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Crosscutting Relations and Relative Ages of Ridges and Faults in the Tharsis Region of Mars

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Observations of ridge–fault crosscutting relationships on the ridged plains units surrounding the Tharsis region of Mars have led to the development of a classification scheme involving three distinct types of intersections. Ridges crosscut by faults are designated Type C and account for 81% of the observed intersections. Ridges terminated at one end by a fault (Type T), as well as those superposed on grabens (Type S), are less numerous. Interpretation of the morphology of these intersections and the angles of intersection between ridges and faults with radial trends to major topographic features in the Tharsis region have led to the following conclusions: (1) the major ridge forming events in the Tharsis region were roughly coincident with, and in some cases possibly prior to, the extensional events that produced the faulting of the Tempe and Mareotis regions, the Coprates and Memnonia regions, and the rifting of Valles Marineris; (2) the compressional events that formed most of the ridges are restricted in time both by the irrelationship to regional extensional events and by the age of the units on which they formed. The suggestion that compressional ridges are a result of a single long term viscoelastic response of the lithosphere to loading of the crust is not supported by this study. A model involving one or more isostatically compensated uplifts and subsequent relaxation of the crust after the emplacement of the ridged plains volcanic units is favored.

INTRODUCTION

Photogeologic observations of structural features in the Tharsis region of Mars have been one of the principal constraints on models for the origin of that province. The two dominant structural forms in the area are faults and ridges. Faults in the Tharsis region appear to be extensional features, probably best defined as graben. However, the classical definition of a graben is difficult to apply in many cases because the resolution of the imaging available does not allow clear observation of the walls or floors of the faults. These faults crosscut every stratigraphic unit from the oldest cratered terrain to the youngest volcanic plains (Fig. 1A). Ridges on Mars, as well as the Moon and Mercury, consist of linear arches, many of which have a sharp prominence that either flanks or occurs on top of the arch. Ridges in the Tharsis region, to a first approximation, form a great circle roughly centered on Pavonis Mons (Fig. 1B) and are exposed at distances greater than 2500 km from that center. The highest density of ridges is found in the Coprates and Lunae Palus quadrangles, although they occur in every quadrangle in the region except Tharsis (excluding those ridges in the Olympus Mons caldera reported by Lucchitta and Klockenbrink, 1981) and Phoenicis Lacus. These ridges appear to be folds formed by regional and/or local compressional stress. An alternative mode of origin may be deformation along preexisting basement faults, although orientations of ridges are not similar to those of surrounding faults systems (Maxwell, 1982).

An integrated understanding of geologic events in the Tharsis region is dependent on the ability to assign relative age relations to structural features. Geophysical models have not yet taken into account temporal

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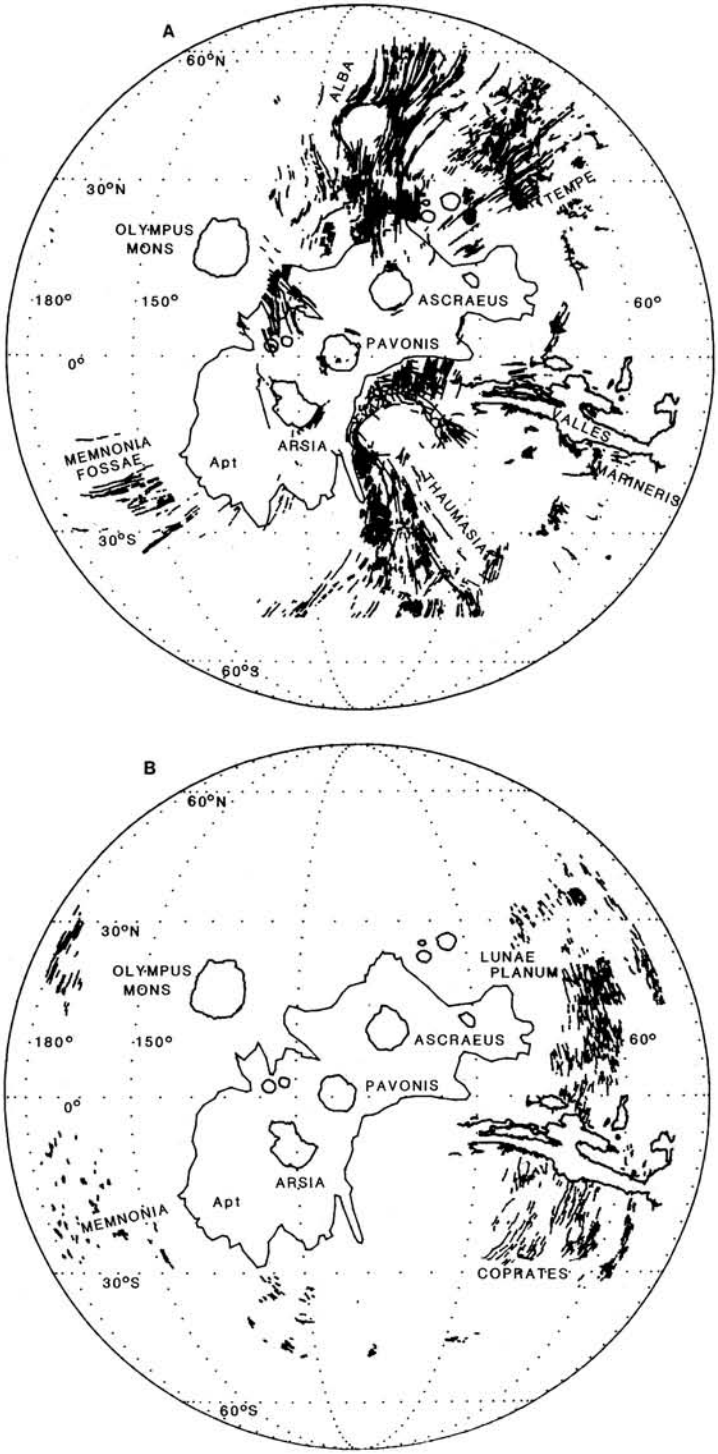

FIG. 1. Structural features in the western hemisphere of Mars. (A) Faults (primarily graben) and large-scale linear fractures many of which can be projected to various topographic features in the Tharsis region. (B) Ridges, developed primarily on the ridged plains east of the Tharsis volcanic province form a great circle roughly centered on Pavonis Mons. Both projections are centered at 0°N, 110°W. Plots represent the digitization of approximately 7000 fault segments and 2000 ridge segments from the 1 : 2000000 controlled photomosaics and individual Viking frames (Apt represents Volcanic Plains of Tharsis Montes Region; Scott and Carr, 1978).

variations in the formation of faults or ridges, and photogeologic interpretations must rely on crater ages, crosscutting, and other stratigraphic relations.

Superposition relationships in the southern part of the Tharsis province indicate that much of the extensional faulting is restricted to areas of old cratered terrain which is embayed by younger cratered plains and ridged plains units (Scott and Carr, 1978). These graben are typically wider than those that occur in the plains units. Nonetheless, extensional stress in the region did occur after the period(s) of emplacement of smooth plains. The resulting graben, along with the ridges thus, provide photogeologic constraints on some of the tectonic events that occurred after the emplacement of the ridged plains units in the Tharsis region.

This paper reports the results of a detailed photogeologic analysis and classification of ridge–fault crosscutting relationships on ridged plains units of the Tharsis region. The problems involved in using the morphology of ridge–fault intersections to determine relative timing of structural events are discussed. Finally, the implications of using intersection angles as well as morphology to determine possible age relationships for the tectonic history of the region are presented.

PREVIOUS STUDIES

Many photogeologic studies have attempted to unravel the complex history of the Tharsis region. Based on Mariner 9 data, Carr (1974) observed that Tharsis was at the center of a roughly radial fracture system that formed as a result of "upwarping" of the crust in the region. Scott and Carr (1978) noted that the ridges east of Syria Planum formed an arcuate pattern around part of Tharsis and suggested that these too were caused by doming of the crust. Masson (1977) mapped two major fracture systems in the Valles Marineris–Noctis Labyrinthus region; a NNW and ENE pattern expressed in stratigraphically older terrain, which was followed by formation of WNW and E–W trending fractures due to the opening of Valles Marineris and vertical movement of Noctis Labyrinthus. Frey (1979) presented evidence for early uplift in the Thaumasia region, which exerted a structural control on Valles Marineris. The stresses which formed Valles Marineris were attributed to uplift in the Tharsis region.

