MORPHOLOGY AND ORIGIN OF RIDGES IN LOW-LATITUDE AREAS OF MARS

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(Received 4 April, 1984)

Abstract. The Martian ridges present a larger diversity of forms and patterns than the lunar ridges. The main explanation is the following: unlike the lunar-ridges, the low latitude ridges on Mars are not related to volcanism, but are in close connection with hydro-lithosphere. Their morphologic similarities with the lunar ridges are probably due to a similar dynamic origin – i.e., compression of a thin crust lying unconformably over the substratum (on Mars, porous sediments saturated with water). It is suggested that in some areas Martian ridges are mainly of extrusive origin (material extruded from the hydro-lithosphere), unlike the lunar ridges.

Résumé. Les rides de Mars présentent une plus grande diversité de formes et de dispositions que les rides de la Lune. Alors que les rides de la Lune sont liées au volcanisme des mers, les rides de Mars sont en étroite relation avec l'existence d'une hydrolithosphère, et là résidue sans doute la cause des différences observées. Les analogies morphologiques avec les rides de la Lune s'expliquent le mieux par une origine dynamique comparable, à savoir la compression d'une croûte suffisamment mince reposant en discordance sur un substratum constitué sur Mars par des sédiments poreux gorgés d'eau. Il est suggéré que dans certaines régions de Mars les rides sont surtout des formes extrusives, constituées par du matérial originaire de l'hydrolithosphére.

1. Introduction

It is usually recognized that ridges on Mars have the same morphology and the same origin as their counterparts of the lunar maria (Lucchitta, 1977). In both cases, these landforms are observed often in flat or nearly flat areas, such as the floors of the lunar maria, the plains and plateaus of Mars. Ridges are observed not only in the low latitude areas but also in the intermediate and high latitude plains and plateaus (Fernandez-Chicarro, 1982). This study refers only to the features located between N.30° and S.30° latitudes. On the Moon and on Mars, ridge morphology is characterized by two main morphological features:

- an elongated bulge, more or less largely arcuated, up to 10 km wide, and no more than 300–400 m in height (generally 50–100 m);
- a continuous or 'en echelon' ridge, occasionally narrow, forming a crest with steep slopes, surimposed on the elongated bulge.

Each ridge can be several hundreds of kilometers long. In most places, ridges are more or less parallel. On Mars, their groups may extend over several thousands of kilometers.

Earth, Moon, and Planets **31** (1984) 49–61. 0167-9295/84/0311-0049$01.95.

