I. ORIGIN AND EVOLUTION OF THE MOON

https://doi.org/10.1017/S0074180900097710 Published online by Cambridge University Press

FLUIDIZATION ON THE MOON AND PLANETS

A. A. MILLS
Depts. of Geology and Astronomy, Univ. of Leicester, England

Abstract. A dual origin of lunar formations by both exogenous and endogenous mechanisms is now generally accepted. These processes are normally equated with impact and volcanism respectively, but many aspects of the latter cannot be readily identified with present-day terrestrial volcanism. It is proposed that lunar volcanism involved large volumes of gases and volatiles, so that 'fluidization' of particulate systems occurred. Terrestrial fluidization structures and model studies are described and illustrated. Certain lunar rilles and transient phenomena are also suggested to result from degassing of the interior. Some possible applications of fluidization to Mars and the synthesis of electropolymers are mentioned.

When Galileo turned his telescope on the Moon he was able to distinguish broad, dark, uniform plains – the maria – and a multitude of ring-shaped structures which have come to be called 'craters'. Subsequent centuries of Earth-based telescopic study enabled maps to be drawn on a scale limited mainly by atmospheric aberrations [1]. In the last few years automatic and manned lunar probes have vastly increased our knowledge of lunar topography, [2, 3] and added direct measurements of a number of physical and chemical properties. [4] In particular, it has been shown that the far side of the Moon is extensively cratered, the maria being almost entirely confined to the Earth-facing hemisphere.

The Mariner 4 television pictures of 1965 demonstrated that Mars too is cratered; a discovery confirmed and amplified by Mariners 6 and 7. It is suspected that Mercury and the larger satellites of Jupiter are similarly marked, so it would seem that the cratering mechanism – whatever it may be – has been of widespread importance in the evolution of the Solar System. However, the proximity of the Moon naturally renders it the major source of data.

1. Impact vs. Volcanic Origins

At one time two major schools of thought could be distinguished for the origin of lunar craters: those supporting impact in some form on the one hand, and those favouring volcanism on the other [5]. However, even before the advent of space probes the boundary was becoming less distinct, each school having accepted a modicum of the claims of the other to produce a number of dualistic approaches. [1, 2, 6] None has met with universal acceptance, the chief point of dispute being the ratio between impact and volcanic structures.

Proponents of the impact hypothesis pointed to the expected ubiquity of debris and collision processes (especially in the youth of the Solar System) and drew attention to the circular characteristics resulting from the explosive impact of bodies colliding at cosmic velocities. [7] Considerable emphasis was placed on plots of crater diameter vs. depth – the interpretation of which has not passed unchallenged. [6, 8, 9]

Urey and Runcorn (eds.), The Moon, 407–425. *All Rights Reserved.*

The rival school stressed the alignments and groupings that may be distinguished among the lunar craters as evidence for an endogenous mechanism, and drew analogies with terrestrial calderas and other volcanic formations. [10–14] However, those terrestrial calderas formed by destruction of the apex of a volcanic cone are elevated *above* the surrounding terrain, [15] while collapse calderas are not remarkable for their circularity. [16] And why are there no large 'intact' parent structures on the Moon? A more fundamental objection is the absence on the Moon of evidence for the active convection which has led to plate tectonics, continental drift and fold mountains on Earth, and provided an energy source for the restricted distribution of volcanic belts along the edges of moving plates. [17, 18] It would seem that if an endogenous mechanism has contributed to the shaping of the lunar surface, then it must be very different from that which is normally identified with present-day terrestrial volcanism. [19] Several authors have suggested that some form of 'gassy' endogenous process is responsible. [8, 15,18]

It is particularly desirable that any postulated mechanism be capable of the formation of both single and multiple craters by a comparatively quiet, gentle process extending over an appreciable period of time – as contrasted with the sudden destructive violence of impact or explosive evisceration. [1, 11, 20–23] The general rule that where lunar craters intersect the broken formation is the larger points to the available energy diminishing with time. [24]

2. A Return to First Principles

As neither impacts nor conventional volcanism satisfactorily explain all aspects of the morphology of the lunar surface, let us return to first principles to search for additional or alternative mechanisms. It is now many years since Urey promulgated the idea of a *cold* accretion process in the early stages of planetary evolution. [25] There now seems to be a very general agreement that such a process did indeed occur, although argument continues over mechanism, time-scale, and many other important factors.

The composition of the solid primordial material appears to be most closely approached by the Type I carbonaceous chondrites, but this would have been associated with a much greater mass of volatile material – water, carbon dioxide, ammonia, methane, etc. – in the form of ices. [26] These grains of 'dirty ice' are suspended in the hydrogen and helium of the primeval solar nebula. There are obvious parallels with Whipple's theory of the composition of cometary nuclei, [27] and with the presumed compositions of the Jovian planets. (Recently, it has been shown that under certain conditions even hydrogen may condense on interstellar grains, [28] and that comets are associated with enormously larger clouds of hydrogen, oxygen, and other volatiles than was previously suspected [29]).

Let us now suppose this icy material to accrete into protoplanets without passing through any intermediate high-temperature stage. It would seem likely that a substantial proportion of the volatiles would thereby be incorporated in the interiors of the growing bodies. [26] However, when a certain size is achieved, gravitational and radioactive heating result in warming-up and consequent degassing. [1, 8, 26, 30–33] This could be concomitant with the final stages of accretion – when impact heating and modification of the surface is also important – and would seem to lead to a situation where we have gasses rising through a deep, particulate, outer shell. Initially, the gases would be expected to be largely methane, ammonia, carbon dioxide and water vapour; but with increase of temperature at depth hydrogen and carbon monoxide would become dominant. [34] The evolution of only 10% volatiles from the mass of the Moon gives 19 tonnes/cm^2 to be lost from the lunar surface.

3. Fluidization

Now it has long been established by experiment and practice in quite different contexts that if a stream of gas is introduced beneath a bed of solid, particulate material, then a series of phenomena may be distinguished as the rate of flow is gradually increased: [35, 36]

(I) At very low rates the gas merely percolates through the stationary bed.

(II) As its velocity increases there comes a point at which the viscous drag on the particles becomes equal to their weight. The bed then begins to expand and to display many of the properties of a liquid – such as flow, wave, and buoyancy phenomena. It is than said to be 'fluidized.'

(III) With somewhat greater gas flow the fluidized system becomes more expanded, less dense, and flows even more easily.

(IV) With still greater gas flow 'bubbles' appear in the fluidized bed, giving the appearance of boiling. But, of course, the bubbling bed need not really be hot at all; and the 'bubbles' show many features which render them quite distinct from bubbles in true liquids. [37]

(V) Finally, with still greater gas flow, this phase passes into one of pneumatic transport of the particles in the gas stream.

The turbulent motion and intimate contact between solid and gaseous phases make fluidized beds very efficient in the exchange of heat and mass, and in the promotion of chemical change. They are therefore finding wide application in technology today. [38] Industrial practice and theoretical investigation commonly employ spherical particles of narrow size range, and such irregularities as agglomeration, channelling and slugging in the fluidized bed are minimized by careful engineering design.

It has been suggested [39] that conditions for widespread fluidization were temporarily achieved on the young Moon and other bodies destined to become the terrestrial planets: this is the sought-for 'gassy endogenous process' mentioned above. The duration of intense activity would be comparatively short, but it is expected that regionalised, and later localised and sporadic, escape of gas from the interiors would persist over a long period – indeed, up to the present time (see below).

This hypothesis provides a necessary mechanism for the effective removal of heat from the interiors of the evolving bodies, [40] while exposure to the hot reducing gases would result in extensive and efficient chemical alteration of the original material, including reduction of iron and transport or loss of a proportion of volatile elements and those forming volatile hydrides or halides. As the gas flow diminishes so the depth which can be held in the fluidized state decreases, and the resulting static levels can be indurated by sintering, pressure, and chemical alteration.

