TECTONIC IMPLICATIONS OF THE MARE-RIDGE PATTERN OF THE CENTRAL PARTS OF OCEANUS PROCELLARUM ON THE MOON

J. RAITALA
Aarne Karjalainen Observatory, University of Oulu, Oulu, Finland

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Abstract. A structural analysis is presented of the mare ridge pattern in an area of about 1 000 000 km^2 in the central parts of Oceanus Procellarum.

The penetration of magmas through the crust at the Marius Hills and Aristarchus Plateau/Harbinger Mountains volcanic complexes may have happened along pre-existing deep zone of weakness. Associated with these zones are present mare ridge ranges, some of which can be regarded as having formed radial or subradial ridge swarms to the complexes as they were strengthened by stress field changes caused by upward doming and penetrating magmas.

The present moonquake epicentres within this area seem to be connected with mare ridge ranges. Focal depths from about 800 to 1000 km indicate a decreasing trend of tectonic activity. One shallow moonquake epicentre also lies within the mare ridge sets.

1. Introduction

Oceanus Procellarum, the largest of the lunar lava-covered areas, is situated in the western part of the Moon's near side. The western limb of the Oceanus Procellarum basin abuts on old lunar terra, while northern, eastern and southern limbs merge into adjoining lava-flooded circular and non-circular lunar basins. Two prominent volcanic topographic features, the Marius Hills and Aristarchus Plateau/Harbinger Mountains, rise above the surrounding plains. The ages of these volcanic areas have been mapped by Wilhelms and McCauley (1971) as ranging from Imbrian and Eratosthenian to Copernican and "*they appear to be the sources for much of the central Procellarum mare fill*" (Whitford-Stark and Head, 1977).

The geology of the Marius Hills is described by McCauley (1967), Guest (1971), Greeley (1971), and Schultz (1976). Volcanic domes and cones, sinuous rilles, mare ridges, and scarps are common in this region. Judging by positive gravity anomaly around the Marius Hills (Sjogren *et al.*, 1972) extruded lavas may appear as local thick layers. The Aristarchus Plateau with adjoining Harbinger Mountains is a more complicated formation with old terra outcrops, relatively young volcanic plateau extrusives, and the relatively young crater Aristarchus. Different features of the Aristarchus area have been interpreted by Moore (1965), Strain and El-Baz (1976), and Schultz (1976).

Mare ridges of Oceanus Procellarum form narrow parallel ridge ranges which may be seen to continue as discontinuous linear or en echelon ridge associations through considerable parts of the lava-covered Oceanus Procellarum basin. It has been proposed that the positive relief of mare ridges and adjoining mare arches were caused by tectonically

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controlled volcanic extrusions, sills or laccoliths (Fielder, 1965; Quaide, 1965; Strom, 1971; Colton *et al.*, 1972), by buried topography controlled 'squeeze-ups' (Morris and Wilhelms, 1967; Hodges, 1973), by compressional folding (Baldwin, 1963; Tjia, 1970) or by only a little compacted surface material over shallow mare areas (Quaide, 1965; Colton *et al.*, 1972).

The occurrence of mare ridges seems to be analogical to the geometry of some simple shear structures (Tjia, 1970; Raitala, 1978a, b). Lucchitta (1977) found evidence of vertical displacements and faulting along mare ridges. According to Scott (1974) there are positive gravity anomaly axes associated with major mare ridge systems suggesting that the ridges are the surface expressions of fractures and faults in the crustal zones of weakness intruded by basaltic dikes. Maximum global principal compressive stresses acting in an approximately north–south direction (Fielder, 1965; Whitford-Stark, 1974; Tjia 1970) or in an approximately east–west direction (Tjia, 1970; Fagin *et al.*, 1978) have been suggested as the cause of the lunar tectonic systems. Implications of slightly oblique stresses (Raitala, 1977) and of more complicated lunar stress history (Karlstrom, 1974; Casella, 1976; Raitala, 1977) are, however, proposed.

In the present paper mare ridge patterns in the central Oceanus Procellarum have been examined from the standpoint of tectonogenic units. The locations and influences of major volcanic complexes are also discussed.

2. Mare Ridges

2.1. About Methods

The nearly vertical (camera tilt angles are less than 3°) Lunar Orbiter IV photographs $138H_1$ and H_2; $144H_1$, H_2 and H_3; $145H_1$; $150H_1$, H_2 and H_3; $151H_1$; $157H_1$, H_2 and H_3; $158H_1$ and H_2; $162H_1$, H_2 and H_3; $163H_1$ and H_2; $169H_2$ and H_3; $170H_1$ and H_2 were used to identify mare ridges, mare ridge sets and to measure the direction and length of active ridge segments with some help from Lunar Orbiter II photographs 213M and 215M, Lunar Orbiter V photographs 188M, 209M and 213M, and Apollo 15 and 17 metric photographs 2333–2348 and 2928–2932, respectively. U.S. Air Force maps LAC-23 (Scott *et al.*, 1973), LAC-38 (Moore, 1967), LAC-39 (Moore, 1965), LAC-56 (McCauley, 1967), and LAC-57 (Hackman, 1962) were used as reference maps.

The strikes of measured 1386 active ridge segments with a total length of about 10 000 km were arranged within 10° groupings for statistical treatment and presentation as histograms and rose diagrams with 2.6σ, where σ is the standard deviation.

2.2. Major Ridge Sets

As is to be seen from the author's previous papers mare ridge swarms and ranges can be considered to form ridge sets which extend through considerable parts of the examined areas (Raitala, 1978a), having, too, possible continuations on the adjoining lunar terra (Raitala, 1978b). The identification and inspection of such ridge sets in the studied area offers a good starting point for an areal structural survey.

