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SOME FEATURES OF THE LUNAR GRID SYSTEM

by

BRIAN WARNER

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INTRODUCTION

In two previous papers[1,2] the writer has drawn attention to certain features of the lunar surface that are intimately connected with the lunar grid system. The first of these papers dealt primarily with the relative dating of individual parts of the grid system and introduced ideas such as 'old' small craters.

Also discussed were the elongated craterlets. This latter topic was elaborated in the second paper, which also discussed fracture patterns around lunar craters.

The present contribution extends some of these ideas and introduces some new observational material. In a subject of this kind, where there is a large amount of material to work with, it is necessary to systematize one's approach in any way possible. Accordingly, this paper is sub-divided into a number of short essays, one on each aspect of the grid system. Each of these essays defines both a method of attack on the problem at hand, and shows also what can be deduced from each approach. It is to be hoped, of course, that each of these paths will eventually converge to a single unambiguous solution of the stress history of the lunar surface.

In the course of the discussion it will be necessary to introduce concepts, such as erosion, that are not immediately connected with the grid system. This is inevitable for any complete survey of the present situation.

The production of this paper has been aided to an incalculable degree by the recent publication of the *Photographic Lunar Atlas*.[3] The best plates in this *Atlas* should provide students of the lunar grid system with a wealth of information for years to come.

RELATIVE AGES OF LUNAR CRATERS

A well-established and often quoted rule is that of the non-overlapping of large craters on smaller ones. Supporters of the igneous origin of lunar craters have used this rule as a weapon in the battle against those holding impact origin views. It is maintained that the larger craters must have originated first and the smaller ones progressively later, implying a non-random distribution of crater diameters with respect to time.

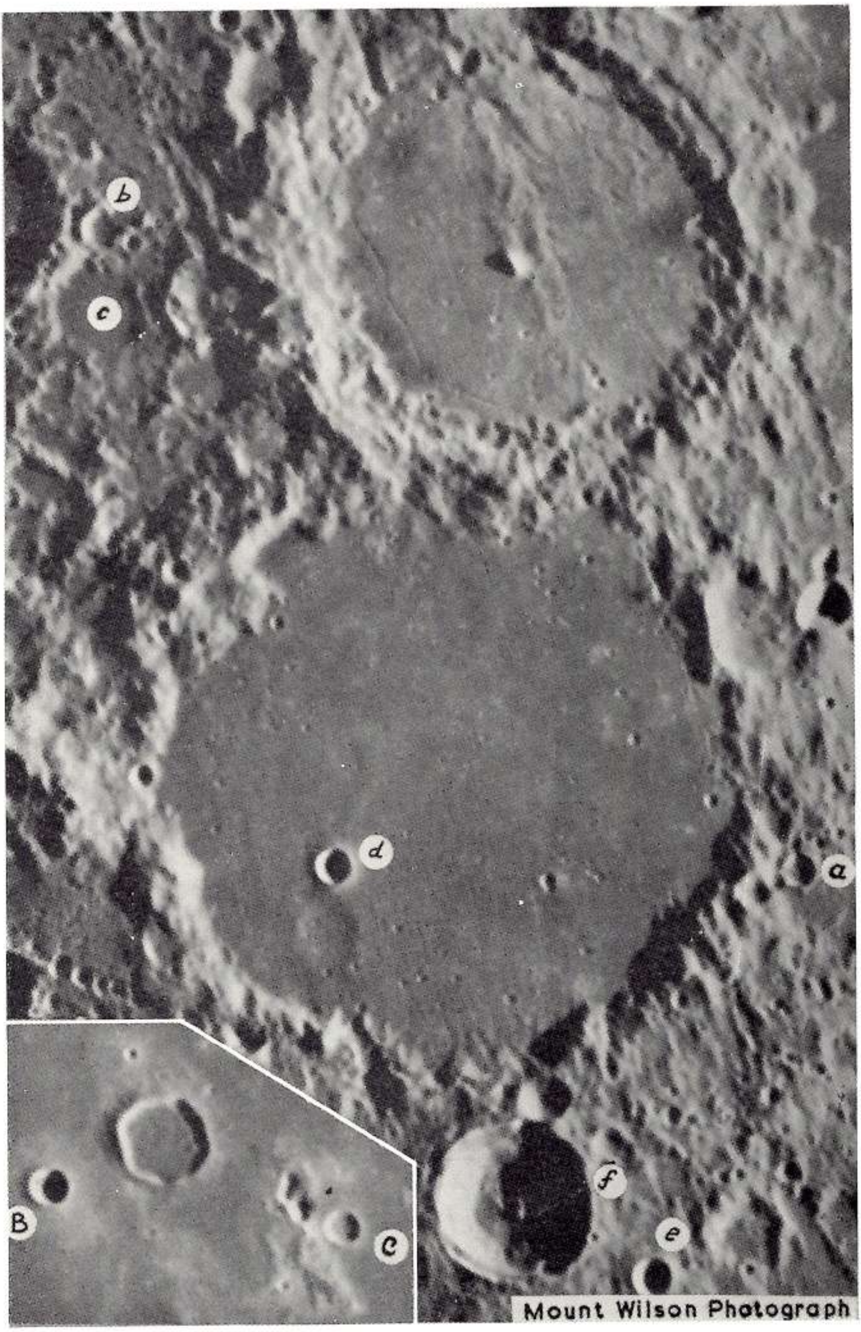
Recently, however, Fielder[4] has argued that a number of low rings in the Hyginus region are considerably older than well formed craters of similar dimensions. The writer[1] has independently arrived at a similar conclusion in showing that some craterlets (diameters <15 km) exist that have been distorted by stresses in the lunar crust and are presumably older than undistorted ones of similar size.

