Formation of Glass Spheres on the Lunar Surface

B. Scarlett, R. E. Buxton and R. G. Faulkner

Phil. Trans. R. Soc. Lond. A 1977 **285**, 279-284
doi: 10.1098/rsta.1977.0066

Phil. Trans. R. Soc. Lond. A. **285**, 279–284 (1977)

Printed in Great Britain

Formation of glass spheres on the lunar surface

By B. Scarlett†, R. E. Buxton† and R. G. Faulkner‡

†*Department of Chemical Engineering*, ‡*Department of Materials Technology*,
Loughborough University of Technology, *Leicestershire*

[Plate 1]

The lunar fines contain an appreciable proportion of spherical glass particles. They are formed by local melting and splash due to meteorite impact. The observed particle size of the spheres is discussed in relation to the physical processes controlling their formation. Detailed studies of the structure of some larger spheres have been made. Three aspects are reported and discussed, the secondary cratering on the surface, the porosity of the spheres and their chemical homogeneity.

Introduction

The lunar fines contain an appreciable proportion of spherical glass particles. We have previously reported an Apollo 11 sample to contain 2 % of such particles (Scarlett & Buxton 1974). In the next section we summarize the conclusions of the previous paper regarding the size of the spherical particles. The other sections describe the findings of further investigations into the detailed structure of some of the larger spheres, approximately 200 μm in diameter, obtained from Apollo 14 samples. These spheres were embedded in Araldite and polished sections were then prepared enabling the internal structure of the spheres to be studied. The specimens were investigated both with a scanning electron microscope and an electron microprobe analyser, enabling both physical and chemical inhomogeneities to be detected.

Particle size of the spheres

It is probable that the spheres have been formed by local melting due to meteorite bombardment of the lunar surface. The wide range in chemical composition (Winchell & Skinner 1970) and appearance (Fulchignoni 1971) of the spheres points conclusively to their formation by many discrete events as opposed to volcanic activity. If the impact has sufficient energy to cause a splash it will lead to individual ligaments or jets which may then break to form the individual droplets. The presence of dumbells in the samples is probably due to cooling before the oscillations in the subsequent distorted droplet have been damped and is good corroborating evidence for this mechanism.

The breakup of a jet is due to the growth of instabilities (Lord Rayleigh 1879) and is a function of the diameter of the jet and the velocity at which it is moving. The diameter of the particles produced cannot be more than twice that of the jet.

We have previously reported (Scarlett & Buxton 1974) on the particle size distribution of the spheres. The particle size range spans four decades from 0.1 to 1000 μm. We have related this range to the magnitude of jet diameters and velocities which can exist on the lunar surface.

The summarizing diagram is reproduced in figure 1. Each line represents an estimated locus of one of the following limitations on the velocity or diameter:

(*a*) The velocity must not be so high that the particles can escape from the lunar surface.
(*b*) The velocity must not be so high that the particles will remelt on falling back to the surface.
(*c*) The velocity must not be so high that the particles will fracture on returning to the surface.
(*d*) The velocity must be sufficiently large to form a ligament against the surface tension.
(*e*) The jet breakup time must exceed the cooling time.
(*f*) The particle cooling time must be less than the time of flight.

The lines corresponding to these mechanisms confine the formation of spherical particles to the range of jet diameters and velocities shown by the shaded area. It is seen to accord with the observed particle size range.

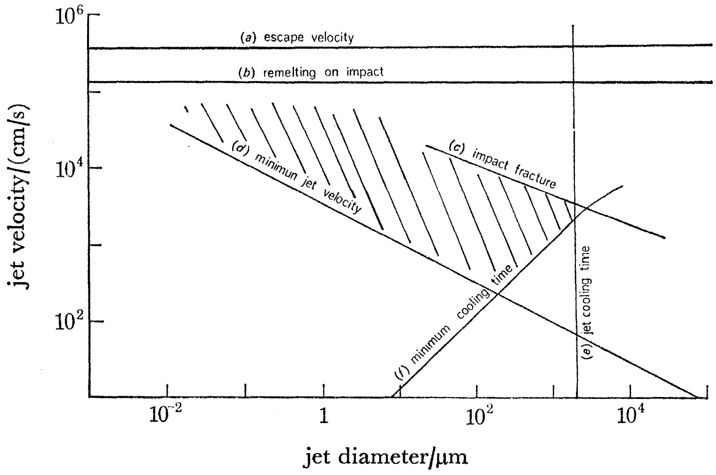


FIGURE 1. Physical limitations to sphere formation.

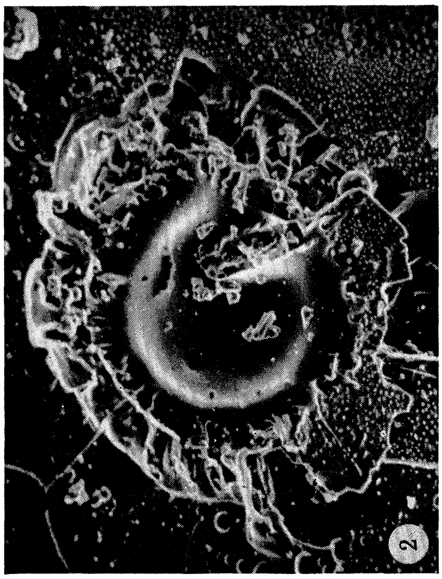
IMPACT CRATERS

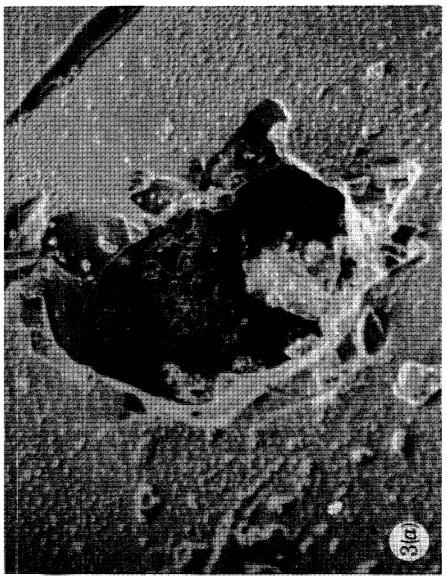
When a meteorite strikes the surface of the Moon, it may possess sufficient kinetic energy to melt its own volume of rock several times. If the meteorite strikes an object which is larger than itself, most of the energy is absorbed in the melting process.

Many of the spheres, particularly the larger ones, themselves bear the evidence of such impacts by micrometeorites. The scanning electron micrograph in figure 2, plate 1, shows the result of such an impact on the surface of a sphere of 200 μm diameter.