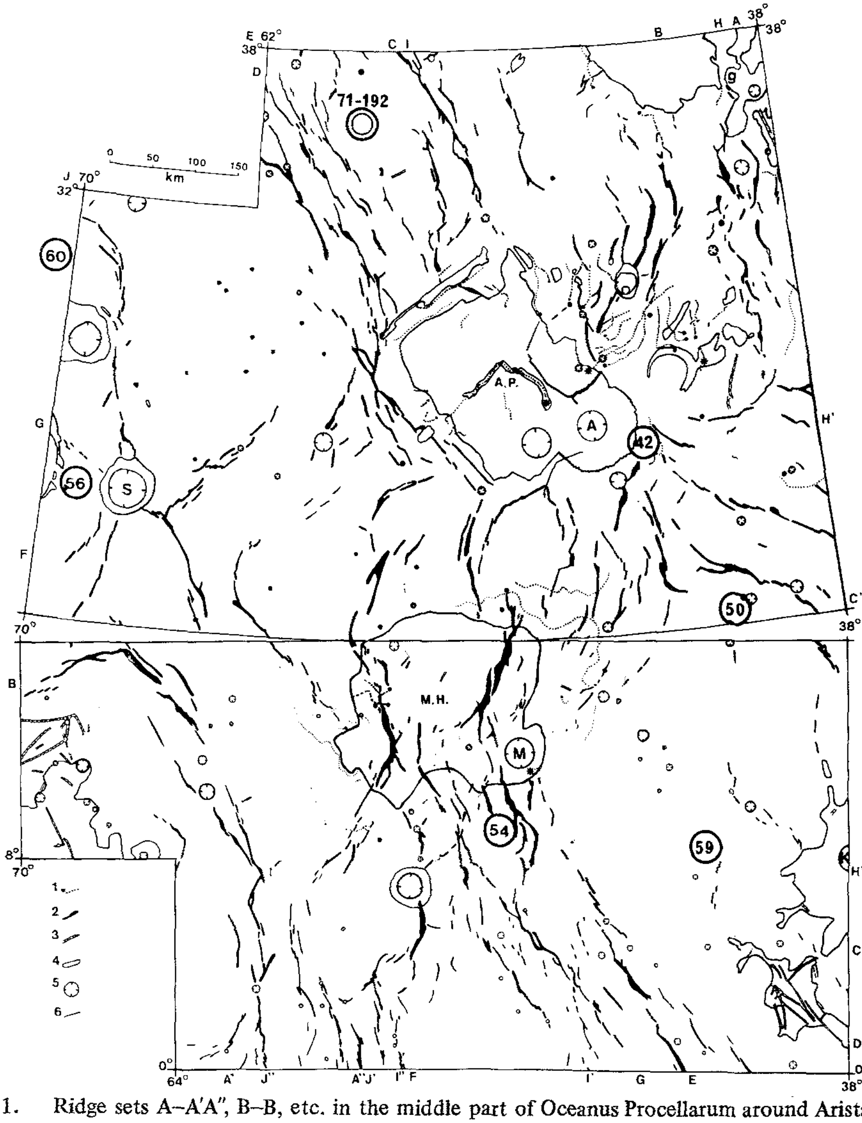

Fig. 1. Ridge sets A–A′A″, B–B, etc. in the middle part of Oceanus Procellarum around Aristarchus Plateau (A.P.) and Marius Hills (M.H.) A = the crater Aristarchus, g = the Gruithuisen dome area, M = the crater Marius, K = the crater Kepler, S = the crater Seleucus. Single circles denote deep moonquake epicentres and a double circle indicates a shallow moonquakes epicentre (Lammlein, 1977). Map symbols: 1 = sinuous rilles and their source vents, 2 = major mare ridge ranges, 3 = straight rilles, 4 = terra areas, 5 = craters, and 6 = faults.

The ridge sets of the area studied include different kinds of ridge ranges and arrangements. The ridge set A–A′A″ (Figure 1) extends from the Gruithuisen dome area via volcanic areas in the Aristarchus Plateau/Harbinger Mountains and Marius Hills to the southwest through the central Oceanus Procellarum. The ridge set strike is clearly connected with volcanic vents of the Harbinger Mountains and the source of Vallis Schröter also lies within the thoroughfare of the set. To the southwest of the Aristarchus Plateau ridges form curve ridge ranges extending to the Marius Hills volcanic dome field. The ridge set A–A′ points forward to the terra lineaments north of the crater Crüger. Set B–B with about the same direction as the isolated oblong terra outcrop beside the Aristarchus Plateau has a weak appearance at its northeastern end. It is more clearly seen in the vicinity of the crater Seleucus.

The northwest–southeast ridge set C–C′C″ runs from the volcanic Rümker Hills dome field. It seems to control the occurrence of the volcanic vents just northeast of the Aristarchus Plateau. Branch C–C′ bends slightly eastward while the weaker branch C–C″ is directed roughly towards the crater Kepler. The most remarkable NW–SE ridge set is marked with the letters E–E. It passes the Rümker Hills in the northern Oceanus Procellarum running to the westernmost corner of Aristarchus Plateau and forward along its southwestern margin to the ridge set A–A, where after a bend along A–A it continues from the crater Marius area southeastwards towards the Flamstead ring formation. The direct mare ridge set extension to the crater Kepler area could be expressed by D–D. It has a nearly parallel analogical mare ridge set G–G running from the Flamsteed area northwestward, touching the Marius Hills domes and continuing through the crater Seleucus. Set F–F also has a roughly parallel strike.