This model leads to the accumulation of massive primordial atmospheres around the larger proto-planets, [41] making it necessary to appeal to the enhanced solar wind from a hotter, younger, Sun passing through a T-Tauri stage to drive them off. [26, 42] This also removes heavy volatiles like mercury, which are hard to lose by a Jeans mechanism.

It is generally agreed that the present atmosphere and hydrosphere of the Earth are (with the exception of free oxygen) derived by secondary degassing processes. [43, 44] The Moon is insufficiently massive to retain a permanent atmosphere. [45]

4. Fluidization on the Earth

Any structures formed by the primary degassing of the proto-Earth could not be expected to survive the turmoil of further accretion and the subsequent convective history. Present-day examples must necessarily be on a restricted scale.

The best-known natural fluidized systems are *nuées ardentes*: remarkable forms of volcanism where particulate material is suspended in, and transported by, the associated hot gases. [46] They can be extremely destructive – as was the type example which erupted from Mt. Pelée to overwhelm the town of St. Pierre in Martinique in 1902. [47] *Nuées ardentes* are infrequent in modern volcanism, and the few recent examples have fortunately been confined to sparsely-inhabited areas. However, they appear to have been much more common in the geological past, apparently erupting from fissures to lay down vast deposits in the American Middle West, South America and New Zealand. [48] With loss of the fluidizing gas the mass settles and compacts: the hotter central region of the flow commonly undergoes sintering and thermal alteration to produce hard, crystalline rocks now known as welded tuffs or ignimbrites, but at one time mistaken for true lavas. There is, understandably, a paucity of information on the mechanics of *nuée ardente* flow; but important observations were made by Perret, [47] while more recently McTaggart [49,50] and Brown [51] have contributed laboratory experiments and calculations. Salient points are

(a) Compositions range from nearly basic to acid.

(b) Temperatures of emplacement range from 700–1000 °C.

(c) The presence of fine material markedly increases the mobility, whereas addition of quite large amounts of coarse material to a bed of fine particles produces only a small change in characteristics. Surprisingly low rates of gas supply are sufficient for fluidization if fine material is present.

(d) There is little lateral sorting according to size: enormous blocks may be 'rafted' for miles. Perret [47] shows photographs of both rounded and angular examples, as well as of the block-littered surface of the spent flow. The fine material may be seen to contact the entire perimeter of a block – there is no trace of the concave depression that would be produced by its fall as an aerial projectile.

(e) Once a thick bed of particles is fluidized, considerable time is required for it to deflate completely. (A problem familiar to the manufacturers and packers of numerous powdered products.)

(f) True lavas may be found co-existing with ignimbrite deposits, having flowed over the surface or been intercalated between layers.

Doris Reynolds [52] first promoted the wider application of fluidization in geology, suggesting that certain intrusive granites were emplaced by this mechanism. Her ideas were taken up and extended by Holmes [53], who demonstrates the applicability of fluidization to the Swabian tuffisite pipes, kimberlite diamond pipes, and other diatremes. Of particular significance in the present context is Holmes' discussion of what he terms 'fluidization craters' – flat-floored ring structures with low ramparts found in the Rift Valley region of Africa. Holmes illustrates his textbook with a photograph of Lake Nyamununka – a ring crater about 2 miles in diameter – for which he believes fluidization to offer the only possible genesis. (For location of this crater see ref. 54.) The border between 'fluidization craters' and the gas-explosion structures called 'maars' is not well-defined: research is urgently required on the entire spectrum of types. Ollier [55] points out that maars are usually associated with basaltic rather than acidic igneous activity, and gives cross-sections of various examples, some with igneous masses (tholoids) extruded within the crater. The Wangoom maar in Australia would be a fluidization crater in Holmes' terminology. [56]

King and Sutherland [57] believe fluidized transport occurred in the carbonatite complexes of eastern Uganda. A review of fluidization as a volcanological agent was presented by Reynolds [58] at a recent meeting of the Geological Society of London devoted to this topic.

5. Fluidization on the Moon

The first description of a fluidized bed (although not by this name) appears in Robert Hooke's 'Micrographia' of 1665 [59], where he describes the appearance and properties of a bowl of 'boyling alabaster' (hot calcium sulphate dihydrate losing its water of hydration). Later in the same book this remarkable man compares the structures left on the surface of the alabaster with the craters of the Moon! It would seem that the application of fluidization to the origin of lunar surface features does, in fact, antedate both the volcanic and impact theories! The idea lay fallow for three hundred years, until independently resurrected by a number of workers [39, 60–64] in the 1960's as a result of growing interest in space exploration. However, two earlier papers which contain the germ of this idea should not be overlooked. [65, 66]

Particularly important is the work by O'Keefe and Adams [67], which includes a mathematical treatment of proposed lunar ash flows. They show that the amount of gas required to induce fluidization is inversely proportional to the square of the gravitational attraction at the site: lunar flows therefore require only $\frac{1}{36}$ of the gas content of their terrestrial counterparts. It seems reasonable to expect the terrestrial fluidization crater Lake Nyamununka mentioned above to be equivalent to a 10–12 mile diameter ring structure on the Moon.

The only study of the effect of reduced pressures on fluidization appears to be that of Miller and King. [68] They found that the effect of vacuum is to cause the top surface of the bed to erupt into a dilute phase and produce extensive elutriation. They suggest that any lunar flows must therefore have been accompanied by an extensive dilute phase, soon falling back after the end of the eruption. A sufficiently elevated temperature would presumably result in melting, as individuals, of a proportion of the suspended grains; surface tension then pulling them into the glassy spheres found in fly-ash and the returned lunar samples. [69–71]

Experimental craters have been produced in the laboratory by Emmons [62], Mills [72] and Schumm. [73] Mills found that ring structures were generated at the surface of a slowly-collapsing, aggregative, inhomogeneous fluidized bed. In such an environment the gas does not escape uniformly, but instead finds and maintains

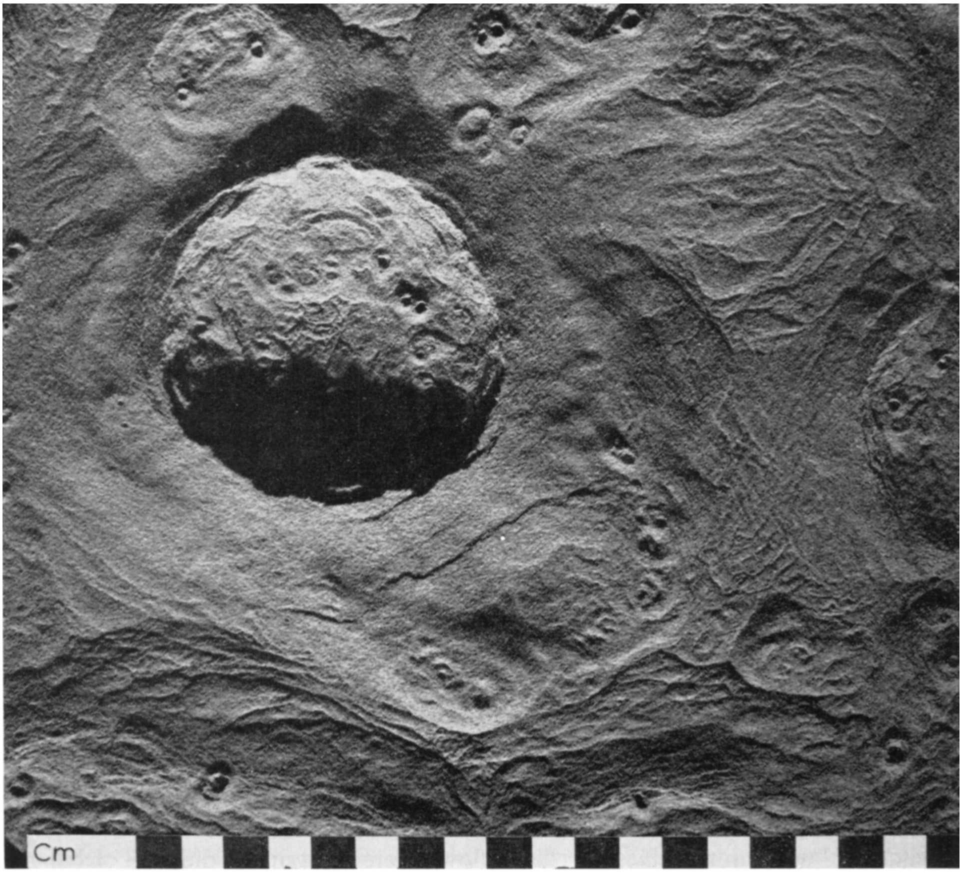

Fig. 1. Model single crater. Note the concentric slump terraces and the flow structures on the right.