It seems appropriate, therefore, to give further examples of relative dating of lunar craters, using the grid system as an *aide accompli*. The region near Ptolemaeus has been studied and a photograph of the area is reproduced in Plate 7.

Ptolemaeus itself must be one of the oldest craters in this particular part of the Moon; it has been distorted from its presumably original circular outline into a nearly perfect hexagon. Any crater of the same age must have this shape if it lies near to Ptolemaeus. It can be seen (Plate 7) that the craters marked a, b, c mimic Ptolemaeus both in hexagonal shape and in orientation. On the other hand, the craters d, e, f, which are respectively of similar dimensions to a, b, c, are circular in outline. Thus there is a clear distinction in age of craters with the same dimensions. This clearly violates the stated implications of the non-overlapping rule.

PLATE 7

SOME FEATURES OF THE LUNAR GRID SYSTEM



The lunar surface in the vicinity of the crater Ptolemaeus.
(Inset) The Lunar craters Lassel B and C.

[*facing page* 182

A striking property of craters a, b, c, is not merely that they are hexagonal, but also that they have flat dark floors. This seems to be a fairly general rule: the more a crater has suffered from the effects of crustal stresses the larger its flat floor is. Furthermore, these 'anomalous' distorted small craters usually appear eroded by some means or other. It is tempting to suggest that the flat floor is the result of erosion products. It would be important to establish the general applicability of the correlation between age and flat floor. We could then, for instance, say that the two craters (Lassel B and C) shown in inset are of different age. Certainly C has a pronounced flat floor and its walls appear somewhat lower than those of B. Both craters are situated on the Mare Nubium and are so close together that it is difficult to attribute their differing appearance to anything other than age differences.

We have established, therefore, that there is a dispersion in age of craters with a given diameter. We may still wonder why the 'non-overlapping' rule holds. There are probably two facts to consider here. Firstly, if the *average* diameter diminished with time during production we would expect fewer violations of the rule than if they were randomly distributed. Also, we may look at what we know is a recent *large* crater, viz Tycho. Examination of the surroundings of Tycho shows that there is no bona fide case of Tycho itself overlapping a smaller crater. The reason is not clear why this should be. There appears to be a general raised area outside Tycho and it looks as if when Tycho was formed material was moved horizontally away and neighbouring craters were consequently also moved bodily.