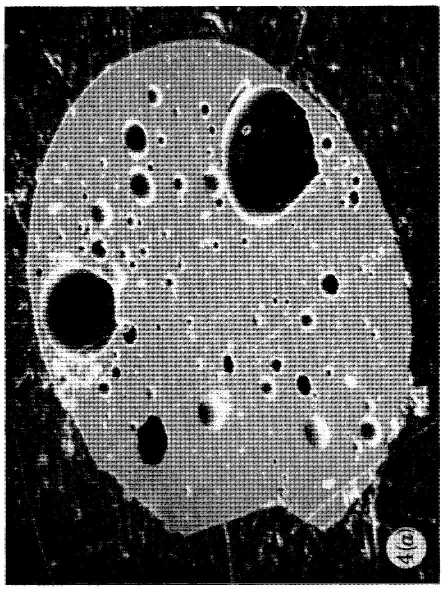
DESCRIPTION OF PLATE 1

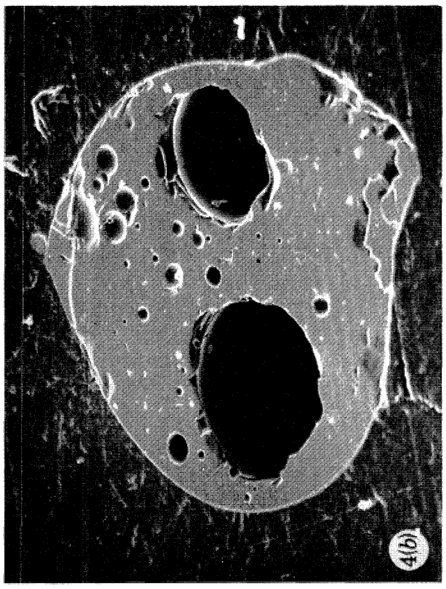
FIGURE 2. Impact crater on surface of sphere.
FIGURE 3. (*a*) Irregular fracture on hollow sphere; (*b*) smooth puncture of hollow sphere.
FIGURE 4. Polished sections of embedded spheres.
FIGURE 5. Microprobe scanning photograph of particle cross section (Fe radiation).
FIGURE 6. Scanning electron micrograph of particle inclusion.

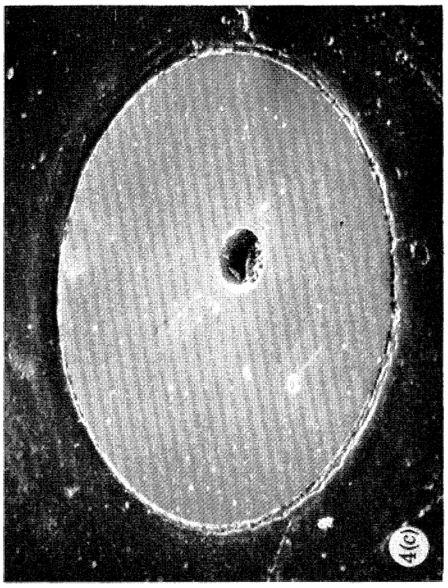

2

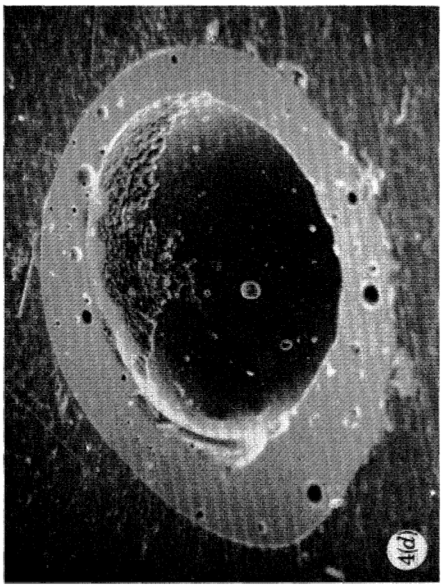

3(a)

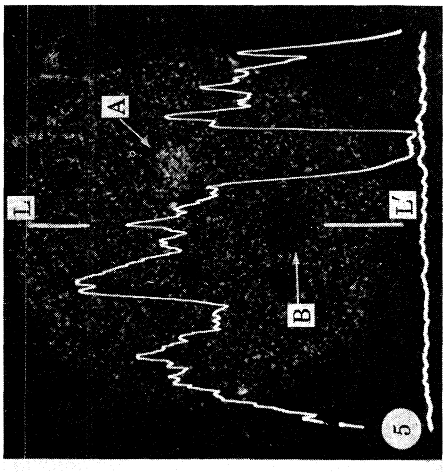

3(b)


4(a)

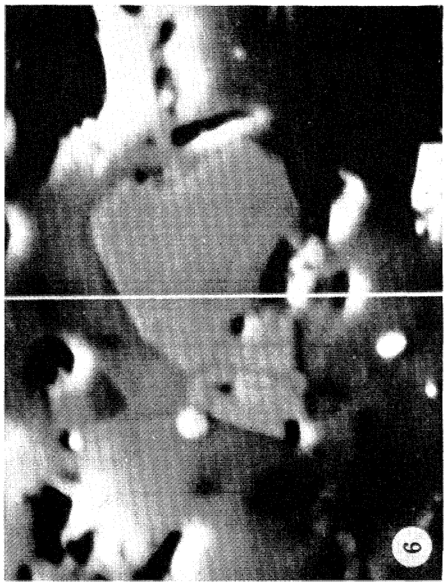

4(b)


4(c)


4(d)



5


6

FIGURES 2–6. For description see opposite.

This particular sphere had three such craters on different parts of its surface showing that they had occurred at different times and that the soil is continually turned by the impacting meteorites. The smooth spallation dish is presumably the volume from which molten material has been ejected around its perimeter in the form of a corona which subsequently breaks into individual ligaments and hence droplets. The dish is contained in a larger volume which has partially separated from the main sphere. When a stereoscopic view of such a crater is made, the fractured area is raised and partially detached from the sphere. Some spheres which are hollow have irregular holes which may well be due to such an impact occurring on a thin portion of the wall and causing complete detachment of the impact area. An example of an irregular hole is shown in figure 3*a*, plate 1. These holes are completely different to the smooth puncture holes formed by an excess internal pressure as shown in figure 3*b*.

We do not think that all meteorite impacts lead to the formation of spheres in this way. If the meteorite impacts into a set of particles comparable to its own size, a cloud of particles is flung out and much of the kinetic energy is transferred to the other particles with only a little local melting occurring at the impact. We have simulated this action by firing a particle of lead into a bed of similar particles with sufficient kinetic energy to melt its own volume three times. Only partial melting is produced and there is no evidence of the jet mechanism which occurs from the dished spallation. A characteristic crater such as is found on the Moon is left in the powder bed.