https://doi.org/10.1017/S0074180900097710 Published online by Cambridge University Press

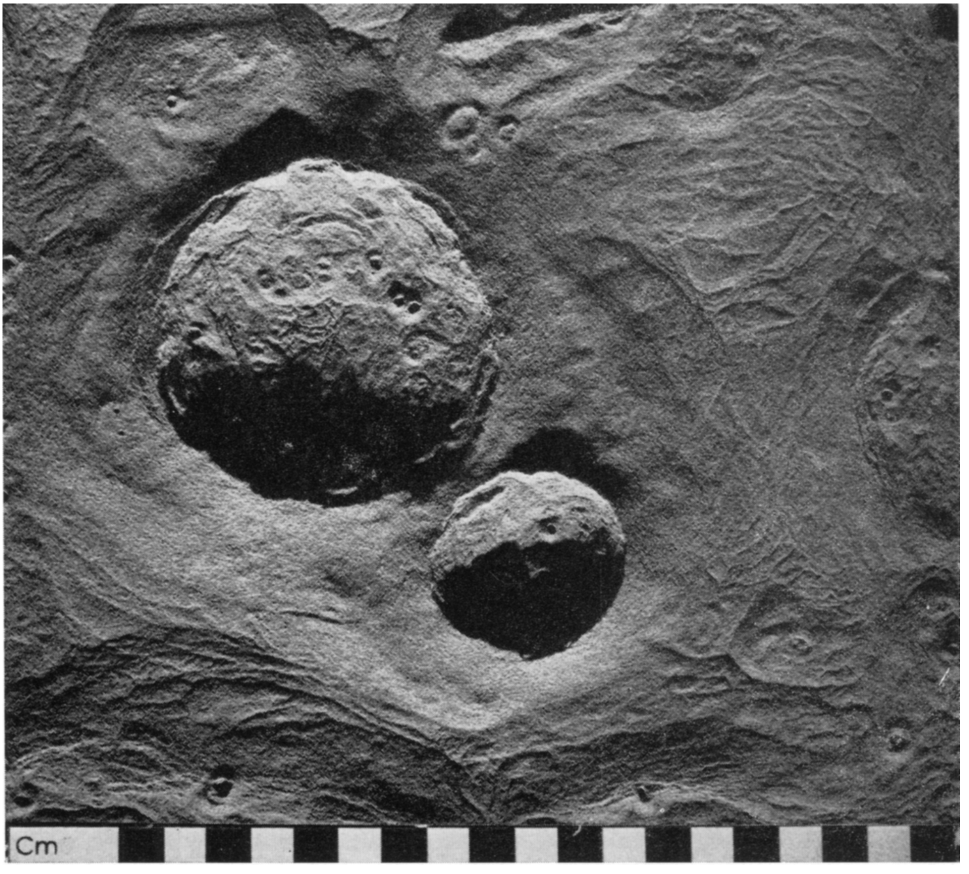

Fig. 2. Model craters. A second, smaller, crater has been produced at a short distance from the single crater shown in Figure 1.

certain channels of preferential escape. [74] (Discontinuities are inherent consequences of the fundamental equations of fluidization [75]) It was observed that

(a) A structure with a strong tendency towards a circular plan is produced independently of the shape of the area of enhanced gas release, and its diameter may exceed the depth of the bed.

(b) Formations may be abruptly intercepted by the walls of the apparatus.

(c) A large, shallow, depression in the original bed may be transformed into a flat-floored, raised-rim crater by fluidization of its interior.

(d) The height of the structures could be small compared with their diameter, strong side-lighting being required to delineate them clearly. It was later found that the relief is controlled by the degree of overall (or 'background') fluidization. A high level of mobility 'dissolved' any structure, a moderate level produced craters with shallow slopes, and an immobile background resulted in craters of funnel-like section.

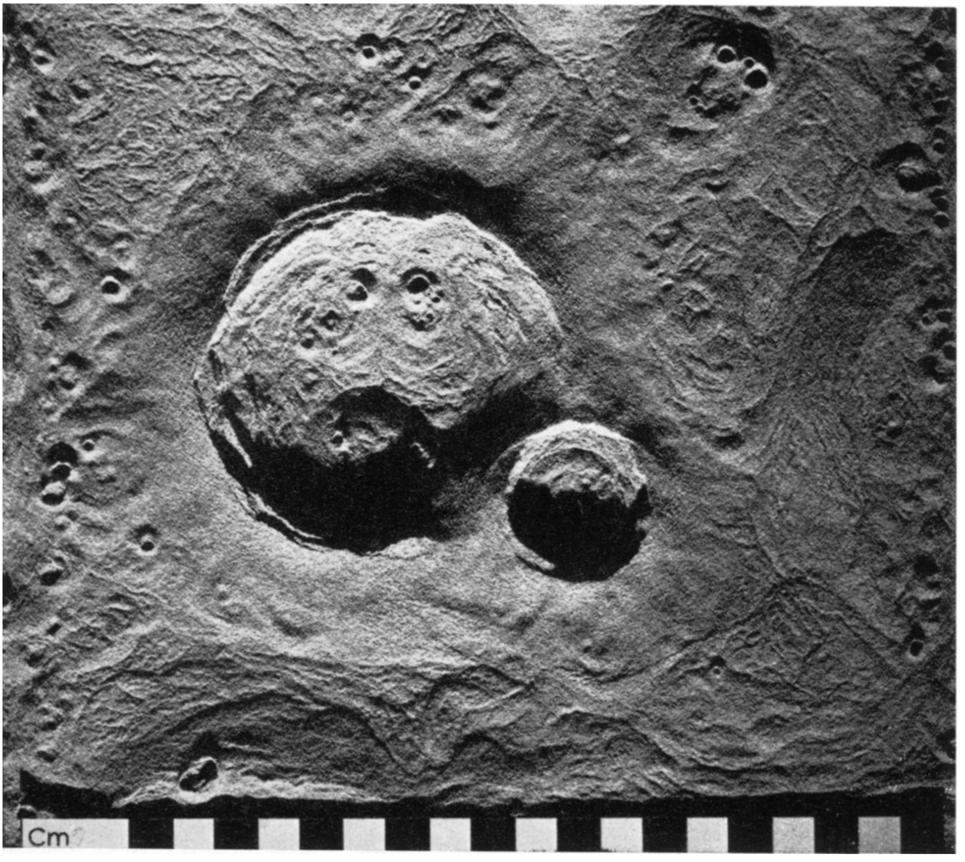

Fig. 3. Model craters. A second crater has been produced nearer an original large single crater, resulting in penetration. Note how the smaller crater intrudes the larger, producing a talus slope (but otherwise little destruction) within it.

(e) The process of formation is comparatively gentle, and may operate over an extended period of time with quiescent intervals.

(f) The extent to which two or more structures interact with one another depends on their distance apart and sequence of formation. Figures 1–4 illustrate this.

(g) Concentric slump terraces appear within the ring as the gas supply diminishes and bed contraction ensues.

(h) The terminal stage is commonly the formation of small craterlets within the ring. Tapping the apparatus at this stage often results in transient activity confined to these craterlets.

(i) The lobate flows apparent in the illustrations might be termed the results of *nuées froides* – they were neither true liquids nor hot.