If we assume, therefore, a statistical decrease in diameter during crater formation, and consider also the observational difficulties in determining exceptions to the 'non-overlapping' rule and the horizontal movement referred to above, there does not seem to be any objection to a dispersion in age of craters of a given diameter.

ELONGATED CRATERLETS, RILLES AND WRINKLE RIDGES

Although very prominent in the region to the east of the Mare Tranquillitatis the grid system apparently practically disappears when it reaches the eastern border of this mare. This is quite characteristic of the grid system: it is difficult to trace on the maria. For this reason, G. Fielder, in constructing his latest chart of the lunar grid system,[5] has omitted nearly all grid lines on the maria.

The present writer has shown,[2] however, that elongated craterlets on the maria provide directions that are natural extensions of the grid system on the surrounding continents. Moreover, on the Mare Tranquillitatis, elongated craterlets closely follow the same directions as extensive linear wrinkle ridges. Other, weaker indications of the grid system exist in the central regions of Mare Tranquillitatis in the form of rilles, and short lunarite ridges (see, for example, Warner[6]). We may suppose, therefore, that the grid system is just as well developed on the Mare Tranquillitatis, but is more difficult to trace because of the lack of lunarite material.

The situation on the other maria is different. It is difficult to trace any parts of the grid system across the maria Humorum and Crisium. Both of these maria have wrinkle ridges but they do not conform to the grid directions. Neither mare has any sizeable rilles on its interior and both are free of elongated craterlets and domes. The writer has looked in vain under the best seeing conditions for any rilles, even very fine and short ones, crossing the interiors of maria Humorum and Crisium.

In contrast, Mare Tranquillitatis has very many elongated pits, has several rille and fault systems on its interior (e.g. Warner[6]) and has many domes. We can therefore think of Mare Tranquillitatis as having had an active history and the maria Crisium and Humorum as having a quiet history. Activity here refers to rille, dome, and elongated craterlet formation. On these lines, Mare Serenitatis would have had a fairly active life and Mare Imbrium, Mare Nubium and Oceanus Procellarum a fairly quiet life.

The reasons for these dissimilarities in marial surface character are connected with the stress history of the Moon's surface. Some of the difficulties of interpreting the data will be given in what follows.

It would seem reasonable, at first sight, to suppose that these dissimilarities arise purely from the effects of age differences in the maria. If the maria are of different ages their surfaces would be more disturbed the older they are. Thus we might infer that Maria Crisium and Humorum were formed *after* the rille, etc., forming period. However, both the Maria Crisium and Humorum contain wrinkle ridges, and it has been suggested[1] that wrinkle ridges are older than rilles. Thus we may expect that all the maria gave gone through both wrinkle ridge and rille forming stages. Then the lack of rilles on certain maria simply means that the stresses set up during the rille-forming period were insufficient to cause rock failures and no rilles were actually produced.

Differences in marial surface detail cannot be attributed, therefore, to age differences alone but must be partly a result of environmental and stress history differences. Before continuing any further with this line of thought we will consider some more properties of rilles, wrinkle ridges, and elongated pits. We may then be able to determine in what manner these features were formed.

The writer has made an especially close study of the Mare Tranquillitatis rilles and elongated craterlets, both visually, using the 18-inch refractor of the University of London Observatory, and on photographs (in particular sheet B4d of the *Photographic Lunar Atlas*[3]). Probably the most striking fact arising from this study is that all, without known exception, of the elongated craterlets on Mare Tranquillitatis are in fact short craterchains. Many have up to five component craterlets but do not usually exceed 8 km in total length. The writer has previously pointed out[2] that the elongated craterlets around Copernicus are all at least pairs of craterlets. One of the elongated craterlets, just S.W. of Jansen, lies on a rille, and there are three similar instances W. of Sosigenes. Fielder[8] has found a similar association near Aristarchus.

We conclude from the previous paragraph that rilles, craterchains and elongated craterlets are closely related objects and were all formed by a similar process. It has been shown[9] that the lunar surface has at one stage been subjected to tensional stresses. It will be argued elsewhere (see *Distorted Craters*) that the lunar surface was originally (before the tensional phase) subjected to compressional stresses.