Wise *et al.* (1979) presented a model of an early topographic rise of the Tharsis region, followed by extensive, long-lived volcanism. Analysis of stereographic plots of fractures and ridges confirmed a predominantly radial orientation of the faults and a circumferential arrangement of ridges. Based on crater ages, they suggested that the ridges were approximately coincident in time with the main radial fault system. Deviations from Tharsis-related orientations were attributed to crustal anisotropy in a NE direction, parallel to the great circle line of Tharsis volcanoes.

Studies of the ridged plains by Saunders and Gregory (1980) and Saunders *et al.* (1981) led them to suggest that the ridge spacing was controlled by a dominant wavelength of folding (based on a theoretical model proposed by Biot, 1961). Plescia and Saunders (1981) have suggested that the ridges formed late in the tectonic history of Tharsis after the formation of Valles Marineris. In a preliminary study of ridge–fault intersections in the Tharsis region, Watters and Maxwell (1981) suggested that ridge formation occurred before the last phase of radial faulting. Sharpton and Head (1982), using the time of formation of lunar ridges for an analogy, suggest that ridge formation may postdate faulting.

Thus, photogeologic investigations of structures in the Tharsis region indicate a complex history of both extension and compression related to possible updoming and long-term support of the volcanic load on the lithosphere. Both structural studies by Wise *et al.* (1979) and recent mapping of lava flows by Scott and Tanaka (1980) suggest that the Tharsis volcanoes have been active over an extremely long period of Martian geologic history, and continuing studies of extensional features indicate that some graben can be related to activity of individual volcanic centers (Plescia and Saunders, 1982).

CLASSIFICATION

Three distinct types of ridge–fault intersections have been identified based on observations of 166 crosscutting relationships in plains units surrounding the Tharsis plateau. The classification was developed using the following scheme: (1) a ridge crosscut by a fault is designated Type C (Fig. 2); (2) a ridge terminated at one end by a fault is designated as Type T; (3) an intersection where a ridge is superposed on a graben is designated Type S (Fig. 2). In this classification scheme, Type C ridge–fault intersections are distinguished from Type S by the presence of fault scarps that clearly extend through the crosscut ridge. A dissected portion of the ridge may or may not occur on the floor of the graben depending on the style of faulting. Also, due to the limits of the resolution of Viking Orbiter images, possible ridge segments within the graben may not be identifiable.

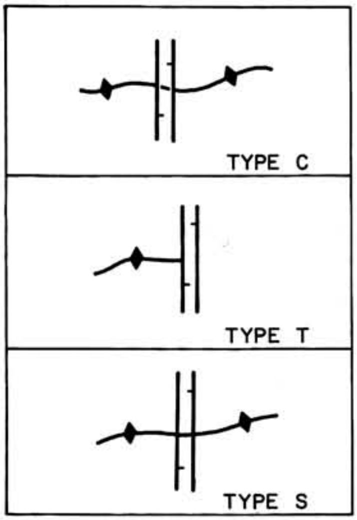

FIG. 2. Schematic diagram illustrating the three types of intersections in the Tharsis region. Type C, a ridge is crosscut by a graben (the dissected portion of the ridge may or may not be present or visible on the graben floor); Type T, a ridge terminates at boundary of a graben; and Type S, a ridge is superposed on a graben.

Examples of Type C intersections are present in the Coprates region and in the ridged plains north of Kasei Vallis (Fig. 3). In the Coprates region a generally N–S trending ridge system intersects an E–W trending fault swarm (Fig. 3A). These faults resemble *en echelon* tension gashes in terrestrial rocks. Perhaps the clearest example of a Type C intersection is shown in an enlargement of the same area (Fig. 3B). Here, the ridge appears to have been cut by the graben with the dissected portion of the ridge visible on the graben floor.

In the area north of Kasei Vallis (25°N, 80°W) roughly N–S trending ridges are crosscut by NE trending faults forming Type C intersections (Fig. 3C). One ridge in this area (see the lower left corner of Fig. 3C) is cut by six separate faults, five trending NE and one trending roughly NW. The NW trending fault seems to cut a portion of the eastern flank of the ridge, whereas the NE trending faults cut the ridge into clear segments. The ridge appears to have structurally controlled back-wasting in the area.

The clearest examples of Type T intersections are found in the Coprates region (Fig. 4). This area is approximately 200 km east of the region in Fig. 3A. In this area, ridges trending roughly N–S are terminated by an E–W fault swarm. This fault swarm appears to be part of the same fault system present in southern Coprates region (Fig. 3A). As the name of the intersection type implies, the ridges sharply terminate at the walls of the graben, and in many cases the angle between the graben wall and the ridge is nearly 90°. The ends of some of the ridges in this area are dissected by splay faults.

An example of one of the few Type S intersections is also located in the Coprates quadrangle (Fig. 5A). In this area, N–S trending ridges crosscut a degraded graben

