STRESSES IN THE SURFACE OF THE MOON

By Brian Warner

Introduction

Considerable evidence has been accumulated during the past few years to illustrate that the surface material of the Moon has been subjected to large-scale stresses. Spurr(1) first pointed out that regions near craters often show linear structures indicative of the relief of surface stresses. More recently, Firsoff(2) and Fielder(3) have shown that the whole surface of the Moon is covered by a network of aligned ridges and valleys, superimposed on the general uneven and irregular terrain. This network is the lunar grid system. We are therefore led to suppose that the outer parts of the lunar crust have been subjected to widespread stresses, possibly caused by an expansion or contraction of the Moon as a whole.

Furthermore, it is evident that the production of the lunar craters themselves, irrespective of the processes involved, would set up stresses in the neighbourhood of the craters. The evidence for this has been briefly discussed in a previous paper.(4)

It is the purpose of this paper to indicate a method by means of which relative magnitudes of certain of these stresses can be obtained. At the same time, an explanation will be given of the stress systems near lunar craters (as evidenced by observations to be described) in terms of simplifying assumptions of the nature of the lunar surface. Also, a class of object—the elongated craterlets and double craterlets—will be discussed at length to demonstrate that these objects are intimate members of the general grid system, and that their nature reveals much about the formation of craters in general.

Observations

The writer has made a study of the *Photographic Lunar Atlas*, edited by G. P. Kuiper,(5) and supplemented this with observations made with the 18-inch refractor of the University of London Observatory. Throughout this paper numbers in square brackets, e.g. [D4a], indicate where the object in question may be seen in the *Photographic Lunar Atlas*.

Firstly, to facilitate their further study, a catalogue of elongated craterlets will be given. Because the elongated objects are usually small (dimensions $\lesssim$ 10 km) they are most easily detected on the maria. In this sense the catalogue is far from complete: not including possible cases on the continents.

The form of individual elongated craterlets differs from place to place. Those around Copernicus (see Plate 27a) are all pairs of craterlets, the dividing walls being low or absent. Most elongated pits when seen under the best conditions appear double in this manner. There are a few objects, however,

Catalogue of elongated craterlets

[A5b]	S.E. of Langrenus. E. of Langrenus. N.E. of Langrenus
[A5d]	S.E. of Pickering. S.W. of Goclenius
[A6a]	W. of Cook
[B1a]	S.W. of Gartner
[B2a]	N.E. of Hercules. S. of Atlas and Hercules. Near Grove. W. of Daniell
[B3a]	N.W. of Dawes
[B3e]	N. of Dawes
[B4a]	N. and S. of Maskelyne
[B4b]	S. portion of the Mare Tranquillitatis
[B4d]	S. portion of the Mare Tranquillitatis
[B5b]	N. of Torricelli
[B5d]	On plain S. of Guttemberg. S. of Theophilus
[C1a]	N. of Aristotles. Far W. of Aristotles
[C1d]	Around Aristotles
[C2a]	On Lacus Mortis. S. of Lacus Mortis. On Mare Serenitatis
[C2b]	W. of Aristillus
[C2d]	E. of Cassini
[C4b]	Plain S.E. of Manilius
[C4d]	W. of Sosigenes
[D1a]	S.E. of Archytas
[D2a]	E. of Piton. W. of Piton
[D3a]	W. of Pytheas. W. of Eratosthenes. E. of Wallace
[D3d]	N.N.W. of Eratosthenes. S.W. of Pytheas. S.E. of Timocharis
[D4a]	Around Copernicus
[D5b]	W. of Guerike. S.E. of Guerike B. N.W. of Bonpland
[D6b]	S.W. of Kies A. N. of Hesiodus Rill. S. of Opelt
[D6c]	N.W. of Bullialdus. N.W. of Kies
[D6d]	S. of Opelt. S. of Birt. E. of Hesiodus A
[D7b]	W. of Hesiodus A
[D7f]	N. of Hesiodus Rill. W. of Bullialdus
[E2a]	N.W. of Delisle
[E3d]	E. of Pytheas. W. of Delisle and Diophantus
[E4d]	N.E. of Hortensius. S.E. of Milichius
[E6a]	E. of Kies. S.E. of Bullialdus

FIG. 1. The distribution of elongated craterlets on the surface of the Moon. Short lines indicate the orientation of these features.

such as the one between Piazzi Smyth and Kirch (see Plate 27b) that are definitely single and often have elliptical shapes.

