# TECTONIC PATTERN OF THE CRATER GRIMALDI REGION OF THE MOON

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**Abstract.** The tectonics of the Grimaldi area are described and analyzed in detail from high-resolution Lunar Orbiter photographs.

Rille grabens are long and narrow fault zone structures of lunar terra. The polygonal rille graben pattern indicates the importance of lunar internal activity with an adjoining thin lithosphere in the areal tectonics at the time of rille grabening. The graben subsidence developed during tensional bending of this thin terra lithosphere. The en échelon graben offsets indicate the existence of strike-slip movements along the main fault under tensional lithosphere conditions.

In some places mare ridge ranges continue in the direction of the rille graben indicating the connection of these structures to each other as part of the lunar tectonic evolution. The very thin mare lithosphere was affected more easily and over a longer period of time by lunar internal forces. The effect of older structural units is thus less conspicuous within mare areas. Proposed Riedel-shear-like structures indicate a slight shortening and compression of the mare basin lithosphere during movements along lava-covered zones of weakness.

## 1. Introduction

### 1.1. RILLE GRABEN AND MARE RIDGE ZONES

Straight and arcuate rilles are commonly interpreted as tectonic grabens (Baldwin, 1963; Quaide, 1965; Ronca, 1965) bounded by inward-dipping normal faults (McGill, 1971, Golombek, 1979), thus representing part of the lunar global tectonic grid (Fielder, 1961; Strom, 1964) and probably an Imbrium pattern (Mason *et al.*, 1976). Major rilles are situated in the vicinity of the major lunar basins (Whitford-Stark, 1974a). The role of these and other local phenomena in the rille graben formation is also stressed in numerous papers (Quaide, 1965; Ronca, 1965; Whitford-Stark, 1974b; Head, 1974; Mason *et al.*, 1976; Guest *et al.*, 1976; Raitala, 1977 and 1978a; Solomon *et al.*, 1979; Golombek, 1979).

Mare ridges are identified as part of the lunar grid (Strom, 1964; Fielder, 1965) or radial (Strom, 1964; Scott *et al.*, 1975; Raitala, 1980), circular (Baldwin, 1963; Ronca, 1965; Maxwell *et al.*, 1975; Scott *et al.*, 1975) and tectonic zone (Raitala, 1978a, b, 1980) systems. They are interpreted as having been caused by volcanic activity (Quaide, 1965; Hodges, 1973) with tectonic location control (Fielder, 1965; Tjia, 1970; Colton *et al.*, 1972; Young *et al.*, 1973; Scott *et al.*, 1975; Lucchitta, 1977; Raitala, 1978a, b, 1980) or by compressional folding, wrinkling and compaction of the lunar surface (Baldwin, 1963; Ronca, 1965; Quaide, 1965; Morris and Wilhelms, 1967; Bryan, 1973; Lucchitta, 1976 and 1977).

The crater Grimaldi on the southwestern terra border of Oceanus Procellarum is one of the old (Stuart-Alexander *et al.*, 1970) mascon basins. In the present paper contrasting

