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by

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Introduction

It is a fairly general rule that all lunarite ridges on the Moon's surface form parts of crater walls. In many cases the craters have been destroyed to such an extent that only a dark region remains which is bordered by a few lunarite peaks. The large scale problem of the orogenic interpretation of all lunarite ridges and peaks is thus intimately tied with the processes involved in the origin of the craters themselves.

In this paper I want to consider some discrete features of the lunar surface that may not be so closely connected with the *origin* of the craters, but may be secondary phenomena. That is, some of the presently observed features that may have formed as a result of, but at a later stage than, the formation of the lunar craters.

Secondary phenomena on the lunar surface are far from unknown. A lesson that can be learnt from a full discussion of the lunar grid system is that it is unwise to attempt a formulation of a theory of the origin of the craters before we know what changes have taken place in intervening times. For instance, it seems to me that the polygonality of lunar craters and the semi-radial pattern of ridges and furrows around the Mare Imbrium neither speak for nor against an igneous or an impact origin since they are both representative of the general grid system, which is a secondary phenomena.

We must be careful, therefore, to investigate whether any given lunar surface features *could possibly be the result of secondary activity*. The features to be listed and discussed in this paper are those that are difficult to account for on either theory of the *crater* origin. If anything, the second two types of features that will be discussed may be thought to point to an igneous origin of the craters, but it will only here be established that the features themselves are of igneous descent and are probably of a secondary nature. An alternative theory of the origin of central mountains in craters will be given, the method of formation being of a secondary nature.

Central Elevations within Craters

The telescopic and photographic appearances of central mountains within craters are extremely deceptive. Whereas one may gain the impression that these structures are lofty, craggy masses, the true picture is one of gentle slopes. The reason for this deception is quite clear: vertical relief is greatly exaggerated by low illumination. A typical lunar central peak would have a height of about 0·5 km and a base of some 10 km in size. The central eminences are thus hardly more than domical structures.

Kuiper[1] has expressed the view that central mountains appear to have been pushed up from beneath the floor of the crater, and it is just this mechanism that I want to discuss here. The production of a central mountain will be attributed to isostatic adjustments of the lunar surface in the neighbourhood of craters.

We know that in general the floors of lunar craters are depressed below the level of the surrounding surface. In particular, most young-looking craters possess this property. Therefore unless the viscosity of lunar rock is virtually infinite there will be a tendency for the floor to rise to an equilibrium level. That is, as a result of the weight of the crater walls and the surrounding country there will be upward forces acting on the crater floors. If the original profile of a crater was concave the centre of the floor will be the lowest point, and the greatest hydrostatic forces will act there.

The precise mechanism of subsurface rock flow due to uneven surface loading has been demonstrated by Belousov[2]. He shows that at the weakest (lowest) point of the surface a 'piercing core' is formed. The initial and final stages in the formation of a piercing core are illustrated in Figure 1.

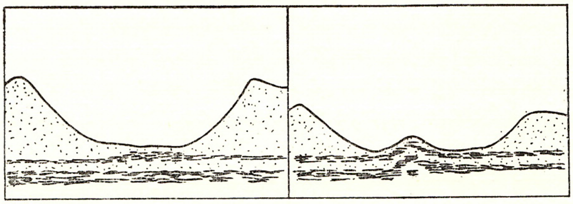

FIG. 1. Initial and final stages in the formation of a 'piercing core'.

At the present stage the time scale for the formation of a central mountain by this process is difficult to estimate. Quite a lot depends on whether the Moon has a lithosphere distinct from the inner material.

Since we cannot decide a *priori* whether central elevations are formed by the process outlined above we can only attempt to predict some relationships that can be tested against observations.

Firstly we note that the deeper the crater the greater the upward forces will be. Hence we may expect that deep craters have large central elevations. However, this is only for craters of a given diameter and unfortunately no statistics are available for these circumstances. On the other hand, the larger craters have had more material moved away and the depth increases with diameter. We might expect, therefore, that the hydrostatic processes in the floor centre to increase in intensity with increasing diameter. In support of this notion we can refer to Baldwin[3] who states:

> 'On the average, the larger the crater, the larger the central peak or group of peaks, but wide graduations exist.'