Many features, e.g. wrinkle and lunarite ridges, have structures that seem to demand a compressive rather than a tensional origin. Other features, e.g. rilles, craterchains, could be formed either by tensions alone, or compressions followed by tensions.[4] These processes are consistent with the relative ages of wrinkle ridges and rilles.[6] The writer finds it difficult to understand, however, why a compressive stage should produce both wrinkle ridges and rilles: two very different types of object. It is suggested, therefore, that rilles are products of the tensional stage.

Fielder[4] has argued that rilles show no signs of the result of horizontal (lateral) movements of the crust, and maintains that they are collapse features. He shows that the most probable type of fault to produce the Ariadaeus Rille and the western portion of the Hyginus Rille is a wrench fault. This theory is only applicable to the few rilles not parallel to the grid system; for those that are, tensional fault origins are suggested here. If the lunar surface is composed of a highly porous, froth-like, low density material, a suggestion by Firsoff[10] that is supported by the writer, then it would collapse if tensional cracks were formed underneath it.

Returning to the larger scale problem of differences in marial surface character we note that nearly all the maria have rilles running concentrically with some part of their borders. Any tensional stresses that produced the rilles must therefore have been more effective at the edges of the maria and decreased towards the interior. If the maria as a whole were in a state of tension such that fracturing could almost take place all over their surface then the addition of grid system tensions in preferred directions could cause the surface to crack at its weakest points. The ensuing escape of gases would produce the short craterchains. On this suggestion, assuming that the grid system tensions were more or less uniform over the whole Moon,[9] we have the following order of severity for the tensional states of the maria:

Tranquillitatis, Serenitatis, Nubium, Imbrium, Humorum, Crisium.

The origin of the greater tensile stresses in the maria must be more or less independent of the grid system tensions. This is because the rilles running concentrically with the edges of the maria often ignore the grid system directions. The writer suggests that if the maria were at one time molten then cooling would produce tensions that increased towards the periphery of the maria since at their edges the maria are presumably thinnest and the rate of cooling would be greatest.

It was thought at one time[2] that some of the elongated craterlets (the non-multiple ones) may have been old small craters that have been subjected to crustal stresses since they were formed. This view has now been abandoned for the following reasons:

(a) the recognition that the majority of elongated craterlets are in fact multiple shows that their structure is inherent in their formation,

(b) other small craters that have been distorted do not get elongated but just have parts of their walls shifted bodily inwards, and

(c) other small distorted craters are eroded[1] and, so far, no elongated craterlets are known that have suffered from the effects of erosion.

The writer hoped that the observed ellipticities of elongated craterlets would provide a means of determining relative stresses in the lunar surface. If a and b are respectively the major and minor axes of a single elongated craterlet then it might be reasonable to suppose that $(a-b)/b$ gives a measure of S_h/S_f, where S_h is the horizontal stress in the surface at the time of formation and S_f is the stress that just produces fracturing.[9] However, this ratio should not be larger than unity unless very sudden increases of S_h are encountered. Some single elongated craterlets have ellipticities much greater than unity so it is evident that during their formation a running crack ensues that cannot be treated theoretically. However, for small ellipticities the observed a and b give an upper limit for S_h/S_f that may be useful. For example, the observed ellipticity of the elongated craterlet near Piazzi Symth[2] is 0·8, after correction for foreshortening. This is not greatly different from the value of 0·5 found for the surface when Aristillus was formed.[9]

Finally, the writer's distribution chart of elongated craterlets[2] could now be greatly extended as many such objects have been found on the continents. One can be seen to the S.E. of Herschel (Plate 7).