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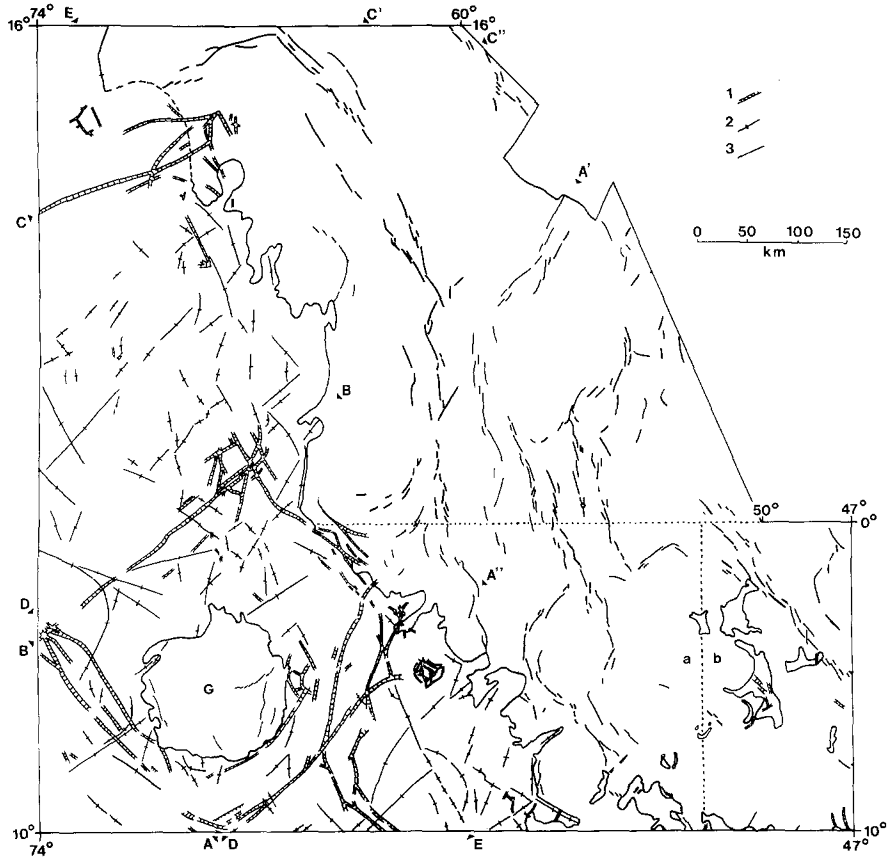


Fig. 1. Rille grabens (1) and major lineaments (2) of the Grimaldi (G) area with ridge ranges (3) of Oceanus Procellarum. For zones A–A'A", etc. refer to Figure 3(III) and for areas a and b refer to Figure 5.

styles of tectonism on lunar terra and mare are discussed with reference to the SW border of Oceanus Procellarum around the crater Grimaldi area (Figure 1).

## 1.2. About Methods

Grimaldi rille grabens and adjoining mare ridge structures were identified from the nearly vertical Lunar Orbiter IV photographs 161$H_2$ and $H_3$, 162$H_1$ and $H_2$, 168$H_2$ and $H_3$, and 169$H_1$ and $H_2$ with some help from U.S. Air Force maps LAC-56 (McCauley, 1967), LAC-74 (McCauley, 1973) and LAC-75 (Marshall, 1963).

After mapping and measuring, the rille graben and mare ridge structures were treated statistically and analogically to interpret the kinematics and dynamics of the tectonic development of the Grimaldi area.

### 1.3. Shear Zone Structures

The en échelon offsets of tectonic zones can be inspected in terms of second order fractures (Cloos, 1928; Riedel, 1929; Tchalenko and Ambraseys, 1970; Raitala, 1978a, etc.). Variations in the angle between second order faults or gashes and the strike of the main fault plane are most indicative of the direction and magnitude of local tectonic forces (Deng *et al.*, 1966; Lajtai, 1969).

The most important factor in second order fracture formation is the normal stress acting on the fault plane. Tension fractures develop at low normal stress, Riedel-shears form at medium rate normal stress, leading towards direct shear zone formation at high normal stress (Lajtai, 1969). The angle between the shear zone and tension gashes increases from about 0° during tensional normal stress conditions to about 45° at zero normal stress. At higher compressive stress the tension gashes should be more rotated, but with increasing normal stress the development of Riedel-fractures becomes more probable. Riedel-fractures also rotate with increasing normal stress (Figure 2; cf. Deng *et al.*, 1966; Lajtai, 1969).