(j) The effect of bed depth is illustrated by Figures 5–7. A shallow bed results in a large number of 'blowholes', but as the depth increases these tend to be replaced by

https://doi.org/10.1017/S0074180900097710 Published online by Cambridge University Press

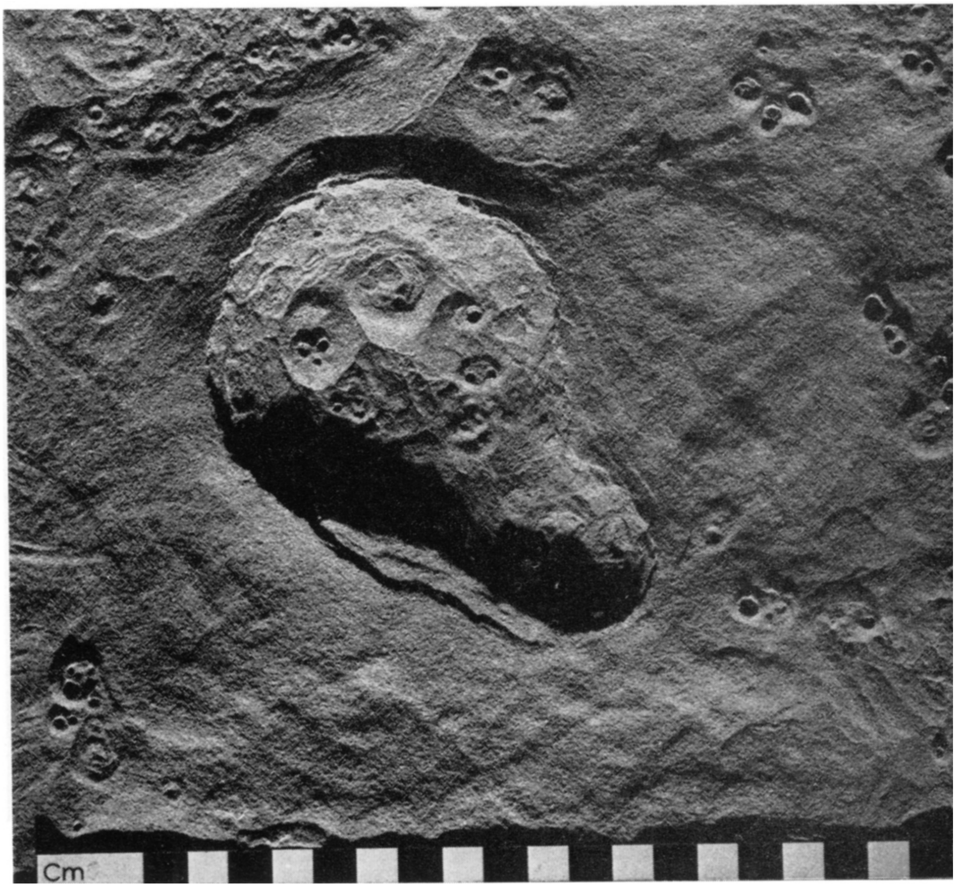

Fig. 4. Model craters. Dimultaneous production of craters may result in either a straight dividing wall or coalescence of the two structures, depending on the amounts of gas involved. Here we see a coalescent structure bearing resemblances with, for example, the lunar crater Fauth.

zones of fluidization and a smaller number of escape channels. Certain areas on the Moon exhibiting excess crater numbers (e.g. the lunar 'playas') might well be associated with terminal gas release through a thin particulate cover.

The concept of 'regional fluidization' is shown diagrammatically in Figure 8. It is essential that this scheme be clearly distinguished from any hypothesis involving bubbles in viscous liquids. [5] Not only is it impossible to form very large bubbles, [76] but the liquid phase would flow back level again! [77] However, the property of the moving cavities ('bubbles') in boiling fluidized beds of bringing up patches of underlying material [37] may be relevent to the genesis of lunar dark-halo craters.

Although bearing many visible resemblances with the surface of the Moon, [78] it is freely conceded that these laboratory simulations are not true-scale models, and

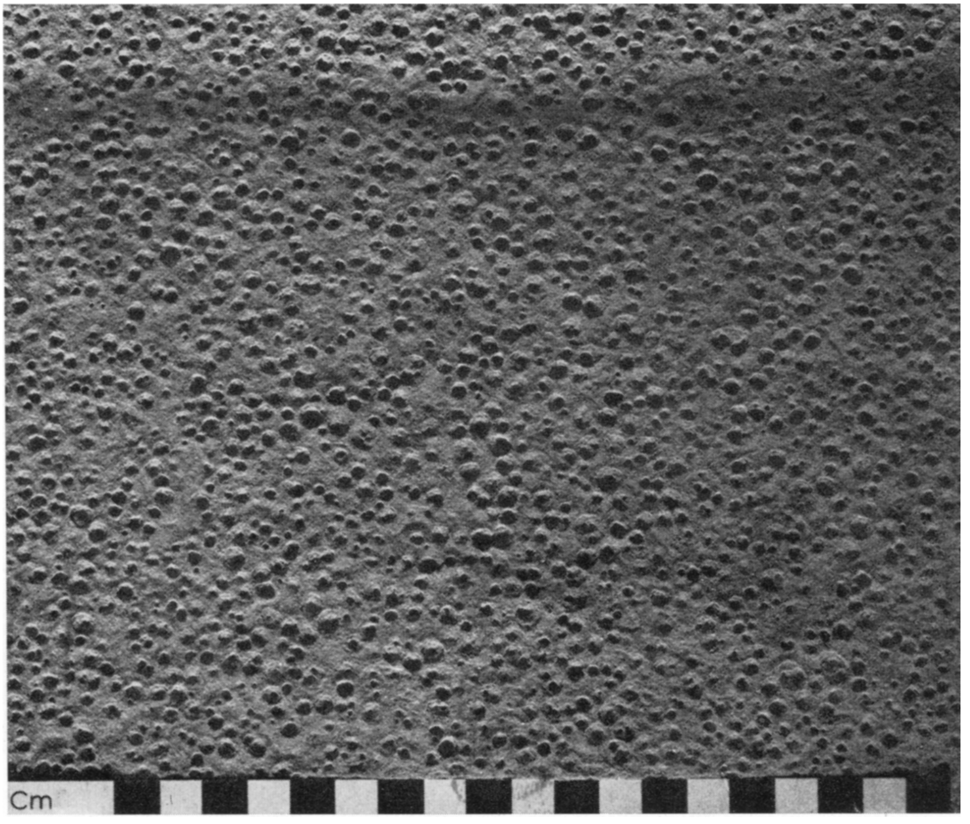

Fig. 5. Result of passage of gas through a bed of rock powder ½″ deep.

that the greatest caution is required in extrapolating them to any natural situation. Similar objections apply to cratering experiments with accelerated dust-size particles. All these experiments are perhaps best considered as aids to the conception of hypotheses to be tested in the field – in the manner so successfully used by Kuenen [79] in his pioneering work on marine turbidity currents.

Murray, Spiegel and Theys [80] have published a preliminary attempt to quantify aspects of fluidization on the Moon. Unfortunately they employed data derived from the *secondary* degassing of the Earth, thereby arriving at an unacceptably low value for the period during which large-scale fluidization could be simultaneously supported over the entire surface of the Moon. Substituting the above-mentioned value of 19 tonnes/cm^2 for degassed volatiles gives the more realistic figure of 10^3 yr.

