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THE CONTRACTION AND EXPANSION OF THE MOON

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Abstract—Measurements of craters near to the centre of the Moon's disk are used to show that the craters are distorted preferentially, their longer axes lying parallel to the most prominent family of the grid system. It is shown that, on average, the percentage distortions are greater for the older craters, and that the large craters are generally older than the small craters which we now see; but old, small craters would be effaced by crustal movements. At any given time, craters of all sizes were possibly being produced. Taken together with other evidence for a recent tensional phase in the Moon's history, the present results lead to the conclusion that the crustal stresses which distorted the craters by thrust-faulting decreased in magnitude as time elapsed, and then reversed in sign.

It is proposed that, in the early history of the Moon, a general protuberance of the body of the Moon in the direction of the Earth tended to settle, gradually, to a form corresponding to a state of minimum gravitational potential. It is also suggested that, during this time, radioactivity was heating the Moon and that heat accumulated most rapidly in the innermost parts of the Moon, so that the volumetric expansion of the core exceeded that of the crust. As time elapsed, the crust itself was, therefore, subject to two opposing forces. The crustal pressures were reduced, the crust passed through a state of zero stress, and the stresses reversed in sign, to become tensions.

1. EVIDENCE FOR COMPRESSION OF THE MOON'S CRUST

Various phenomena in the Ariadaeus-Hyginus regions of the Moon (Fig. 1) may be explained[1] on the hypothesis that there were, at one time, uniform thrusts in the Moon's crust.† One difficulty of this hypothesis is that the Ariadaeus and Hyginus Rilles are supposed to have originated in wrench fractures in which dykes formed; and it is known from geological studies that the magmas of dykes are seldom intruded along wrench faults because the residue of the thrusts which formed them usually prevents the fractures from opening. In order to overcome this difficulty, the writer suggested that there was a tensile phase in the Moon's crustal history which post-dated the compressive phase and, hence, opened the fractures. Evidence in support of this suggestion has now been found. (See Section 3, below).

Von Bulow[2,3] prefers to explain the origin of the rilles in this region of the Moon by postulating a widespread updoming which gave rise to tensions in the surface. This hypothesis would not, by itself, explain the particular relative orientations of the major rilles and ridges in the Ariadaeus-Hyginus regions. It is also important to consider whether the major-distortions of the many evidently very eroded craters in this area can be explained at all without resorting to a surface compressive phase.

The craters in the area delineated by the Mount Wilson plate C4-b of Kuiper's *Photographic Lunar Atlas*[4], which depicts the Ariadaeus-Hyginus regions, have now been measured in order to obtain quantitative data on the degrees of distortion which they display. Of the craters identified in Fig. 1, 134 were found to be suitable for measurement. Now the most

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† In this discussion, frequent mention will be made of the "crust" of the Moon. There is no evidence that the Moon has a crust which is in any way analogous to that of the Earth, but the concept of a lunar "crust" and "core" will be used, here, to distinguish some shell of rock which is closest to the surface from the remainder of the Moon.

Fig. 1. Identification of craters.

prominent family of the grid system [7] in this vicinity of the Moon runs, on average, roughly parallel to the limb, and there is a less well-developed family of distortions which runs orthogonally to it. Measurements y and x (cf. Fig. 2), the orthogonal axes of craters, were made in the directions of these two most prominent families, respectively, and no restrictions were imposed on the selection of craters by virtue, for example, of their size or degree of erosion, except in so far as that no attempt was made to measure craters $\lesssim$ 3 km in diameter. The measurements were then corrected for curvature, account being taken of the librations.

In Fig. 2, R represents the original radius of a crater and d and c the displacements of its walls

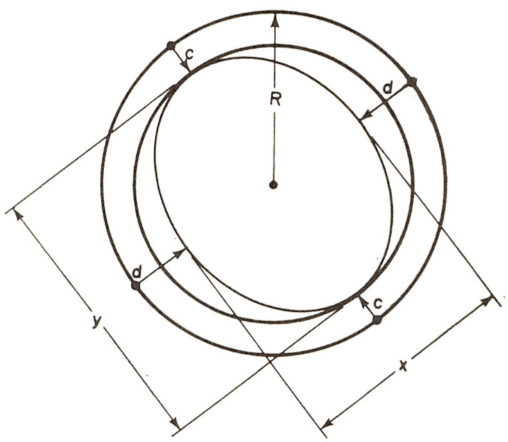

Fig. 2. The distortion of a crater.