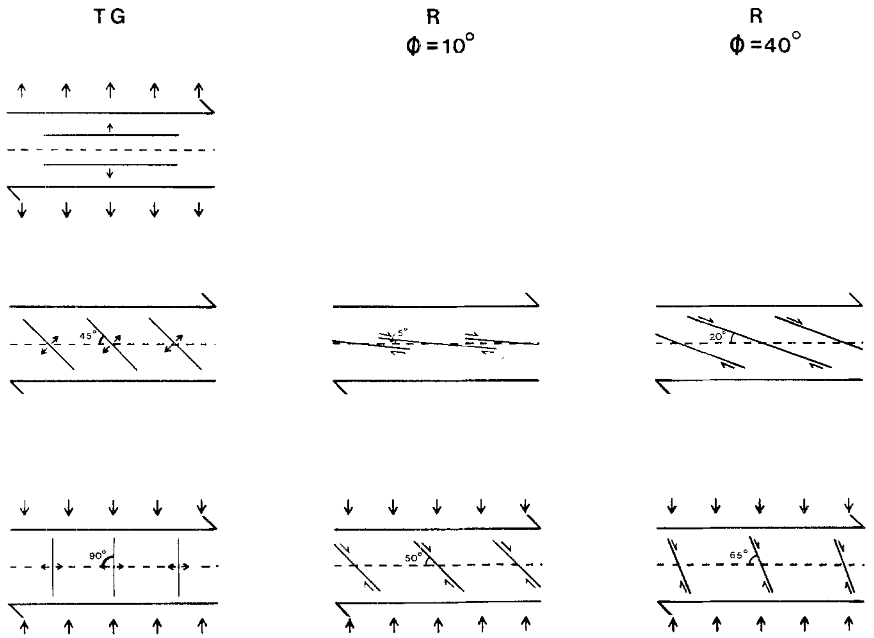


Fig. 2. The rotation of tension gashes (TG) and Riedel-shears (R) developed at different normal stress. The Riedel-shear orientation depends also on the angle of internal friction of the material ($\phi$; Lajtai, 1969). The angle between the shear zone and tension gashes increases from about 0° during tensional normal stress conditions to about 45° at zero normal stress. With increasing normal stress the development and adjoining rotation of Riedel-fractures becomes more probable.

## 2. Grimaldi Rille Grabens

### 2.1. Rille Graben Statistics

The major terra lineament and rille graben strike distributions were measured and presented by means of histogram plots in 10° groupings (Figure 3). The interpretations of terra lineaments is in many ways ambiguous, especially within the Grimaldi area belonging to the Hevelius formation (McCauley, 1967 and 1973). Terra lineaments are, however, not without structural significance (Whitford-Stark, 1974b; Karlstrom, 1974; Raitala, 1977; Gifford *et al.*, 1979).

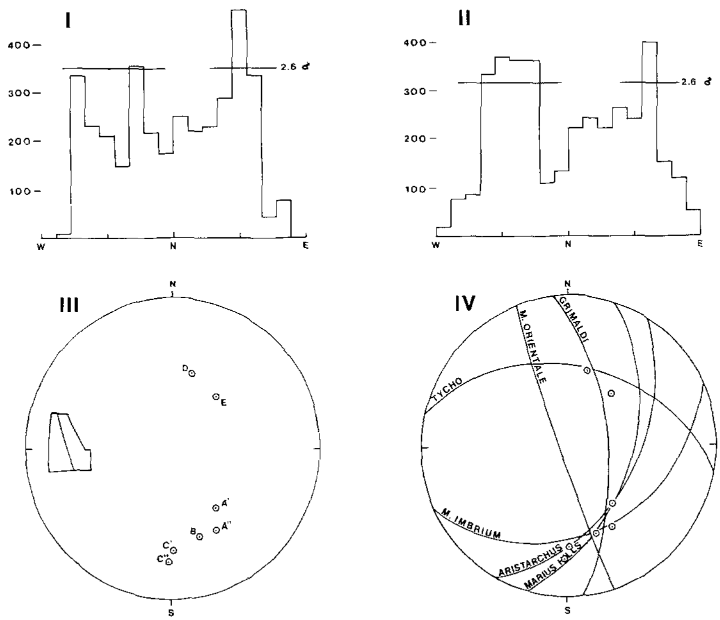


Fig. 3. The strike distribution of major terra lineaments (I) and rille grabens (II) with main rille graben zones thought of as parts of lunar great circles and represented as points on the Schmidt net (III). Planes corresponding to the centre points of Imbrium, Orientale and Grimaldi basins, of craters Aristarchus and Tycho, and of Marius Hills area are also shown (IV). Numbers indicate total length (km) of the features considered in diagrams.