Voidage of the sphere

It has been reported by ourselves (Scarlett & Buxton 1974) and others (Fulchignoni 1971) that the spheres have varying degrees of porosity. Polished sections of four different spheres are shown in figure 4*a*, *b*, *c* and *d*. There is, of course, an element of chance about where the polishing plane intersects the sphere but, nevertheless, it is clear that some of the particles are almost completely hollow whereas others exhibit varying degrees of porosity in the form of dispersed bubbles. We envisage the formation of this porosity as being a competition between the growth of the bubbles and their coalescence and the cooling of the droplet. We had previously (Scarlett & Buxton 1974) speculated that the formation of the bubbles is due to the volatilization of lighter elements, for example magnesium. However, we have found no evidence in these sections of concentrations of lighter elements near to the bubbles. A recent estimate of the total amount of gas which could be present, primarily implanted hydrogen, gives a value as high as 6×10^{19} atoms/cm^3 (Davies *et al.* 1975). We estimate that an amount of gas about one fifteenth of this value would be sufficient to cause the necessary excess pressure to form a completely hollow sphere 200 μm in diameter at 150 °C. This value would be within the range of that determined by Hayes (1972). It does, therefore, seem possible that there is sufficient gas present at the surface of the Moon if it is somehow occluded into the molten glass, to cause the porosity of the spheres. Presumably, if the gas is unevenly distributed, some spheres will exhibit greater porosity than others. Since there seems to be no correlation between the presence of the bubbles and the concentration of lighter elements we suggest now that the implanted gas is the primary cause of the bubbles and porosity and that the temperature of the glass has not exceeded 2000 °C.

Homogeneity of spheres

The electron microprobe was used to scan the sections of five spheres for chemical homogeneity. The main elements present are Fe, Mg, Si, Ti, Ca, Al. Four of the spheres were completely homogeneous in all elements but the proportions varied from sphere to sphere. These observations confirm those already made by Winchell & Skinner (1970) who found twenty nine homogeneous particles in a sample of thirty. The fourth particle in our sample contained two small regions, within the cross section, which are different in chemical composition. In illustration the X-ray scanning picture corresponding to iron is shown in figure 5, plate 1. The two arrows show one region deficient and the other excessive in iron compared to the sphere. The line scan, which is also plotted, was passed along the vertical diameter of the particle (LL^1) and intersects region B. It was found that region A is rich in magnesium, silicon and iron while region B was rich in calcium, aluminium and silicon. Region B can, in fact, be distinctly seen in the scanning electron microscope and is shown in figure 6, plate 1.

There are at least three possible reasons for the presence of such inhomogeneities.

(i) Crystallization from an originally homogeneous sphere. This phenomenon has been reported in discussion by other investigators in the orange glass found by the Apollo 17 mission.

(ii) Transformed materials formed by shock induction as suggested by Fredriksonn *et al.* (1970).

(iii) Capture of particles by the sphere while still molten and in flight.

In this case, the third mechanism is the most probable since there are two regions of completely different composition present in the same droplet, widely spaced and those compositions correspond chemically to minerals commonly found on the moon. At least one of the inclusions is still relatively angular. This sphere is 220 μm in diameter and the inclusions are both about 27 μm. In the absence of an atmosphere, the droplet and particle could easily impinge. However, they would need to have sufficient relative velocity for the particle to be absorbed into the droplet against the surface tension. In addition, if the particle is to penetrate the interior of the droplet it would need further kinetic energy in order to overcome the viscous drag. The energy necessary to cause absorption in a droplet of diameter D can be estimated by the formula given by Pemberton (1960)

$$\tfrac{1}{2}mv^2 > \tfrac{2}{3}\pi D^2 T.$$

The velocity necessary to cause the particle, diameter d, to move a distance, S, through the droplet is given by the following equation:

$$V = \frac{18\mu S}{\rho d^2}.$$

With the position of the particles in this sphere, we estimate that a relative velocity of 15 m/s would be necessary to overcome a surface tension of 300 dyn/cm (30 μN/cm). Such a relative velocity is possible and would lie within the range of velocities shown in figure 1. However, in order to penetrate the sphere further to their final position the particles would need a relative velocity of 6×10^4 m/s against a viscosity of 1000 poise (100 Pa s). Such a velocity is considerably greater than the particle escape velocity and is very improbable. The most likely mechanism is that the particles are captured while the droplet is still fluid but not yet completely formed. The particle is then transported from the surface as the droplet is pulled into the spherical shape.

This mechanism would require a relatively narrow window of temperature at the time of impact. If the temperature was low, below 1300 °C, the surface tension would be too high for the particle to be absorbed. If the temperature is high, above 1700 °C, most absorbed particles would be rapidly melted.

We thus postulate that the collision of a particle and a droplet may result in three possible states, all of which are found in the lunar samples:

(i) Many spheres have smaller particles embedded into the surface, presumably collected during the later stages of cooling.

(ii) Some spheres are perfectly homogenous and were presumably able to escape the dust cloud and to melt any included particles before cooling below 1700 °C.

(iii) A few spheres have collected particles but have not been sufficiently hot to melt them. In discussion other investigators have reported that many of the dumbell objects contain inclusions. Since they are formed at modest temperatures, they may be an example of collection of particles at intermediate temperatures around 1500 °C.

Conclusions

This paper presents observations on some of the spherical glass particles found in Apollo 11 and 14 samples. We have attempted to combine those observations and those reported by other laboratories with the existing knowledge of the processes of particle mechanics and of atomization to deduce the most probable mechanisms in the formation of these spheres. The deductions are necessarily retrospective and speculative about processes which were clearly complex. We nevertheless believe the following conclusions to have considerable substantiation.

(i) Glass will be formed when a meteorite impacts. The best spheres are probably formed when the impact is on a particle or rock large compared to the projectile enabling a clean splash and breakup to occur. The subsequent formation of spheres which will solidify in flight and return to the surface is dependent on the jet diameter and velocity. The constraints on these parameters limit the size of sphere which can be formed in this way and remain on the Moon to the particle size range 0.1–1000 μm.

(ii) Most of the spheres contain bubbles and in some cases are almost completely hollow. The bubbles are caused by the presence of gas occluded in the sphere which generates a pressure of several kilopascals. This gas is most probably primarily the implanted gas already present in the surface layers of the Moon.