It must also be reiterated that it is not suggested that fluidization is the only mechanism shaping the lunar surface. Impact craters occur on Earth, and must surely be represented on the Moon. The constitution of the impacting bodies was at one time generally considered to be identical with that represented by the meteorites in our museums, but in view of the surprisingly low concentration of such meteoritic material

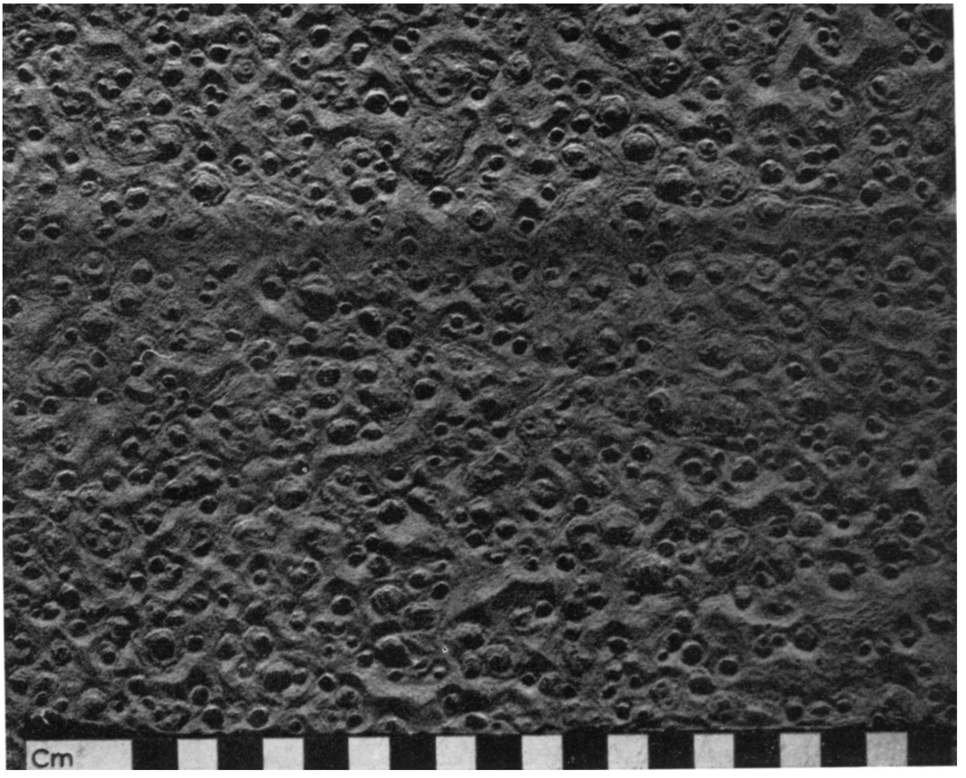

Fig. 6. Result of passage of gas through a bed of rock powder 1″ deep.

in returned lunar samples [81–83] there is now an increasing body of opinion that weakly-cohesive or icy masses were important, and might even have predominated. The possibility of base surges [84] and fluidization induced by their impact [85] should be considered. [86, 87]

6. The Deeper Structure of the Moon

Loss of all but traces of its volatiles leads to the following picture of the present-day Moon

I – A fragmented and particulate surface layer, containing much fine material and up to several metres deep. [88–90]

II – A sintered, heterogeneous, vesiculate breccia crust some 3–5 km thick, gradually passing into –

III – Increasingly compacted rubble and breccia making up a thick mantle.

IV – A small core, probably with no distinct boundary.

This model appears to be in accord with the low density, seismic observations, [91–93] and measurements of the electrical characteristics of the Moon. [94, 95]

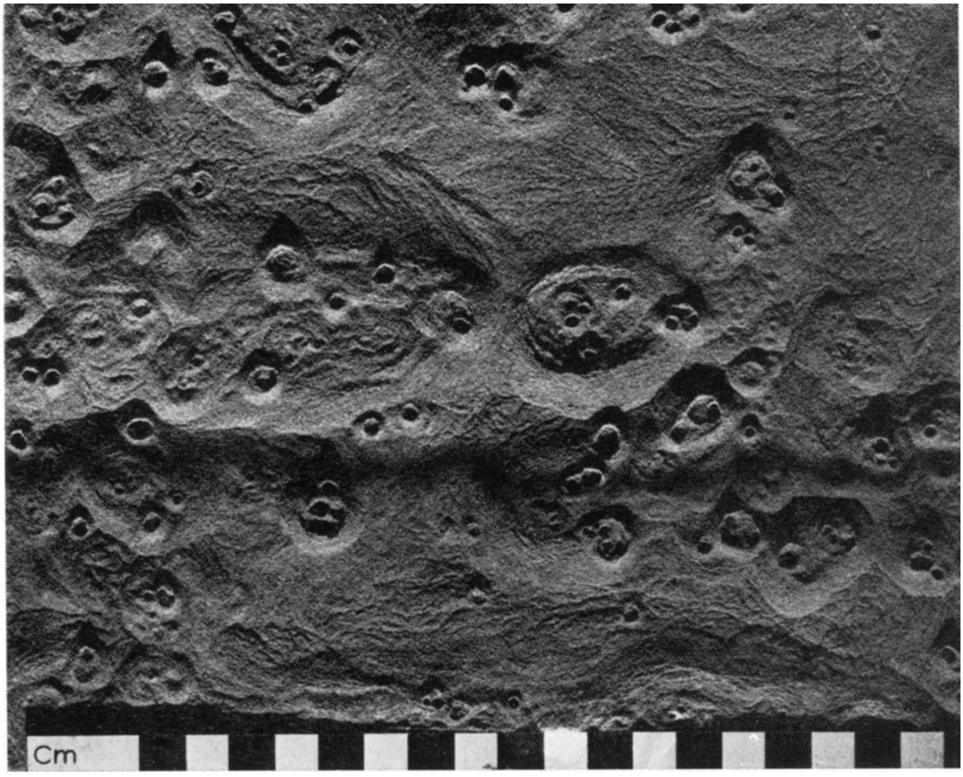

Fig. 7. Result of passage of gas through a bed of rock powder 2″ deep.

The crystalline material in the returned lunar samples indicates that actual melting has occurred within or below the maria (perhaps with the assistance of extra energy on the Earth-facing hemisphere) to allow true lavas and igneous differentiation products to form. Lava may flow out at the surface (wrinkle ridges?) or be injected between other deposits (giving domes as 'quelkuppen' [46]). However, the returned lunar basalts cannot represent the bulk composition of the Moon, for transformation to eclogites at depth would give too high a density. [96] It is considered more likely that local melting beneath the maria has occurred, rather than that the Moon has ever been molten on a global scale. [97, 98] Mackin's [64] scheme for the origin of maria allows material to be brought into the basin from the edges, thus giving rise to mascons.

7. Lunar Rilles

Two distinct types of rille are immediately obvious – the straight and the sinuous – although intermediate and other forms may be found on further study. Straight rilles (Figure 9) extend for tremendous distances over the lunar surface, maintaining their linearity without regard to surface topography. [2, 3] Craters are divided with no sign

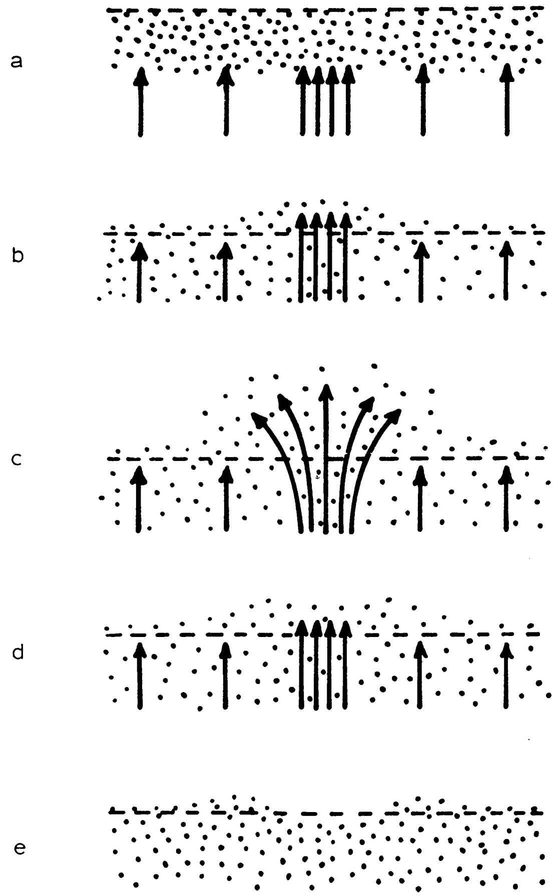

Fig. 8. Successive stages of regional fluidization. a, Release of gas from depth; b, bed expansion, with doming over channel of preferential escape; C, lateral flow of basal fluidized system beneath a disperse cloud; d, gas flow diminishing-activity subsiding within the ring structure; bed contraction is accompanied by ring slumping; e, cessation of gas flow and general consolidation results in an approximately circular depressed area surrounded by a raised wall.