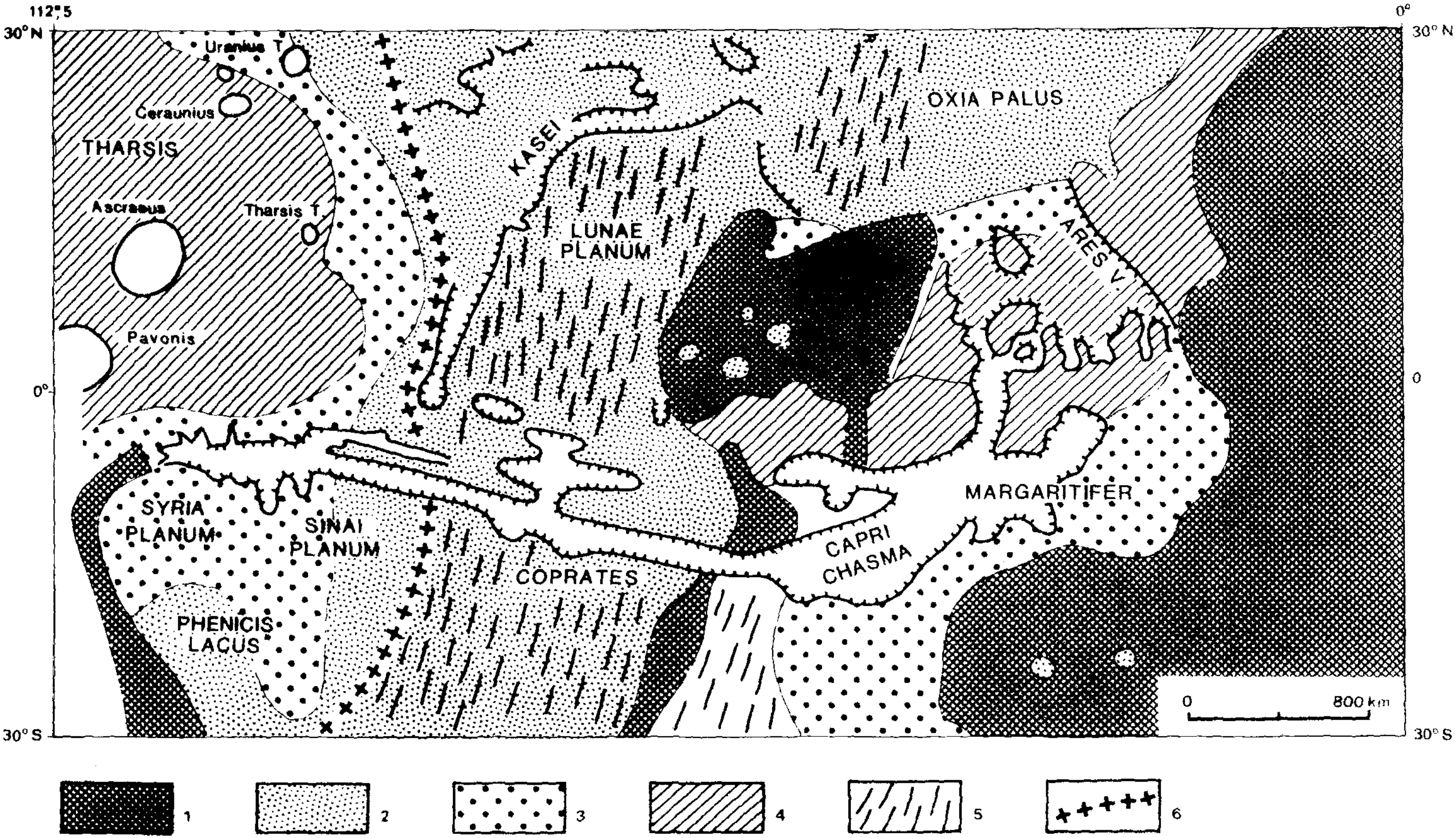

Fig. 1. Distribution and depth of the hydrolithosphere at the lower latitudes of Mars, between 0° and 112°,5 longitude. (1) discontinuous hydrolithosphere or lack of hydrolithosphere (generally old heavily cratered terrains); (2) depth of the top of the hydrolithosphere: 750 *m* (± 500 *m*); (3) depth of the top of the hydrolithosphere: between 1 and 2 km; (4) depth of the top of the hydrolithosphere: more than 2 km; (5) fields of wrinkle ridges; (6) lava flows cover limit of the Tharsis volcanic region. The scale is approximate.

2. Formation of the Lunar Mare ridges

Most of the authors agree that there is a relationship between the ridges, the upfilling of depressions by mare basalts, and the subsequent tectonic processes. Arching is due to the compression of a thin lava crust lying unconformably over underlying lavas (Colton *et al.*, 1972; Bryan, 1973). It implies a tectonic process due to isostatic adjustment. The 'en echelon' pattern is due to shifting movements that occur during the subsidence (Tjia, 1970).

Upon the fact that some ridges are extending to highland lineaments, Strom (1972) proposed the hypothesis that the lave crust could have been distorted by subsurface sill of intrusive laccoliths. Sometimes, lavas has broken up the surface crust, generally in the axis of the bulge, and intruded materials are responsible for the narrow ridges surimposed to the bulge in some places.

3. Different Types of Low Latitude Ridges on Mars

Martian ridges present a larger diversity of forms than the lunar ridges. Arches without surimposed narrow ridges are found as on the Moon and with similar sizes (Figure 2c). Most often a narrow crest with steep slopes (narrow ridge type), some hundred meters in width, is surimposed to this ridge type. This narrow ridge type is situated in the axis (Figures 2b and 4) or in the side (Figure 5) of the bulge of the plain ridge. However, it can be clearly separated from the bulge and it can extend laterally or farther than the bulge in the same direction (Viking 068A45).

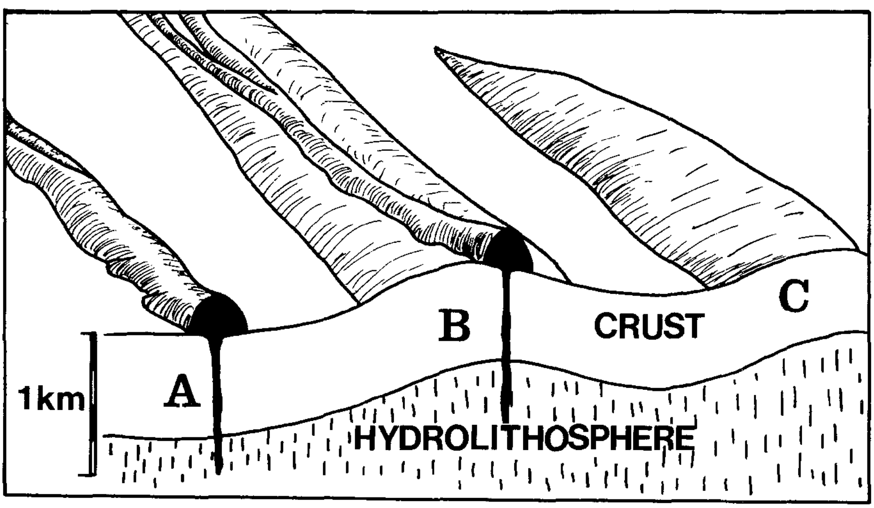

Fig. 2. Three typical forms of ridges on Mars. (a) extrusive type (narrow ridge); (b) mixed type with an extrusive part (narrow ridge) and deformation of the crust (arch); (c) type with only arching of the crust.