(iii) The chemical homogeneity of the spheres depends on their temperature history while they are formed. At temperatures of 2000 K or more the spheres will be homogenous and will have time to form a good spherical shape. As they cool, they may collect other particles which are not melted but retain their identity. At lower temperatures, less than 1300 K, the surface tension will increase and any captured particles will remain on the surface. If the chemical composition is favourable, partial crystallization may then occur.

We wish to acknowledge the efforts of various members of technical staff who have participated in this project. In particular we wish to mention the following:

Mr M. Hayles for his skilful polishing of the specimens and manipulation of the electron microscope.

Mr T. Hopkins for his expertise in using the electron probe.

Mr G. Boyden for the high speed photography of the simulated impacts.

We are especially grateful to Professor G. Eglinton and Dr C. T. Pillinger of the University of Bristol, indirectly to the National Aeronautics and Space Administration for making the specimens available.

We have benefited especially from discussions with Dr C. T. Pillinger of the University of Bristol and Dr R. M. Housley of the North American Rockwell Center, California.

References (Scarlett *et al.*)

Davies, P. R., Eglinton, G., Pillinger, C. T., Erents, S. K., McCraken, G. M., Naziri, H., Stevenson, A. & Housley, R. M. 1975 *Proc. 6th Lunar Sci. Conf.* (in the press).

Fredriksson, K., Nelen, J. & Melson, W. G. 1970 *Proc. Apollo* 11 *Lunar Sci. Conf.* **1**, 419–432. Pergamon Press.

Fulchignoni, M., Funiciello, R. & Taddeucci, A. 1971 *Proc. 2nd Lunar Sci. Conf.*, *Geochim. cosmochim. Acta Suppl.* 2, **1**, 937–948.

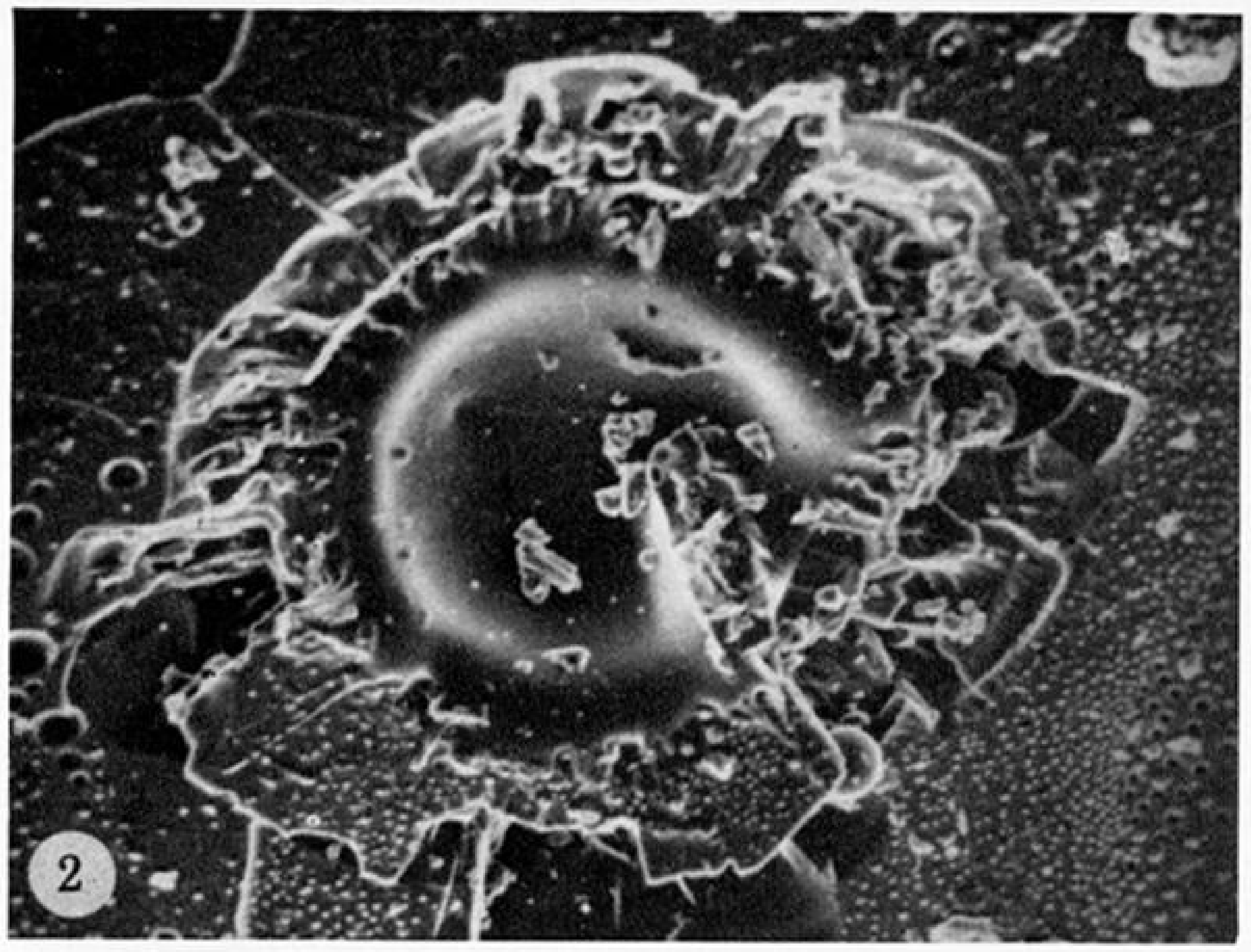
Hayes, J. *et al.* 1974 *Proc. 5th Lunar Sci. Conf.* **2**, M.I.T. Press.