In Figure 1 the general distribution of the elongated craterlets has been plotted. The short lines indicate the orientation of the major axes of the pits in the respective areas. It can be seen that at any one place the axes are approximately aligned in one of two directions.

A comparison should be made of Figure 1 with Fielder's chart of the lunar grid system.(6) It will be seen that whenever elongated pits are situated in an area where Fielder shows the direction of the grid system, then the axes of the pits are approximately parallel to that direction. In other places, for instance on the Mare Tranquillitatis, where there is insufficient data to define the grid system accurately, the directions of the pits form a natural extension of the grid system in the neighbourhood.

We therefore conclude that elongated pits form an intimate part of the grid system and future modifications to present charts of the grid system should take these objects into consideration.

Plate 27a shows the elongated craterlets near Copernicus. Figure 2 shows

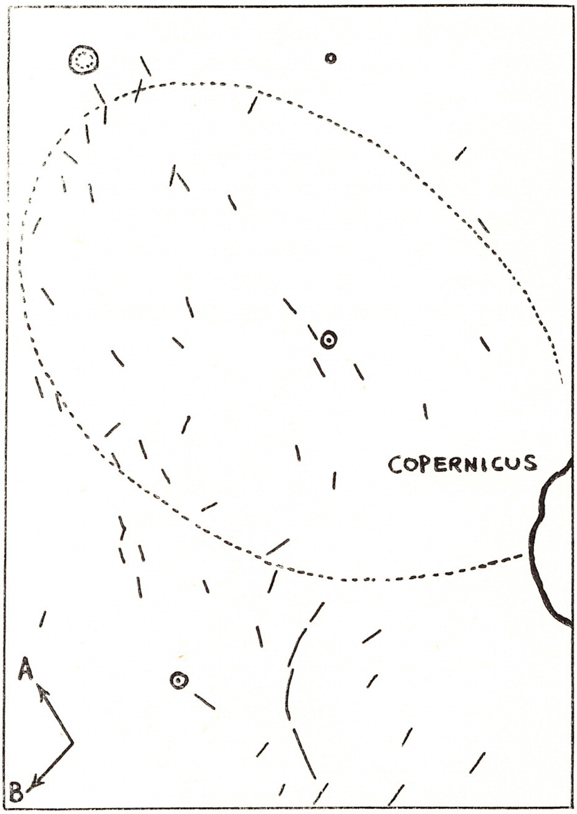

FIG. 2. The distribution of elongated craterlets near Copernicus. Compare with Plate I.

the directions of the axes of the craterlets in the same region. The dotted ellipse is the bright elliptical ray extending S.W. from Copernicus.

The conclusions that we will draw from Plate 27a and Figure 2 apply in general to all elongated craterlets near large craters.

Firstly, it will be noticed that the pits are not, as is often maintained, distributed completely radially to Copernicus. They are arranged with their axes parallel to the two directions indicated (**A** and **B**) in the bottom left-hand corner of Figure 2. These directions correspond with the general directions of the grid system near Copernicus.

Furthermore, in the upper part of Figure 2, most pits lie with axes S.W.–N.E., while in the lower part their axes are N.W.–S.E. We conclude, therefore, that the pits are arranged radially to Copernicus only when they are also aligned in the same direction as the grid system.

A further point, mentioned previously(4) is that the elongated and double craterlets lie mainly on bright rays. In particular many cluster along the elliptical ray indicated in Figure 2.

It should be noted of the crater chain N.W. of Copernicus that at its S. end it lies along direction **B** of the grid system, while at its N. end it lies in direction **A**. Moreover, at its N. end although it lies along direction **A** its component craterlets are elongated in direction **B**.