Of the ridge sets with an approximately north–south strike the one marked H–H″ extends from the Gruithuisen area to the crater Kepler. The ridge set H–H′ probably has a curved trend and may be considered to belong to Imbrian edge ridge swarms. The ridge set I–I′I″ has a very complicated occurrence and it may be seen to consist of ridges whose occurrence is either moderated or strengthened by interactions of other more obvious ridge sets. Both I–I′ and I–I″ ridges partly strike along other sets but they are, however, identifiable. The ridge set J–J′J″ runs from the north through the crater Seleucus to the southwestern Oceanus Procellarum.

2.3. Radial Patterns

Ridge sets with roughly NNW–SSE and NW–SE strikes are most abundant (Figure 2, II) but set A–A′A″ with a NNE–SSW strike is significant, too. It is, however, also possible to inspect other kinds of ridge systems in the studied area.

Some ridge ranges seem to be radial roughly to the crater Seleucus in the western Oceanus Procellarum (Figure 1). The significance of this pattern is worth bearing in mind when puzzling over the tectonics of Oceanus Procellarum.

More important radial ridge systems are around the Aristarchus Plateau and Marius Hills, two major volcanic areas of the central Oceanus Procellarum (Figure 1). Although mare ridge ranges are not strictly radial to any known point within the Aristarchus Plateau they obviously point mostly to about the middle part of this area around the source vent of the Vallis Schröter. In the Marius Hills area the ridges are radial to about the southern central part of this volcanic dome field. The ridge ranges between the Aristarchus Plateau and the Marius Hills are curved like the field lines between two adjacent magnetic poles.

If the ridge sets are thought of as parts of lunar great circles they can be represented as

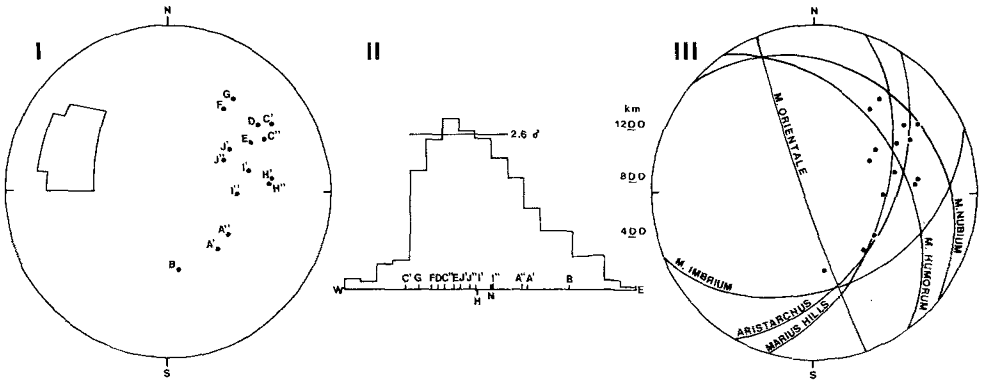

Fig. 2. Ridge sets as points on the Schmidt net (I) with a resulting graph of all measured ridge segments indicating main strikes of these ridge sets (II). Planes corresponding to the centre points of Humorum, Imbrium, Nubium and Orientale basins and of the crater Aristarchus and Marius Hills areas are also shown (III).

points on the Schmidt net (Figure 2, I). There seem to be no clear groupings on the Schmidt net and the point distribution is relatively scattered. Figure 2 III represents on the Schmidt net some planes which correspond to the centres of Mare Humorum, Mare Nubium and Mare Orientale. None of ridge sets of this area is radial to Mare Imbrium centre and there are only some sets pointing to the centre of Mare Nubium. Many sets with a NW–SE strike point to approximately Mare Humorum and one set (B–B) points to approximately Mare Orientale. Planes corresponding to the centres of the crater Aristarchus and the Marius Hills area (Figure 2, III) run via most points.

2.4. Statistics

Active mare ridge segments (Figure 3) were measured and their strike distribution was represented by means of rose diagrams and histogram plots for nine separate mare areas (Figure 4).

The statistical analysis of the data from the Seleucus area (area I in Figure 4) exhibits the existence of a major distribution peak at N30°–50°W. The set G–G has a strike of about N44°W. The peak at N10°–20°W indicates the existence of dextral ridges ranges of J–J′J″. Another important trend of the ridge strike is that around N49°E (B–B) at N40°–50°E. The low peak at N0°–10°E may consist of ridge crests dextral to the J–J′J″.

The graphs of areas II and III both have only one strong peak at about N20°–30°W, approximately along the sets E–E (or D–D) and C–C″ respectively. Peaks are relatively wide, evidently indicating interactions within parallel ridge swarms.

Ridges of the area IV have main strikes at N10°–30°E along set A–A′A″ with a strike of about N20°–23°E. There are also some curved ridge ranges and ridges with strikes similar to the sets of adjoining areas.

The two peaks of area V are at N0°–10°E and N10°–20°W. While set H–H′H″ has a strike of about N5°–N10°W these ridges form both dextral and sinistral patterns around it.