In the histogram presentation of major lineament strikes in the Grimaldi area (Figure 3, I) three peaks are to be seen situated at N40°–50°E, at N20°–30°W, and at N60°–70°W. The lineament direction of N40°–50°E is possibly strengthened by Orientale effects although the most obvious radial Orientale streaks were excluded. The deficiency of E–W lineaments is clear.

The strike distribution histogram (Figure 3, II) of rille grabens of the Grimaldi area (Figure 1) has a broad northwestern peak at N20°–60°W and an equally high narrow northeastern peak at N50°–60°E. There is a deficiency of east–west rille grabens.

## 2.2. Kinematics and Dynamics

The major lineament strike distribution somewhat resembles that of scarps on the western border terra area of Mare Humorum (Raitala, 1977) with slightly narrower graph peaks. Thus traces of the global grid are to be seen (Fielder, 1961; Strom, 1964) except that there is a NNW distribution peak instead of the proposed N–S direction.

The rille graben pattern of the crater Grimaldi area could be investigated as part of the global grid with approximately NE–SW and NW–SE but without approximately N–S rille graben directions. This exception prompts us to seek more local or areal causes for the rille graben distribution. It is an easy matter to establish that the NW rille grabens approximately parallel both the southwestern border of Oceanus Procellarum (Figure 1) and the NW directed mare ridge ranges (cf. area I in Raitala, 1980). The NE rille grabens approximately continue (Figure 1) in places the NE directed mare ridge range zones (Raitala, 1980). Connections of these rille grabens to the Imbrian pattern are also indicated (Mason *et al.*, 1976) but the relatively late formation (Lucchitta *et al.*, 1978) of rille grabens may indicate the decisive final importance of re-activation of old zones of weakness roughly during the local climax phase of lunar endogenic activity (Raitala, 1977; Golombek, 1979).

The beginning of the rille graben formation may derive its origin from the time of the initial fracturing of the old lunar lithosphere indicated by terra lineaments (Whitford-Stark, 1974a; Karlstrom, 1974; Raitala, 1977). These old structural flaws were later re-activated in places, possibly even repeatedly, by major impact effects (Mason *et al.*, 1976).

The en échelon structures of lunar rille grabens (Figure 4), as also the termination mode of some rilles (Raitala, 1978b), indicate the significance of strike-slip movements along the rille fault zone. The angle of the en échelon offsets points to the existence of small areal tension during shearings along the rille faults (Figures 2 and 4).

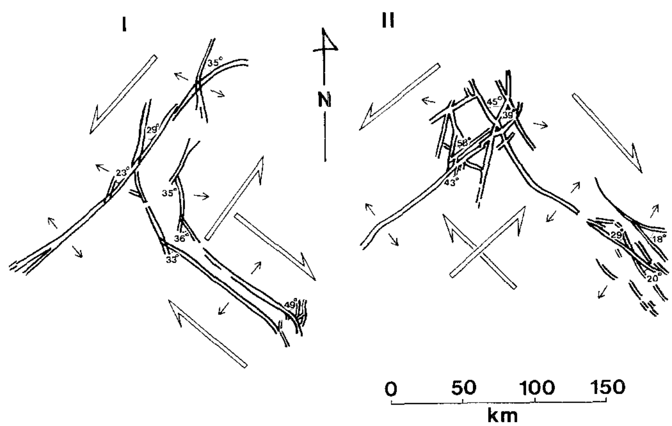


Fig. 4. Two sketches of rille graben offset angles within the Grimaldi area with the proposed tensional (minor arrows) and shearing (major arrows) directions.

According to Head *et al.* (1980a, b) the lunar lithosphere was anomalously thin within the Grimaldi area, thereby allowing the limited lunar internal volcano-tectonic forces to re-activate and deform lithosphere and surface structures. The rille graben formation evidently coincides with the major lunar areal thermal expansion around the present lava-flooded Grimaldi basin prior to 3.6 ± 0.2 b.y. ago (Lucchitta *et al.*, 1978).