Apart from elongated craterlets closely associated with large craters there are numerous isolated ones. The Mare Tranquillitatis is covered with such objects [B4b] while the Mare Humorum seems free of them. The maria Serenitatis and Imbrium have only a few cases (all those on the southern portion of the Mare Imbrium are associated with Copernicus). A notable example of an isolated elongated craterlet is that between Piazzi Smyth and Kirch (see Plate 27b). This object is not clearly associated with any crater in the vicinity, but its major axis is almost exactly parallel to the fractures in the Alps to the west. Most of these isolated cases are not situated on bright rays.

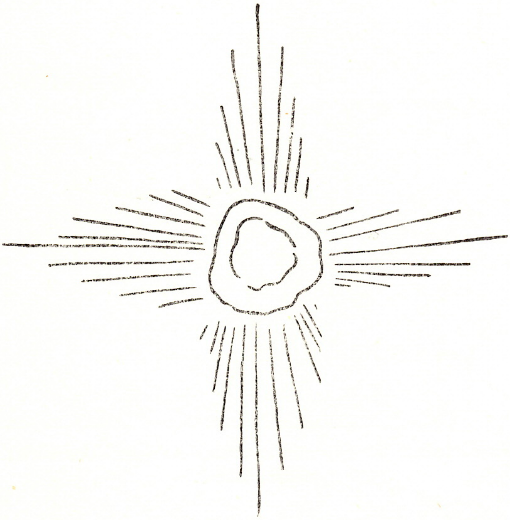

FIG. 3.
Ridge Pattern

Finally, the patterns of ridges around certain lunar craters must be mentioned. For a perfectly formed crater one might expect to get a uniform radial distribution of ridges around the outer walls. This is, however, not the case. Close examination of the ridges around Bullialdus [D7f] and Aristillus [D2a] as well as many other craters shows that the pattern is only radial within certain limits. The general structure of the ridge pattern is shown schematically in Figure 3. The centre of each 'fan' of ridges corresponds closely with the direction of the local grid system.

Discussion of the observations

The foregoing section has summarized the properties of certain features of the lunar surface, the existence of which indicate the presence of stresses in the lunar surface when they were formed.

In the past the elongated craterlets have been explained as grooves formed by the low-angle impact of ejectmenta from craters (see for example Baldwin(7)). It is emphasized here that this explanation is completely untenable: firstly the major axes of the pits are not distributed in a radial fashion about the respective craters, and secondly nearly all of them are double craterlets. The explanation of the latter point may be given in terms of a 'skipping' of the projectile, except that here again the axes would have to be radial to the parent crater.

However, the fact that many of these objects lie on bright rays, in particular on the elliptical ray west of Copernicus and the two rays from Copernicus passing west of Pytheas, indicates that they were initiated by projectiles. One of the problems to be solved in the next section is to explain how, on the one hand, these objects can have the properties of craters formed by mechanisms internal to the Moon (as shown by their double structure), while on the other they have the properties of impact craters.

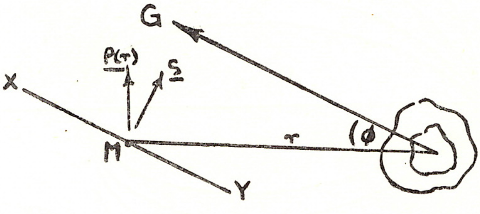

Fig. 4

Theory

Let us assume, for the moment, that the rock forming the lunar surface is able to fracture in one direction only. In Figure 4, **G** represents this direction.

When a crater is formed we may suppose that along any radius vector, with origin at the centre of the crater, there will be a stress $P(r)$ perpendicular to this radius. If a crater is formed in an isotropic medium a pattern of radial fractures will result from the tensional stress $P(r)$. In all cases $P(r)$ will be a monotonically decreasing function of r.

In Figure 4, XY is drawn parallel to **G** and a point M on it has coordinates (r, ϕ) with respect to the centre of the crater, the initial line being in the direction **G**. Then we see that the component S of $P(r)$ perpendicular to XY is given by

$$S = P(r)\cos^2\phi \qquad \ldots 1$$

If the rock will fracture only when there is a tension greater than S_0 across the direction **G**, then we have the condition for fracture at M:

$$P(r)\cos^2\phi \geqslant S_0 \qquad \ldots 2$$

In particular, the locus of points where fracturing will *just* be possible is given by the equality sign in Equation 2.