along the minor and major semi-axes, respectively. It is seen that

$$\frac{d}{R} = 1 - \frac{x}{y+2c}. \tag{1}$$

The quantity c is unknown: it is not measureable, but is likely to be small in comparison with y. Even if c is not very small, the minimum percentage distortion (which will be referred to, simply, as the percentage distortion) is given by

$$\Pi = \left(\frac{d}{R}\right)_{\min} \cdot 100 = \left(1 - \frac{x}{y}\right) \cdot 100\%. \tag{2}$$

A plot (Fig. 3) of Π against y (which may be regarded as a measure of the size of a crater, but is actually the lower limit of the original diameter, as may be seen from Fig. 2) shows that, on average, the percentage distortion of a crater does not vary significantly with its size. Points which lie on the abscissa $\Pi=0$, in Fig. 3, correspond to circular craters. Of the 134 points, 83 per cent of them lie above this line. This proves that the craters are distorted preferentially, with their longer axes in the direction of the most prominent family of the grid system.

In Table 1, the craters have been split into three size-groups y_1, y_2, y_3, defined in units of cm of plate, where 1 cm $\cong$ 13·7 km. The relative age of a crater was decided rather arbitrarily, but quite decisively, by combining characteristics such as ease of recognition of a crater and the height, or degree of erosion, of its walls; but *not* by considering the degree of distortion of its walls. Segregation of the craters (Table 2) in accordance with their age shows, that, in each of the size groups defined above, the mean percentage distortion of the old craters is considerably greater than that of the young craters. On average, $\Pi=16$ per cent for the old craters and only 7 per cent for the young craters. This proves that the forces responsible for the deformations acted on the older craters for longer times.

The actual numbers of old and young craters are given in Table 3. It was found that 71 per cent of the craters in the y_1 group were to be identified with young craters but that only 27 per cent and 22 per cent of the craters in the groups y_2 and y_3, respectively, were young. Hence, in general, it is seen that a small crater is younger than a larger crater.

Again, whilst most craters show a "positive" distortion ($y-x>0$), some show a "negative" distortion ($y-x<0$), and 83 per cent of these are to be identified with the above-mentioned young craters. Of the 23 craters showing negative distortion, 83 per cent are found in the y_1 group and only about 9 per cent in each of the other size groups. The fact that some craters do show negative distortion may be explained, for example, by distortional scatter.

Table 1.

Group	Size range (cm plate: 1 cm ≡ 13·7 km)	Identification of Craters (cf. Fig. 1)		
		Old	Young	Negatively distorted
y_1	0–1·49	1, 14, 22, 23, 24, 35, 38, 45, 52, 57, 58, 60, 67, 72, 75, 89, 100, 107, 108, 110, 112, 114, 118, 126, 138, 140	3, 6, 7, 8, 16 17, 18, 19, 20, 25, 26, 27, 28, 29, 30, 31, 32, 33, 37, 41, 42, 44, 47, 51, 53, 54, 55, 56, 61, 62, 65, 77, 78, 79, 86, 93, 95, 97, 98, 102, 104, 105, 111, 113, 116, 117, 119, 120, 122, 123, 124, 127, 129, 130, 131, 132, 133, 134, 135, 136, 137, 139, 143, 144, 145	3, 6, 17, 33, 44, 51, 55, 56, 75, 93, 100, 102, 107, 111, 122, 133, 135, 139, 145
y_2	1·50–2·99	34, 36, 39, 40, 48, 50, 59, 64, 66, 68, 70, 81, 83, 84, 85, 87, 90, 91, 92, 99, 101, 109, 115, 142	5, 43, 49, 71, 74, 94, 103, 128, 141	49, 94
y_3	3·00–4·5	46, 76, 80, 82, 88, 106	96, 125	73, 125