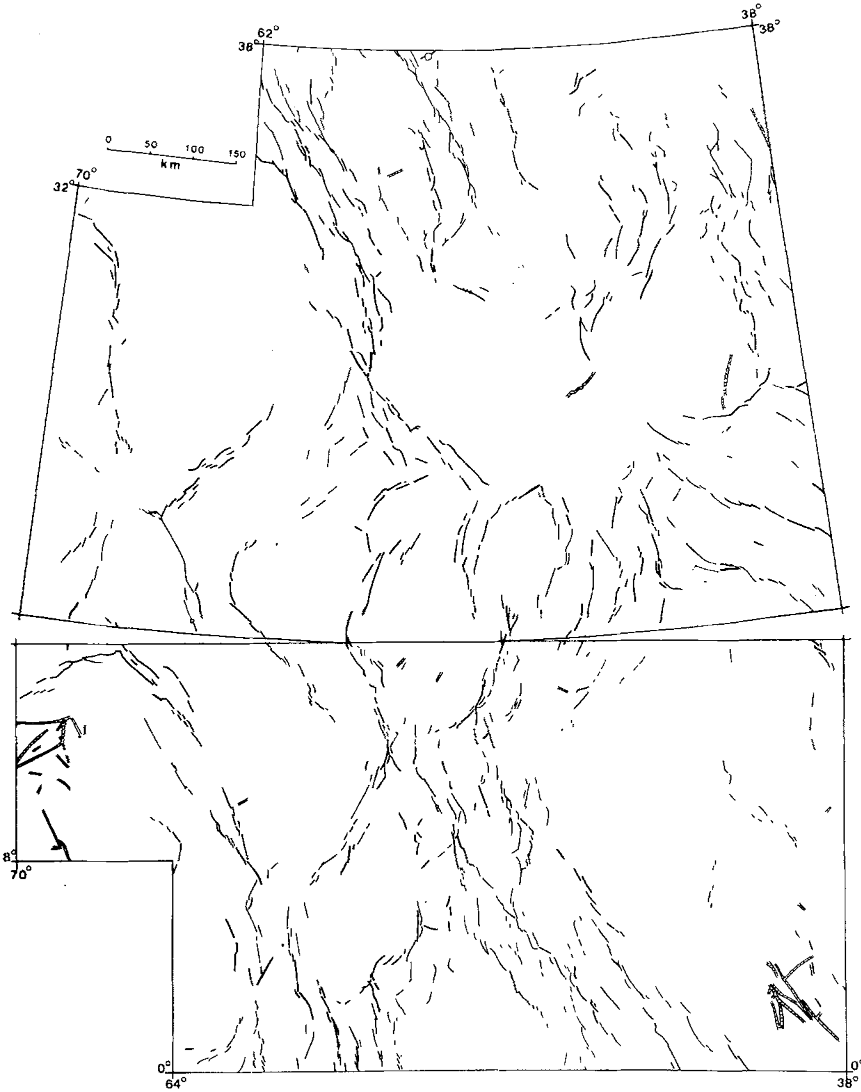

Fig. 3. Active ridge segments identified from LO high-resolution photographs.

Ridges of set H–H″ are also seen in the graph of area VI, the strongest peaks of which occur, however, along sets C–C″ and D–D at N50°–60°W and at N30°–40°W, respectively.

The central part of the studied area, area VII in Figure 4, has only one broad peak at N20°W–N30°E with its most significant direction at N10°–20°E. Mare ridge ranges between the Aristarchus Plateau and the Marius Hills are curved around the strike of set A–A′A″, having also components of set I–I′I″.

The direction of set I–I″ is most clear within area VIII and the highest distribution