For convenience we may suppose that $P(r)$ takes the form:

$$P(r) = P_0 \, . \, r^{-\mathrm{n}}$$

where P_0 and n are constants. Then the locus of the limits of fracturing will be

$$r^{\mathrm{n}} = \frac{P_0}{S_0}\cos^2\phi \qquad \ldots 3$$

The general appearance of this function for various n is shown in Figure 5. We note that $\mathrm{n} = 2$ gives a circular outline to the fractures. Since observational evidence shows that this never happens, we deduce that $\mathrm{n} < 2$.

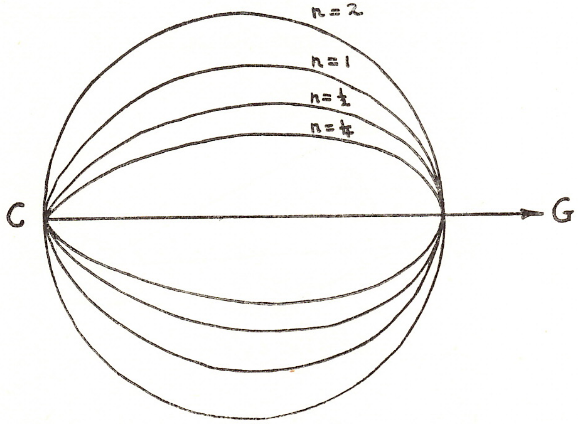

FIG. 5.—Theoretical outlines of the fracture patterns. **C** is the centre of the crater and **G** is the direction of fracture.

The natural extension of the theory to explain the structure of the frac-
res shown in Figure 3 is to allow the rock to fracture in two nearly per-
ndicular directions.

We therefore find that the fracture patterns around lunar craters admit of an explanation in terms of an elementary theory of the nature of the lunar surface rock.

Next we must consider the distribution of the elongated craterlets. The association of these with bright rays demonstrates the fact that impacts have initiated their formation. It is to be noted that elongated craterlets lie in general outside the bounds of the fracture system mentioned above.

We consider what happens when ejectmenta from a crater fall closely outside the crater. At a point just outside the fracture pattern, $P(r)$ will still have a component perpendicular to XY. Therefore it will require only a small additional force to start a fracture at that point. The writer suggests, therefore, that elongated craterlets around craters mark the points where ejectmenta from the crater landed and produced a fracturing of the surface. This fracturing would allow the escape of internal gases, hence producing single or multiple craterlets.

Discussion of the theory

The theory outlined above reproduces the observed distribution of fractures (and craters resulting from fractures) around many large lunar craters. It is interesting to note some additional observational material that supports this theory in greater detail.

If we suppose ejectmenta released gases occluded in the surface material we would also expect the fracture system itself to show signs of the release of gases. This is found to be the case. The fracture patterns often appear as ridges with rows of craterlets between them. Craterchains frequently radiate from the larger craters (e.g. Copernicus, Hainzel, Theophilus), closely following the lines of the stress pattern. Fielder has pointed out to the writer an extensive craterchain running from Tycho [D7a] that lies exactly along the bright ray that runs towards Bullialdus. It is suggested that this craterchain was formed by a single 'bomb' from Tycho that started a fracture through which gases escaped.

The origin of the isolated elongated craterlets may be similar to the ones connected with large craters. It may be, however, that, as suggested previously,(4) these are very old small craters that have been distorted by crustal movements in recent times.

Conclusion

Non-radial distributions of features around lunar craters can be used to derive information about the properties of the lunar surface material. They are also able to give us information about the forces involved in crater formation. It would be of extreme interest to know the variation of P_0 with crater diameter; this can be found by application of Equation 3 to various sizes of craters. The constants n and S_0 can be assumed to be the same for all craters. A preliminary fit of Equation 3 to the fracture pattern around Bullialdus [D6f] gives n $\sim$ 1.

The hypothesis that lunar rock fractures only in one direction should not be taken too literally. The fracture patterns around craters are lined up along the grid system and there are great difficulties in supposing that the whole of the grid system lies along pre-existing fracture planes. It may be that the stresses in the lunar surface that produced the grid system acted so that the surface material was constrained to fracture in the preferred directions.

