# LUNAR 'EN ECHELON WITHIN EN ECHELON' STRUCTURES

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**Abstract.** Some en echelon structures, tension gashes and compressional ridges may form similar patterns. The N-S compression activates diagonal conjugate zones of weakness with tension gashes in the vicinity of the compressional direction. In the case of E-W compression similar arrangements of en echelon compression ridges are generated.

The global N-S compression existing at the time of fracturing of the lava-flooded Oceanus Procellarum basin is arguable. It is possible to interpret some different scale mare ridge arrangements as 'en echelon within en echelon' structures. Major ridge ranges evidently have Riedel and opposite Riedel orientations and they consist of minor en echelon structures which may in places be intruded tension gashes but are evidently mostly sheared and compressed Riedel fractures.

The 'en echelon within en echelon' structures of mare ridges manifest 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 echelon structures also points to the existence of an areal compression during shearings along the zones of weakness. 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 proposed Riedel structures and the mare ridge zones varies within this area, possibly indicating differences in compression and shearing in distinct parts of the shortened basin lithosphere.

## 1. Introduction

The existence of en echelon structures associated with faults and shear zones is confirmed in numerous papers (Cloos, 1928; Riedel, 1929; Lajtai, 1969; Tchalenko and Ambraseys, 1970; Wilcox *et al.*, 1973; Freund, 1974). The origin, development and occurrence of different en echelon structures along major zones of weakness are, however, still problematic. Studies of experimental and natural shear zones have shown that there are similarities between different scale en echelon patterns formed during Riedel experiments, shear box testa and earthquake faultings (Tchalenko, 1970).

Lunar mare ridges and ridge ranges are described as forming en echelon patterns. If they are interpreted to be tension gashes or compressional ridges the possibility of both N-S and E-W compression must be taken into account (Tjia, 1970). Fagin *et al.* (1978) chose the E-W compression alternative with mare ridges as compressional ridges but the N-S compression model with intruded tension gashes is at least equally arguable (Tjia, 1976). The minor en echelon mare ridge pattern within the major en echelon pattern remains, however, unexplained. The identification of mare ridges as Riedel structures (Raitala, 1978a, 1980, 1981), on which more discussion is still required, offers, however, a good starting point for further and more accurate investigations of lunar kinematics and dynamics as well as of the development of fracture zone structures.

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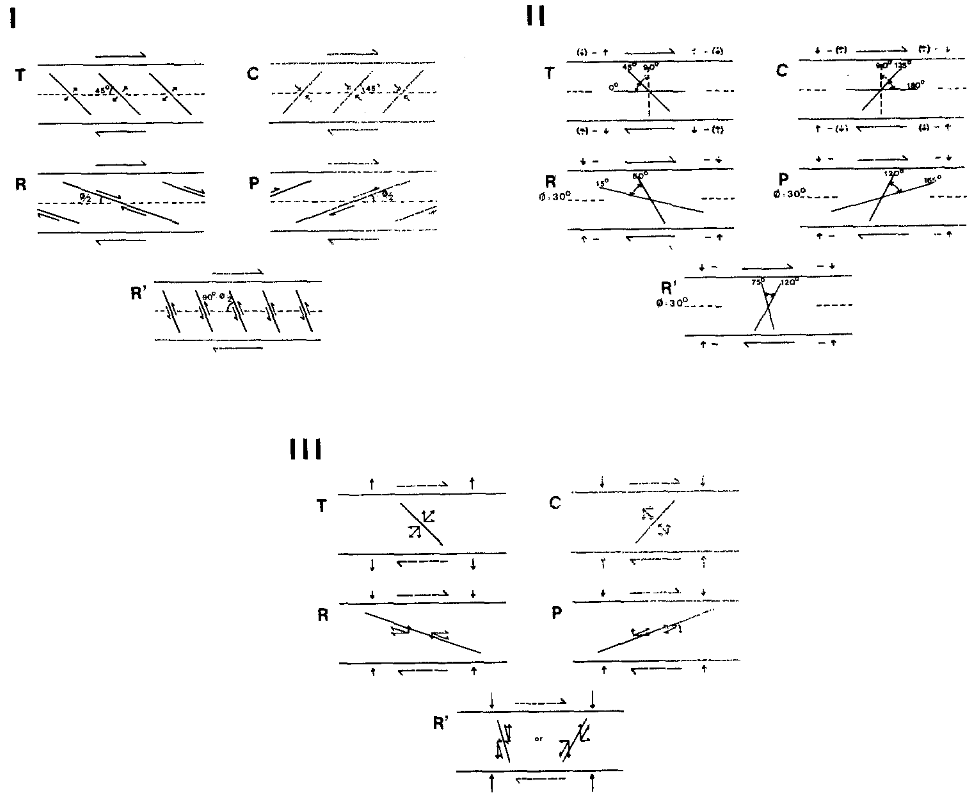