The crest (narrow ridge) can be continuous or divided into shifted segments. In some areas where lithospheric water seems to be very important (craters with many fluidized ejecta showing several elongated lobes), the crest can be so developed that it takes the place of the bulge itself (Figure 2a and central part of Coprates SW 1/2.000.000). This type of ridge progressively changes to a type of ridge unknown on the Moon, that is mainly expressed by a creast form: knotty narrow ridges (Figure 6), twisted ridges, hooked ridges, dotted ridges (Coprates SE 1/2.000.000 between 64° W and 67° W and between 50° W and 58° W).

In Coprates and Lunae Planum, the ridges are nearly parallel and they are generally trending (North-Southward) perpendicularly to the main compressive stress (Phillips and Ivins, 1979; Phillips *et al.*, 1981). In some places, they may cross over each other following the local fracture pattern, and they form a network (Coprates SE) that is not observed on the Moon.

4. Spatial Relationship Between the Martian Ridge Fields and the Presence of Hydrolithosphere

Mars is the only known planet in the solar system with a specific type of meteoritic craters showing ejecta that are flank outflows with widely stretching convex lobes (sometimes named splash craters). Carr *et al.* (1977) studied Yuti crater, and showed that its ejecta have experienced flooding processes after a ballistic period, that extended on several tens of km, and that produced the lobes.

Johansen (1979) and Mouginis-Mark (1979) distinguished the 'flower-type' with thin ejecta blanket, and the 'composite-type' with an inner ring built by a thicker ejecta blanket hiding the substratum.

Since Carr's 1977 study it has been admitted that the ejecta fluidity is related to the water or to the subsurface ice melted by impact. Inventory and mapping of the fluidized ejecta craters provide a method to point out the existence of significant amount of subsurface lithospheric water in pervious rocks (either ice in the permafrost, or water in the lower hydrolithosphere). According to these characters, one can estimate that in the Martian low latitudes, continuous hydrolithospheric areas represent about 65% of the entire surface (Figure 1). The non-hydrolithospheric areas generally correspond to the oldest terrains. In these areas, there are small hydrolithospheric units some hundreds of kilometers in width and corresponding either to floors of partly filled large craters, or to depressions due to other origin.

It seems likely that ridges are in close relation with the hydrolithosphere. The large fields of ridges on the Coprates, Lunae Planum, Western Amazonis, Chryses Planitia, South Elysium, and Syrtis Major plateaus correspond to widespread continuous hydrolithospheric areas. Ridges are also found in small hydrolithospheric units inserted in old terrains. However, ridges are not observed in non-hydrolithospheric areas. One can notice also that large areas with 'splash' craters do not show ridges.