of diversion by cone sheets, feeder pipes, or dykes of strong igneous rock. The depression of the floor of a crater-crossing rille is similar in both mare and ramparts. [99] The orientation of straight rilles seems to follow a pattern – the lunar grid – indicative of an endogenous origin. [2, 100]

In 1885 Osborne Reynolds [101, 102] coined the term 'dilatancy' for the property of close-packed granular masses of expanding in bulk with change of shape, due to the increase of space between individual particles as they change their relative positions. Reynolds' interest in the phenomenon was confined to its application in his mechanistic theory of the ether: the more practical role of dilatancy in geology had to await the investigations of W. J. Mead. [103]

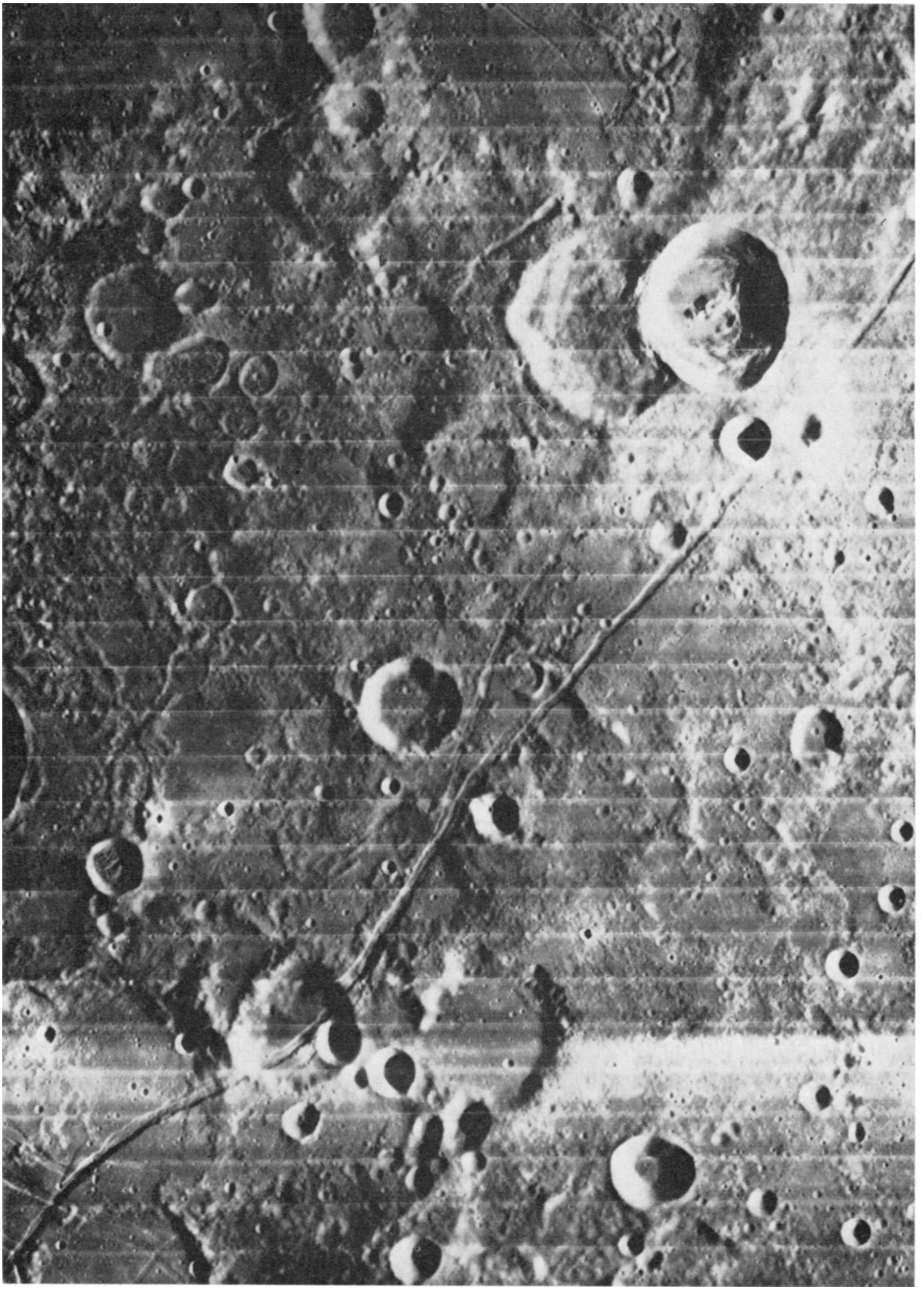

Fig. 9. Part of the Sirsalis rille: an example of a long, straight rille. It is named from the 32 km Sirsalis at upper right. (NASA/National Space Science Data Center; Orbiter 4 – 161H).

In a modification of one of Reynolds' experiments, Mead shows that if sand is placed in an impervious elastic container (itself of negligible strength, such as a toy balloon) and the air pumped out, then

(a) The mass becomes exceedingly rigid, and
(b) If the mass is stressed to failure it responds as a *brittle solid*, failing along definite shear planes.

i. e. granular masses free to dilate deform by flow, but when dilation is prevented or restricted by relatively slight confining pressure deformation causes *fracture*. This manner of failure requires a minimum increase in volume, involving dilation only in the shear zone.

It is suggested that the straight rilles are simply an analogous expression of tensional failure in the weakly-cohesive lunar crust. Whether the tension is a result of cooling or doming is not yet clear. The relief of pressure and extra space created along these deep fractures (or set of closely-spaced fractures) permitted dilatancy and plastic flow to occur, giving the present depressed flat floors of the rilles.

Besides providing an escape route for gases from below, Mead himself pointed out

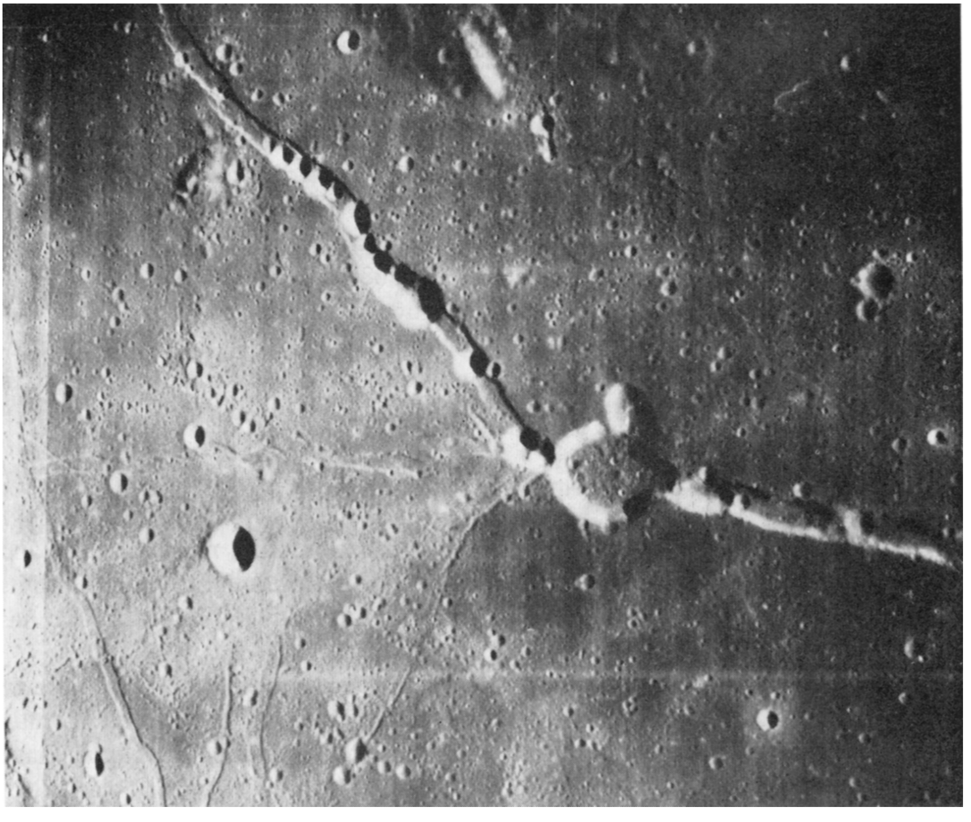

Fig. 10. The Hyginus rille. The largest crater, Hyginus itself, is about 6.5 km in diameter. (NASA/National Space Science Data Center; Orbiter 5 – 96M).

https://doi.org/10.1017/S0074180900097710 Published online by Cambridge University Press

that this mechanism leads to lateral migration of any fluids contained in the surroundings towards the zone of fracture and dilation. Movement and escape of gases could lead to fluidization or maar-like excavations within the rille, depending on quantity, rate, and point of release. The Hyginus rille (Figure 10) is put forward as an example of a rille modified by such an escape of gas.