Lunar internal thermal expansion against the thin lithosphere (Head *et al.*, 1980a) caused tension, which was strengthened around the lava loaded basins (Solomon *et al.*, 1979; Golombek, 1979; Head *et al.*, 1980b) and mostly released after thermal energy loss. This tension may have been the final cause of rille formation (cf. Whitford-Stark *et al.*, 1977; Raitala, 1977; Solomon *et al.*, 1979; Head *et al.*, 1980b) together with the contemporaneous global N–S (Fielder, 1961; Tjia, 1970, 1976; Raitala, 1977, 1978a) or E–W (Tjia, 1970; Fagin *et al.*, 1978) major principal stress. The considerable additional detail in the rille graben formation may have been brought by the mascon loading (Melosh, 1978) and the lithosphere bending during the partly independent floodings and loadings of Procellarum (Whitford-Stark *et al.*, 1977), Grimaldi and Crüger (Raitala, 1977) basins. This event occurred simultaneously with the escape of a considerable amount of lunear internal thermal energy accompanied by lithosphere thickening and freezing of tectonic terra structures.

### 2.3. Discussion

Rille grabening was preceded by pre-Imbrian global tectonic forces and by major impact events. Post-Imbrian terra tectonics culminated in the rille grabening. These conditions were characterized by the relatively thin terra lithosphere affected by the limited, but areally centralized lunar internal forces around major basins to cause tensional shear zones (Figure 8). This happened at least during the last major climax of lunar volcanic development lasting until about 3.6 ± 0.2 b.y. ago (Lucchitta and Watkins, 1978). The escape of lunar internal energy led at first to thickening of the terra lithosphere and to calming of terra tectonics.

The polygonal rille graben pattern evidently developed during a combination of normal and strike-slip faultings approximately along the crest lines of lithospheric tension bulges and under proposed global N–S compression conditions, respectively, around the Grimaldi basin (Figure 8).

## 3. Mare Ridges

### 3.1. Mare ridge statistics

Statistical analysis of mare ridges of the central parts of Oceanus Procellarum (Raitala, 1980) and of the Letronne-Montes Riphaeus region (Raitala, 1978a) have already shown the northwestern ridges to dominate within the Oceanus Procellarum. The main graph peak at N40°–50°W of the area b (Figure 5) is in the same direction as an important peak of the Flamsteed area (area I in Raitala, 1978). The distribution graph of area a (Figure 5) has peaks at N30°–40°W and at N0°–20°W resembling the strike distributions of areas I and VIII, respectively (in Raitala, 1980).

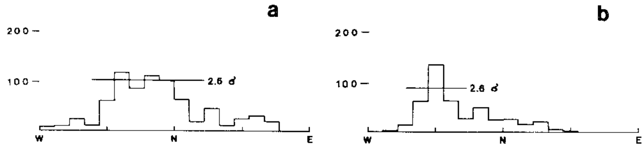


Fig. 5. The strike distribution of ridge segments of areas a and b in Figure 1. Numbers indicate total length of the ridges considered in the diagrams (km).

### 3.2. Kinematics and Dynamics

The identification of en échelon ridge ranges (Raitala, 1978a, 1980) resembling shear zone structures (Tchalenko, 1970; Tchalenko and Ambraseys, 1970) is also valid within this mare area. Old zones of weakness were covered by mare basalts and reactivated during lunar volcano-tectonic development. Most important mare ridges form mare ridge zones approximately diagonal to the present lunar rotation axis direction. Very numerous NW–SE directed mare ridge zones also approximately parallel the SW border of Oceanus Procellarum. Some important mare ridge zones of the central Oceanus Procellarum are radial to the major volcanic Aristarchus and Marius Hills areas (Raitala, 1980).