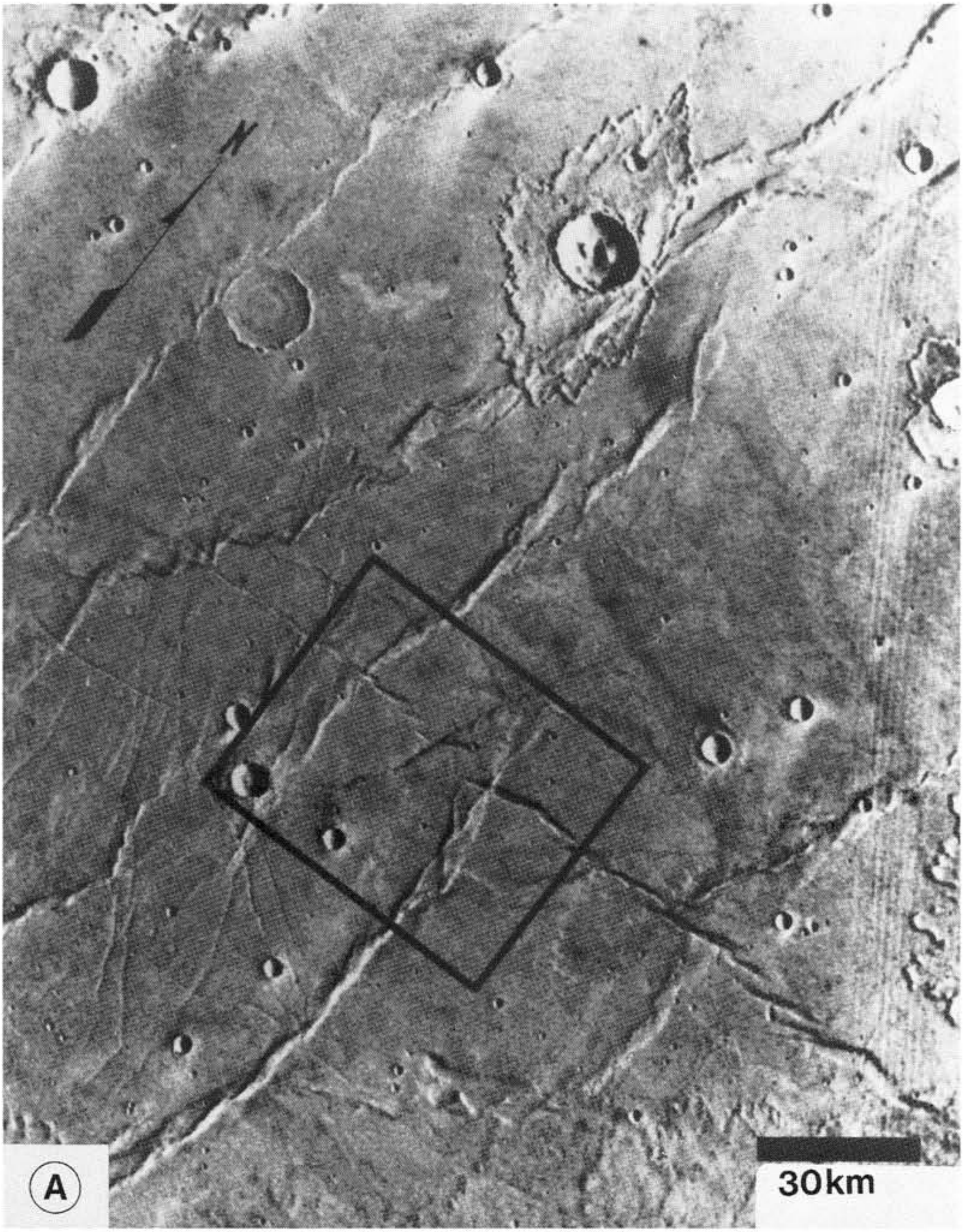

FIG. 3. (A) Intersections of ridges and graben in the southern Coprates region (19.5°S, 72°W), showing Type C intersections. (B) An enlargement of the boxed area in Fig. 3A. Ridges near the center of the image show evidence of the fault continuing across the ridge crest (Viking Orbiter Frame 608A49). (C) Type C, ridge–fault intersections north of Kasei Vallis (26°N, 78°W). Northeast trending faults are generally radial to Tharsis and crosscut both the N–S trending ridges and ejecta of a crater (arrow; Viking Orbiter Frame 519A09).

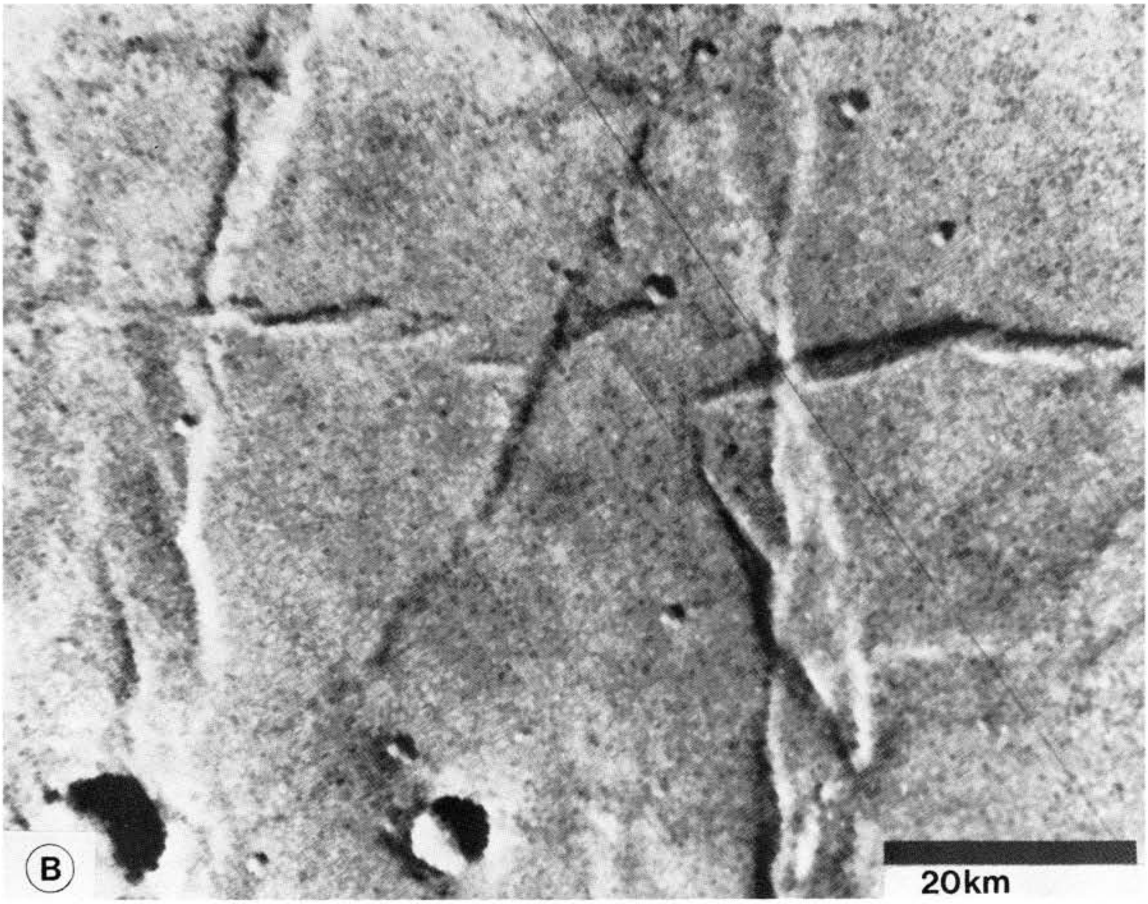

FIG. 3—*Continued.*

that trends WNW, nearly parallel to smaller graben in the region. This depression does not exhibit the sharp boundary scarps of the 2–5 km wide fresh appearing graben developed on the ridged plains of Coprates and Lunae Palus, but is here interpreted to be a graben based on its similar orientation and continuity with faults exposed in older terrain to the east. An enlargement of the area (Fig. 5B) shows the ridge apparently suffered little or no loss of relief crossing the graben.

IMPLICATIONS FOR RELATIVE AGE

At least three models must be considered in order to interpret the relative age of each ridge–fault intersection in the Tharsis region: (1) ridges crosscut by faults are older than the crosscutting faults; (2) ridges and faults formed roughly simultaneously, resulting from the same stress event; (3) ridges are younger than the faults which crosscut them.

Arguments in support of the first hypothesis can be made by contrasting the morphologic differences between Type C and S ridge intersections. If Type S intersections are used as a "type example" for a ridge forming after the graben, then such ridges do not appear to be affected by the preexisting fault. No trace of the fault scarps are visible across the crest of the ridge. Conversely, the Type C intersection described in Coprates (Figs. 3A and B) shows that the ridge segment within the graben is dimensionally and morphologically similar to the