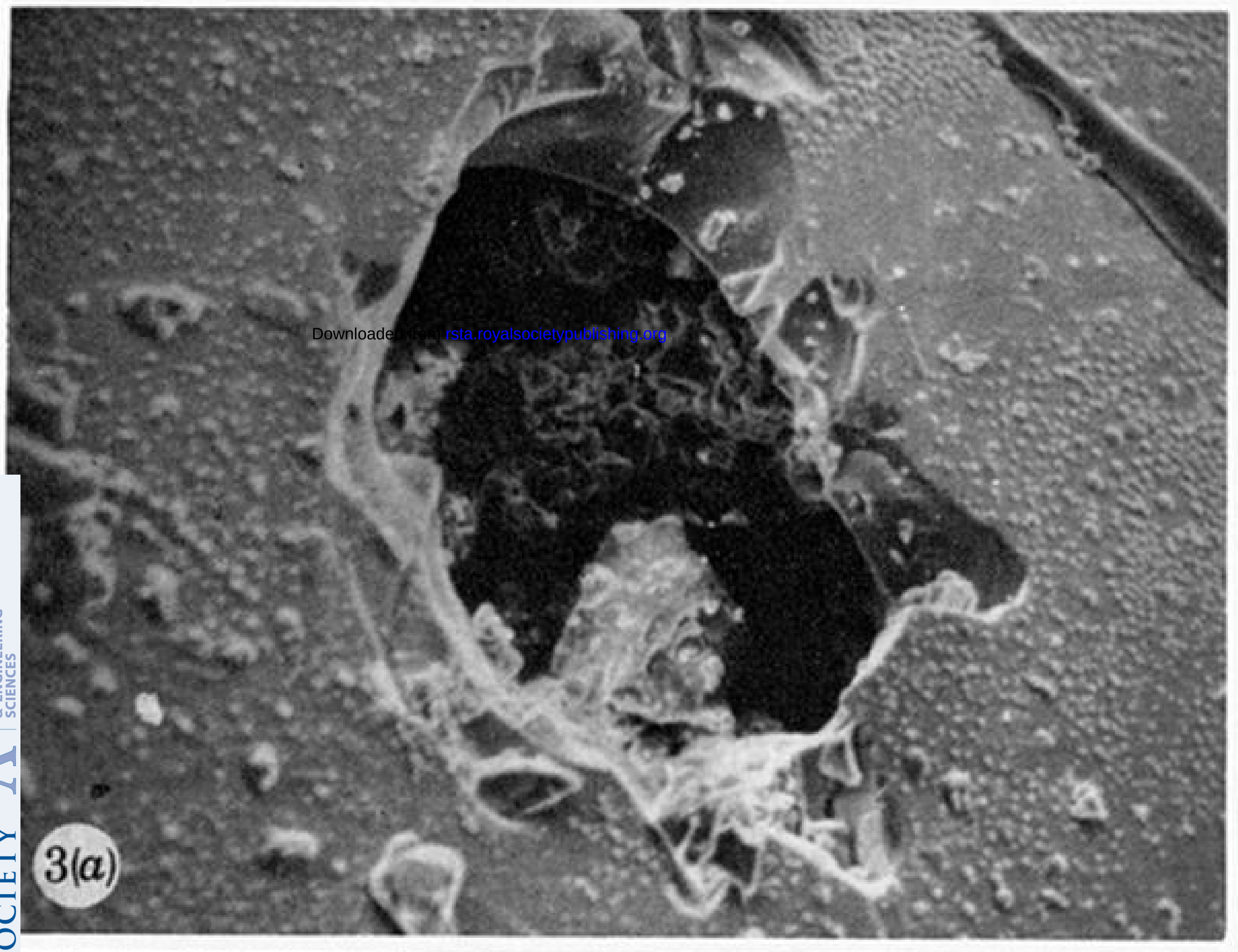
Pemberton, C. S. 1960 *Scavenging action of rain – aerodynamic capture of particles* (ed. E. G. Richardson). London: Pergamon Press.

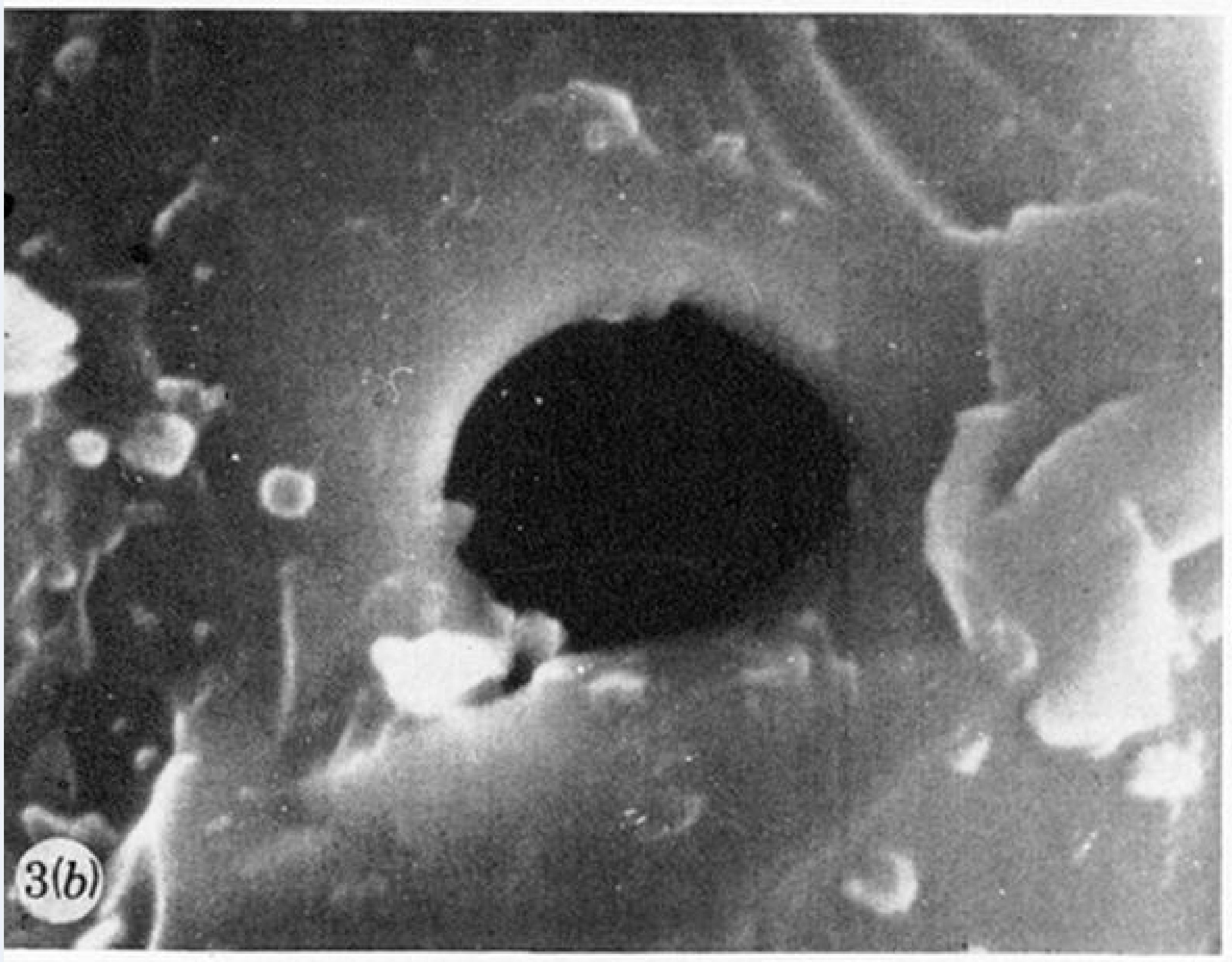
Rayleigh, Lord 1879 On the instability of jets. *Proc. London Math. Soc.* **10**, 4–13.

