

The origin and geological significance of lunar ridges

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Received May 18, 2006; accepted October 20, 2006

Abstract Lunar ridges are a kind of familiar linear structures developed on the lunar surface. The distribution pattern, formation mechanism and research significance of lunar ridges are discussed in this paper. Single lunar ridges are usually distributed in the form of broken lineation, and, as whole, lunar ridges are trapezoidal or annular in shape around the maria. As to the formation mechanism, only volcanism or tectonism was emphasized in the past, but the two processes are seldom taken into combined consideration. On the basis of detailed analyses, the authors thought that tectonism is a prerequisite for the formation of lunar ridges, while volcanism is the key factor controlling their particular shapes. Finally, the authors pointed out that it is very significant in the study of lunar ridges to link the course of lunar structure evolution with the stress state in the lunar crust.

Key words lunar ridge; tectonism; volcanism; stress system

1 Introduction

With the progress of international lunar exploration and the establishment of lunar detection project in China, the study of lunar structures has become a hotspot of great concern. Except for circular structure, linear structures are another important kind of structures on the lunar surface (Institute of Geochemistry, 1977; Ouyang Ziyuan, 2005), and they had been obviously detected by Lunar Orbiters images, and lunar ridges are the most popular structures among them (Charles and Wayne, 1967). Analysis of the formation mechanism and deduction of the geological significance of lunar ridges are of great importance for the study of the history of lunar evolution and lunar geological characteristics.

Lunar ridges are relatively young linear structures developed on the lunar surface. At the base is a broad gentle arch, while a sharp and strophic ridge appears at the top. Lunar ridges are distributed mainly in lunar maria. Single lunar ridges are distributed in the form of broken lineation, and, as a whole, they are staggered, overlapped or annularly distributed. Tectonism and volcanism are the two mechanisms used to interpret the formation process of lunar ridges in the past; the former mechanism emphasizes the role of lunar structures while the latter one takes it into consideration the relationship between volcanic

eruption and the formation of lunar ridges. But it is strange that the two mechanisms were seldom taken into combined consideration in previous studies. The authors analyzed the two mechanisms of formation of lunar ridges and thought that the two mechanisms of formation were not independent but significantly coordinated with each other. The former is a requisite for the formation of lunar ridges while the latter is a crucial factor affecting their appearance. It is not wise to emphasize one aspect and neglect the other. Since lunar ridges are the result of lunar tectonism and volcanism, they are the important foundation to deduce lunar structures. Having analyzed the orientation of lunar ridges in four maria, we found a good correlation between lunar ridges and grid structures on the lunar surface, indicating that a long-term east-westward compression occurred on the lunar surface, and lunar ridges were formed just in this process. The compressive stress has lasted till now and it still has an influence on lunar ridges at present time (Muehlberger, 1974).

2 Formation and distribution of lunar ridges

Lunar ridges are long, low mountain ridges which are concentrated mainly in lunar maria, and some also extend from the edges of maria to lunar highlands. Only a small number lie on lunar highlands. The minimum width is less than 1 kilometer while the

maximum width is more than 20 kilometers. Lunar ridges can extend over long distance from several kilometers to several hundred kilometers, and vary in height from several meters to 300 meters. Many lunar ridges are asymmetrical, very steep on one side, like the sudden halt of magma flow, while very flat on the other side.

Large-scale lunar ridges are usually distributed in the surroundings of lunar maria (Guest and Fielder, 1968), such as those on the western edges of Mare Tranquillitatis (Fig. 1). In the case of single lunar ridges, they are usually distributed in the form of segments, intersect and overlap, or are trapezoidal in shape (Fig. 2). The orientation of lunar ridges is consistent with the principal linear structures on lunar highlands, i.e., grid structure (Bryan, 1973). This consistency indicates that lunar ridges have relations with the compressional structure. At the turning point of some lunar ridges, many small hills with a mass of silicon can be found. These hills are probably made up of post-Imbrian lavas.

A lunar ridge usually consists of two independent yet interrelated parts: (1) a broad arc-like bottom; and (2) a cone-like top. The width of the crest is likely to be 25%–60% of the base. Usually these cone-like ridges are jointed with filling materials in the craters of highlands nearby. For example, in the Imbrian basins there exist lavas from lunar ridges of highlands nearby, which indicates the filling materials in the craters and the lunar ridges are of the same intrusive origin.