Fig. 1. The general orientation of tension gashes (T), compressional ridges and troughs (C), synthetic Riedel-shears (R), synthetic opposite Riedel-shears (P), and antithetic Riedel-shears (R′) within a shear zone (I) and their rotation with increasing normal stress and shearing rate (II). The vector presentation (III) further clarifies the importance of the normal stress and shearing rate relation in the orientations and development of different en echelon structures. The fracture orientation is also dependent on the angle of internal friction of the material ($\phi$).

## 2. En echelon Shear Zone Structures

The existence of synthetic (R), opposite (P) and/or antithetic (R′) Riedel fractures in addition to or in place of tension gashes or compressional ridges allows us to determine the sense of movements along fault zones indicated and characterized by these second order structures (Figure 1). The situation is, however, not at all simple because of rotation of both tension gashes, compression ridges and three different Riedel shears with increasing normal stress (Deng *et al.*, 1966; Lajtai, 1969) and shearing rate (Tchalenko, 1970; Freund, 1974).

The formation of a fault zone begins with small overlapping fractures with tensional openings and/or shearings (Cloos, 1928; Riedel, 1929). En echelon tension gashes seem to develop at low normal stress (Lajtai, 1969), rotating more against the fault direction with decreasing normal stress and with the progression of the simple shear faultings.

Synthetic (R) and antithetic (R′) Riedel shears form at intermediate values of normal stress (Lajtai, 1969). Antithetic conjugate Riedel shears (R′) do not appear in every case and owing to the large angle they make with the fault direction they soon rotate, become inactive and disappear with further movements (Tchalenko, 1970; Freund, 1974). With progressive movements and with increasing normal stress the synthetic Riedel shears (R) are deformed, rotated and bent (Lajtai, 1969; Tchalenko, 1970; Freund, 1974). Linking synthetic Riedel shears (P) develop to join the R-shears together towards direct shear conditions at higher normal stresses and at progressive shearings until a continuous shear zone is formed. Tension gashes and compressional ridges may also be formed in addition to the R- and P-shears.

Tchalenko (1970) has found that a synthetic Riedel shear (R) may consist of a subsystem of minor en echelon fractures. On the large scale of the principal displacement zone of the Dasht-e Bayaz earthquake fault the minor en echelon structures within major Riedels were formed both in the Riedel attitude and in the form of tensional cracks with respect to the host Riedel shear.

During certain phases of the principal displacement zone development different scale movements take place analogically even within the same principal fault zone. The similarities in structure between shear zones of different magnitude (Tchalenko, 1970) may thus in certain cases be generalized even on different scale structures in one shear zone. Towards the peak stage just at the point when the first second order fractures appear the deformation may be considered to take the form of the simple shear type occurrence. At this stage the major part of total displacement may take place along just generated Riedel shears. The formation of minor en echelon structures is possibly to be found in places within major Riedel shears where the synthetic shearings cause the minor scale en echelon fracturing.

## 3. Different Scale Mare Ridge Patterns

Lava sheets of lunar mare basins have horizontally covered old pre-existing zones of weakness. Re-activations of these juncture zones have then given rise to deformations of the lava sheets. Thus we can consider the deformations along lava-covered zones of weakness within mare areas as nature's own tectonic experiment which does not suffer restrictions caused by the small scale and surrogate materials of laboratory tests (Raitala, 1978b).

The rates and relative directions of movements along lunar crustal zones of weakness are difficult and ambiguous to record. There is a lack of qualified markers separated by fault movements or other deformations. Thus it is necessary to take great pains in observing, mapping and measuring surface features for statistical and analogical treatment leading towards geometrical, kinematical and dynamical interpretation.