FRACTURE PATTERNS

The discussion of fracture patterns around lunar craters was initiated by the writer[2] and a more rigorous approach was later developed.[9] It turns out that the specific distribution of ridges and valleys around certain lunar craters can only be interpreted by assuming that the lunar surface was in *tension* at the time of formation of those craters. A list of eighteen craters was given[9] around which fracture patterns could be detected. These craters, together with further examples, are listed below in three groups. Group 1 contains those craters around which the fracture patterns are prominent; this list is probably complete. Group 2 contains those of less prominence and Group 3 those where the pattern is difficult to detect. The latter two groups probably have many more members, as yet undiscovered.

1 Aristillus, Aristotles, Autolycus, Bullialdus, Davy, Eratosthenes, Herschel, Millas, Plinius, Timocharis.

2 Archimedes, Aristarchus, Burg, Copernicus, Harpalus, Hercules, Lambert, Langrenus, Thebit, Theophilus, Tycho.

3 Delisle, Euler, Landsberg, Manilius, Triesnecker, Reinhold.

All of the craters listed, with the exception of Archimedes and possibly Davy, are well-formed, non-eroded craters with central mountains. Thus it can be argued that the tensional stage of the lunar surface was recent in the Moon's history. Various arguments point to the fact that the tensional phase must have been preceded by a compressive stage (see *Distorted Craters*, and Fielder[11]). The compressive stresses were dominant shortly after the largest craters were formed and eventually decreased in magnitude and reversed in sign. Whether this decrease was sudden or gradual is not yet known.

Craters formed during and before the compressive stage will be discussed in *Distorted Craters*. The present Section deals with those craters (listed above) that are representative of craters produced during the tensile stage.

It must first be noticed that the above list is subjected to selection effects. Fracture patterns are most easily discernible on the maria, and in general it is difficult to find them on the continents. For instance, the pattern around Tycho is masked by the array of old craters in the region: if Tycho had been formed on a mare it would have a fracture pattern as prominent as that of Aristillus. The pattern around Herschel is instructive: it is easily seen where it crosses the floor of Ptolemaeus in the direction of the most prominent family of the grid system, but is only just traceable to the north. It is important to obtain a really good photograph of this pattern on the floor of Ptolemaeus. Then the methods in reference 9 can be used to determine the 'propagation index' of the material of the floor of Ptolemaeus. It would be of significance if this were different from the propagation index of $\sim 0{\cdot}35$ found for the marial material around Aristillus and Bullialdus. The Millas case is also instructive. The pattern here runs roughly SW and is parallel to a secondary family of the grid system and not to the prominent family 'radiating' from the Mare Imbrium. Thus when Millas was formed the stresses that formed the latter family must have been already relieved—this is confirmed by the fact that Millas itself has not been noticeably distorted by the predominant grid pressures and by the fact that it appears in any case to have been formed after the main valleys in the region as it lies on top of such a valley. Such consistent data is very encouraging!

We can also learn something about the nature and history of the maria by studying fracture patterns around craters. For instance, the patterns around Aristillus, Bullialdus, and similar craters show that the maria were solid when those craters were formed. What is more, the existence of fracture patterns on the maria precludes the possibility that the maria are formed of dust as deep as has been maintained by Gold.[12] There are two reasons for this: in the first place it is unlikely that dust could fracture at all and, secondly, if dust is accumulating on the maria at the rate suggested by Gold then the fracture patterns would be covered up in a few thousand years.

On the other hand, the two craters Archimedes and Davy may be able to tell us even more. Both of these craters lie on the edge of a mare and their fracture patterns do not appear on it. Thus in the case of Archimedes the fracture pattern only appears in the highlands to the south where it is largely masked by mountains. The part of the fracture pattern running SE from Archimedes disappears on reaching the mare on the other side of these highlands. Some indications of a fracture pattern running towards Aristillus also exist. In the case of Davy no fractures run eastwards onto the Mare Nubium but a system runs westwards across the floor of an old crater. The direction of these fractures is parallel to one of the weaker families of the grid system.

There are three possible explanations of this effect. Firstly the maria may not have been solid at the time Archimedes and Davy were formed; or the accumulation of dust on the maria may be sufficiently fast to destroy all trace of the fracture patterns belonging to craters produced nearer the beginning of the tensile stage. Another possibility is that the maria were melted after Archimedes and Davy were formed. In all of these cases the two craters in question would have to be older than the others listed at the beginning of this Section. This is consistent with the fact that both have flat floors and appear more eroded than the other craters listed.