The strike-slip (Tjia, 1970 and 1976; Raitala, 1978a, b and 1980) and vertical (Lucchitta, 1976, 1977; Lucchitta and Watkins, 1978) movements along mare ridge zones emphasize the importance of the thin-lithosphere conditions. Only within mare basins and adjoining volcanic areas was the lunar lithosphere thin enough to be broken by lunar weak tectonic forces even during late-volcanic periods.

The considerably thin basin lithosphere tectonics of Oceanus Procellarum (Head *et al.*, 1980a, b) may be expressed in terms of lunar internal thermal energy development (Solomon *et al.*, 1979), of older structural systems (Raitala, 1978a, b, 1980) and of lunar global development (Tjia, 1970; Lucchitta, 1977; Fagin *et al.*, 1978). Attention must be paid to volcano-tectonic forces (Raitala, 1980), e.g., to regional internal energy sources below Oceanus Procellarum maintaining thin-lithosphere conditions (Head *et al.*, 1980a, b), to energy transport through the lithosphere (Raitala, 1980), to sinking of the Procellarum basin caused by cooling and contraction of lunar interior and by regional lava fill loading (Whitford-Stark *et al.*, 1977; Solomon *et al.*, 1979). The influence of the even still existing global stress must also be taken into the account.

The en échelon structures of mare ridges (Figures 6 and 7) express the significance of different scale strike-slip movements along the lithosphere zones of weakness indicated by present mare ridge zones. The orientation of these Riedel-fracture-like en échelon structures points to the existence of a slight areal compression during shearings along the zone of weakness (Figures 2, 6 and 7). The Oceanus Procellarum basin sinking caused by lava loadings and lunar internal cooling led to the lithosphere shortening and to compressional circumstances. The angle between interpreted


Fig. 6. The directions of mare ridge zones and of mare ridge ranges of SW Oceanus Procellarum (cf. Figure 1 and also Figure 6 in Raitala, 1980).

Riedel structures and the mare ridge zones varies within this area, possibly indicating differences in compression (Lajtai, 1969) in different parts of the shortened basin lithosphere.

## 3.3. Discussion

Mare ridge formation would have occurred subsequent to the rille grabening period. The very thin Oceanus Procellarum basin lithosphere was evidently strongly affected by all major tectonic forces but only some hints of these have retained through the last

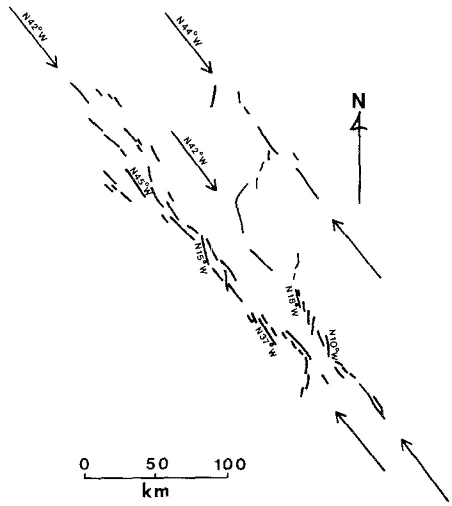


Fig. 7. The directions of mare ridge ranges and of some mare ridge segments of the area b in Figure 1 (cf. also Figure 7 in Raitala, 1978a).

major volcano-tectonic deformation phases. Different tectonic forces caused vertical and horizontal movements along lava-covered zones of weakness and gave rise to fracture opening in the compressional mare basic environment (Figure 8). These fractures were forced by volcanic materials. Ridge formation possibly continued over a long period of time until lunar internal energy dissipated and became insufficient to have essential effects on the thickened basin lithosphere.

## 4. Conclusion

Terra rille grabens and mare ridge ranges indicate the existence of lithosphere zones of weakness. Along these zones both strike-slip and vertical movements have taken place. Some of these zones continue through the terra-mare boundary, changing their tectonic style (Figures 1 and 8). It is possible to express contrasting tectonics styles of terra and mare areas on the SW border of Oceanus Procellarum in terms of lunar internal energy dissipation and lithosphere development.