The study of ridges of the SW Oceanus Procellarum area allows major en echelon patterns of crossing mare ridge zones to be found. These patterns consist of major mare ridge ranges with dextral and sinistral en echelon arrangements along the NW-SE and

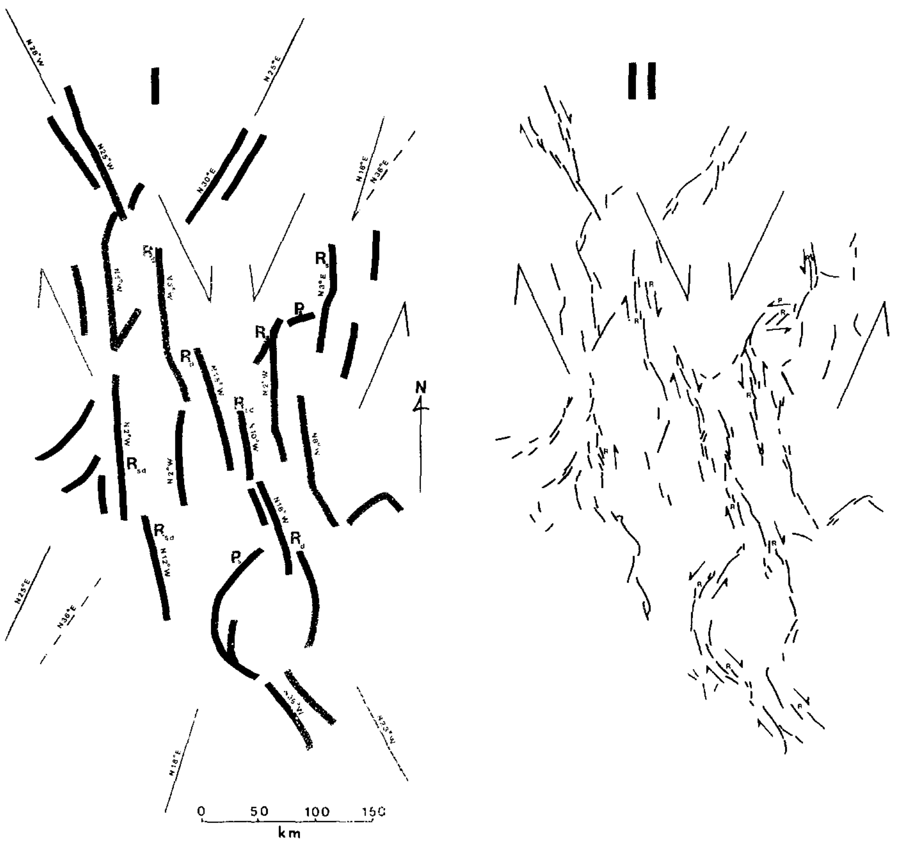


Fig. 2. Simplified ridge range pattern SW of Marius Hills with measured directions of mare ridge zones and of mare ridge ranges in the R or P attitude to the main zones (I). Proposed minor R- and P-structures are also indicated (II). Arrows show the senses of main movements. Footnotes d and s mean dextral and sinistral, respectively.

NE-SW zones, respectively. It is possible to find that each major mare ridge range consists of a subsystem of several individual mare ridges with minor en echelon arrangements of their own (Raitala, 1978a, 1980). This double 'en echelon within en echelon' pattern offers a good starting point in interpreting lunar crustal deformations within mare areas.

The mare ridge pattern of the mare area SW of Marius Hills (Figure 2) is complicated by interactions of crossing mare ridge zones (Raitala, 1981), all of which consist of major en echelon mare ridge ranges. The ridge ranges of the NW-SE zone form dextrally arranged en echelon pattern while the ridge ranges of the crossing NE-SW zone have a sinistral major en echelon arrangement with some linking major ridge structures (P in Figure 2). Both crossing mare ridge zones evidently consist of major en echelon Riedel-structures (R) of mare ridge ranges joined towards the zone directions by reverse inclined major P-structures.

Many individual ridges within mare ridge ranges have an average inclination of Riedel

(R) shears or low angle tension gashes when compared to the strikes of major ridge ranges. Dextrally arranged major en echelon ridge ranges of the NW-SE zone consist of individual ridges which also seem to have dextral en echelon arrangement with respect to the ridge ranges. Major sinistral en echelon pattern along the NE-SW zone consist analogously of ridge ranges with minor sinistral en echelon ridge pattern. These orientations are in agreement with the synthetic occurrence of R-shears when compared to the main shear zone movements.