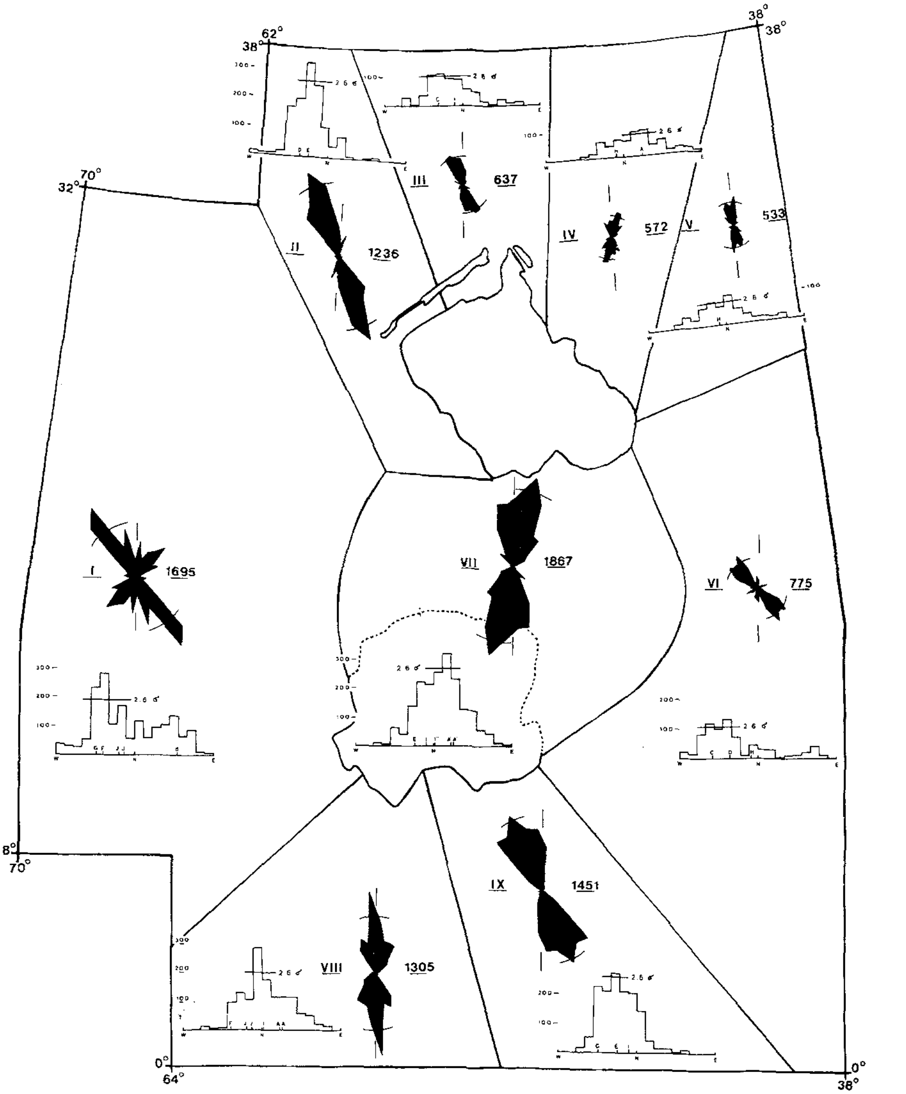

Fig. 4. The strike distribution of active ridge segments from nine different mare areas (I, II, etc.; indicated by base map drawings) are represented by means of rose diagrams and histogram plots. Numbers indicate total length (km) of the ridges considered in the diagrams.

peak of this area is just at N0°–10°W. This direction may also be interpreted as forming sinistral and dextral en echelon patterns to sets A–A′A″ and J–J′J″, respectively.

The distribution graph of area IX resembles that of area II with one clear peak at N20°–30W. However, there are also ridges of sets G–G and I–I′ in this area and this leads to the whole peak extending from N50°W to N10°E.

The compound histogram (Figure 2, II) is based on the sum of the numbers of the active ridge segments for each interval of ten degrees. NW–SE features are seen to

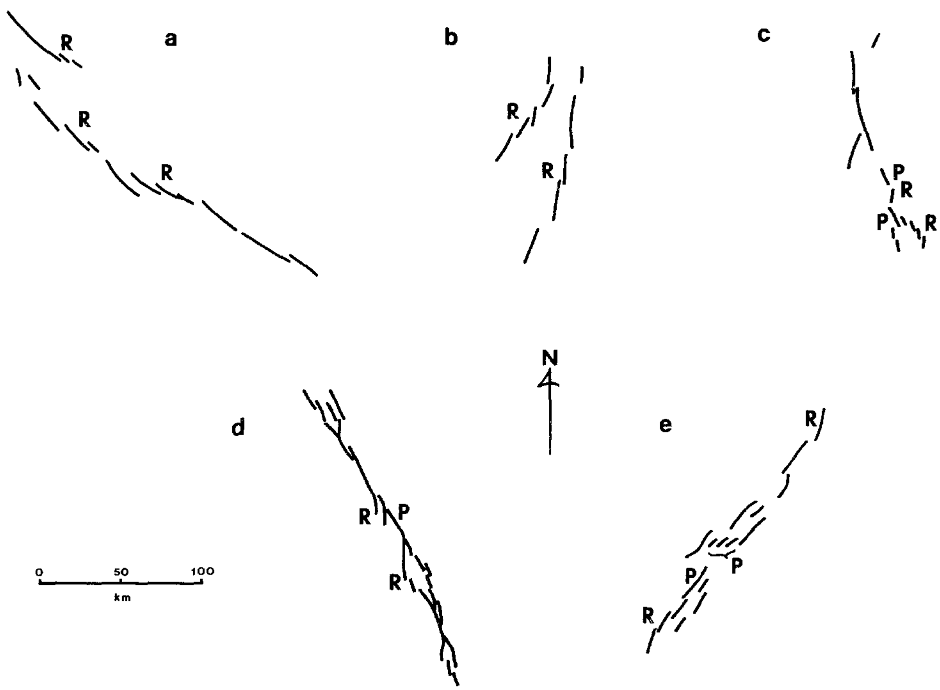

Fig. 5. Selected Oceanus Procellarum ridge ranges with interpreted R-structures (a and b) which are complicated by possible P-structures (c, d and e) finally developing toward a direct shear zone (d).

predominate, as do also ridge sets in approximately this direction. There is a clear deficiency of ridge features with a more or less E–W strike.

3. Kinematic and Dynamic Aspects

3.1. Shear Zone Structures

Different shear zone structures are discussed in numerous papers (Cloos, 1928; Riedel, 1929; Tchalenko and Ambraseys, 1970; Tchalenko, 1970; Freund, 1974 for example). The share of features with analogical geometry within lunar mare ridge patterns is described by Tjia (1970) and Raitala (1978a, b).

The relations of mare ridges and ridge ranges in the area studied are in many cases best understood in terms of shear zone structures. It is possible to identify mare ridges which form patterns comparable to those of Riedel shears (R), conjugate Riedel shears (R′), opposite Riedel shears (P) and tensional (T) or compressional (C) en echelon fractures along a simple shear zone (Raitala, 1978a).