The form of the sinuous rilles has suggested to various workers that they have been created by actual flow of some material – water, lava (in channels or tubes) or nuées ardentes. [104] This is difficult to reconcile with the observable penetration of topographic highs, and the occasional breaks in continuity. [105, 106] It is considered more likely that fine underlying tensional cracks are responsible, allowing gas release with

(a) The formation of closely-spaced craters which have coalesced, leaving only their cuspate walls.

(b) Fluidized flow in those sections of a rille where the topography is appropriate.

These flows need be neither continuous nor hot.

In the absence of gas release the finest fractures remain masked by the superincumbent particulate material. Experimental investigations along these lines have been conducted by Schumm [73] and Mills (unpublished).

8. Transient Lunar Phenomena

That a small amount of gas is even today being evolved from the Moon is suggested by the temporary obscurations and light emissions known as transient lunar phenomena (TLP's). Gas venting is also considered a likely candidate for the fixed-location seismic signals observed on the Moon, [107] while the cold-cathode gauge left behind by the astronauts has yielded some interesting preliminary results.

TLP's continue to be observed and catalogued [108]: correlations with perigee [109] and seismic events [110] have been reported. However, postulated origins in luminescence or thermolominescence have proved inadequate [111, 112], leaving electrostatic glow discharges (generated by friction in dust-laden gas discharges) as almost the only contender. [113, 114] This subject will be discussed at greater length elsewhere.

9. Application of Fluidization to Other Systems

The surface of Mars displays eroded craters of enormous size, rilles, 'chaotic' and 'featureless' ground. [115] There is some evidence for a Martian grid system, with its implications for the participation of endogenous processess. [116] Fluidization has been suggested as a possible cause of the featureless terrain of Hellas. [117]

The possibilities of electrostatically-charged fluidized systems for the abiogenic generation of electropolymers and other necessary precursors of life have recently been discussed by Sylvester-Bradley. [118] Carbonaceous chondrites may have experienced a fluidized stage. [119]

It is concluded that fluidization has been of importance in many aspects of the evolution of planets and satellites.

References

[1] Kopal, Z.: 1966, *An Introduction to the Study of the Moon*, D. Reidel Publ. Co., Dordrecht-Holland.
[2] Lowman, P. D.: 1969, *Lunar Panorama*, Weltflugbild, Zurich.
[3] Kosofsky, L. J. and El-Baz, F.: 1970, *The Moon as Viewed by Lunar Orbiter*, NASA SP-200.
[4] Levinson, A. A.: 1970, *Proceedings of the Apollo 11 Lunar Science Conference*, Pergamon.
[5] Green, J.: 1967, in *Encyclopedia of Atmospheric Sciences and Astrogeology* (ed. by R. W. Fairbridge) Reinhold.
[6) Mutch, T. A.: 1970, *Geology of the Moon*, Princeton Univ. Press.
[7] Baldwin, R. B.: 1963, *The Measure of the Moon*, Univ. of Chicago Press.
[8] Green, J. and Poldervaart, A.: *Report of the 21st Int. Geol. Congress 1960*, Part XXI, pp. 15–33.
[9] Steinberg, G. S.: 1968, *J. Geophys. Res.* **73**, 6125.
[10] Von Bülow, K.: 1965, *Ann. N. Y. Acad. Sci.* **123**, 528.
[11] McCall, G. J. H.: 1965, *Ann. N. Y. Acad. Sci.* **123**, 843.
[12] Fielder, G.: 1965, *Lunar Geology*, Lutterworth.
[13] Moore, P. and Cattermole, P. J.: 1967, *The Craters of the Moon*, Lutterworth.
[14] McCall, G. J. H.: 1969, *J. Brit. Astron. Assn.* **80**, 19 and further parts in this series.
[15] Miyamoto, S.: 1965, *Ann. N. Y. Acad. Sci.* **123**, 776.
[16] Smith, R. L. and Bailey, R. A.: 1968, in *Studies in Volcanology* (ed. by R. R. Coats, R. L. Hay and C. A. Anderson) Geol. Soc. Amer. pp. 613–62.
[17] Miyamoto, S.: 1964, *Icarus* **3**, 486.
[18] Dietz, R. S. and Holden, J. C.: 1965, *Ann. N.Y. Acad. Sci.* **123**, 631.
[19] Emmons, R. C.: 1965, *Tectonophysics* **1**, 541.
[20] McCall, G. J. H.: 1963, *Nature* **197**, 273.
[21] Moore, P.: 1963, *Nature* **197**, 273.
[22] Moore, P.: 1966, *J. Brit. Astron. Assn.* **76**, 256.
[23] McCall, G. J. H.: 1969, *Nature* **223**, 275.
[24] Moore, P.: 1967, *J. Brit. Astron. Assn.* **77**, 119.
[25] Urey, H. C.: 1952, *The Planets*, Yale Univ. Press.
[26] Ringwood, A. E.: 1966, in *Advances in Earth Science* (ed. by P. M. Hurley), MIT Press.
[27] Whipple, F.: 1950, *Astrophys. J.* **111**, 375.
[28] Lee, T. J., Gowland, L., and Reddish, V. C.: 1971, *Nature Phys. Sci.* **231**, 193.
[29] Biermann, L.: 1971, *Nature* **230**, 156.
[30] Bernal, J. D.: 1961, *Times Science Review*, No. 40, pp. 3–4.
[31] Green, J.: 1965, *Ann. N.Y. Acad. Sci.* **123**, 403.
[32] Kopal, Z.: 1968, *Exploration of the Moon by Spacecraft*, Oliver and Boyd.
[33] Nagy, B. *et al.*: 1971, *Nature* **232**, 94.
[34] Ringwood, A. E.: 1972, Private communication.
[35] Lewis, J. B.: 1961, *Times Science Review*, No. 40, pp. 15–8.
[36] Davidson, J. F. and Harrison, D.: 1963, *Fluidised Particles*, Cambridge Univ. Press.
[37] Rowe, P. N.: 1965, *Sci. J.* **1**, 59.
[38] Lewis, J. B. and Partridge, B. A.: 1967, *Nature* **216**, 124.
[39] Mills, A. A.: 1969, *Abstr. Meeting on Fluid Mechanics in Relation to Natural Phenomena*, Newcastle.
[40] Anderson, D. L. and Phinney, R. A.: 1967, in S. K. Runcorn (ed.), *Mantles of the Earth and Terrestrial Planets*, Wiley.
[41] Urey, H. C.: 1954, *Astrophys. J. Suppl.* **1**, 147.
[42] Keays, R. R., Ganapathy, R., Laul, J. C., Anders, E., Herzog, G. F., and Jeffrey, P. M.: 1970, *Science* **167**, 490.
[43] Brancazio, P. J. and Cameron, A. G. W.: 1964, *The Origin and Evolution of Atmospheres and Oceans*, Wiley.
[44] Condie, K. C.: 1968, *J. Geophys. Res.* **73**, 5466.
[45] Öpik, E. J.: 1969, *Sci. J.* **5**, 67.
[46] Rittmann, A.: 1962, *Volcanoes and Their Activity* (transl. by E. A. Vincent), Wiley.
[47] Perret, F. A.: 1935, *Carnegie Inst. Wash. Pub.* **458**.
[48] Ross, C. S. and Smith, R. L.: 1961, *U.S. Geol. Survey Prof. Paper* **366**.