Individual mare ridges seem in places to bend progressively and they are joined towards the ridge range direction by reverse inclined mare ridges. The en echelon ridge structures which are coupled together by reverse inclined ridges resemble the situation in which opposite Riedel (P) structures or rotated tension gash ends interconnect en echelon arranged fractures. Thus it is possible to interpret these minor en echelon arrangements as indicating both the complicate post-peak phase synthetic Riedel structures and rotated tension gashes of strike-slip movements along major shears.

The simplified mare ridge pattern of the crater Herigonius area (Figure 3) indicates some major en echelon structures along the NW-SE or NWW-SEE mare ridge zone. Major ridge ranges of the dextrally arranged en echelon pattern are only slightly oblique compared to the mare ridge zones, thus evidently representing Riedel (R) structures. Some of them are more inclined, possibly indicating the existence of tension gash-like fracture opening or preferably Riedel (R) shear rotation under compressional circumstances. Dextrally arranged major en echelon ridge ranges are in places linked together by ridge ranges with a reverse inclination. These ridge ranges interconnecting pairs of Riedel-structures may be so-called opposite Riedel (P) structures.

Major en echelon R-structure-like ridge ranges seem to consist of linear groups of minor individual ridges with a low-angle dextral en echelon arrangement. Because R-shear movements are synthetic with respect to the main fault or shear zone movements this may indicate the overall dextral movements along the main mare ridge zone as well as along R-shear-like oriented mare ridge ranges. This interpretation is confirmed by the P-structures, which seem to consist of linear groups of also dextrally arranged en echelon minor individual ridges, a situation which agrees well with the synthetic occurrence of P-shears compared to the main shear zone movements.

Dextrally arranged minor structures forming the main P-structure-like mare ridge ranges have such inclinations that they in many places may be tension gash-like openings as well as rotated minor R-structures. Two proposed main P-structures consisting of minor tension or Riedel fractures cut down a graben-like trough. This major trough runs approximately in the same direction as compressional ridges and valleys of fault and shear zones with a dextral sense of movement (Raitala, 1978a).

The low angle of the proposed major Riedel (R) structures and the existence of some opposite Riedel (P) structures are both consistent with results of analogous zones in laboratory tests and in earthquake faults (Tchalenko, 1970; Freund, 1974), and also with theoretical examinations (Lajtai, 1969). The variations in the inclination angle between major en echelon mare ridge ranges and the mare ridge zones possibly