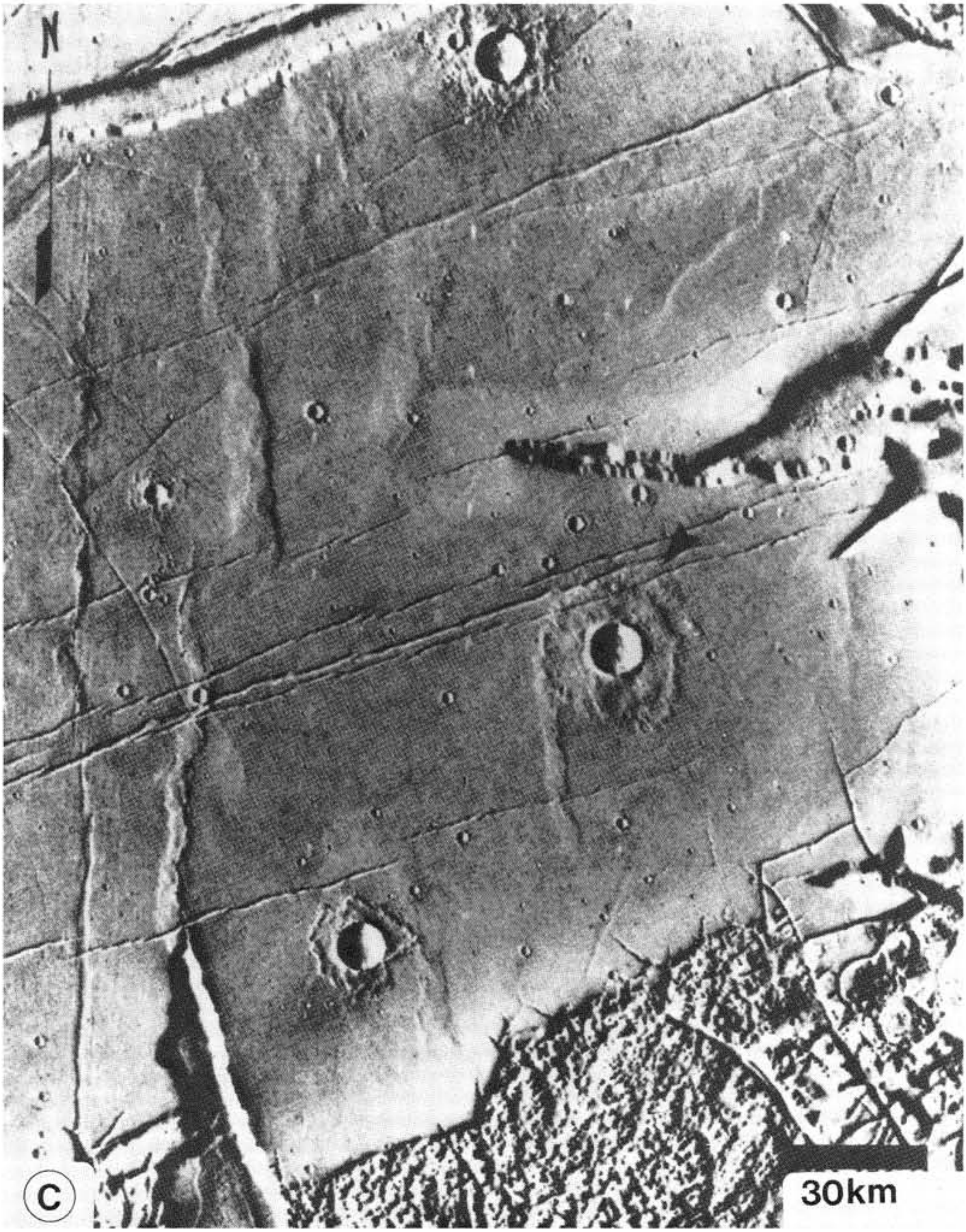

FIG. 3—*Continued.*

ridge outside and exhibits sharp edges on both walls of the graben. Based on the morphologic distinction between these two types of intersections, we believe that some of the Type C intersections indicate graben formation that post dates the ridge-forming event(s) (Model 1). The determination of those Type C intersections formed by graben cutting preexisting ridges is dependent on both the angle of intersection of the two

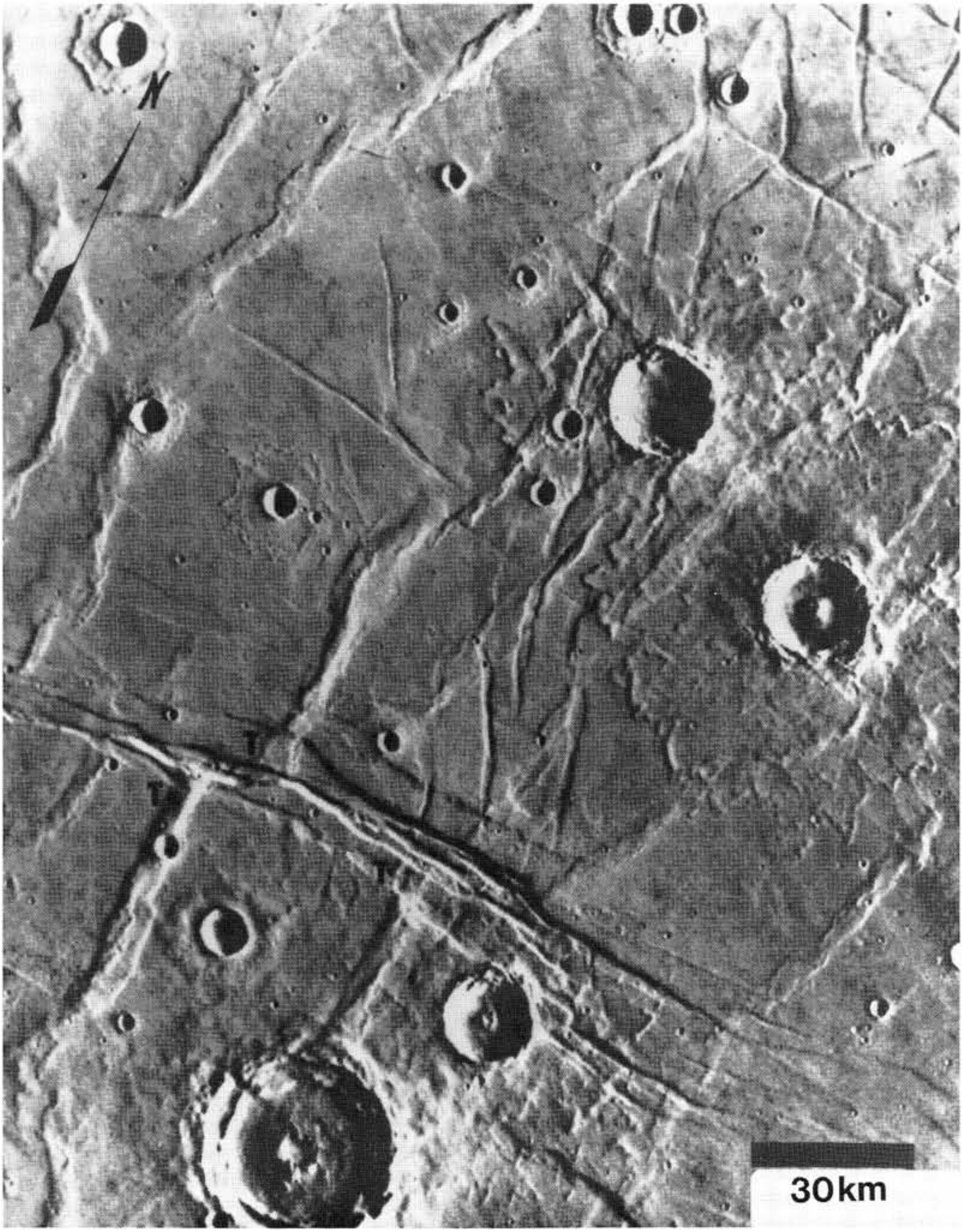

FIG. 4. Type T intersections in southern Coprates (19.5°S, 66°W). Ridges (marked T) appear to terminate at the walls of graben, although in some cases, the ends of ridges are cut by faults that splay off from the main graben (Viking Orbiter Frame 610A03).