3 Origin of lunar ridges

Much information about the genesis of lunar

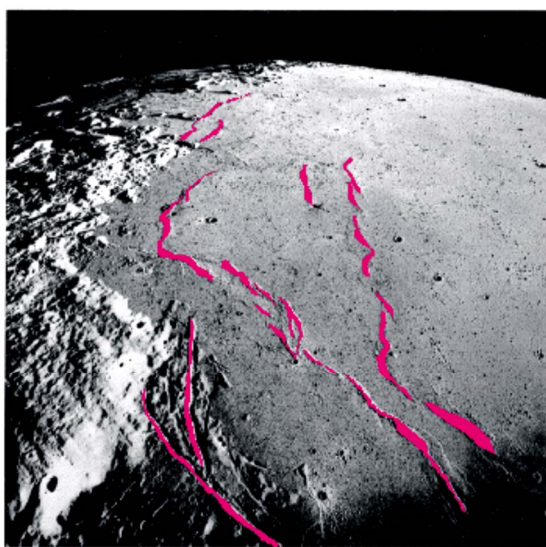


Fig. 1. Lunar ridges at the edges of Mare Tranquillitatis, where the lunar ridges are distributed as rings (the red lines represent lunar ridges, the image is from Apollo17 mission M-952).

ridges has been gradually acquired after the high resolution images of the lunar surface were obtained by Apollo missions. Although there are many sorts of explanation, both tectonism and volcanism are usually taken into consideration. However, in the past researchers only emphasized either of the geological processes. Some authors considered that volcanism played an important role in the formation of lunar ridges (e.g. Colton et al., 1972; Young et al., 1973; Scott et al., 1975), and tectonism only exerted little influence on the formation of lunar ridges. Hodges (1973) even considered that lunar ridges had completely resulted from lunar magma intrusion. On the contrary, some investigators proposed that tectonism was the unique process through which lunar ridges were engendered, and many structural patterns (including surface fractures) were put forward. The authors analyzed these formation mechanisms, and considered that tectonism was a requisite for and volcanism played a key role in the formation of lunar ridges. The two geotectonic processes are equally important, and it is not wise enough to emphasize one but ignor the other.

3.1 The importance of tectonism in the formation of lunar ridges

From the following aspects we can see the reason why tectonism is emphasized in the formation of lunar ridges: (1) lunar ridges have traversed geological units of different geological ages and shapes, so they represent a kind of later activities overlapping other tectonic activities, and the preceding tectonic activities controlled the localization and formation modes of lunar ridges; (2) in local regions, lunar ridges

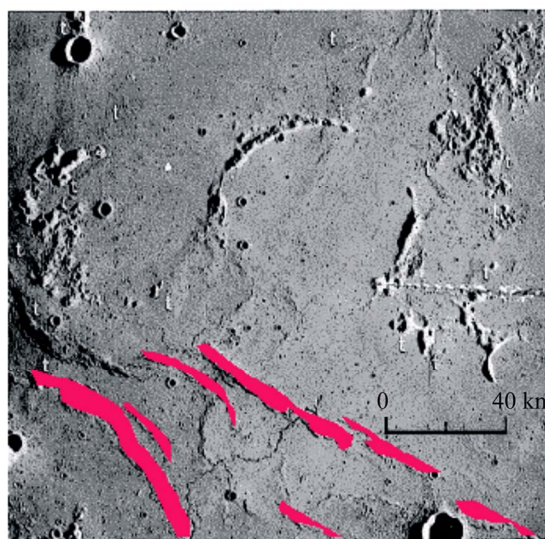


Fig. 2. Lunar ridges in Oceanus Procellarum, which are trapezoidal in shape (the red lines represent lunar ridges, the image is from Apollo16 mission M-2837).

truncated impact craters but the upper half of the craters is still present, which indicates that there occurred geological activities involved in the formation of lunar ridges; (3) lunar ridges are widely distributed around maria but few lunar ridges are observed on lunar highlands and they usually become steep cliffs on one side. So the geomorphic features controlled the formation of lunar ridges; and (4) no younger basalt has been found in Apollo 17 samples collected from lunar ridges, which shows that almost no volcanic activity is of occurrence following the formation of lunar ridges.