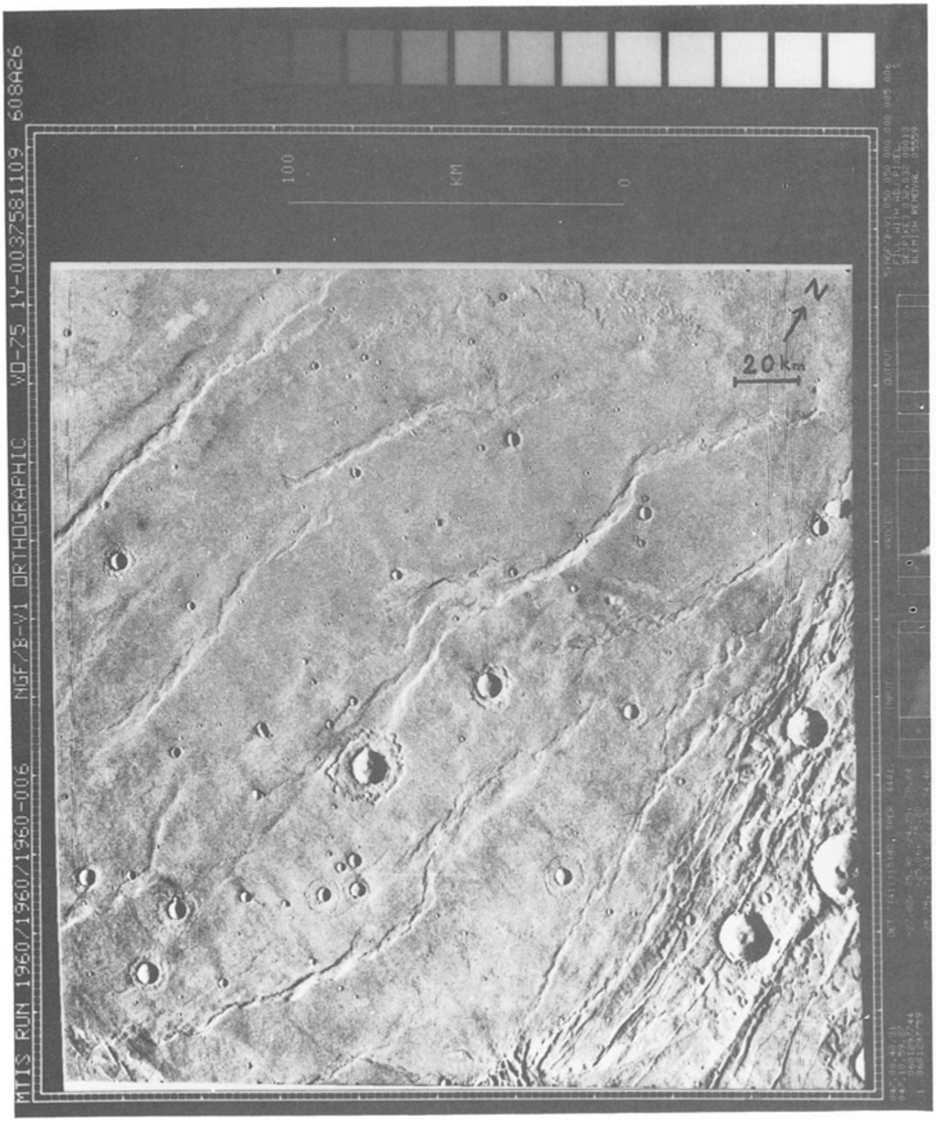

Fig. 3. Wrinkle ridges on Coprates Plateau (23°–27° S, 72°8–76° W). On the most part of the photograph, hydrolithospheric terrains with ridges and meteoritic craters with fluidized ejecta from 5 km diameter. In the corner of the photograph, older terrains with poor hydrolithosphere, heavily fractured. Ridges and the main fractures are in parallelism. The scene is 240 km across (608 A 26). NASA photograph.

5. Relations Between the Ridges and the Hydrolithosphere Depth

In order to estimate the depth of the hydrolithosphere top, Carr (1979) proposes to use the diameters of the fluidized ejecta craters. Based on a depth-diameter ratio equal to 1/5