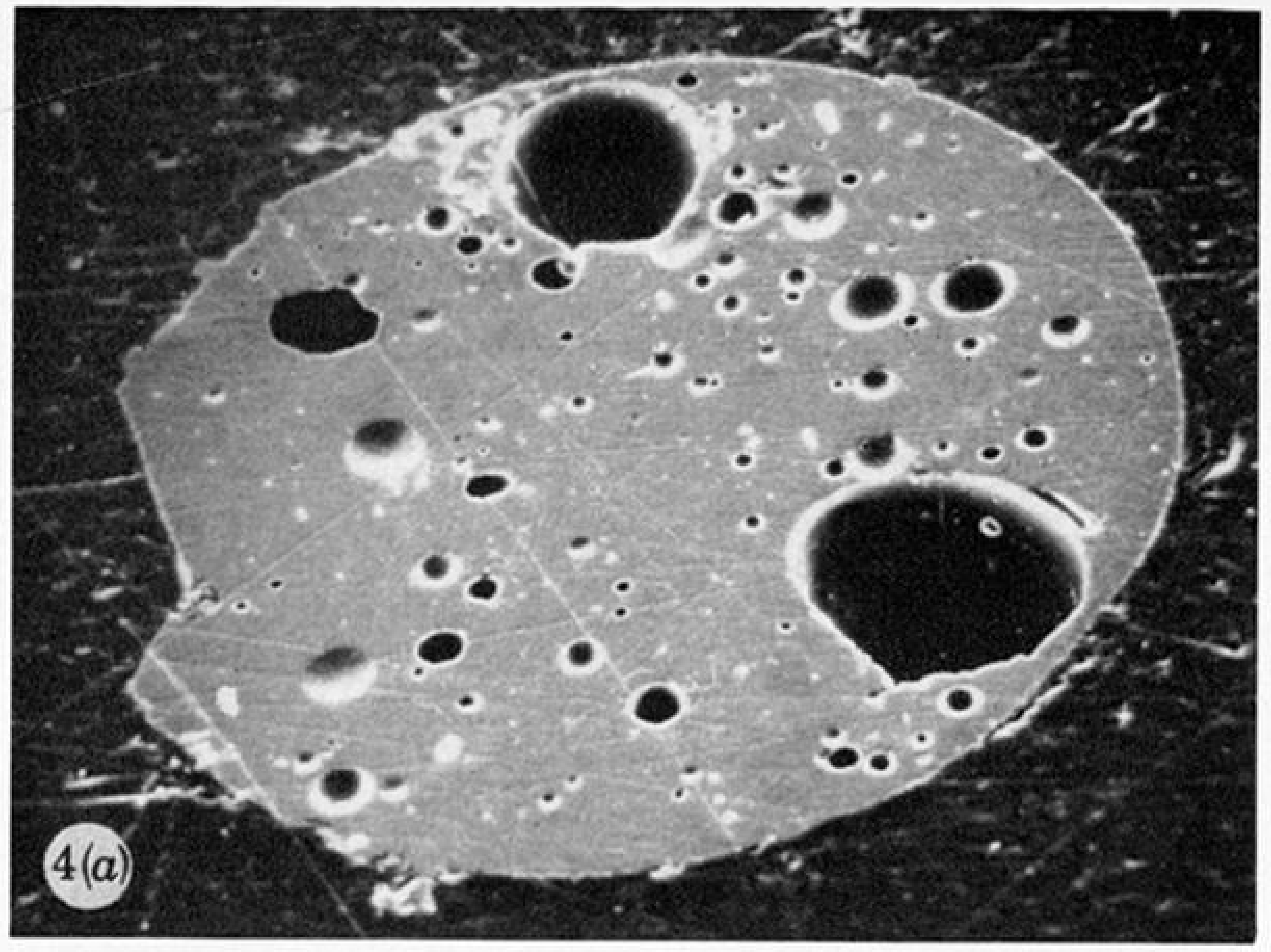
Scarlett, B. & Buxton, R. E. 1974 *Earth Planet. Sci. Lett.* **22**, 177–187.

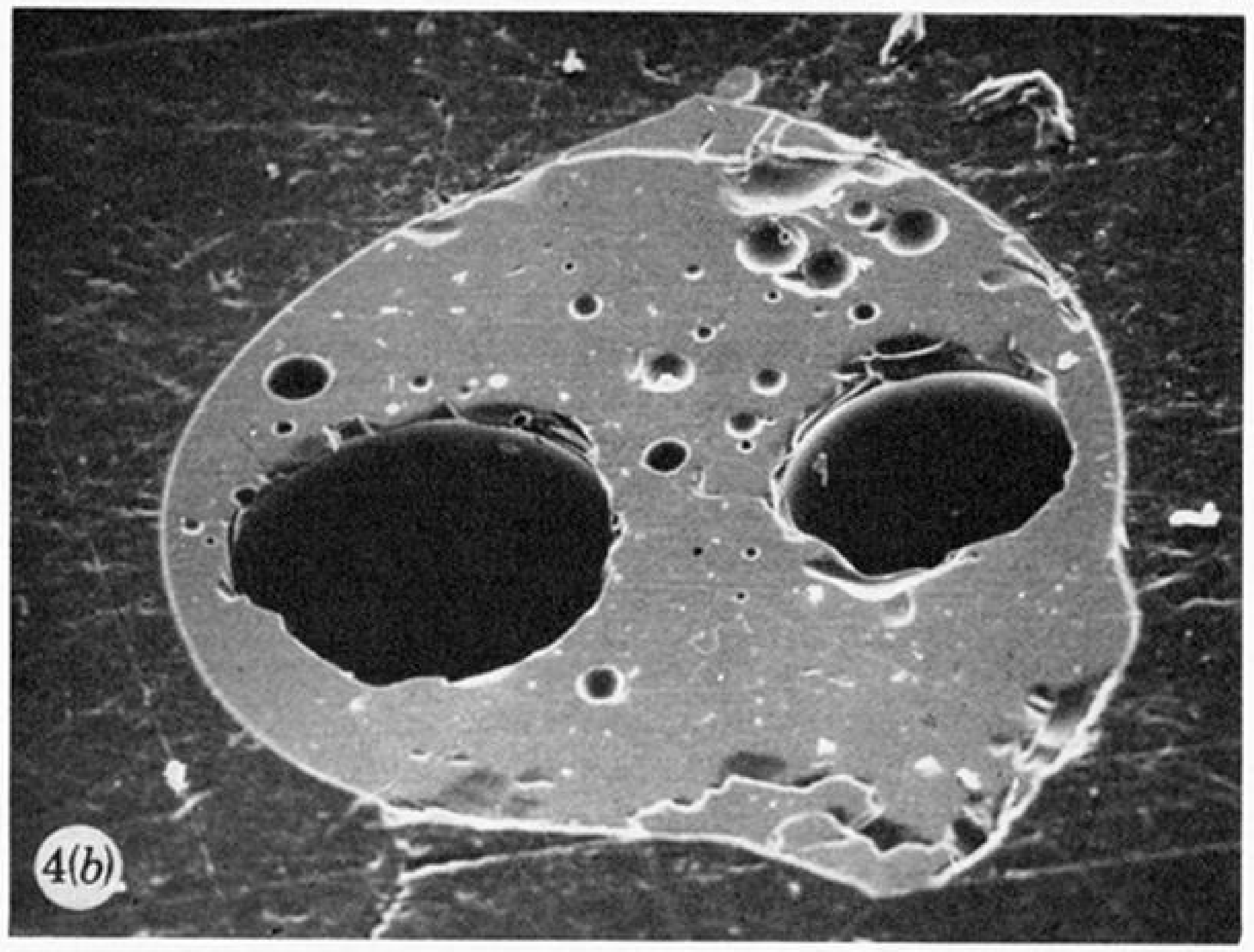
Winchell, H. & Skinner, B. J. 1970 *Proc. 2nd Lunar Sci. Conf.*, *Geochim. cosmochim. Acta Suppl.* 2, **1**, 937–948.