Lee-Lincoln near the landing site of Apollo 17 is a lunar ridge that has been relatively well documented (Fig. 3), it is asymmetric on both sides, with complicated steep cliffs on one side and gentle slopes on the other. It is 10–30 m high and extends for 7.5 km from south to north (N20.25°, E30.75°). Around Lee-Lincoln is the Mare Serenitatis, which is characterized by a broad base in the mare and an irregular, sharp-pointed ridge at the top; Lee-Lincoln extends from Mare Serenitatis to a highland nearby, and only its top can be seen from the highland. Its one lateral face is very flat and the other is very abrupt like a steep cliff. This lunar ridge is composed actually of many small-scale segments. Lucchitta (1976) studied this lunar ridge using a high resolution stereoscope and made a relief map on a scale of 1:25000 with the contour interval of 10 meters (Fig. 4). He considered it a very steep fault plane, as revealed by structural analysis techniques. The data from the lunar ridge Lee-Lincoln showed that tectonism played an important role in the formation of lunar ridges.

3.2 The tectonic mechanism of formation of lunar ridges

As for the formation mechanism of lunar ridges, Howard and Muehlberger (1973) thought that the compression of rocks in the interior of the Moon led to the formation of thrust faults. Bryan (1973) and Maxwell et al. (1975) explained that such the compression was caused by the vast subsidence of maria, and the subsidence is more prominent in the thicker basalt-distributed area. The compression was developed in a concentric form in the thinner basalt-distributed area. Lucchitta (1976) also agreed with the hypothesis of subsidence, and considered that lunar ridges were distributed along the fault system which includes normal and thrust faults. These faults showed compressional characteristics on the lunar surface. It is believed that the subsidence of maria could exert stress on the lunar crust, but a crucial factor, i.e., tidal stress between the Earth and the Moon, could play a key role in controlling lunar crust structural pattern. The authors considered that there

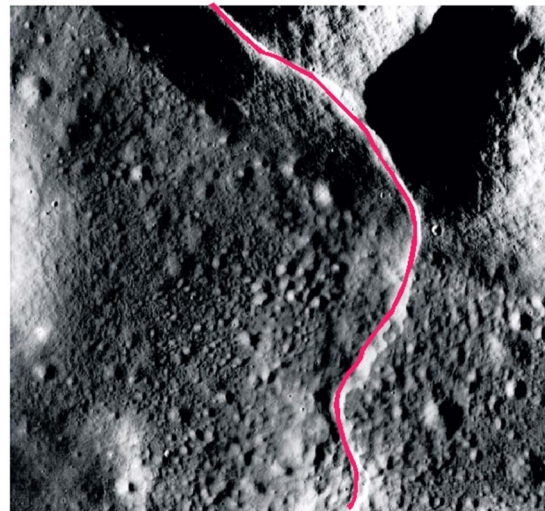


Fig. 3. The image of the lunar ridge Lee-Lincoln. It extends from mare plain to highland, and its one lateral face is very abrupt while the other is very flat (the red line represent lunar ridges; the image is from Apollo 17 frame P-2309).

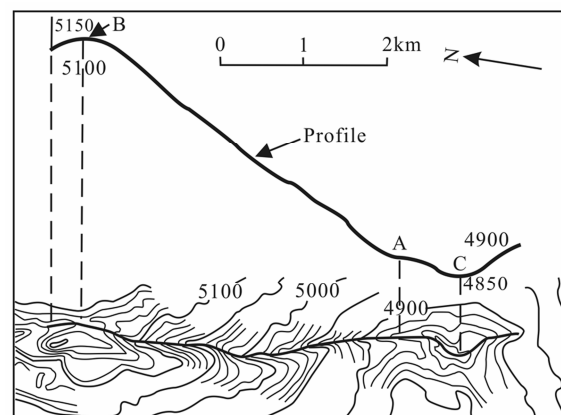


Fig. 4. Scarp trace and topographic profile of the lunar ridge Lee-Lincoln. Changes in gradient at A along straight fault trace indicates a near-vertical fault plane. Changes in gradient at B and C with corresponding changes in trend suggest, respectively, high- and low-angle reverse faults (after Lucchitta, 1976).

were three geological processes involved in the formation of lunar ridges, one is the reverse fault which resulted from tectonic compression, and the second is the normal fault which is the result of tectonic tension, and the last one is the vertical tectonism due to gravity unbalance or magma upwelling.