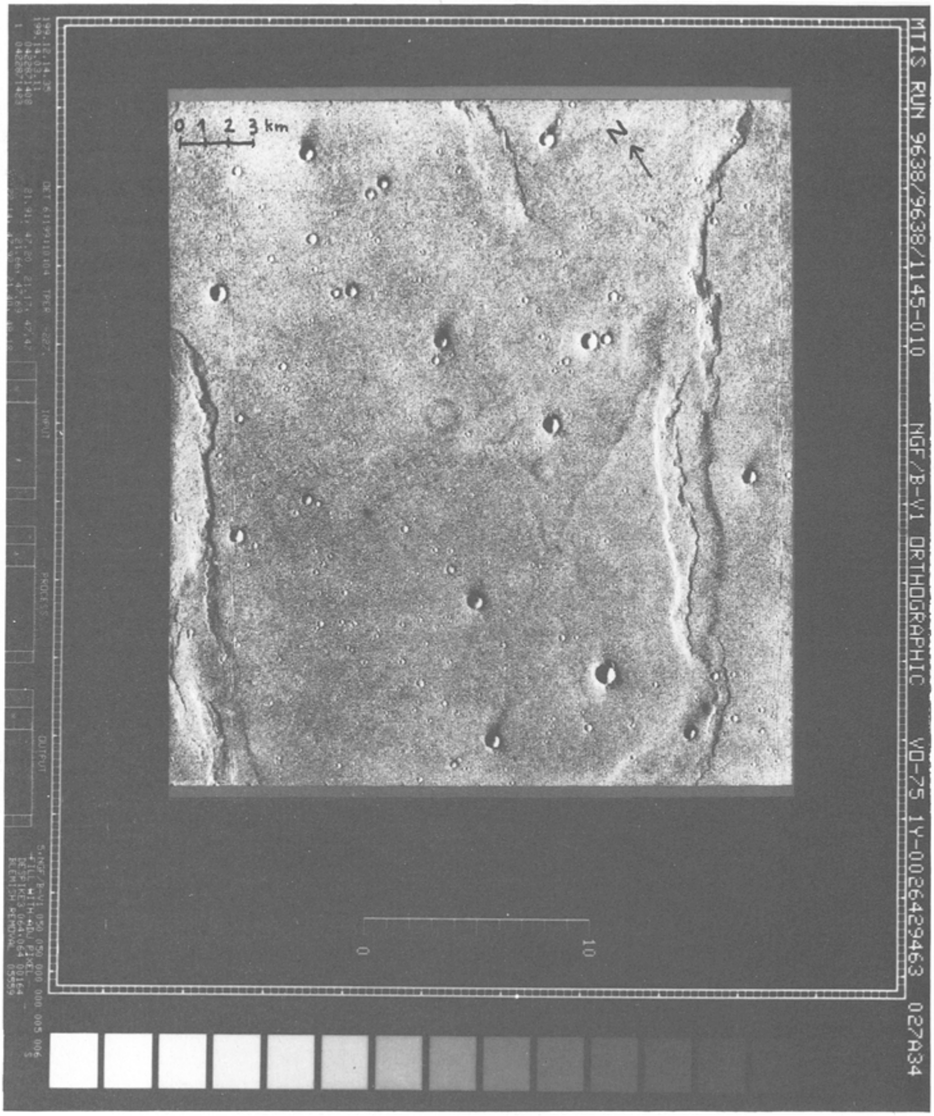

Fig. 4. Ridges of the mixed type on Chryses Planitia (21°5 N, 47°5 W) with deformation of the crust crested with an extrusive narrow ridge. The meteoritic craters, under 2 km diameter, are without fluidized ejecta. The scene is 28 km across (027 A 34). NASA photograph.

(Boyce, 1979) a 5 km in diameter crater with fluidized ejecta would indicate that the hydrolithosphere top is at 1 km depth. The ratio proposed by Boyce is a convenient estimate for large areas, such as the largest part of Coprates and Lunae Planum plateaus. However, the hydrolithosphere top is deeper than 1 km in the Tharsis and Elysium volcanic areas. Figure 1 shows areas where some craters of 5 to 10 km in diameter still reach the lithospheric water (top of hydrolithosphere from 1 to 2 km depth). In order to reach the underlying hydrolithospheric level, meteoritic impacts went through a cover of recent lava flows more or less thick, up to 4 km in some places (Battistini, 1984). Besides the two large volcanic areas mentioned previously, a lower level of the hydrolithosphere top is also observed on the plateaus located on each side of Valles Marineris. It is noticed that ridges are only observed in areas where the hydrolithosphere top is at a shallow depth, i.e. in areas where the superficial crust is thin enough. Ridges are totally missing on the margins and in the center of the Tharsis and Elysium volcanic area, as well as on the eastern plateau that dominate Valles Marineris where the crust is thicker.

6. Structural Conditions for Ridge Formation

Unlike the lunar ridges, the Martian low latitude ridges are generally not related to volcanism. They are totally missing in the Tharsis and Elysium volcanic areas. Their morphological similarities with the lunar ridges are probably due to a similar dynamic origin, i.e. compression of a thin crust lying unconformably over the substratum.

The structural conditions for the formation of ridges in the Martian low latitudes are the following: existence of thick porous terrains saturated with water located at a depth ranging from some hundreds of meters up to about 1 km. The water ratio in the Martian upper lithosphere is closely related to the porosity (Carr and Baker, 1982). The highest porosity is unlikely found in grained rocks or lavas microbroken up by tectonics or by impacts (porosity of 0.1 after Carr, 1979; 1982). On the other hand it is probably located in volcanic ashes and lapillis, and mostly in eolianites and accumulations built up by large flows (outflow channels). It is possible to observe some outcrop of these terrains on the walls of Valles Marineris and Kasei Vallis. These formations are apparently sedimentary coherent rocks, several thousand meters thick, probably rather soft when not iced. They are covered by a hard crust, some hundreds of meters thick, overhanging by places (Bousquet and Bodart-Jourdain, 1982). This surface crust extends with the same thickness over hundreds of thousand square kilometers that is not in agreement with volcanic materials (McCauley, 1978, Phillips *et al.*, 1981). It seems likely that this crust is built by accumulations. It is possible that a crust too thick is not competent for arching by a compressive stress, nor to be intruded by the plastic material of the narrow ridge.

In addition, we assume that the depressions in the old terrains with discontinuous hydrolithosphere (and often with ridges), were not filled by lavas as commonly admitted, but probably by fine eolian materials, able to become a rich hydrolithosphere and to be indurated in surface.