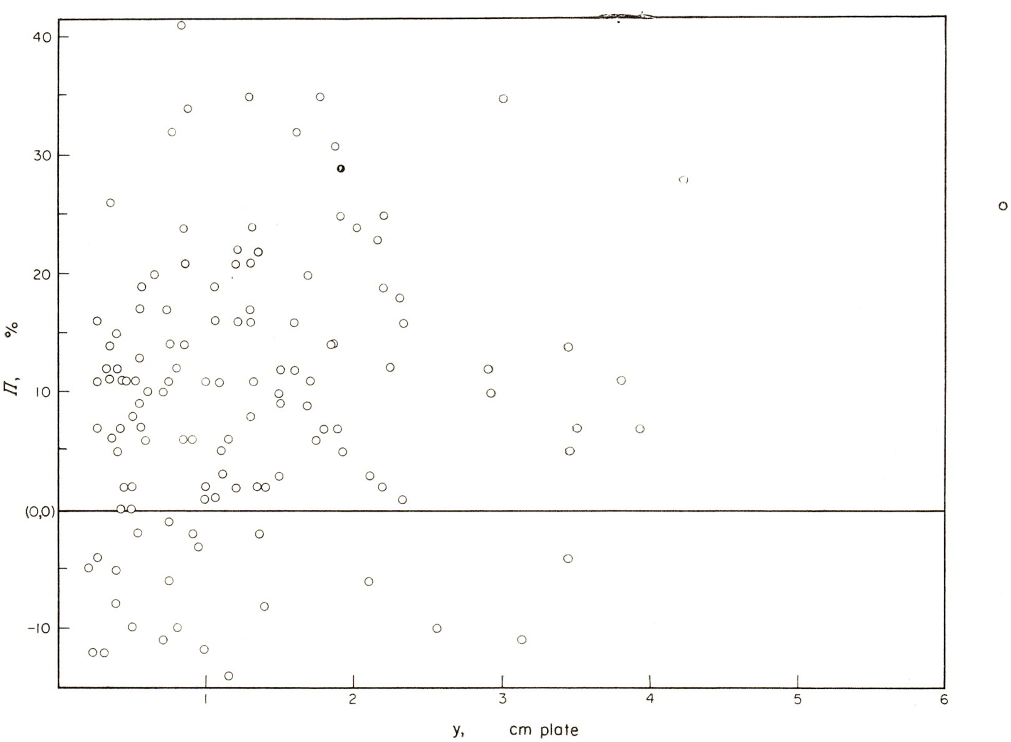

Fig. 3. The percentage distortions of craters in the Hyginus region.

Table 2.

Group	Mean percentage distortion		Mean actual distortion (cm plate)	
	Old	Young	Old	Young
y_1	16·7	6·1	0·12	0·05
y_2	16·9	4·7	0·38	0·11
y_3	14·6	1·9	0·55	0·07

Table 3.

Group	Total number of craters	Number of old craters	Number of young craters	No. of neg. distorted craters	Percentage of young craters
y_1	91	26	65	19	71
y_2	33	24	9	2	27
y_3	9	6	2	2	22

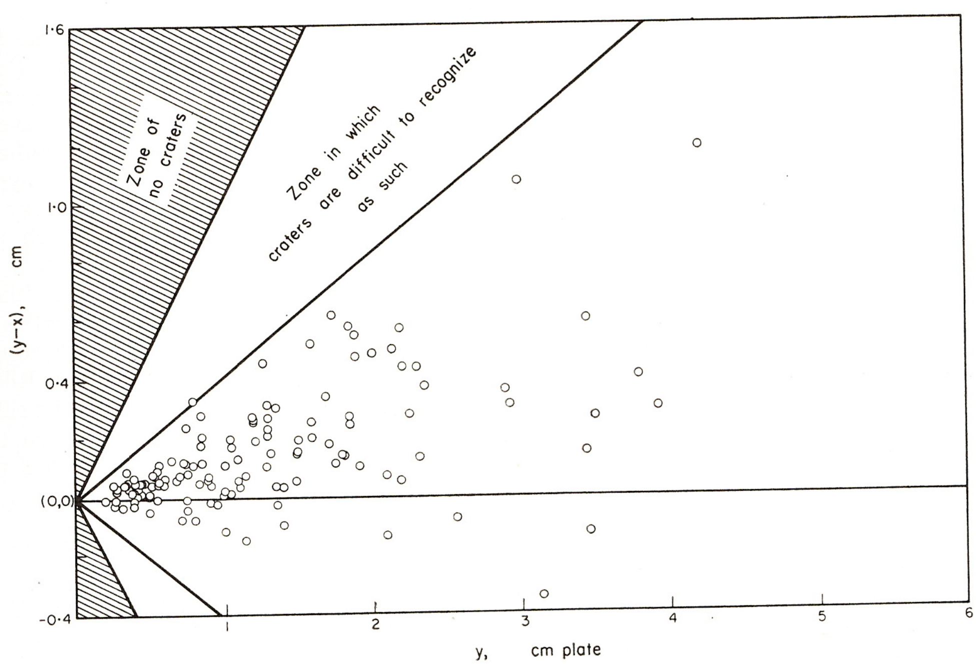

Fig. 4. The actual distortions of craters in the Hyginus region.