3.2.1 The formation mechanism of faults in the initial stage of lunar evolution

Because of the influence of the Earth's tidal stress on the Moon, there occurred E-W-extending compression and N-S-extending tension. The Moon

has been gradually away from the Earth since its formation, so the tidal stress on the lunar surface was different in each stage. The stress in the lunar crust changes with varying tidal stress. The Moon was probably a magma ocean at the initial stage of its formation, and then became cooler gradually. The characteristics of the lunar crust also changed during this stage, and the properties of the faults are determined by the two factors.

Solomon and Head (1979) once established a diagram showing stress variation with time. They pointed out that the stress on the lunar surface was tensional in nature at 3.5×10^9 years ago (Fig. 5). As a result, only normal faults were formed in the early stages of lunar evolution, accompanied with the formation of mare basins. The concentric steep cliffs in lunar maria and complex linear structures are the manifestation of normal faults on the lunar surface. In the past 3.5×10^9 years (post-Imbrian), the lunar surface has experienced tectonic compression characteristic of stress and some thrust faults were formed during the period.

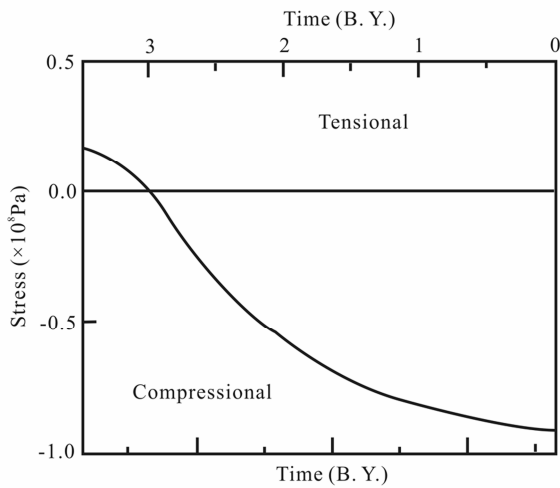


Fig. 5. Diagram showing the variation of lunar stress with time (Solomon and Head, 1979).

As for either normal or reverse faults, the angle (θ) between the greatest principal stress direction and the fault plain satisfies the following formula:

$$\theta = (1/2) \arctan(1/F)$$

where, F refers to the coefficient of friction. For terrestrial planets, F varies between 0.75 and 1.5, which has an intimate relation with the properties of lunar rocks, and F varies greatly from the early stage to the late stage of lunar evolution. Prior to the Imbrium epoch, F is about 1.5 (Alan, 1982), and the dip angle for normal faults is about 73° . In the past 3.5×10^9 years (post-Imbrium), F is about 0.75, and the dip angle for the reverse faults is about 17° .

Therefore, two phases of tectonism were involved in the formation of lunar ridges: the former phase is represented by high-angle normal faults and the latter phase by low-angle reverse faults. Alan (1982) proposed that the steep cliffs were produced by the thrust faults on the lunar surface, and the more recently the cliffs are formed, the more deeply they will extend. The steep cliff planes are arranged in a circular pattern (Fig. 6), just like the distribution pattern of lunar ridges as we can see now.

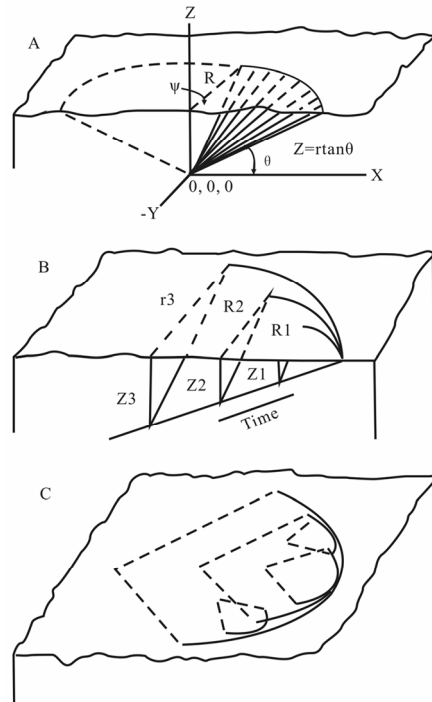


Fig. 6. Sketch map showing the development of thrust faults on the lunar surface (Alan, 1982).