7. Geodynamic Processes for the Ridge Formation

On Mars as on the Moon, ridges are interpreted by most of the authors as compressional structures (Fernandez-Chicarro, 1982). The ridge orientation on the Coprates and Lunae Planum plateaus is obviously related to the Tharsis bulge (Carr, 1981). The ridges are perpendicularly oriented to the main compression stress (Phillips and Ivins, 1979, Wise *et al.*, 1979; Phillips *et al.*, 1981). The regional compression accounts for the formation of one feature of the ridges: the arching of the crust. The formation of the narrow ridges (extrusive features) is difficult to explain by the same process because compression tends to close rather than to open the fractures. But, we must account the compression of more plastic saturated terrains of the underlying hydrolithosphere. These terrains were able to migrate up to the surface along the crust fractures. These fractures are either multidirectional networks (ridges of Coprates SW and SE) on breaks of the same age as the arching process, and they follow more or less the arching axis. In the case of ridges showing arch and crust, there is no evidence that the arching process is of the same age as the intrusion. Up to now, the formation of Martian ridges was only explained in terms of the processes observed on the Moon. Our opinion is that the subsurface water (hydrolithosphere) was the main agent, although other agents could have contributed to the ridge formation on Mars. Indications of important climatic variations on Mars are noticed, but their importance and periodicity are not well known (Pollack, 1979; Baker, 1982). Climatic variations and other processes, such as variations of the geothermal gradient, could have latered the lower limit of the frost. Consequently the permafrost volume changed that produced internal stresses, mostly along the fracture trends, and subsequent distortions of the superficial crust. On the other hand, the instability and the mobility of the lithospheric water and the reservoir terrains, produced some important geomorphologic features such as: subcircular depressions of sorted size and oriented along fractures trends, collapsed depressions of large size, catastrophic flows responsible for the outflow channels, landslides at the foot of the great slopes, etc. . . . The mobility of the hydrolithosphere could have produced collapses of the crust at regional or microregional scales. These processes possibly contributed to the formation of:

(1) the wrinkle in the old terrain depressions,
(2) the crests (or narrow ridges), often more important than on the Moon, and the ridges entire of extrusive origin,
(3) the ridge network, mainly of extrusive origin (Coprates SW and SE).

Finally, impact of big meteorites could have extruded materials of the hydrolithosphere, along preexisting fractures, producing ridges of the last type in the surroundings (Figure 5, meteoritic impact produced a crater 30 km in diameter).

8. Ridge Erosion

For age dating of the Martian geomorphologic units, crater density is currently used, as on the Moon. Soderbloom *et al.* (1974) showed that on Mars and on the Moon, the heavy bombardment rate took place 3.9 billions of years B.P., and that it decreased significantly up to now. According to this method (Hartmann *et al.*, 1981), the ridges of Lunae Planum and Coprates could be 3.2 billions years old. The ridges are older than caterization, and they are probably of the same age as the surface itself. However they are not obviously eroded. The same observation is made for lobated ejecta of the splash craters.