The quantity $y-x$ is a measure of the minimum value of the actual distortion of a crater, and this has been plotted (Fig. 4) against y. Because small craters which were formed earlier than a certain epoch in the Moon's history would be completely effaced by crustal movements (see the zone of no craters in Fig. 4, bounded by the line $x=0$) it is possible that craters of all sizes were being produced at all times, there being, at any given time, more small craters than large. Whether this is so, or whether there were relatively fewer small craters in the past, in no way affects the argument, confirmed by the above tests, that the small craters which we see at the *present* time, are, in general, the youngest.

These results lead to the general conclusion that the largest craters in the area in question were formed first, and that either

(i) the crustal stresses which distorted the craters decreased in magnitude as time elapsed, or

(ii) the crustal stresses were more or less uniform in magnitude throughout lunar history.

In the opinion of the writer, the results can only be explained on the hypothesis of crustal overthrusting.

2. A TENSILE PHASE IN LUNAR HISTORY

Observing from the Pic-du-Midi, the writer[5] studied the fine array of ridges which radiate in a north-easterly direction from Aristillus. On photographs, these ridges look like thin, straight rays; however, they were, in fact, observed to cast shadows. It was quite impracticable to think of these radiating spines and valleys as having been formed by blocks of matter ejected horizontally, during the formation of Aristillus, to plough grooves in the Moon's surface, for the ridges were too straight and uniform in width. The writer had the impression that this was a system of rift valleys caused by block-faulting. In theory, such faults could be produced by lateral thrusts *or* tensions. Several lunar craters exhibit these phenomena.

A theoretical approach to the problem of the nature of the Moon's crustal stresses, based on measurements of radiating ridge-systems of this type, led B. Warner[6] and the present writer to conclude that, when certain craters were formed, the surface layers of the Moon were in *tension*. This apparently unambiguous result was unexpected, because it appeared to contradict the results mentioned above.

3. RELATIVE AGES OF SOME LUNAR FORMATIONS

The few well-formed large craters in Fig. 1, such as Godin, Agrippa, and Manilius, are evidently to be considered as younger than the greatly eroded ghost craters in the same area. Now the characteristic patterns of radiating ridges which are associated with craters formed in a medium in tension have been detected by Warner[6] around the following craters:—

Agrippa, Archimedes, Aristillus, Aristoteles, Autolycus, Bullialdus, Burg, Copernicus, Davy, Eratosthenes, Harpalus, Hercules, Herschel, Lambert, Plinius, Thebit, Theophilus, Timocharis.

Without exception, these craters have comparatively cleanly-sculptured ringwalls. All, except for Archimedes, have, in addition, central eminences. Such features are characteristic of young craters. It therefore appears that the tensile phase is recent; and the surface of the Moon may be in tension even at the present time. (This condition would seem to have a counterpart in the much discussed hypothesis of the expansion of the Earth's core, the hypothesis being based largely on the discovery of mid-oceanic ridges containing rifts which are thought to be tension features.)

The difficulty of the origin of the rilles, mentioned in section 1, is now automatically removed. It is well known that rilles are young features, and if the Ariadaeus and Hyginus Rilles owe their origin to wrench fractures[1], the rilles themselves would have formed only when the recent tensions in the Moon's crust opened the fractures, causing subsidence* of the surface.

4. THE HISTORY OF THE MOON'S CRUSTAL STRESSES

Recapitulating, it is thought that the oldest craters have been deformed so greatly from the

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* Rilles themselves are emphatically not cracks, as many people seem to believe. See, *e.g.*, G. Fielder[7].

circular shape that the deviations from radial symmetry cannot be explained by tensions alone. It is suggested that the deformations arose as a consequence of thrust faulting. However, many recently-formed craters, at least, have originated during a surface tensile phase of the Moon, and the rilles—recent graben features—may also require crustal tensions for their formation.

All the observations may be explained by supposing that the crust of the Moon was in compression when the oldest visible craters were formed and that, more recently, the stresses reversed in sign, to become tensions. Such a reversal of sign could not occur suddenly. Hence, case (ii) of section 1 must be rejected, and it must be concluded that the *early compressive stress in the Moon's crust tended, generally, to decrease in magnitude as time elapsed.*

An estimate of the time required for this reversal of sign may be made, in principle, from two independent approaches. First, a suitably well-developed theory of erosion could be applied to estimate the time required to transform one of the young craters, discussed above, into one of the old. Secondly, attention might be paid to the possible time-scales of the compressive and tensile phases of the Moon's crust.