Other large craters lying on the edge of maria, e.g. Plato, Posidonius, Gassendi, Pitatus, have no trace of fracture patterns, though in the case of Plato the semi-radial features found by the writer[13] may be the last traceable remnants. This must mean that either they were formed so long ago that the fractures in the mountains have been obliterated and the fractures on the maria obscured, or they never had fracture patterns as defined by the writer.[2,9] Fracture patterns formed during the compressive stage would not look at all like those formed during the tensile stage.

There should, of course, be a perfect correlation between those craters that have not been distorted by compressional stresses and those having fracture patterns (compressional and tensile stages being mutually exclusive). This is in general true: those craters listed are mostly large craters that have been distorted only by small amounts. Why they should have been distorted at all will be discussed in *Distorted Craters*. The crater Kepler has a ray system and is presumably fairly young. It has no fracture pattern and is considerably distorted from circularity: this is consistant with the picture outlined above if the region around Kepler was one of the last to change from the compressional to the tensile phase.

Apart from aiding in a study of marial history, fracture patterns enable to us date certain other lunar features in a relative manner. A few examples will be discussed.

Aristillus: Fielder[14] has discussed his observations of the fractures running NE from Aristillus. He points out (and this can be seen on sheet D2a of the *Photographic Lunar Atlas*) that the fractures pass over a wrinkle ridge. This establishes that Aristillus is younger than the ridge and is consistent with the suggestion[9] that Aristillus was produced during the tensile stage. The bright rays from Aristillus also cross over several wrinkle ridges. The fractures also cut through an old ring lying to the north of Aristillus. This then is a clear cut case of a large crater having been formed after a smaller one. It is instructive to see how Aristillus has obliterated the S wall of this ring.

Archimedes: Returning again to the fracture pattern running from the S wall we see that it has to cross over several rilles. The writer suspects that all the rilles cut through the fracture pattern. It is difficult to be certain of this for the major rilles running SW–NE, but it is quite definite for the finer, curved rille that runs almost E–W.

Plinius: The fracture pattern on the N runs into the rilles that follow the edge of the Mare Serenitatis. So far the writer has been unable to decide which feature lies on top of which.

Two final points must be made. The 'radial' system of valleys and ridges associated with the Mare Imbrium may well be a fracture pattern. Certainly these features can hardly be described as radial on the western border of the mare, where they exhibit a 'gap' very similar to that found in fracture patterns around craters.[2,9,14] This gap can be seen on Fielder's chart of the grid system[5]—drawn long before the patterns around craters had been noticed.

Also, the writer suggests that there may be two or more types of fracture patterns. The first is represented by Aristillus, Bullialdus, Eratosthenes and Herschel, where the fractures are very delicate and thread-like. The second is represented by Aristotles, Copernicus and Theophilus, where they are much more rugged and blocky. And a third type may exist, represented by Aristarchus, Burg, Harpalus and Timocharis, where the fracture patterns are complex and individual fractures may even intersect.

The interpretation of these types is a problem for the future.

DISTORTED CRATERS

Plate 7 illustrates a region of the lunar surface in which a large proportion of the craters have been considerably distorted from circularity. There have been three stresses acting at approximately 60° to each other and they have produced predominantly hexagonal structures. Now it seems most likely that the distorting stresses must have been thrusts: it is difficult to imagine how tensile stresses could distort craters in such a manner. Also the walls of craters are occasionally associated with wrinkle ridges, which must surely be pressure ridges. For example the ridge crossing the floor of Alphonsus (Plate 7) is an extension of the E wall of Ptolemaeus and has all the characteristics of a wrinkle ridge rather than a lunarite ridge. Presumably whatever force moved the E wall of Ptolemaeus at the same time produced the ridge across Alphonsus.