These are two phases of tectonism, and the dip-angle difference of fault planes reaches 56° . So the possibility is excluded that the thrust faults are the result of activity of early-stage normal faults. But the early-stage normal faults affected the location of formation of the early-stage thrust faults. Sanford (1959) put forward the process of formation of lunar ridges. And he pointed out that lunar ridges are approximately vertical in the deep interior of the lunar crust, while they are the result of superposition of the two faults on the lunar surface. Lucchitta (1976) also proposed similar opinions and worked out the sketch map showing the process of formation of lunar ridges (Fig. 7).

3.2.2 The role of magma eruption in the formation of lunar ridges

Even if those who support the hypothesis of tectonic origin for lunar ridges also considered that

lunar ridges are made up of two independent but associated parts: broad bases and steep tops. The conclusion that lunar ridges resulted from magma eruption is based mainly on the composition and characteristics of materials at the top of lunar ridges. Robert (1972) also agreed with the hypothesis of magmogenesis of lunar ridges, and he pointed out that there is developed a kind of obviously ropy structures at the top of lunar ridges in Mare Tranquillitatis, which is a manifestation of magma flow. Moreover, the magma flow even extends to the impact craters on highlands nearby. At the turning points of lunar ridges there are also some small, light-colored hills, which are the vents formed in the process of formation of lunar ridges. In some locations lunar ridges extend from maria to lunar highlands. A common feature is that these lunar ridges are very small in length on lunar highlands and the front of magma flow can also be observed. That is because the lunar crust on the highlands is very thick but the source region of magma is located in the deep interior of the lunar crust, so magma flew over a very short distance before it stopped. Therefore, lunar ridges on the highlands are very small in scale and have almost no broad arc-like bases (Fig. 8). This is what we see today on the lunar surface. In fact, the lunar surface is covered by a layer of soil, which is composed mostly of KREEP rocks (Zou Yongliao et al., 2003, 2004), so we can seldom see the lunar ridges as clearly as in the images.

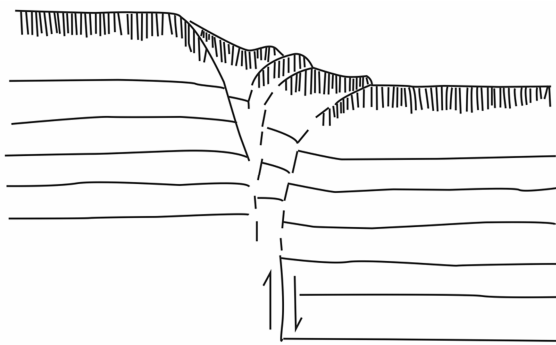


Fig. 7. Sketch map showing the formation mechanism of lunar ridges (Lucchitta, 1976).

Don Wilhelms (1987) also proposed this

formation mechanism in his monograph “The Geological History of the Moon”. He considered magma intrusion played a very important role in the formation of lunar ridges, and some small circular lunar ridges are the product of magma eruption.

3.2.3 Summary

The Moon also experienced magmatic exhalation during the post-Imbrium period (3.5×10^9 years ago) along the fractures produced during the formation of maria. It is not wise to emphasize tectonic activities but neglect the role of magma eruption in the formation of lunar ridges.

The whole process of formation of lunar ridges is described below in combination with volcanism and tectonism: (1) highly viscous basalt magma filled in mare basins; (2) gravity isostatic compensation and tidal stress between the Earth and the Moon produced normal and reverse faults; (3) broad arc bases of lunar ridges appeared; (4) highly viscous magma erupted on the top of the arc bases; and (5) lunar ridges finally were formed. In summary, although there is a lot of controversy on the origin of lunar ridges, we still can draw such a conclusion that lunar ridges are a kind of relatively young structures developed on the lunar surface and their formation has altered the characteristics of the lunar surface.