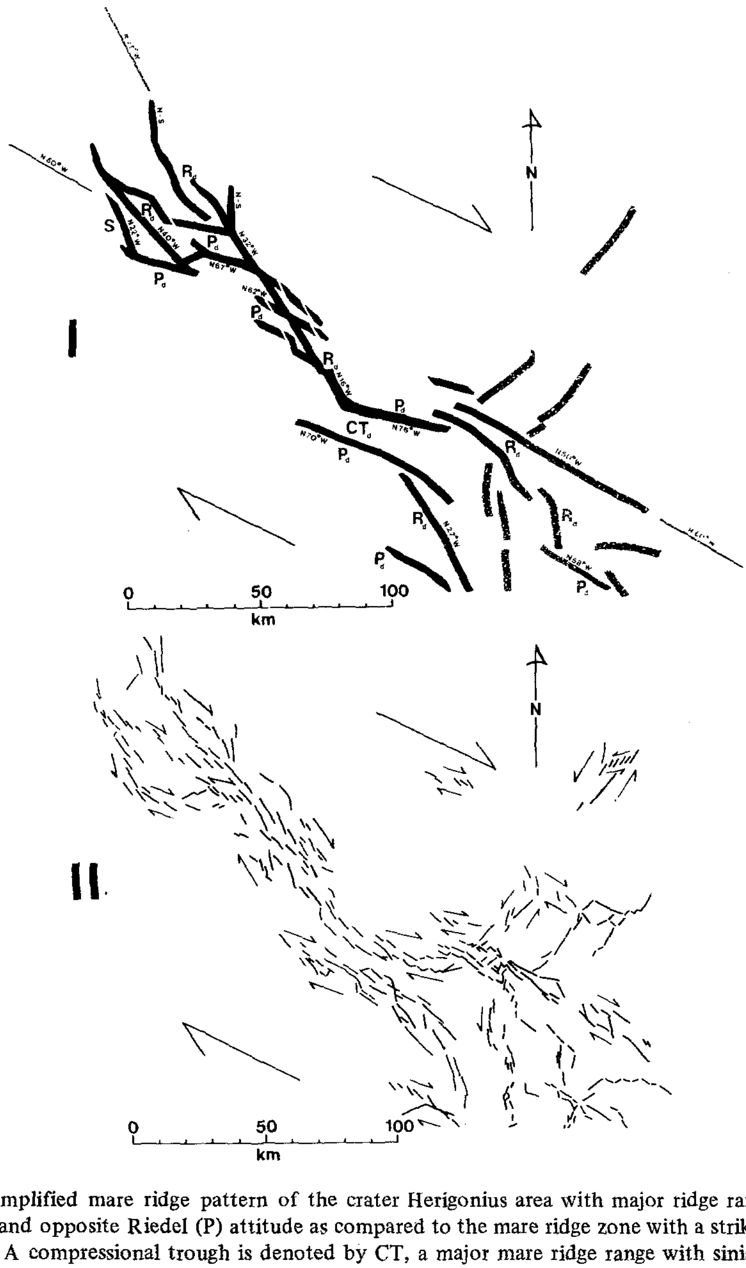


Fig. 3. Simplified mare ridge pattern of the crater Herigonius area with major ridge ranges in the Riedel (R) and opposite Riedel (P) attitude as compared to the mare ridge zone with a strike of about N60°W (I). A compressional trough is denoted by CT, a major mare ridge range with sinistral minor ridge arrangement is denoted by S (cf. Raitala, 1978a, 1980). The footnote d indicates the dextral sense of R- and P-structures. Individual mare ridges and ridge crests are also indicated (II). Arrows show the senses of main movements.

indicate differences in compression or in shearing. Bending of major Riedel structures is typical just near post-peak phase of shearings of the Riedel experiment and earthquake faulting (Tchalenko, 1970). The major en echelon structures consisting of ridge ranges may thus represent the peak and early post-peak phase of deformations along Oceanus Procellarum zones of weakness.

## 4. Discussion

The very thin mare lithosphere (Head *et al.*, 1980a, b) was affected very easily and over a long period of time by lunar internal forces. Old zones of weakness covered by mare basalts were re-activated during lunar volcano-tectonic development. The most important mare ridges form mare ridge zones approximately diagonal to the present lunar rotation axis direction. Some NW-SE directed mare ridge zones also run approximately parallel to the SW border of Oceanus Procellarum (Raitala, 1981). Riedel-fracture-like orientations of mare ridges indicate the compression within Oceanus Procellarum towards the middle parts of the shortened and downwarped basin lithosphere (Raitala, 1981).

The formation of 'en echelon within en echelon' structures evidently reflects the limited effectiveness of lunar tectonic forces. Re-activations of lava-covered zones of weakness were strong enough to give rise to compressional Riedel-fracture formation but they were insufficient to cause the formation of a continuous principal displacement zone. The displacements within major Riedels have taken place along minor en echelon fractures.

Many individual ridges within ridge ranges have an average inclination of Riedel (R) shears or in places also of low angel tension gashes when compared to the strike of the major ridge range. Individual ridges seem in places to bend progressively and then to be coupled together by structures inclined like opposite Riedel (P) shears or rotated tension gash ends. Thus it is possible to interpret these en echelon arrangements as indicating both the complicate post-peak phase synthetic Riedels and tensions gashes of strike-slip movements along major shear zones.

When making a choice between N-S and E-W compression models (Tjia, 1970; Fagin *et al.* 1978; Raitala, 1978a) the N-S compression seems to be more arguable because it allows us to interpret different scale mare ridge arrangements in a logical way by using our knowledge of different kinds of shear zone structures and especially of 'en echelon within en echelon' structures. The Oceanus Procellarum deformation has, however, been more complicated with vertical (Lucchitta, 1977) and horizontal (Tjia, 1970, 1976; Raitala, 1978a) or actually oblique-slip movements along zones of weakness within the shortened and compressed mare lithosphere. Local and areal variations in stress direction and shearing rate may also be responsible for additional details in the formation of the tectonic pattern within mare basins (Raitala, 1980).

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