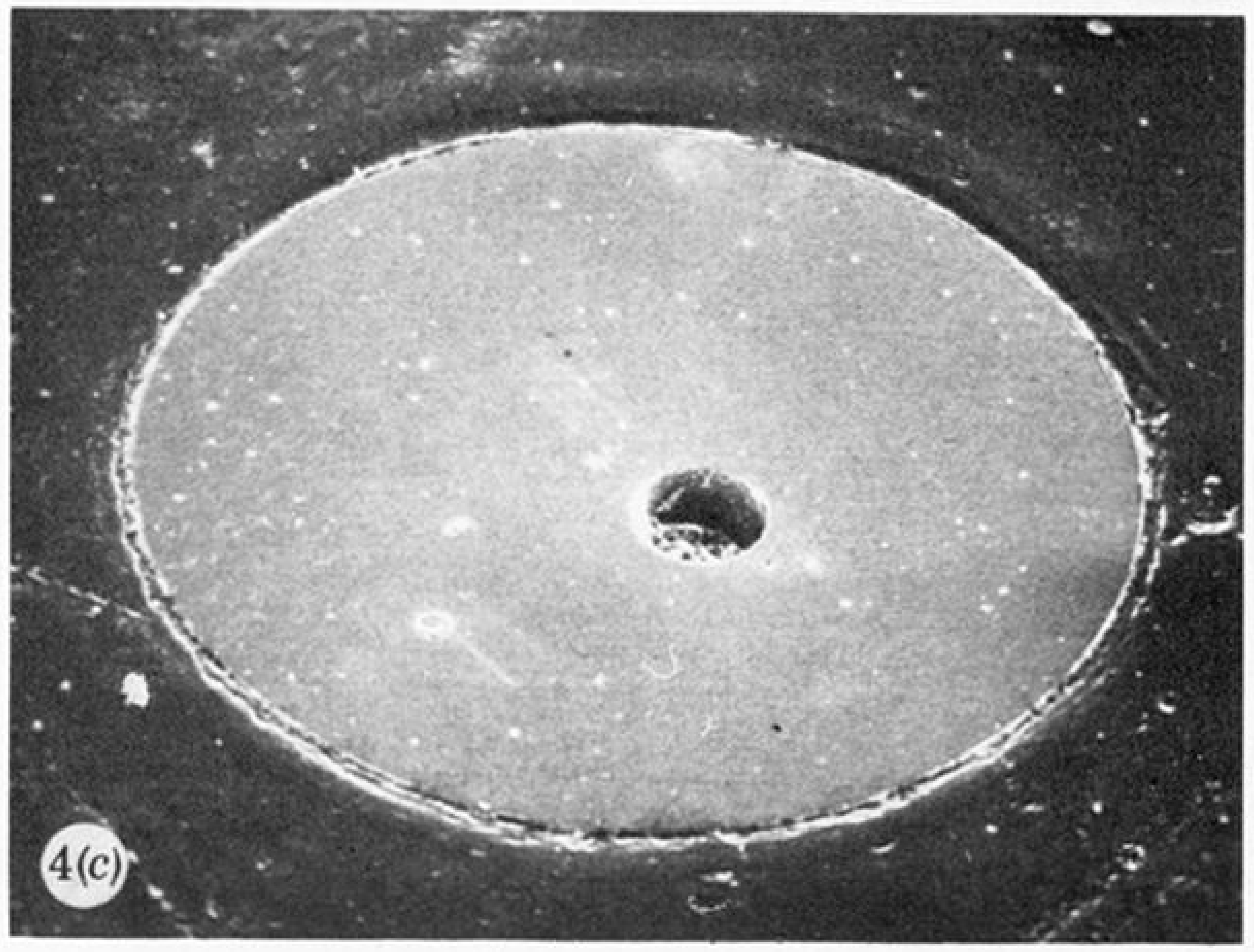

2

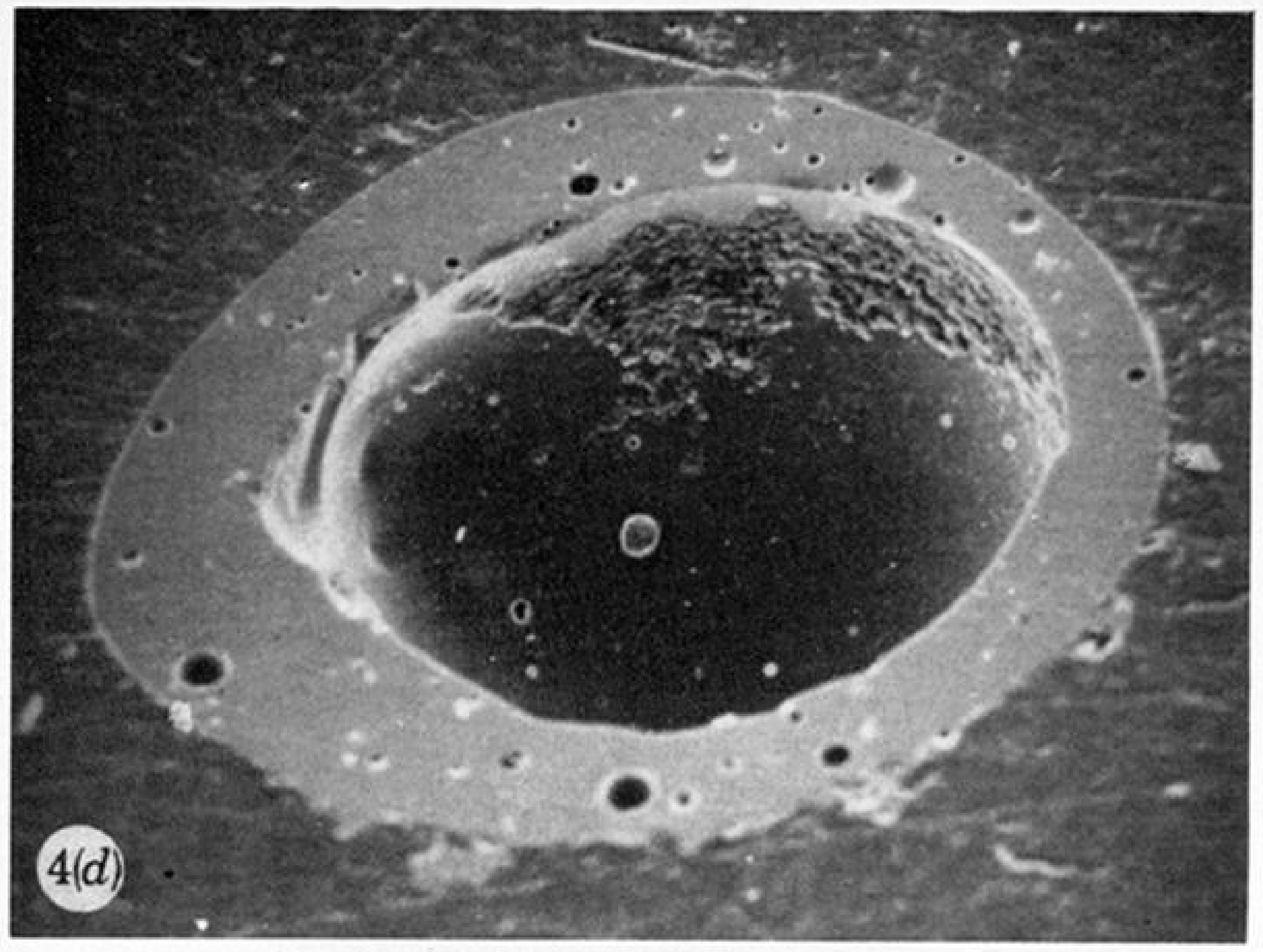