4 Geologic significance of lunar ridges

4.1 Characteristics of lunar ridge orientation

Tectonism is a requisite for the formation of lunar ridges, and in return, lunar ridges provide favorable evidence for us to deduce earlier lunar structures. Fagin et al. (1978) selected lunar ridges in four maria in their study, and they concluded that lunar ridges are the result of E-W compression on the lunar surface.

The four maria are Mare Crisium, Imbrium, Tranquillitatis, and Serenitatis. In each of the maria Fagin et al. (1978) selected a study area to study the characteristics of lunar ridge orientation. In order to reflect the local stress system, he cautiously selected those ridges inconsistent in orientation with the edges of the maria (Fig. 9).

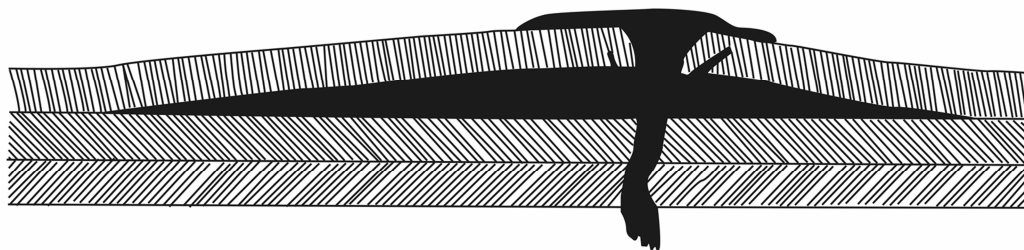


Fig. 8. Sketch map of magmogenetic lunar ridges (Robert, 1972).

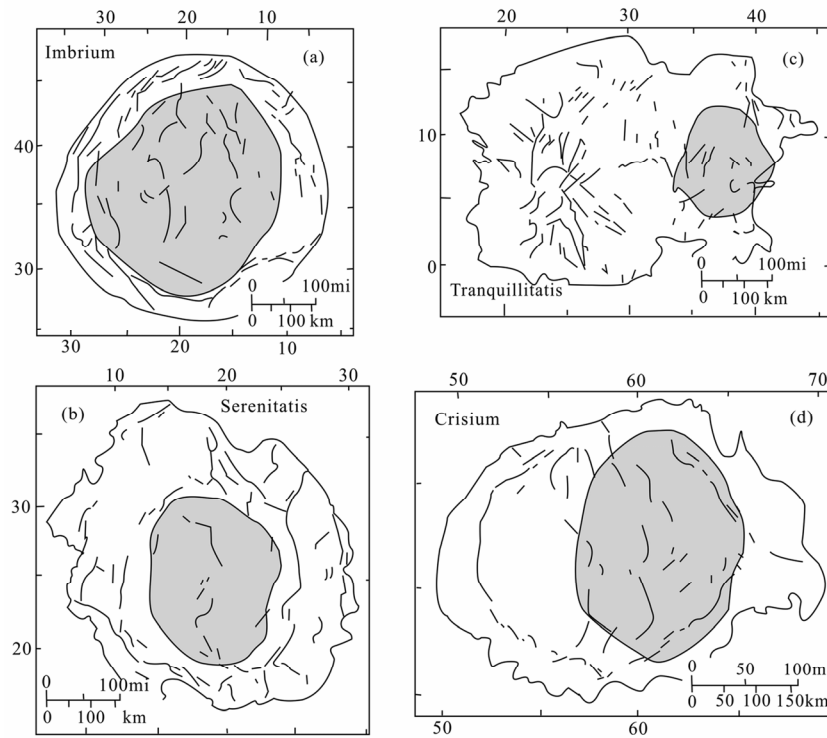


Fig. 9. The distribution of lunar ridges in the maria Imbrium (a), Serenitatis (b), Yranquillitatis (c), and Crisium (d). The shaded area denotes the central area (Fagin et al., 1978).