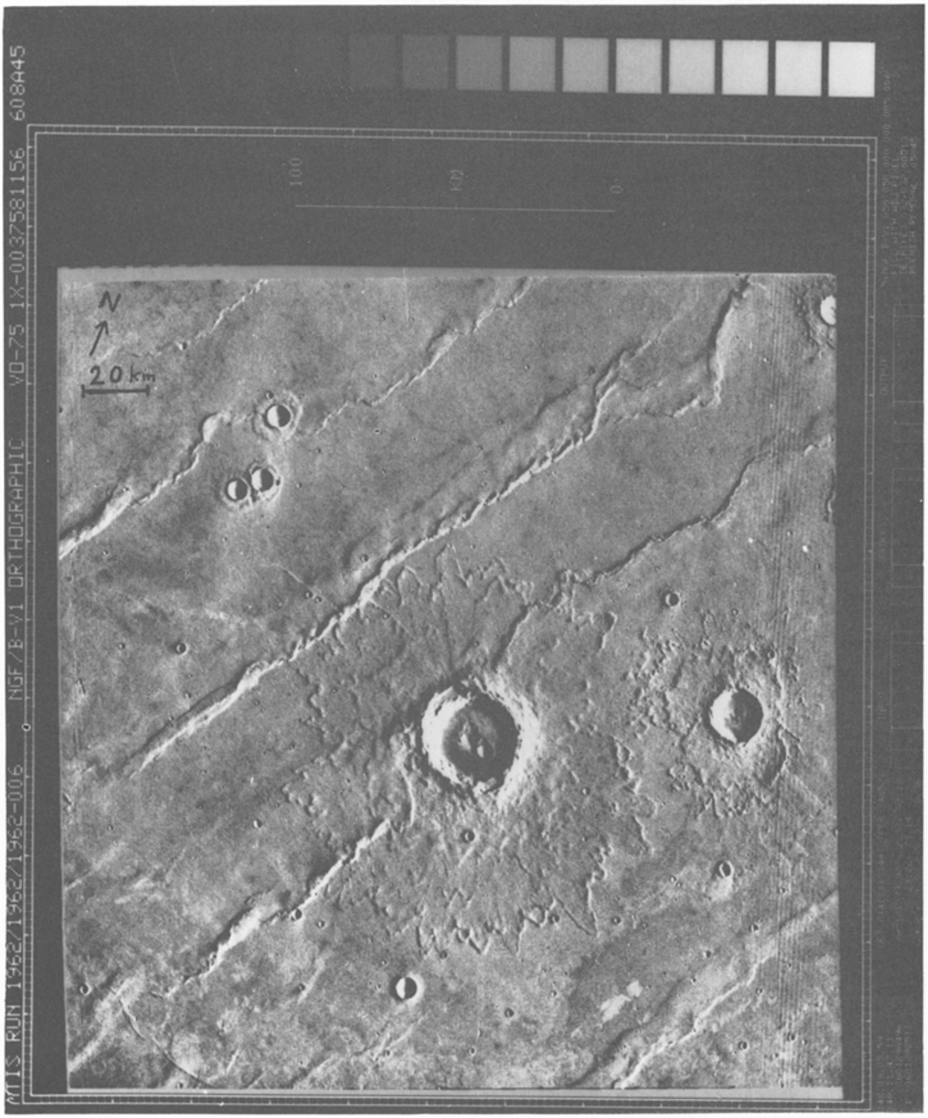

Fig. 5. Wrinkle ridges on Coprates Plateau, south of Valles Marineris (21°–24°5 S, 76°–81° W). We notice arching of the crust associated with important extrusive forms of narrow ridges, and two very beautiful meteoritic craters 30 and 17 km diameter, with lobated fluidized ejecta. The scene is 250 km across (608 A 45). NASA photograph.

This implies a very strong resistance to erosion, even if we account with an eolian erosion lesser active than in the large plains of the northern hemisphere. Such resistance would also concern the arch, the crest, and the lobated ejecta ring that come from the hydrolithosphere by extrusion or ejection. These materials, originally soft, must have been indurated after their deposition.

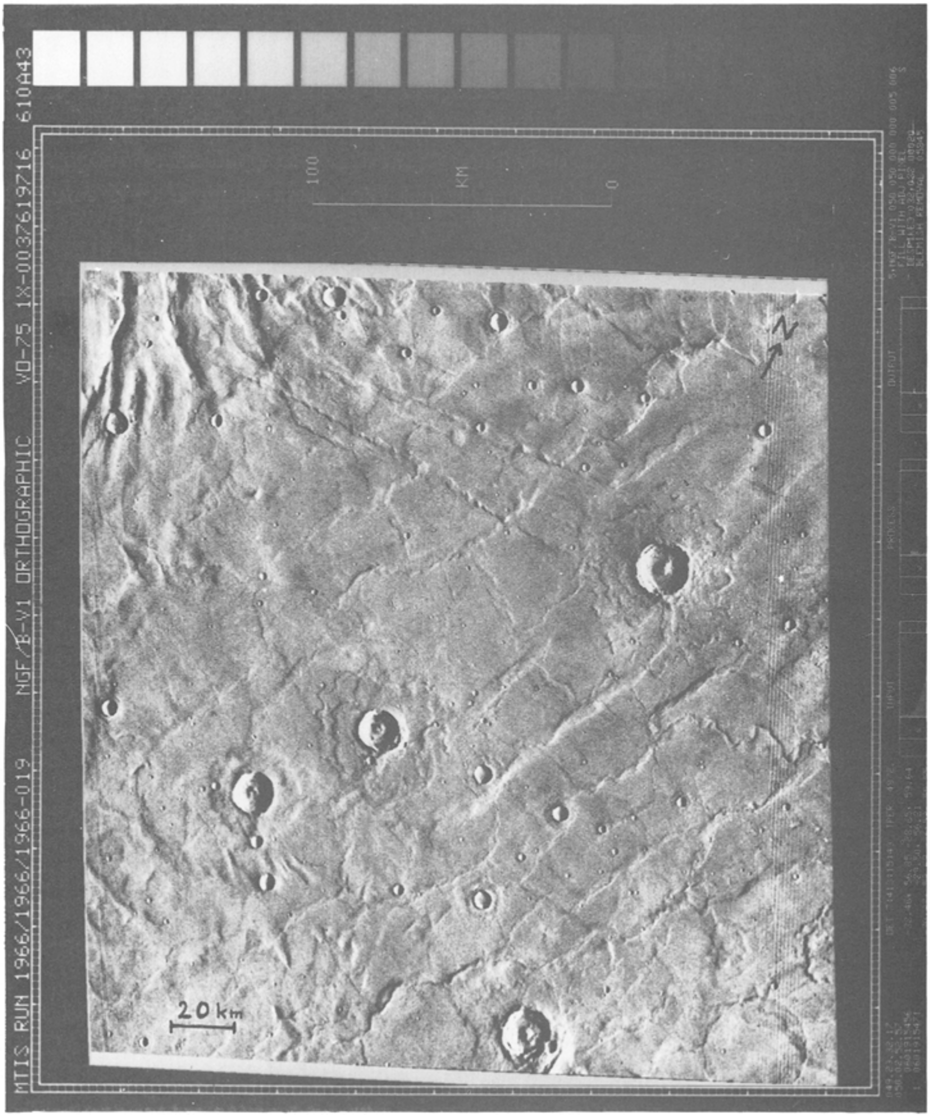

Fig. 6. Network of ridges in the south-east of Coprates Plateau (28°–23° S, 53°–58° 5 W). We notice the dotted type. The scene is 250 km across (610 A 43) NASA photograph.