We cannot hope to get more than statistical relationships between peak size and diameter for a number of reasons. Only coeval neighbouring craters can be expected to have similar central eminences; with all other craters the combined effects of steady erosion of the central mass and irregularities in lithospheric thickness or surface structure combine to produce only statistically evident results. Of interest here is Baldwin's remark:

> '. . . the percentage of craters which do possess this feature decreases steadily from Class 1 through Class 4. It was shown previously that the average

crater depth decreased from class to class in the same order, and there is probably a generic connection between these two sets of facts.'

It should be noted that, as was mentioned above, coeval neighbouring craters would be expected to have similar central peaks. In those cases where these specifications appear to hold we do indeed find similarities in floor details (e.g. Aristullus and Autolycus, Sabine and Ritter, Godin and Agrippa).

A property of central elevations (see Baldwin, p. 148) is that they never rise above the level of the country surrounding the crater. Although this property is not immediately derivable from the ideas given above this sort of relationship is commonly met with in isostatic problems.

Convex floors of lunar craters are common and again these may be attributed to subsurface hydrostatic pressures.

The principal reason for attributing central eminences to secondary effects is that the process of formation is slow and satisfactorily explains their large size and small slopes. Adjustment of the lunar surface towards isostatic equilibrium is something that must have happened and I suggest that the surface expression of these processes is evidenced in the form of the elevations within craters.

There are, however, alternative theories for the production of central peaks and these must also be considered seriously.

Summit Craterlets

An observational paper on this topic was given by Moore[4] some time ago. He stresses the apparently common occurrence of symmetrically placed craterlets on the summits of lunar mountains, demonstrating that any systematic search for these objects, employing large telescopes, is highly fruitful. His view was that summit craterlets are probably the rule rather than the exception. More recently, Fielder[5] has noted that many of the peaks in the Apennines have summit craterlets.

The extensive list of known summit craterlets (*see* Appendix) together with Fielder's observation of the frequency of these objects within a small area surely implies that they are generically associated with lunar orogenic processes. Baldwin's[3] arguments (p. 152) that summit craterlets arise due to chance impacts cannot now be taken seriously. His suggestion (p. 151) that the central craterlet in Timocharis is due to such a chance impact is highly dubious: there is just one sizeable (larger than 2 km) craterlet on the floor of Timocharis and this lies *precisely* in the centre of the floor.

However, with the mechanism proposed in the previous section for the formation of isolated mountains, the summit craterlets are much less of a mystery.

The precise mechanism of formation of a summit craterlet would seem to be as follows. The greatest pressures and movements during the production of a central elevation would occur at the centre of the floor. Splitting of the surface, directly above the piercing core, would occur and can be seen in Belousov's model[2]. This could be accompanied by explosive release of occluded gases. A crater thus formed would be preserved during future orogenic activity since this proceeds so slowly.

Many of the summit craterlets are so small that the resolving power of even large instruments is insufficient to be able to discern their precise nature. Some of the so-called summit craterlets may in fact be roughly circular arrangements of 'peaks'. This again is acceptable from the point of view of the process outlined above.

The igneous nature of summit craterlets gains additional support from the fact that occasionally there is more than one craterlet on the same mountain mass, and these lie on the major axis of the mountain[4]. Also, summit craterlets can be found on wrinkle ridges. I have observed rows of pits running along the tops of the wrinkle ridges to the north of Wichmann.

We may conclude, therefore that isolated mountains (with summit pits) and wrinkle ridges have igneous origins.

Ringwall Craters and Craterchains

These objects have received only casual mention hitherto. They deserve a very careful study for they are probably the most difficult of all lunar features for which to find a mechanism or origin.

There are two kinds of ringwall crater, to only one of which do the above remarks refer. Ordinary large craters have ample supplies of small circular craters on their walls. These were presumably formed by whatever mechanism produced the other craters of similar size.

However, Arthur pointed out[6] that the inner slopes of Tycho are covered with a number of cup-shaped depressions. This aspect was later confirmed by Abineri[7]. I have made a study of these cup-shaped depressions on the inner slopes of craters and have arrived at the following conclusion.