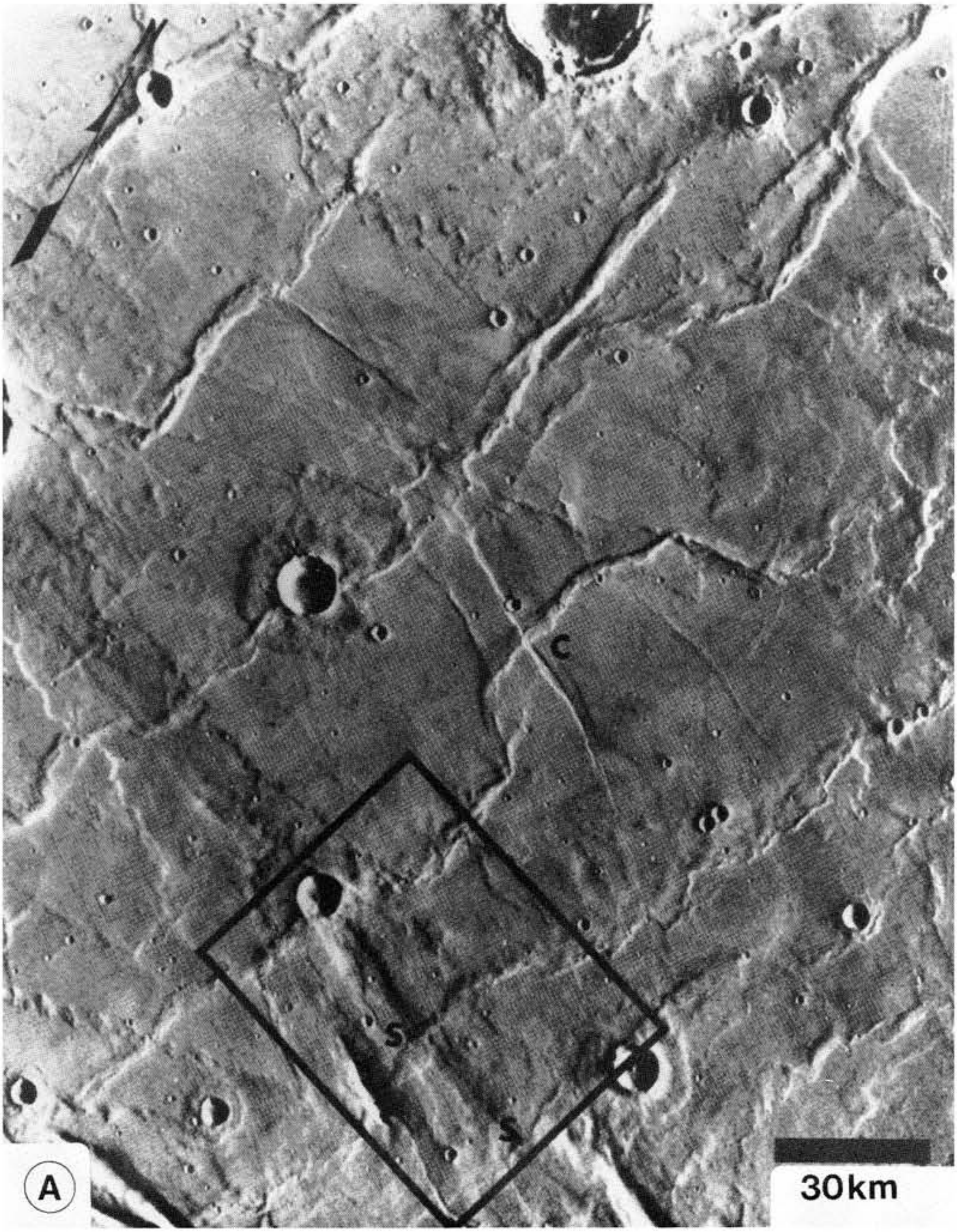

FIG. 5. (A) Type S and C intersections in southeastern Coprates quadrangle (27°S, 64°W). Ridges are continuous across degraded graben (S), in contrast to cross cutting relations seen 30 km to the north (C). Compare the Type S and Type C intersections located near the center of the figure (Viking Orbiter Frame 610A21). (B) Enlargement of boxed area in Fig. 5A, showing continuity of ridge across degraded graben. Compare with Type C intersections (Fig. 3).

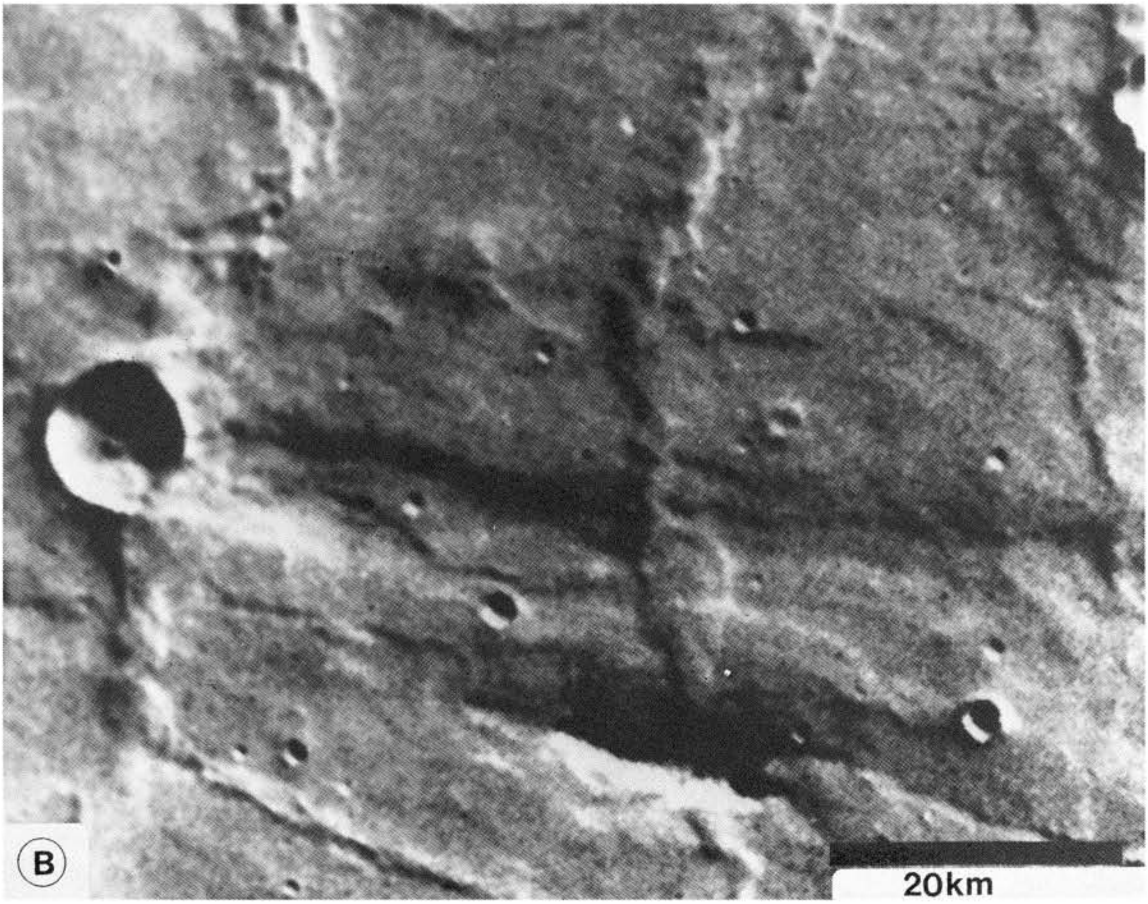

FIG. 5—*Continued.*

features (indicative of the orientation of the stress field or fields) and the geologic interpretation of the ridge structure (thrust faults versus folds).

An orthogonal relationship between tensional and compressional features is suggestive of a single stress field, implying simultaneous formation (Model 2). Phillips and Lambeck (1980) concluded that the orthogonal relationship between the ridges and faults on the ridged plains of Mars was due to failure of the crust due to loading, suggesting that the ridges are thrust faults generated by catastrophic relaxation (Arvidson *et al.*, 1980). However, if the ridges are interpreted as compressional folds with the maximum principal stress (σ_1) perpendicular to the fold axis and the minimum principal stress (σ_3) vertical, then a single stress field generating coincident formation of both features is inappropriate. Applying a classical structural interpretation (e.g., Anderson's work as described by Price, 1966) to graben formation in the Tharsis region, σ_1 is vertical and σ_3 is horizontal and perpendicular to the plane of failure (parallel to σ_2). In the alternative situation, where σ_1 and σ_3 are horizontal and σ_2 is vertical, the resulting stress would generate shear or strike slip faulting (not observed on Mars). Therefore, it is difficult to envision a single contemporaneous stress system that would produce orthogonal extensional and compressional features (less resorting to a horizontal couple). The interpretation that seems most defensible is that the orthogonal ridges and faults were generated by two distinct stress fields, separated in time, that shared a roughly common stress center.

Orthogonal Type C and T intersections, therefore, can be interpreted as formation of a ridge (by folding of the near surface layer or layers) and a graben resulting from the same center of tectonic activity but not from a single stress event. Nonorthogonal Type C intersections and Type T intersections with nonorthogonal faults are composites of at least two stress fields operating at different times and having different stress centers.

The third alternative that ridges are younger than the crosscutting faults, must be based on arguments of material strength (particularly where ridges are seen within the base of the graben), the vertical and horizontal extent of the faulting (which may be obscured by later mass wasting or burial by more recent volcanic units), and the degree of strain recorded in the folding across the ridged plains. If ridge formation occurred after faulting, then all the observed crosscutting relationships could result from (1) slumping of the ridge into the graben, leaving a detachment scarp similar to the pre-existing fault scarp, (2) formation of a ridge across a graben with insufficient strain to obscure the walls of the fault.

In a preliminary study, Watters and Maxwell (1982) estimate the degree of strain recorded in the ridged plains of SW Coprates to be between 0.6 and 1.1%. Since Type S intersections do exist in the region, it seems plausible that this degree of strain was sufficient to completely obscure the walls of at least some of the faults, especially those with relatively small horizontal extent (1–2 km) compared to the width of the ridges (2–6 km). Their presence further suggests that later slumping of the ridge structure into the graben has not occurred in all cases. Also, since the ridged plains probably represent a volcanic unit (or units) emplaced on an extensive regolith, it is unlikely that the vertical extent of most of the faults exceeded the thickness of the unit (estimated to be not greater than 1 to 1.5 km; Saunders and Gregory, 1980; DeHon, 1981).