[49] McTaggart, K. C.: 1960, *Amer. J. Sci.* **258**, 369.
[50] McTaggart, K. C.: 1962, *Amer. J. Sci.* **260**, 470.
[51] Brown, M. C.: 1962, *Amer. J. Sci.* **260**, 467.
[52] Reynolds, D. L.: 1954, *Amer. J. Sci.* **252**, 577.
[53] Holmes, A.: 1965, *Principles of Physical Geology*, Nelson.
[54] Holmes, A.: 1951, *Geol. Mag.* **88**, 73.
[55] Ollier, C. D.: 1967, *Bull. Volc.* **31**, 45
[56] Ollier, C. D.: 1969, *Volcanoes*, MIT Press.
[57] King, B. C. and Sutherland, D. S.: 1966, in O. F. Tuttle and J. Gittins (eds.), *Carbonatites*, Interscience.
[58] Reynolds, D. L.: 1969, *Proc. Geol. Soc. Lond.*, No. 1655 pp. 110–5.
[59] Hooke, R.: 1665, *Micrographia*, Royal Society (Dover facsimile, 1961).
[60] Shoemaker, E. M.: 1962, in Z. Kopal (ed.), *Physics and Astronomy of the Moon*, Academic Press.
[61] Cameron, W. S.: 1964, *J. Geophys. Res.* **69**, 2423.
[62] Emmons, R. C.: 1965, *Tectonophysics* **2**, 83.
[63] Elston, W. E.: 1965, *Ann. N.Y. Acad. Sci.* **123**, 817.
[64] Mackin, J. H.: 1969, *Bull. Geol. Soc. Amer.* **80**, 735.
[65] Macqueen, P. O.: 1936, *Trans. Amer. Geophys. Union*, Part 1, pp. 85–89.
[66] Gaydon, A. G. and Learner, R. C. M.: 1959, *Nature* **183**, 37.
[67] O'Keefe, J. A. and Adams, E. W.: 1965, *J. Geophys. Res.* **70**, 3819.
[68] Miller, G. H. and King, I. R.: 1966, *NASA Contractor Report CR-627*.
[69] Hart, A. B. and Raask, E.: 1969, *Nature* **223**, 762.
[70] Agrell, S. O. *et al.*: 1970, *Science* **167**, 583.
[71] Tolansky, S.: 1970, *Science* **167**, 742.
[72] Mills, A. A.: 1969, *Nature* **224**, 863.
[73] Schumm, S. A.: 1970, *Bull. Geol. Soc. Amer.* **81**, 2539.
[74] Whitehead, A. B. and Young, A. D.: 1967, in H. H. Drinkenburg (ed.), *Proc. Int. Symp. on Fluidization, Eindhoven, 1967*, Netherlands Univ. Press.
[75] Murray, J. D.: 1965, *J. Fluid Mech.* **21**, 465.
[76] Krejci-Graf, K.: 1965, *Ann. N.Y. Acad. Sci.* **123**, 751.
[77] Burns, G. J.: 1902, *J. Brit. Astron. Assn.* **12**, 334.
[78] Apollo 12 commentary from the Moon, Nov. 1969.
[79] Kuenen, P. H. and Migliorini, C. I.: 1950, *J. Geol.* **58**, 91.
[80] Murray, J. D., Spiegel, E. A., and Theys, J.: 1969, *Comm. Astrophys. Space Phys.* **1**, 165.
[81] Ganapathy, R., Keays, R. R., Laul, I. C., and Anders, E.: 1970, in A. A. Levinson (ed.), *Proc. Apollo 11 Lunar Science Conference* **2**, 1117, Pergamon.
[82] Keil, K., Prinz, M., and Bunch, T. E.: 1970, *Science* **167**, 597.
[83] Arrhenius, G. *et al.*: 1970, *Science* **167**, 659.
[84] Fisher, R. V. and Waters, A. C.: 1969, *Science* **165**, 1349.
[85] Hartman, W. K. and Yale, F. G.: 1968, *Arizona Univ. Lunar and Planetary Lab. Commun.* **7**, 131.
[86] Van Dorn, W. G.: 1969, *Science* **165**, 693.
[87] McKay, D. S., Greenwood, W. R., and Morrison, D. A.: 1970, *Science* **167**, 654.
[88] Bastin, J. A., Clegg, P. E., and Fielder, G.: 1970, *Science* **167**, 728.
[89] Fryxell, R. *et al.*: 1970, *Science* **167**, 734.
[90] Quaide, W. L. and Oberbeck, V. R.: 1968, *J. Geophys. Res.* **73**, 5247.
[91] Report in *Nature* **228**, 906 (1970).
[92] Latham, G., Ewing, M., and Dorman, I.: 1970, *Science* **170**, 620.
[93] Gold, T. and Soter, S.: 1970, *Science* **169**, 1071.
[94] Sonett, C. P. *et al.*: 1971, *Nature* **230**, 359.
[95] Kuckes, A. F.: 1971, *Nature* **232**, 249.
[96] Ringwood, A. E. and Essene, E.: 1970, *Science* **167**, 607.
[97] Gilvarry, J. J.: 1970, *Nature* **225**, 623.
[98] Urey, H. C.: 1971, *Science* **172**, 403.
[99] Leatherbarrow, W. J.: 1969, *Brit. Ast. Assn. Lunar Section Circular* **4**, 77.
[100] Fielder, G.: 1967, in S. K. Runcorn (ed.), *Mantles of the Earth and Terrestrial Planets*, Interscience.

[101] Reynolds, O.: 1885, *Phil. Mag.* **20**, 469.
[102] Reynolds, O.: 1886, *Nature* **33**, 429.
[103] Mead, W. G. 1925, *J. Geol.* **33**, 692.
[104] Greeley, R.: 1971, *Science* **172**, 722.
[105] Schumm, S. A. and Simons, D. B.: 1969, *Science* **165**, 201.
[106] McCall, G. J. H. 1970, *Nature* **225**, 714.
[107] Report in *Nature* **229**, 521 (1971).
[108] Moore, P. A.: 1971, *J. Brit. Astron. Assn.* **81**, 365.
[109] Middlehurst, B. M. and Moore, P. A.: 1967, *Science* **155**, 449.
[110] Ewing, M.: 1970, Address to the IAU General Assembly, Brighton, England.
[111] Blair, I. M. and Edgington, J. A.: 1970, in A. A. Levinson (ed.), *Proc. Apollo 11 Lunar Science Conf.* Vol. 3, 2001, Pergamon.
[112] Nash, D. B. and Greer, R. T.: 1970, in A. A. Levinson (ed.), *Proc. Apollo 11 Lunar Science Conf.* Vol. 3, 2341, Pergamon.
[113] Mills, A. A.: 1970, *Nature* **225**, 929.
[114] O'Keefe, J. A.: 1970, *Science* **168**, 1209.
[115] Leighton, R. B., Horowitz, N. H., Murray, B. C., Scharp, R. P., Herriman, A. H., Young, A. T., Smith, B. A., Davies, M. E., and Leovy, C. B.: 1969, *Science* **166**, 49.
[116] Wells, R. A.: 1969, *Geophys. J. Roy. Astron. Soc.* **17**, 209.
[117] Sharp, R. P., Soderblom, L. A., Murray, B. C., and Cutts, J. A.: 1971, *J. Geophys. Res.* **76**, 331.
[118] Sylvester-Bradley, P. C.: 1971, *Proc. Geol. Assn.* **82**, Part. 1, pp. 87–136.
[119] Mills, A. A.: 1968, *Nature* **220**, 1113.