Lunar ridge orientations in these central and marginal areas were measured by Fagin et al. (1978) and the relevant diagrams were plotted for each of the maria (Fig. 10). On the whole, the results indicate that lunar ridges' orientation in the four maria shows a low deviation and approximately points to north in the central mare area. But the ridges in the marginal area have no obvious primary orientation. That is because lunar ridges at the edges of mare basins are only influenced slightly by tectonic compression as compared to subsidence.

From the above analysis we know that the orientation of lunar ridges, especially in the centric area of lunar maria, has a strong tendency of pointing to north. Because the lunar ridge orientation is determined principally by the stress on the lunar surface, we can draw the conclusion that the whole lunar surface has ever experienced the E-W-extending compression.

Fagin et al. (1978) calculated the maximum principal stress orientation (Fig. 11). In addition to the lunar ridge system which shows a strong tendency of trending northwards, a conjugated lunar ridge system

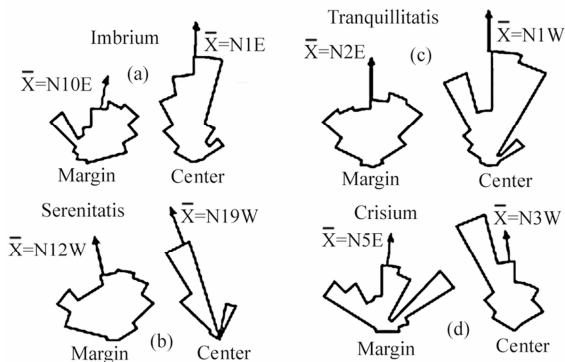


Fig. 10. Diagrammatic maps of lunar ridge orientations (Fagin et al., 1978).

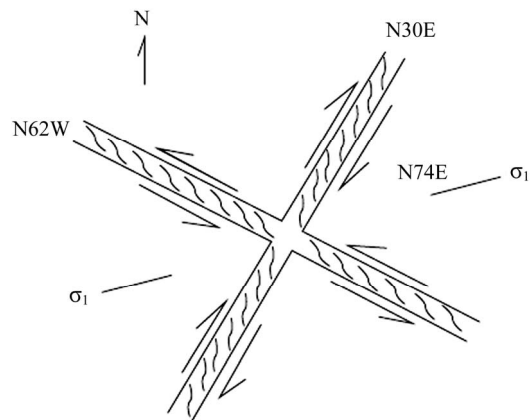


Fig. 11. Sketch map showing lunar ridge orientation and stress system (after Fagin et al., 1978).

4.2 Geologic significance of lunar ridges

was also discovered. And the resulting greatest principal stress direction, N74°E, is approximately consistent with the E-W-expanding compression. In addition, Eppler et al. (1978) found that impact craters are elongated in a north-southern direction which is parallel to the orientation of lunar ridges. This has proven that the result is correct from another point of view.

5 Summary

The formation process of lunar ridges includes two phases. The basement was formed in the early stage, followed by the formation of the sharp top. The basement uplift is mainly the result of tectonism as marked by normal and reverse faults, while the sharp top was formed on the basis of magma eruption. The two processes are linked closely. Tectonism is mainly the result of tidal stress on the lunar crust, and the tidal stress mostly comes from the Earth. Besides tidal stress, the gravity isostatic compensation within the Moon is probably the other process. The magma eruption that produced the sharp top is certainly the result of lunar evolution.

Lunar ridges are the product of lunar crust deformation in the late stage. Lunar ridges began to take shape during the post-Imbrium period, at about 3.5×10^9 years ago, which is consistent with the time when the graben appeared (3.2–3.8 b.y.) as proposed by Lucchitta and Watkins (1978), so lunar ridges are of great significance in the study of lunar evolution in the early history. Lunar ridges are probably undergoing transformation now because the small impact craters at the East Mare Tranquillitatis are changed as a result of the influence of lunar ridges.

On the contrary, we can deduce the characteristics of the stress system in the lunar crust from the orientation of lunar ridges. The orientation of lunar ridges shows that there is a strong E-W-extending compression system on the lunar surface, which led to the formation of lunar ridges. Statistics maps of lunar ridge orientation in the central areas of the maria Crisium, Imbrium and Tranquillitatis show that there is a low deviation in the orientation, approximately pointing to north. The E-W compression is probably still under way even up to now, and this is the major reason why the lunar crust is still under transformation.

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