Based on observations presented above, we favor the following interpretations: (1) Type C intersections crosscut by nonorthogonal faults relative to the trend of the ridge represent a preexisting ridge cut by graben generated in a later unrelated extensional event; (2) Type T and C intersections involving orthogonal faults are the result of stress events related to the same tectonic center but not the same stress field and were not generated at the same time; (3) Type S intersections represent a preexisting fault superposed by a ridge generated in a later compressional event.

CHARACTERIZATION OF INTERSECTIONS

The most common type of intersection in the Tharsis region is Type C, accounting for 81% of the 166 observations (locations shown in Fig. 6A, diamonds). Type T intersections account for 16% of the observed intersections (Fig. 6B, squares). The rarest intersection type in the region is Type S, accounting for only 3% of the observations (Fig. 6B, triangles).

The intersections may be further characterized by the origin of the faults involved. Two types of origins account for most of the faults on ridged plains units in the Tharsis region: (1) faulting whose origin is locally controlled (about 48%); (2) faulting that appears to be related to regional stress centers.

Local Stresses

Most of the faults generated by local stress fields are related to Kasei Vallis or Valles Marineris. Many of the faults are found near scarps, such as those located north of Hebes Chasma (5°N, 76°W), and in some cases appear to act as structural con-

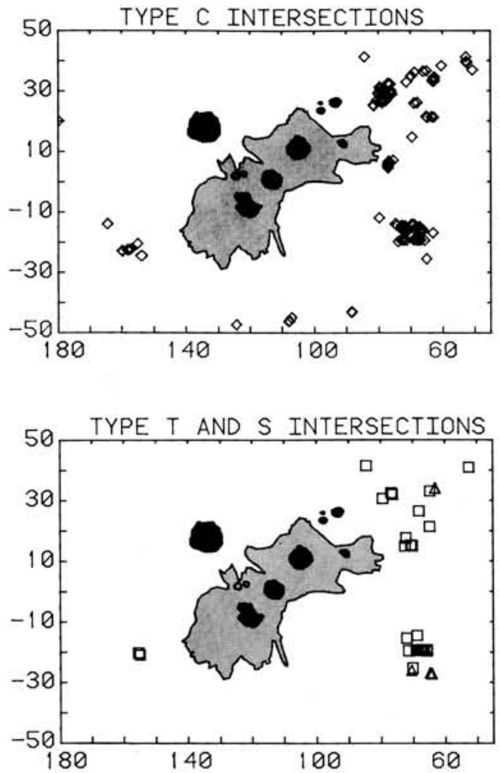

FIG. 6. Locations of intersections surrounding the Tharsis plateau (diamonds = Type C, squares = Type T, and triangles = Type S). The gray shaded area represents the Volcanic Plains of Tharsis Montes Region (Scott and Carr, 1978), and the black shaded area represents the major Tharsis volcanoes.

trols on scarp retreat. Valles Marineris has the largest population of such faults, where release of confining pressure due to cliff retreat may have led to formation of small graben that are oriented parallel to the rim of the canyon. In the region of Coprates Chasma (near 14°S, 66°W) numerous fault swarms form Type C intersections with roughly N trending ridges (Fig. 7). A ridge–ridge intersection involving a relatively larger NW trending ridge overprinted by a smaller N trending ridge (located in the left center of Fig. 7) suggests two distinct compressional events of differing stress orientation.

Southeast of Tempe Fossae (32°N, 62°W), however, a roughly parallel converging set of faults has no apparent link to a major scarp or structural feature (Fig. 8). These faults form both Type C and S intersections with roughly NW trending ridges. The Type S intersections (see upper center of Fig. 8) show two ridges that completely obscure the fault they superpose.

Regional Stresses

Regional stresses involve faults with radial trends that can be projected to various centers in and around the major topographic features of the Tharsis region (Wise *et al.,* 1979; Plescia and Saunders, 1982). Large numbers of intersections involving radial faults on the ridged plains units occur in three areas: (1) the ridged plains south of Tempe Fossae; (2) southern Coprates; and (3) Memnonia Fossae.

Tempe Fossae region. The area south of Tempe Fossae is characterized by three sets of faults, a NE trending swarm radial to a center just north of Ascraeus Mons, a NNE trending set radial to a point SE of Pavonis Mons, and a curvilinear "S-shaped" set of faults trending from NE to N with no apparent radial center (the two radial fault swarms can be seen in Fig. 9). In this region, ridges are terminated and cut by two NE trending parallel faults and NNE trending faults. Farther to the southwest (see left center of Fig. 9) another ridge is terminated by a NE trending fault and crosscut by a NNE trending fault (also see Fig. 3C).

Intersection angles between ridges and crosscutting or terminating radial faults in the Tempe Fossae region indicate that 60% of the 47 observed intersections are orthogonal (orthogonality defined as ±10° of perpendicular) (Fig. 10). The majority of the orthogonal intersection involve the NE trending radial faults, suggesting that ridges formed from stresses generated by the same center of activity as that which created the faults. The NNE trending radial faults appear to produce no orthogonal intersections and, therefore, are interpreted to

FIG. 7. Southern portion of Coprates Chasma (14°N, 66°W) showing numerous Type C intersections of graben with North trending ridges. A ridge–ridge intersection, is possibly indicative of two different compressional stress events (Viking Orbiter Frame 610A04).

post date both the ridges and NE trending faults. This interpretation is further supported by the stratigraphic relationships of the two faulted units. The older NE faults are covered to the west by the cratered plains material (unit Apc of Scott and Carr,

FIG. 8. Type C and S ridge–fault intersections in the Tempe region (32°N, 62°W), showing parallel, converging faults that crosscut ridges. In a few locations (Type S), there is no trace of the fault across the ridge crest (Viking Orbiter Frame 520A33).