5. PROPOSED ORIGIN OF THE COMPRESSIVE AND TENSILE STRESSES

(i) An observed general *crustal compression* may be due to (a) the bulk expansion of the material of the crust relative to that of the core, or (b) the excess weight of a non-equilibrium bulge covering a large portion of the visible hemisphere (and, possibly, of the hemisphere which is averted from the Earth).

(ii) An observed general *crustal cracking* may only have its origin in an expansion of the material of the core relative to that of the crust.

A bulk expansion of any part of the Moon could result from radioactive heating. One can be reasonably sure that this process did operate, whereas other processes which have been listed [8] such as tidal forces and a possible (but not established) dependence of the "constant" of gravitation on time, are not known to have had any measurable effect on the Moon.

Case (a) could have operated as a result of radioactive heating only if the Moon had been differentiated as a whole, in order that the radioactive elements might be concentrated in a less dense crust. But, in this case, the core would have been at a higher temperature previously, and crustal cracking would have been *followed* by a crustal compressive phase. The reverse effects are observed. Consequently, with these assumptions, case (a) must be rejected. This means that the core of the Moon would be expected to be hotter than the crust, at the present time, and that the Moon has never been fully differentiated. It also leaves case (b) as the only mechanism capable of explaining the surface compressive phase. The neglect of processes other than radioactive heating means that these particular conclusions must be regarded merely as an hypothesis.

Warner [9] pointed out that the centre-line of any envelope bounding a fracture-pattern of a lunar crater (see also section 2) was always lined-up with one family of the grid system. This may now be readily understood; for, given that mechanism (i)b of section 5 produced compression failures which were approximately rectilinear when viewed in conical projection from the Earth, one would expect mechanism (ii), acting with similar uniformity of magnitude over the whole Moon, but in the opposite direction, to give rise to tension failures which followed the same general rectilinear pattern.

6. THE TIME SCALE

Two important facts, which arise directly from the observations, are that the actual deformation of a crater increased as time elapsed; and that the rate of deformation decreased as time elapsed. With the formation of craters, and the relief of crustal pressures by thrust-faulting, one might expect the smoothed pressure-time curve to fall exponentially.

Consider a time-scale on which the present time is $t=0$. Let a typical young crater have originated at time $t=-t_1$ and a typical old crater at $t=-t_2$, and let the present observed distortions of these craters be d_1, d_2 respectively (Fig. 5). Now $|t_2|>|t_1|$, and the curves for the old and young crater are, of necessity, iden-

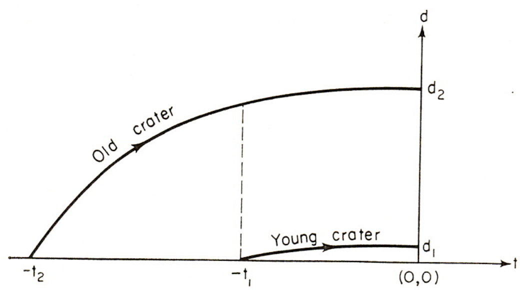

Fig. 5. The age of a crater and its distortion.

tical in form for $0 > t > -t_1$. It follows that

$$t_2 \ngtr \left(\frac{d_2}{d_1}\right) \cdot t_1. \quad (3)$$

The values of the ratio d_2/d_1, obtained from the results given in Table 2, have been rounded off, in Table 4, to the nearest integer. A scale of relative times may be obtained by writing the inequality (3) as an equation. Then, if, one makes the assumption that the oldest craters originated $3 \cdot 10^9$ years ago, the ages of the other craters may be estimated. These assumptions were made in the construction of the age list given in Table 4, which does no more than suggest possible orders of magnitude of the ages of various groups of crater.

The conclusions of this paper, which are based purely on certain observations of the Moon's surface, appear to be in direct conflict with those reached by MacDonald[10] from a theoretical discussion of various models of a Moon heated by radioactivity. A task for the future will be to form a more rigorous theory which is compatible with observation.

Table 4.

Group	d_2/d_1	Suggested age (1 unit$=10^9$ yrs.)	
		Old	Young
y_1	3	0·6	0·2
y_2	4	1·5	0·4
y_3	8	3·0	0·4

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