 'Thick Shell Tectonics on One-plate Planets: Applications to Mars', *J. Geophys. Res.* **87**, 9723–9733.

Carr, M. H.: 1973, 'Volcanism on Mars', *J. Geophys. Res.* **78**, 4049–4062.

Carr, M. H.: 1976, 'Change in Height of Martian Volcanoes with Time', *Geol. Rom.* **15**, 421–422.

Carr, M. H.: 1980, 'The Morphology of the Martian Surface', *Space Sci. Reviews* **25**, 231–284.

Carr, M. H., Greeley, R., Blasius, K. R., Guest, J. E., and Murray, J. B.: 1977, 'Some Martian Volcanic Features as Viewed from the Viking Orbiters', *J. Geophys. Res.* **82**, 3985–4015.

Cattermole, P.: 1986, 'Linear Volcanic Features at Alba Patera, Mars', *Lunar and Planetary Sci.* **XVII**, 109–110.

Golombek, M. P.: 1979, 'Structural Analysis of Lunar Grabens and the Shallow Crustal Structure of the Moon', *J. Geophys. Res.* **84**, 4657–4666.

Greeley, R. and Spudis, P. D.: 1981, 'Volcanism on Mars', *Rev. Geophys. Space Phys.* **19**, 13–41.

Neukum, G. and Hiller, K.: 1981, 'Martian Ages', *J. Geophys. Res.* **86**, 3097–3121.

Plescia, J. B. and Saunders, R. S.: 1979, 'The Chronology of the Martian Volcanoes', in *Proc. 10th Lunar Planet. Sci. Conf.* pp. 2841–2859.

Raitala, J.: 1985, 'Radial Rift and Block Tectonics Around the Tharsis Bulge: Introductional Postulation', *Lunar and Planetary Institute Contribution* No. 569, pp. 118–122.

Raitala, J. and Saunders, R. S.: 'Framework of Tharsis Tectonics', *NASA TM-88383*, pp. 390–392.

Scott, D. H. and Tanaka, K. L.: 1980, 'Mars Tharsis Region: Volcano Tectonic Events in the Stratigraphic Record', *Proc. 11th Lunar Planet. Sci Conf.*, pp. 2403–2421.

Scott, D. H., Schaber, G. G., Horstman, K. C., and Dial, A. L., Jr.: 1981a, 'Map Showing Lava Flows in the Northeast Part of the Tharsis Quadrangle of Mars', *USGS Map* I–1267 (MC-9NE).

Scott, D. H., Tanaka, K. L., and Schaber, G. G.: 1981b, 'Map Showing Lava Flows in the Southwest Part of the Arcadia Quadrangle of Mars', *USGS MAP I–1278* (MC-3SW).

Wise, D. U.: 1976, 'Faulting and Stress Trajectories Near Alba Volcano, Northern Tharsis Ridge of Mars', *Geol. Rom.* **15**, 430–433.