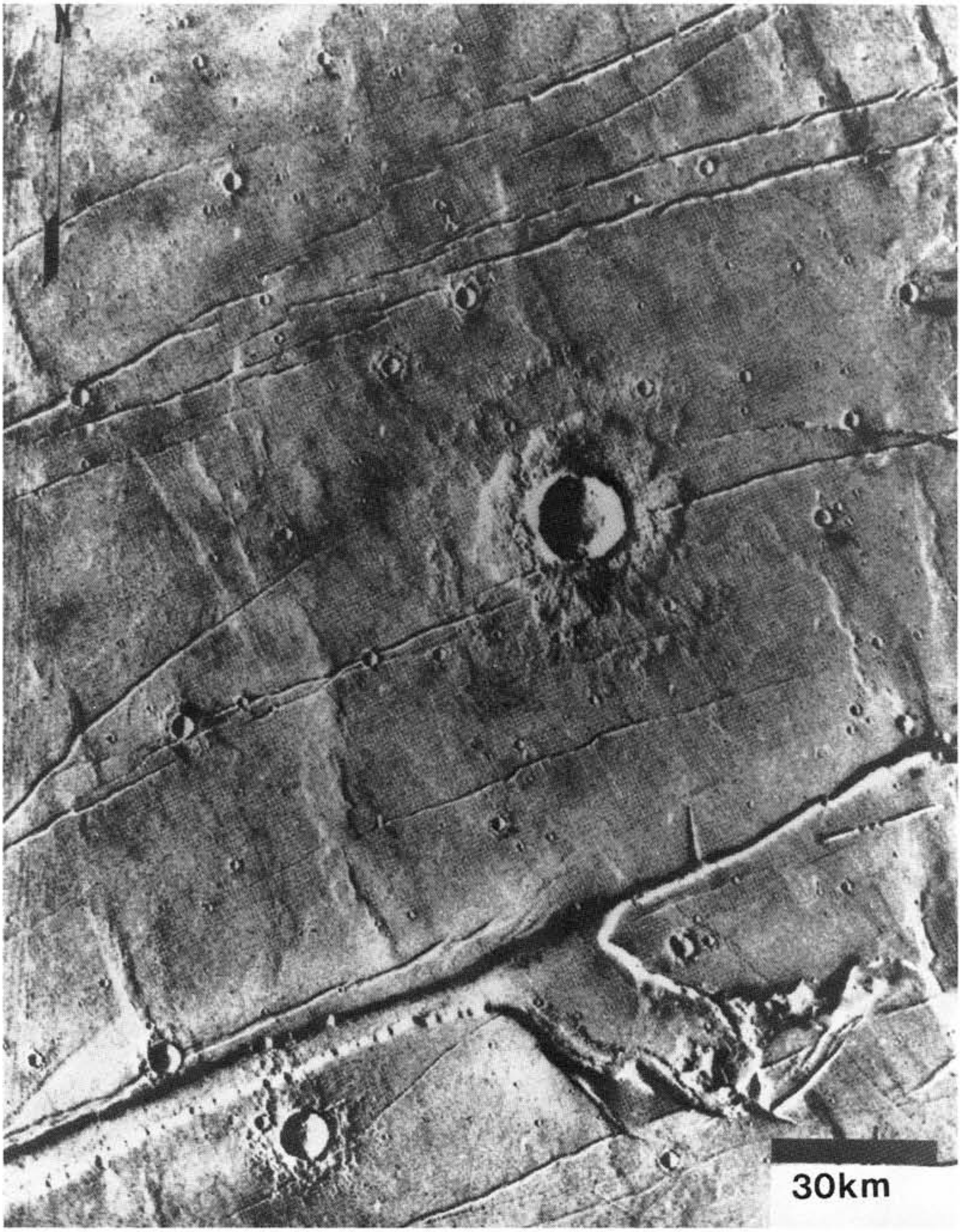

FIG. 9. Area south of Tempe Fossae (31°N, 77°W), where ridges are cross cut and terminated by NE faults radial to an area north of Ascraeus Mons, and NNE faults radial to a center southeast of Pavonis Mons. Orthogonal relations of these intersections suggest that ridge and fault formation was related to the same center of tectonic activity (Viking Orbiter Frame 519A11).

1978), whereas the NNE faults clearly post date the emplacement of this unit and its structures (i.e., those shown in Fig. 9).

Coprates region. In southern Coprates, a single E–W trending fault swarm, radial to a point south of Arsia Mons, forms numerous Type C and T intersections (Figs. 3A, B and 4). In this area, 57% of the 21 observed Type T and C intersections are orthogonal (Fig. 10), which are formed by ridges trending almost due north. Most of these ridges are found in the eastern half of the swarm (Fig. 4). The nonorthogonal Type C intersections, for the most part, are the result of a NE trending group of ridges to the west (19.5°S, 70°W) that are also crosscut by the same E–W faults. These relations suggest that the NE trending ridges developed prior to the tectonic center that generated the E–W faults and their corresponding orthogonal N trending ridges. The interpretation that more than one compressional event may have operated to produce the ridges surrounding the Tharsis region is consistent with a previous study of ridge orientations in the Amazonis, Memnonia, Lunae Palus, and Coprates quadrangles (Maxwell and Watters, 1981).

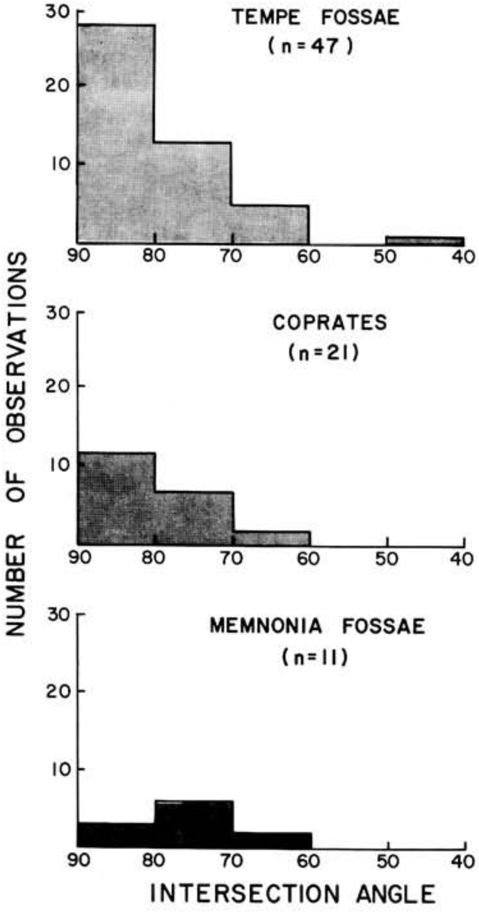

FIG. 10. Histogram of the intersection angles of Type C and T intersections in the Tempe Fossae, southern Coprates and Memnonia regions.

Memnonia Region. The Memnonia region is characterized by a set of faults radial to Arsia and Pavonis Mons. Unlike the other areas, ridges in Memnonia occur on relatively smooth plains that partially fill portions of the cratered plateau material (unit Nplc, Scott and Carr, 1978). In eastern Memnonia, Type C and T intersections are formed by a set of converging *en echelon* faults trending roughly NE and a more subdued ENE fault system that crosscuts NE trending set (Fig. 11). Of the 11 observed intersections in this region, only 3 are orthogonal (Fig. 10), suggesting that most of the ridges in this area formed prior to the development of the NE faults. The orthogonal intersections that do occur consist of ridges crosscut by the ENE trending faults which can be projected to a center near Arsia Mons.

DISCUSSION

Relative Age of Ridge Forming Event(s)

After the emplacement of ridged plains units, a period of tectonic activity with a stress center near Pavonis Mons, generated the following extensional features: (1) the faults of Tempe and Mareotis Fossae; (2) the faults of Memnonia; and (3) rifting of Valles Marineris and the Thaumasia graben (Plescia and Saunders, 1982). This period of activity postdates the faulting of the ancient heavily cratered Thaumasia highlands. The majority of the intersections involving regional stresses in the Tharsis region (i.e., those discussed above in the Tempe Fos-

FIG. 11. *En echelon* northeast oriented faults in eastern Memnonia (21°S, 154°W). Intersections in this region are predominantly nonorthogonal, although the few orthogonal intersections present suggest that ridge formation and ENE faulting are related to the same tectonic center. Most ridges in this region formed prior to formation of the earlier NE faults (Viking Orbiter Frame 637A58).

sae, Coprates, Memnonia region) are formed by faults radial to a broad zone around Pavonis Mons, suggesting that the compressional events that formed the ridges were roughly coincident with, and in some cases prior to, the extensional events that generated these faults. Further, it appears that the major compressional events related to Tharsis did not extend beyond this period, as indicated by the absence of compressional ridges on any stratigraphically more recent unit than the ridged plains (unit Hprg of Scott and Carr, 1978). On the plains north of Kasei Vallis, ridges occur as close as 20 km from the contact between the ridged plains and the cratered plains material unit (Apc) that covers Syria Planum and most of Sinai and Solis Planum. The cratered plains units also overlie the ridged plains to the west, yet no ridges have formed on this unit. In southwest Coprates ridges appear to be partially covered by flows related to the cratered plains material units (Fig. 12) Watters and Maxwell, 1983).

The relative age of Valles Marineris with respect to the compressional events that affected the ridged plains is difficult to determine since it is impossible to know the extent of the initial rift, and since the present contact of the walls with the ridges may be due to mass wasting. If Valles Marineris formed before the formation of the ridges, then the initial rift would have presumably acted a "free surface" effectively attenuating the compressive stress near its walls, resulting in a zone free of compressional ridges (R. S. Saunders, personal communication, 1981). This is supported by the lack of ridges on the plains between Ophir Chasma and Melas Chasma and on the plains around Tithonium Chasma. However, north of Hebes Chasma a group of WNW trending ridges superpose the regional NNW trending ridge systems (see Viking frame No. 682A27). These ridges may represent an expression of the compressional stress on the flanks of Valles Marineris. Further, in the area of Coprates Chasma, four ridges intersect the wall of Valles Marineris, one of which is terminated to the north by Valles Marineris and in the south by a large parallel graben (near the center of Fig. 7). The area between the southern wall and the graben has been heavily dissected by numerous subparallel to oblique faults. If the ridge formed after the development of the faults, the principal compressive stress (σ_1) operating perpendicular to the ridge axis would have resulted in movement on the preexisting faults rather than the formation of a compressional ridge. In addition, ridges intersecting the walls of Valles Marineris in the relatively narrow regions of the canyon (i.e., Coprates Chasma, see Viking frame Nos. 610A09 and 610A28) suggest that some ridges formed prior to and roughly coincident with the rifting event.