The mare ridge pattern geometry along the southeastern end of set C–C′ seems to be consistent with the existence of right-lateral R-shears (Figure 5(a)). This kind of structure could be interpreted as being caused over a buried fracture zone with a dextral sense of

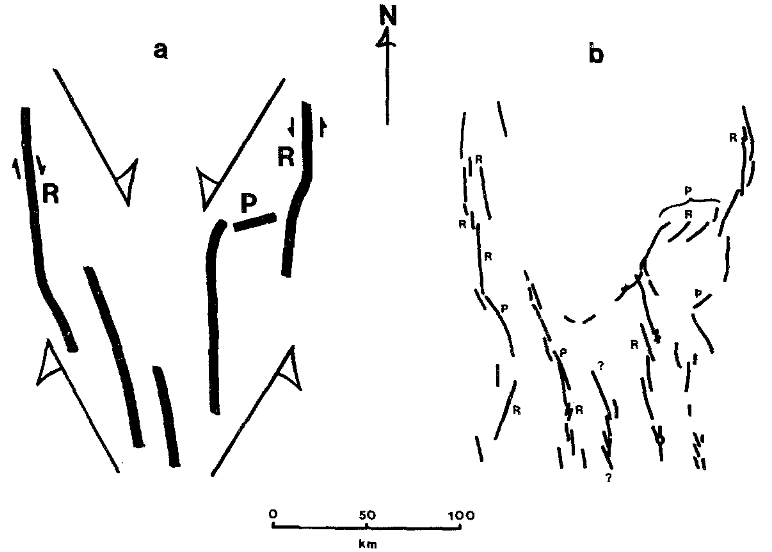

Fig. 6. Simplified ridge range pattern of the crossing area of the ridge sets A–A" and F–F with arrows showing sensens of main movements (a). Some R- and P-structures of ridge ranges are indicated (b). The ridge range indicated by question-marks may belong to both crossing ridge sets, thus giving rise to dextral as well as sinistral minor dislocation pattern interpretation.

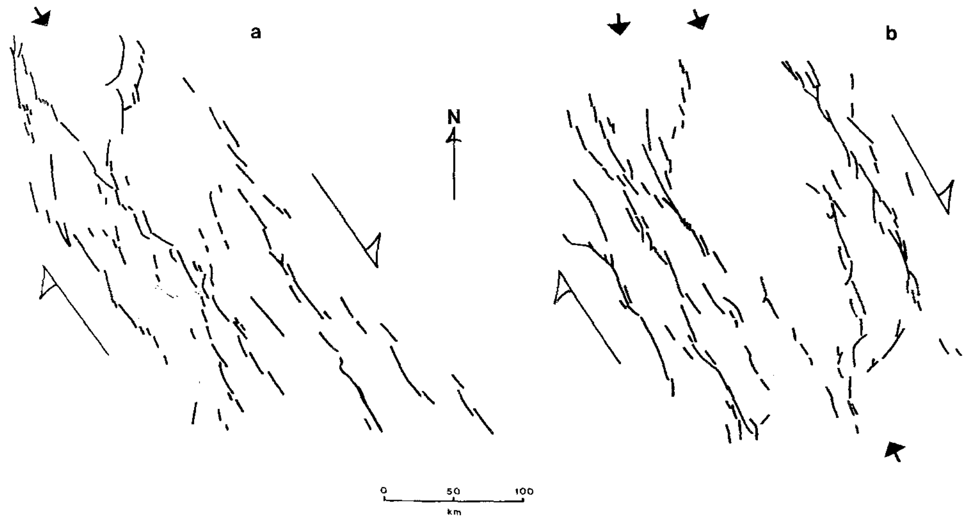

Fig. 7. Major dextral ridge ranges SE from the Marius Hills (a) and NW from the Aristarchus Plateau (b) with subsidiary ridges between major ridge ranges. Black arrows indicate secondary thrusts radial to Marius Hills (a) and Aristarchus Plateau or Rümker Hills (b) volcanic areas. Owing to repeated and in some places also to opposite movements the essential ridge ranges have developed toward direct shear conditions.

movement. An analogical example with an opposite ridge arrangement is seen SW of the crater Seleucus (Figure 5(b)).

Looking at the ridges of the northern end of set J–J′ it is obvious that dextrally arranged ridges with R-shear-like occurrence are joined toward the set direction by opposite ridges with possible P-shear-like occurrence (Figure 5(c)). There are also analogical ridge patterns along set B–B NE from the crater Seleucus (Figure 5(e)) and along the NW end of set C–C′C″ (Figure 5(d)).

Such ridge structures are, however, quite simple because they are all situated within only one mare ridge set. In the case of two or more mare ridge sets crossing more complicated interactions are found. In the crossing area of the main ridge sets A–A″ and F–F (Figure 6) a different scale mare ridge pattern is seen. The major ridge ranges with approximately N–S strikes form dextrally and sinistrally arranged en echelon patterns along the strikes of sets F–F and A–A″, respectively. Ridges clearly connected to the ridge set F–F have minor ridge structures which seem to be consistent with the existence of dextrally arranged R-shears joined towards the ridge range direction by sinistrally arranged P-shears. Ridges connected to ridge set A–A″ have nearly similar mare ridge patterns with an opposite sense of en echelon ridges. The existence of adjoining ridge sets J–J′ and I–I″ complicates the situation with some additional details, but these do not essentially alter the above-mentioned structural interpretation.

The geometry and interactions of ridges NW from the Aristarchus Plateau and SE from the Marius Hills along the ridge set E–E with strong parallel mare ridge swarms and ranges are very complicated (Figures 1, 3 and 7). As seen already from the mare ridge distribution graphs (Figure 4) ridges are arranged both sinistrally and dextrally to the main strike of set E–E. Within both subareas of this set there are three major ridge ranges, the middle ones of which could be interpreted as being the essential mare ridge ranges. The middle ridge range SE from the Marius Hills (Figure 7(a)) seems to have most intense ridges arranged dextrally to the average ridge range strike. They are linked together by adjoining sinistrally arranged mare ridges resembling the above-mentioned situation where Riedel shears within a shear zone are straightened at higher strains towards the shear zone direction by P-shears. The ridges of the adjoining two parallel ridge ranges also have clear dextral en echelon patterns. There are some ridges between these three ridge ranges the orientation of which could be understood in terms of tensional en echelon structures between shear zones (Wilcox *et al.*, 1973). In the NW part of set E–E the middle ridge range is probably affected by more complicated forces or it is developed more toward direct shear zone conditions like the adjoining parallels. The interaction between the ridge sets E–E and C–C′C″ may have strengthened the occurrence of set I–I′I″ (Figure 7(b)).