During the major mare volcanism the terra lithosphere of the Grimaldi area was thick enough to retain traces of the older global and areal structures but thin enough for part of these structures to be re-activated and deformed leading to tensional rille grabening. The waning of internal energy with subsequent terra lithosphere thickning reduced the role of tectonics to the present minimum.

The very thin mare lithosphere was affected more easily and over a longer period of time by lunar internal forces. There must have been major energy sources below

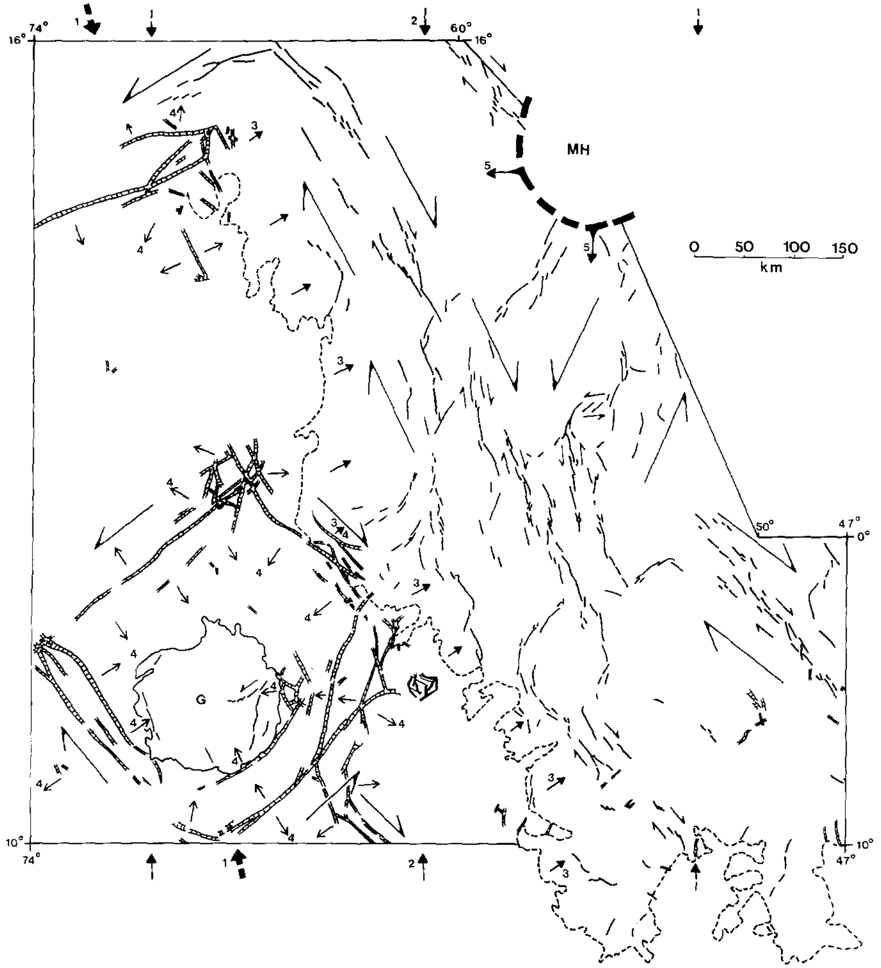


Fig. 8. Sketch of the tectonics of the Grimaldi (G) and SW Oceanus Procellarum area with the proposed but highly questionable first global NNW–SSE compression phase (direction 1) and with the second global N–S compression phase (direction 2). Arrows also indicate the compression direction of the SW border of Oceanus Procellarum towards the middle parts of the shortened basin lithosphere (3), tensional directions coupled to the rille grabening or compressional directions when coupled to basin ridge formation (4), and the radial stresses against lithosphere blocks around the Marius Hills (MH) area (5). Half-arrows indicate the senses of important shear movements.

Oceanus Procellarum just maintaining the thin lithosphere conditions and repeated volcanic pulses. The effect of older structures is thus less conspicuous within mare areas. The highly compressional environment indicated by the Riedel-fracture-like orientations of mare ridges and ridge ranges was caused by downwarping and shortening of the basin lithosphere.

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