Whereas under fairly high lighting many large craters appear to have deep terraces, under a lower illumination (and then only as certain angles) the terraces appear as separate lenticular-shaped depressions. Usually these depressions run in chains concentrically with the crest of the crater wall, but sometimes they run over the crest. Depression chains occasionally appear on the outer glacis as well. Perhaps the peculiar objects outside the eastern wall of Smith (Wilkins) belong to this latter class.

Fielder[5] has noted these lenticular depressions on the walls of Archimedes and Aristillus.

As mentioned above, I find it impossible at the present time to envisage a process that could form these tenticular objects. Even if their original form was circular and they have been distorted since their inchoation it is still difficult to account for rows of craters on the inner slopes of larger craters. The order of size of these enigmatic objects is around 3 to 6 km.

A list of craters in which I have detected ringwall craterchains is given in the Appendix. This list is not intended to be exhaustive, it includes only those objects that I have accidentally found and noted during the past seven years. Probably all prominent well-formed large craters have these features.

Conclusion

As mentioned previously, the three types of lunar surface feature discussed in this paper all appear to be of igneous descent. However, and this cannot be overstressed, if these particular objects were formed after the craters in which they reside, then they must not be used in arguments for or against either the impact or the igneous theories.

I would like to express my gratitude to Mr Patrick Moore for supplying the list of summit craterlets.

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APPENDIX

(i) *A Catalogue of Summit Craterlets*

Only those craterlets situated on mountain masses are included here. Omitted are the many craterlets appearing in the centres of domes.

Most of these objects were found by P. Moore and H. P. Wilkins. A few additional examples have been added by myself.

The coordinates are meant to be only a rough guide to the positions. In a few cases I have been unable to discover the exact positions. Those coordinates given in italics are estimated from Wilkins' map, the rest are estimated from the *Orthographic Atlas of the Moon*[8].

When more than one craterlet appears on the mountain the number is put in brackets after the name.

(*a*) Craterlets on Central Peaks

Alpetragius	−075	−277
Alpetragius	−075	−274
Aristarchus	−674	+401
Petarius (2)	*+788*	*−427*
Theophilus	+435	−158
Cepheus	*+542*	*+650*
Pythagoras	*−400*	*+891*
Romer	+535	+428
Eratosthenes	−191	+248
Eratosthenes	−190	+252
Xenophanes	*−532*	*+835*
Goclenius	+695	−175
Arzachel (2)	−036	−314
Gutenberg (3)	+651	−150
Herschel	−037	−099
Kant	+338	−183
Rheita	*+585*	*−608*
Metius	*+518*	*−646*
Neper	*+980*	*+156*
Taruntius	*+720*	*+092*

Craterlets on Central Peaks—continued

Piccolomini	+463	−493
Vitello	−524	−506
Landsberg	−446	−006
Burg	+334	+709
Pitatus	−207	−495
Pallus	−029	+092
Gassendi	−612	−295
Walter (2)	+015	−545
Capella	+567	−132
Moretus	−*023*	−*938*
Delambre	+300	−034
Suspected		
Langrenus (2)	+*866*	−*154*
Manilius	+150	+250

(*b*) Summit Craterlets on Hills or Ridges within craters

Cleomedes	+*730*	+*467*
Poisson	+15–	+51–
Regiomontanus	−02–	+48–

(*c*) Summit Craterlets on Isolated Peaks

Schneckenberg	+107	+157
La Hire	−378	+463
Reinhold	−382	+033
Plinius	+367	+268
Aristillus	−025	+617
Agrippa	+161	+079
Beer	−139	+447
Archimedes	−113	+504
Archimedes	−109	+507
Cape Banat	−44–	+28–
Piton	−002	+653
Deluc	−03–	−81–
Lindenau	+335	−540
Mount Huygens	−044	+349
Gambart	−250	−004
Pico	−106	+716
Suspected		
Manilius	+189	+268

(ii) *Examples of Ringwall Craterchains*

Timocharis	NE and E inner walls
Geminus	W and NW inner walls, and E glacis
Mairan	E inner wall
Aristillus	SE inner wall
Hausen A	SE inner wall
Inghirami	E inner wall
Hesiodus	E walls entirely composed of crater chains
Hainzel	NE wall: lenticular-shaped depression
Scheiner	NE inner wall
Smith	Oval Depressions on E glacis and inner W wall
Phocylides	E inner wall
Tycho	All inner walls
Archimedes	NE and E walls