Implications for Models of Origin of the Tharsis Rise

There are currently three models that attempt to explain the origins of the stresses responsible for the tectonic features in the Tharsis Region: (1) isostatically compensated uplift (Wise *et al.*, 1979; Finnerty and Phillips, 1981); (2) simple loading (Solomon and Head, 1982; Willemam and Turcotte, 1982); and (3) a combination of isostatically compensated uplift and flexural loading (Banerdt *et al.*, 1982).

A net crustal expansion after perhaps several pulses of uplift and relaxation is manifest in Valles Marineris, the Thausmasia graben, and Noctis Labyrinthus. This type of activity can be explained by the model proposed by Finnerty and Phillips (1981) suggesting uplift and net volumetric expansion of the Tharsis crust as a result of partial melting of the mantle coupled with solidification of low pressure, low density mineral assemblages.

Models invoking simple loading suggest that the ridges formed as a result of a long term viscoelastic response of the lithosphere to the volcanic loading of the region. This does not appear to be the case since

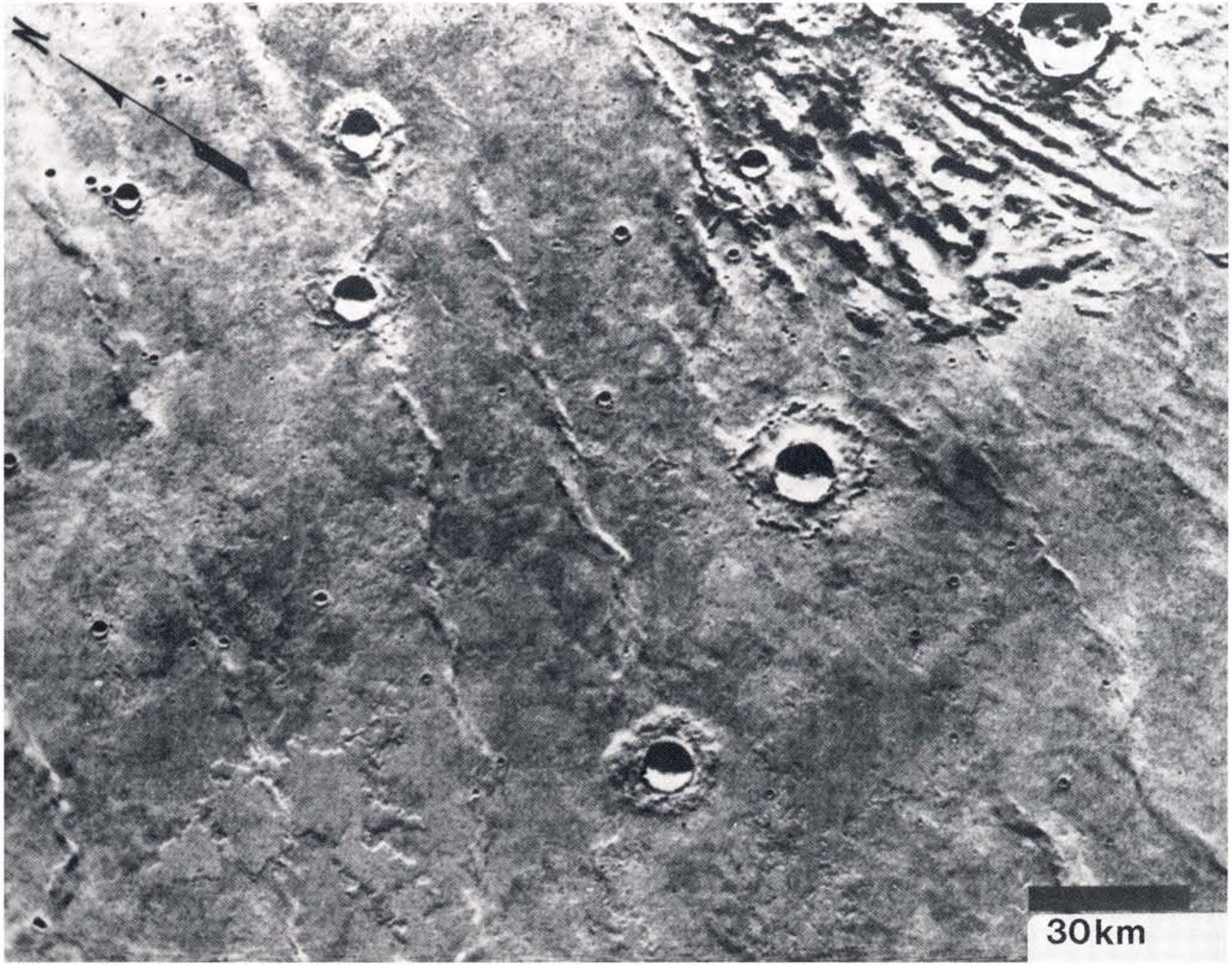

FIG. 12. Western Coprates region showing recent volcanic flows of the cratered plains material (Apc; Scott and Carr, 1978) partially covering ridges formed on the ridged plains unit (Hprg; Scott and Carr, 1978) (Viking Orbiter Frame 608A22).

the compressional events that formed the ridges appear to be restricted in time both by their relationship to regional extensional events and by the age of the volcanic unit on which they formed.

The predicted regional stress trajectories obtained from a flexural loading model do not fit the observed locations and principal orientations of the compressional ridges (see Fig. 3C in Banerdt *et al.*, 1982). The relative age sequences for tectonic events presented in this study favors a model involving one or more isostatically compensated uplifts of the crust after the emplacement of the ridged plains units. These uplifts followed by relaxation generate periods of regional compression with possibly two or more stress centers. Predicted regional stress trajectories obtained from a isostatic model agree well with the observed orientations and locations of the compressional ridges (see Figs. 41 and 42 in Phillips and Lambeck, 1980; and Fig. 3b in Banerdt *et al.*, 1982).

If the evolution of Tharsis progressed from isostatically compensated uplift to flexural loading, as Banerdt *et al.* (1982) have suggested, then the evidence presented here indicates that the compressional events that formed ridges on the ridged plains units occurred during the isostatic stage and not during the period where flexural loading has dominated.

CONCLUSIONS

Based on observations of crosscutting relations in the Tharsis region of Mars, a classification scheme involving three distinct types of ridge–fault intersections has been developed based on the following criteria: (1) Type C, a ridge crosscut by a fault; (2) Type T, a ridge terminated at one end by a fault; (3) Type S, a ridge superposed on a graben. The most abundant intersection in the Tharsis region is Type C, accounting for 81% of the observations. Relative age relationships based on these intersections types are interpreted as follows: (1) Type C intersections crosscut by nonorthogonal faults relative to the trend of the ridge represent a preexisting ridge cut by a later extensional event; (2) Type T and C intersections involving orthogonal faults represent stresses associated with the same tectonic center but are not the result of the same stress field; (3) Type S intersections represent a preexisting fault superposed by a ridge generated in a later unrelated compressional event.

Examination of ridge–fault intersections on the ridged plains involving regional stress (those involving faults with radial trends to major topographic features in the Tharsis region) have led to the following conclusions: (1) the major ridge forming events in the Tharsis region were roughly coincident with, and possibly prior to the extensional events that produced the faulting of the Tempe and Mareotis regions, the Coprates and Memnonia regions, and the rifting of Valles Marineria; (2) the compressional events that formed most of the ridges are restricted in time both by their relationship to regional extensional events and by the age of the units on which they formed.

Models involving loading of the crust, implying the compressional ridges are a result of a long term viscoelastic response of the lithosphere, are not supported by this study. A model involving one or more isostatically compensated uplifts and subsequent relaxation of the crust after the explacement of the ridged plains volcanic units is favored.

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