It is possible, however, that a tensile stage would distort the craters in some manner. Most probably the amount of distortion would be much less than that produced by compressions, but it would of course still follow the grid system directions. This may explain why craters with fracture patterns (see *Fracture Patterns*) have their walls displaced by small amounts.

There is a pecularity that is particularly noticeable on Plate 7. If the three major stresses were produced one after the other then the walls of Ptolemaeus and all other local craters would be moved inwards one at a time. However, this would mean that crater a had also been moved bodily, and if this is so why has it still got a perfect hexagonal shape? In fact there are upwards of six craters in this region with perfectly hexagonal structures. They range in size from Ptolemaeus (diameter 150 km) down to crater a (diameter 9 km) and their walls are all orientated in the same way. If the stresses had become effective one after the other why should they have had the same effects on craters of widely different sizes? It looks as if the three stresses acted simultaneously and were of the same magnitude. This would produce the same *percentage distortion* in all coeval craters.

From the very existence of a distorted crater as small as a shown in Plate 7 we may make an interesting deduction. The distortions of craters will be accompanied by fracturing of the lunar surface as a whole, and we may expect there to be a smallest feature below which size crustal movements cease to produce distortions but produce a *bodily* shift of the feature instead. Presumably this smallest feature must be at least an order of magnitude smaller than the diameter of crater a. This ties in nicely with an observation reported by Fielder.[8] Under the very best conditions at the Pic du Midi Observatory, Fielder was able to detect minute criss-crossing lines and fractures on the lunar surface. These lines were in the directions of the grid system, and the distance between fractures was about ½ km or less. The writer suggests that these are the smallest features of the grid system and that pits with diameters less than 0·5 km will not be distorted no matter how old they are.

DOMES

It has not hitherto been claimed, to the writer's knowledge, that domes are in any way connected with the grid system. We will present here some evidence showing that domes might be loosely associated with the grid system.

Domes are not distributed randomly but tend to collect together in well defined regions. Often they are in a region where rille activity has been prevalent (Arago, Cauchy, Darwin, Menelaus) but there are other dome regions (Hortensius, Milichius) where rilles are almost non-existent. The writer has maintained[1] that domes are older features than rilles. Consequently we may suspect that the distribution of domes is divorced from the grid system.

We may obtain more positive indications by looking at lines of domes: if these exist they might be aligned in the direction of the grid system. Very few of these dome chains are known and the writer suggests that a search should be made for them.

Two such dome chains are at present known to the writer. Within Capuanus are many small domes that tend to arrange themselves in three strings with slightly raised areas between. These chains run approximately SW–NE, being parallel to the aligned ridges outside Capuanus[7] and in the direction of of the grid system. The other chain consists of three domes NE of Arago. These were found visually by the writer and can be seen on plate C4d of the *Photographic Lunar Atlas*.[3] This chain is inclined slightly to the direction of the grid system.

There is thus a slight indication that some domes have been produced by grid system activity.

CONCLUSION

It is hoped (by the writer) that this survey has demonstrated what can be deduced about the history of the lunar surface by careful visual and photographic studies. There has been too much emphasis in the past on attempting to prove or disprove the many theories of the origin of lunar craters without sufficient appeal to observations. A study of the lunar grid system shows that many features mentioned in the arguments for or against these various hypotheses have in fact nothing to do with the method of formation of the craters at all, but are secondary phenomena. The recognition of the grid system in its entirety shows that the valleys and ridges radial to the Mare Imbrium are merely the most prominent members of a much more general system of alignments. Consequently, in the writer's opinion, all previous remarks and investigations concerned with the effects of projectiles coming from within the Mare Imbrium are *redundant*. The writer submits that, apart from the small craters lying on bright rays,[2] there is no evidence for projectiles having been ejected from any of the craters or maria. The origin of the craters could not, therefore, have been as violent as some writers suggest, at least in so far as ejectmenta are concerned.

The writer wishes to express his thanks to Dr Gilbert Fielder for reading this paper in its initial stage and suggesting many improvements, and also to Dr G. P. Kuiper for supplying plates from his *Photographic Lunar Atlas* to act as illustrations in this paper.

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