3.2. Pressurized Volcanic Holes

The location of major volcanic areas with adjoining mare ridge patterns in Oceanus Procellarum offers some analogies both to the occurrence of Martian volcanoes (Smith, 1974) and several well-known magmatic rocks with fracture zone control on the Earth.

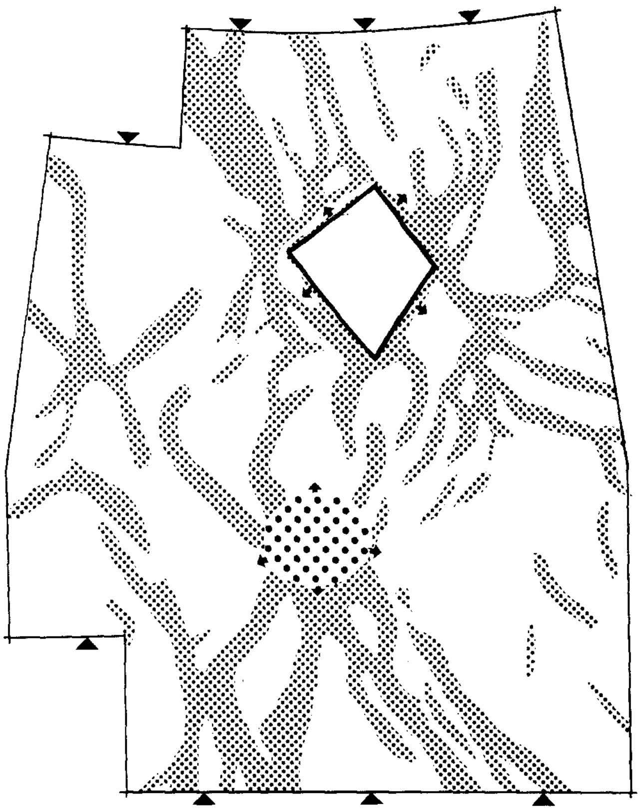

Fig. 8. Sketch of the zones of weakness as boundaries of lithospheric blocks. Large arrows indicate the possible old N–S compression direction. E–W compression phase probability must also be taken into account. Marius Hills (dotted) and Aristarchus Plateau/Harbinger Mountains volcanic areas in the crossing of zones of weakness have strengthened the occurrence of adjoining shear zone structures. Small arrows around volcanic areas indicate the radial stresses against surrounding blocks. Near the crater Seleucus there is a crossing area without major volcanism.

The existence of a central active ridge belt in Oceanus Procellarum is suggested by McCauley (1968) and Guest (1971). Schultz (1976) pointed out that volcanic events in the Marius Hills (and possibly also on the Aristarchus Plateau) may be related to the intersection of NW- and NE-trending mare ridges. This kind of 'pure' mare ridge intersection without major late-stage volcanism is seen near the crater Seleucus.

It is possible to find ample analogies to the existence of radial or subradial lineament and dike patterns focused on volcanic formations (Odé, 1957, Johnson, 1961; Fielder *et al.*, 1974). Numerous mare ridge ranges are associated with the major lunar volcanic complexes, the Marius Hills and the Aristarchus Plateau, forming present radial mare ridge swarms as if their occurrence were influenced by stress field changes caused by upward doming (Ramberg, 1967) and penetrating magmas (Muller and Pollard, 1977).

To understand the ridge pattern development around the Marius Hills and the

Aristarchus Plateau we must consider them as the results of stresses around pressurized volcanic holes located at crossings of pre-existing zones of weakness. The orientation of mare ridges was probably affected both by the pre-existing crustal zones of weakness and by maximum principal stress trajectories around major volcanic areas (Figure 8). Although we have insufficient data on the lunar rock properties and physical conditions at the time of major extrusions it seems remarkable that a good qualitative correlation exists between the stress trajectory models of Odé (1957) and of Muller and Pollard (1977) and the present radial mare ridge patterns. The formation of en echelon ridge segements within the radial patterns may be explained by ridge courses being adjusted to follow the local principle stress trajectory (Pollard *et al.*, 1975). Repeated movements make en echelon structures, too, develop toward direct shear conditions (Figure 7).

3.3. Present Moonquakes

Figure 1 also gives the present moonquake epicentres (Lammlein, 1977) within the studies area. The major moonquake hypocentres lie in the lower lithosphere at a depth of 810–1000 km. The depth of one shallow moonquake hypocentre is about 25 km.

According to Lammlein (1977) these moonquake localities form a northwestern branch to the N–S moonquake belt of the Moon's near side. The moonquake belts may be connected with the major lunar surface structures (Raitala, 1978b) and they "*coincide with the regions of youngest and most active volcanic and tectonic activity*" (Lammlein, 1977). Moonquake epicentres of the studied area seem to be scattered within lunar mare ridge sets.

The most intense moonquake activity took place at the crossings of sets A–A′A″ and C–C′, just east of the crater Aristarchus. A nearly analogical epicentre location is at the crossings of sets A–A″, E–E, G–G and I–I′ south of the crater Marius. These two sites are clearly connected with past lunar volcano-tectonic development. There is also another deep moonquake epicentre located within the mare ridge set C–C′. One of two moonquake epicentres just west of set J–J′J″ is connected with the mare ridges of set G–G near the crater Seleucus. The moonquake epicentre between the craters Marius and Kepler lies within the proposed set D–D. The shallow moonquake epicentre is located between the well-defined ridges of sets E–E and C–C′C″.