Theoretically, it would be possible to obtain some information regarding the subsurface structure of the ridges by studying their outcrop on the large slopes. Usually, nothing appears, probably because of image resolution (with few exceptions). The Viking orbiter picture 520A27 (Lunae Palus NE) shows four ridges cut off by the Kasai Vallis high slope. It seems likely that each ridge is related to dykes on the slope. Viking 684A50 (Coprates NW) is much more convincing. Ganges Catena is a long depression located

50–100 km NE to Ophir Chasma (Figure 7). Its slopes recede by mass wasting and collapse of the superficial crust. This narrow depression is 75 km long, and was created by coalescence of small subcircular depressions trending along EW fractures. The entire system is cut by seven ridges that influenced fundamentally evolution of the depression. They strengthen the terrains, and their erosion on the slopes produced dykes that separated the depressions. There is no doubt that this morphology results of differential erosion between the ridge fracture filling material, more resistant to erosion, and the softer surrounding terrains. Viking picture 913A07 shows another example of this evolution.

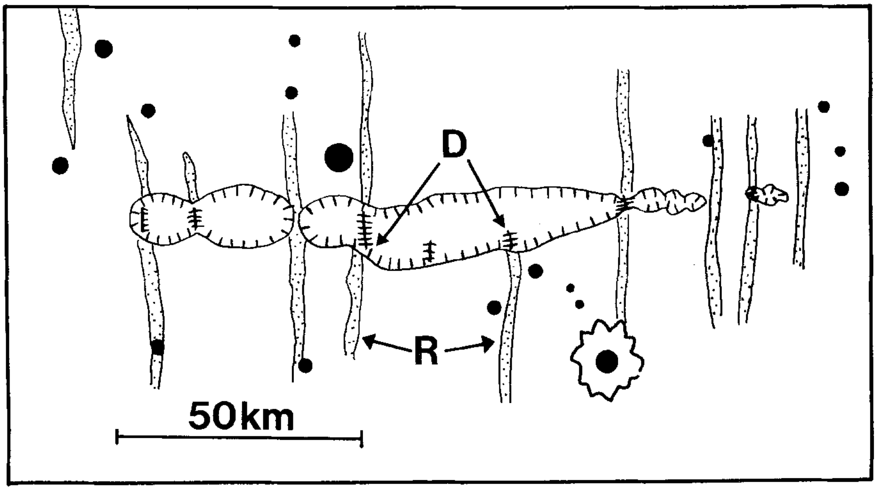

Fig. 7. Ganges Catena, in the north of Ophir Chasma, 2°5 S, 70° W. This long depression has been created by the coalescence of smaller subcircular depressions along a EW fracture. The whole system is cut off by ridges (R) of which erosion gives dykes (D) partitioning the depression.

Erosion of the large ridges by catastrophic flows coming from outflow channels may be observed on Lunae Palus NE (Viking 825A45 and 825A46) and on Chryse Planitia. The outflow has overcrossed the ridges, overdeepening axis depressions in these areas, and dividing ridges in segments. Important eolian erosion in the middle and high latitudes was only able to reduce ridge importance into residual reliefs, and even to destroy completely some of them, as seen in Arcadia Planitia in Cebrenia SE (Viking 776A34).

9. Summary

Unlike the lunar ridges, the low latitude ridges on Mars are not inferred to volcanism. Their morphological similarities with the lunar ridges are due to the same dynamical origin, e.g. compression of a thin crust that relays unconformably over porous sediments saturated with water. The ridge localization is closely related to subsurface hydrolithosphere that is well exemplified by the fluidized ejecta of meteoritic craters (splash craters).

These ridges are mainly observed in areas where hydrolithosphere is widely expressed. They are not observed in the areas where hydrolithosphere is missing, such as in the oldest densely cratered terrains, except the floor of large depressions that seem to be often very large craters partly filled. Ridges are only observed in the areas where the top of the hydrolithosphere is at a shallow depth, i.e. where the upper crust is thin enough (approximately 1 km thick). They are missing in the large volcanic areas of the Tharsis and Elysium Montes where the thickness of the superficial crust increases up to 4 km.

Most of the Martian ridges shows two morphologic characters similar to the lunar ridges: an elongated bulge with a more or less expressed arch. These ridges are possibly topped by narrow ridges. Other types of ridges exclusively observed on Mars are of an extrusive origin. They are usually organized either in fields of several tens of nearly parallel ridges, and in network pattern oriented along several local trends of fractures. These types of organization are not observed on the Moon.

Built up either with the same material as the surrounding terrains, or with material extruded from the hydrolithosphere, the Martian ridges resisted erosional effects during many hundreds of millions of years. Extensive wind erosion succeeded only in destroying the ridges of the medium and high latitudes. Some of them show a basis stronger than the surrounding terrains and are exhumed in dykes by differential erosion.

Acknowledgements

The writer is deeply indebted to Prof. Philippe Masson, Orsay University, France, for his useful suggestions and help during the development of the research.

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