A more elaborate analysis than that given in '*Theory*' is called for. It is an observational fact that the fractures around craters do not remain exactly parallel to the direction of the grid system but wheel round in an attempt to become radial to the parent crater. This is not altogether surprising, but it will result in a decrease of n from that found by an application of Equation 3. We may therefore expect to find that $P(r)$ does not fall off very rapidly with distance from the crater. Photographs of the highest quality are needed to pursue the matter further.

References

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(2) Fisoff, V. A., *J.*, **67**, 309 (1957).
(3) Fielder, G., *J.*, **67**, 314 (1957).
(4) Warner, B., *J.* **71**, 116, (1961).
(5) Kuiper, G. P. (ed.), *Photographic Lunar Atlas* (Chicago, 1960).
(6) Fielder, G., *Structure of the Moon's Surface*, ch. 11 (London, 1961).
(7) Baldwin, R. B., *The Face of the Moon*, p. 164 (Chicago, 1949).

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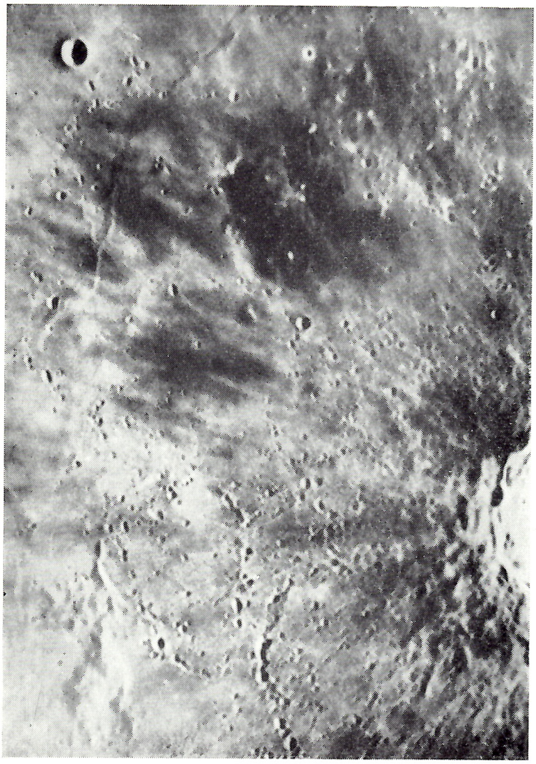
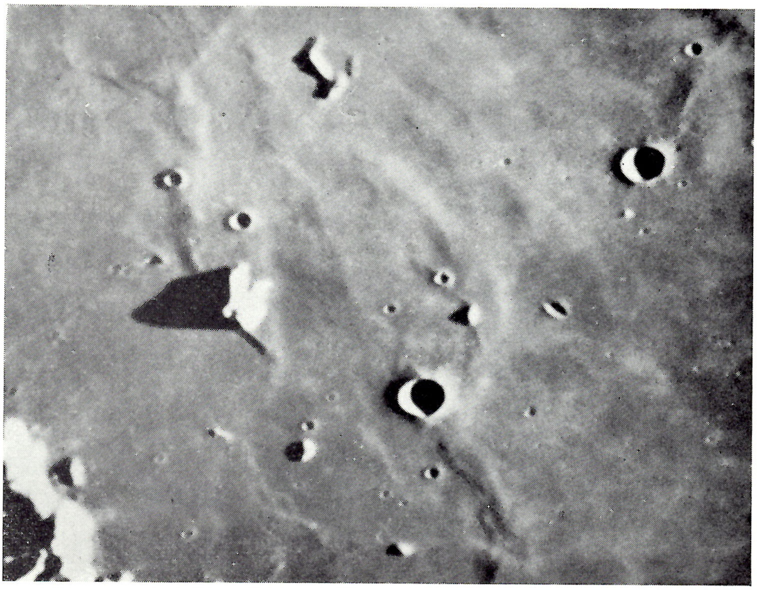


(a)

Mount Wilson Photograph (No. 124)
Region west of Copernicus.



(b)

Mount Wilson
Photograph (No. 121)
Elongated craterlet
between
Piazzi Smyth and
Kirch.