3.4. Discussion

The main tectonic development of this area may be considered to consist of different phases. The significance of the above-mentioned ridge sets and radial patterns could be best understood in terms of lunar dynamical development. The most important ridge ranges of the studied area seem to belong to both linear ridge sets and radial patterns around the Aristarchus Plateau and the Marius Hills area. The Moon's internal activity is still continuing within this area, though more slowly.

The lunar major stress systems (Fielder, 1965; Gash, 1973; Melosh, 1977) may have given rise to the old zones of weakness (Raitala, 1977 and 1978a, b) and the present lineament orientation (Karlstrom, 1974; Whitford-Stark, 1974; Raitala, 1977). The basin excavation (Melosh, 1975) readjusted large parts of lunar outermost layers (Mason *et al.*, 1976). The present central Oceanus Procellarum seems to form a tectonic unit, the occurrence of which is relatively independent of the structures usually connected with the formation of the adjoining major impact basins. Old crustal zones of weakness have been the most obvious failure sites during the Oceanus Procellarum basin filling. Basin and mare volcanism may have affected in turn at least local crustal tectonics.

Owing to the strikes of primary zones of weakness, for example along set A–A′ with a strike of about N23°E and set E–E with a strike of about N22°W both N–S and E–W compression must be taken into account (Tjia, 1970). Fagin *et al.* (1978) chose the E–W compression alternative but the N–S compression model is at least equally arguable (Raitala, 1978a). Many tectonic phases of Oceanus Procellarum and interactions between adjoining parallel zones of weakness complicate the determination of the areal principal stress directions, which must be based on the occurrence and numbers of the Riedel structures (Figures 5, 6, and 7; compare Raitala, 1978a) favouring a N–S compression (Figure 8).

Young volcanic and tectonic structures have destroyed the older ones but for the most part their occurrence has not been independent of previous lithospheric structures. There are many clear connections between recent mare ridge patterns and old volcanic and tectonic forces. Major magmatic events have influenced and changed locally pre-existing stress field structures. Furthermore changes in the stress field may to a certain extent have opened conduits to the magma to penetrate through the bedrock and to form intensive dikes and volcanic vents.

There are several mechanisms and forces connected with the rising of the magma. The magma may melt its way through the roof by assimilation while crystallization takes place at the bottom of the upward-rising magma reservoir or cell. This mechanism needs a uniform solid surrounding medium with necessary energy sources and fluids and is thus possible only in relatively deep asthenospheric conditions. The pressure excess due to volume increase during melting may cause an effective magma uprise. Melts are also lighter than original rocks, and this density difference provides more energy for the magma to rise. Thus the astehnospheric energy transport has at least locally convective properties.

The overlying lithosphere blocks the upward rise of the hot magma and the upward rise may change its mode. The heated and therefore also expanded asthenosphere–lithosphere boundary region gets more mass and energy excess from the asthenospheric upward transport which may be seen in the lithosphere as upward expanding, dome-like upheaval.

Stoping takes place in the lithosphere where pre-existing cracks and deep fractures are always found which evidently open when the upward intrusion forces in. The boiling of the magma during gas separation may be important when breaking the uppermost crust. The pushing of the blocked convective cell, which causes the dome formation and also the fracture opening, and the magma forcing through the fractures both give rise to the horizontal pressure component against surrounding lithospheric blocks. The vertical intrusion of an upward-expanding magma causes horizontal thrust to the lithosphere around the pressurized volcanic hole. The radial or directed nature of the pressure depends mainly on the form of the intrusion conduit. Small local intrusions and adjoining extrusions have in the main only radial thrust to the wallrocks (Muller and Pollard, 1977) when penetrating through the crust. The blocking of a large asthenospheric upward rising magma by lithosphere may also raise horizontal asthenospheric flows, carrying some melt slightly aside from the main uprise. Expanded volcanic area has further large and complicated effects on the crustal blocks (Figure 8), and these blocks also have vertical displacements relative to one another (Lucchitta, 1977).

4. Conclusion

Evidence from fracture structures and small scale laboratory experiments indicates that mare ridges have tectonic significance. Numerous volcanic vents and sinuous rilles along mare ridges indicate the coupling of volcanism with tectonic structures during and after the flooding of the Oceanus Procellarum basin by mare lavas. The initial pre-ridge bedrock flaws may be considered to have been connected with the old zones of weakness. The overflooded structures have been complicated by later re-activative forces during the most intense stages of Oceanus Procellarum development. It is, however, still problematical to determine in every individual case the part played by old tectonic zones and younger tectono-volcanic forces in the formation of the present mare ridge pattern. Both of these must be taken into account.

The formation of subradial patterns of mare ridges around the prominent volcanic areas may thus be described in terms of the pre-existing lunar fracture system, of basin formation period events, of the major lava generation, outburst and flooding with adjoining obvious stresses and stress releases around pressurized volcanic holes with tectonically controlled locations. Beside horizontal shearings vertical displacements have also taken place along zones of weakness indicated by recent mare ridge ranges and sets.

The most intense lunar tectonic and volcanic development evidently took place during the first 1.6×10^9 y of lunar history. The dissipation of the lunar internal energy caused a decrease in activity. The mare ridge sets with adjoining volcanic phenomena and recent moonquakes indicate the decreasing trend of lunar tectonics.

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