3(*a*)

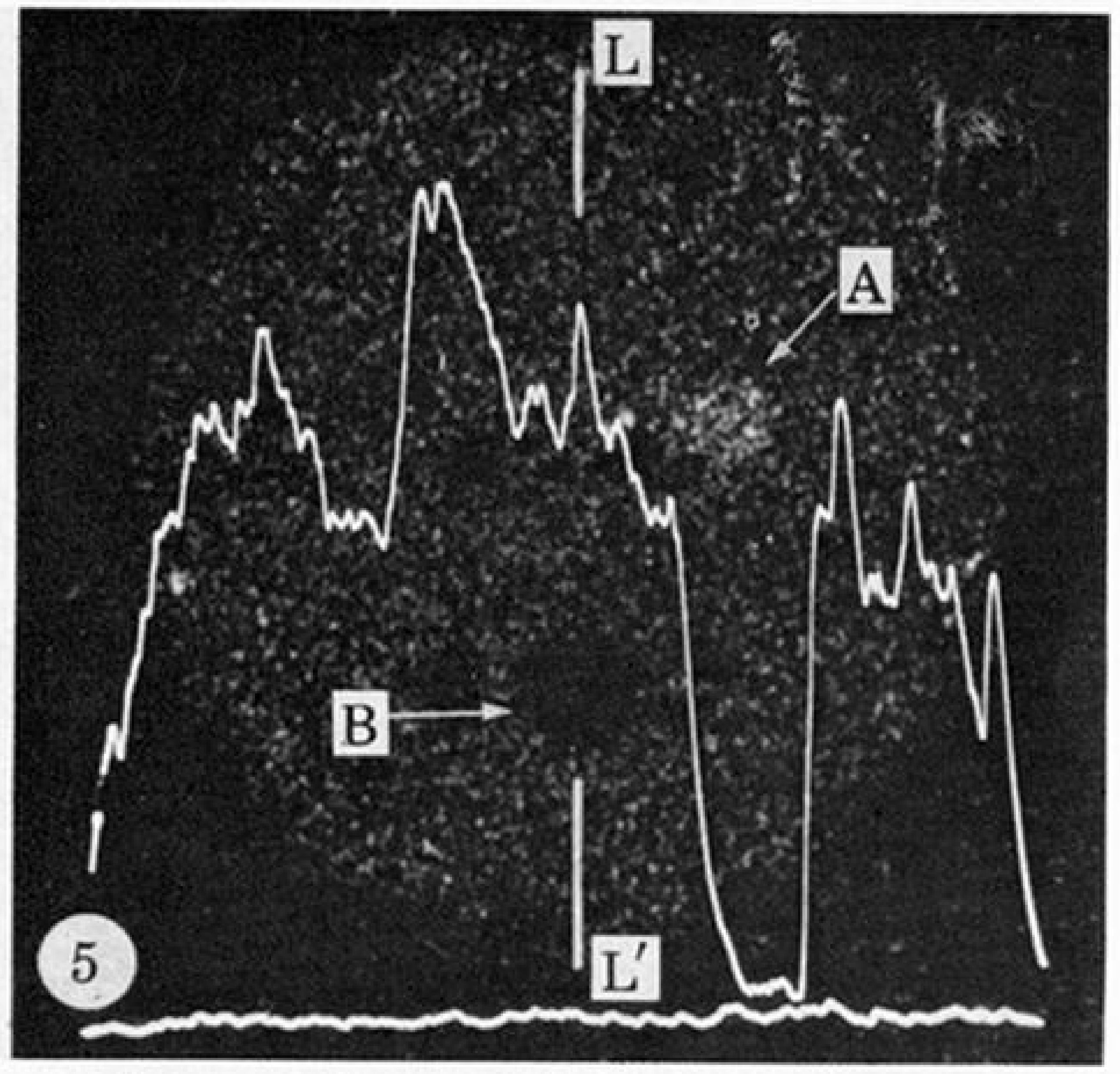

3(*b*)

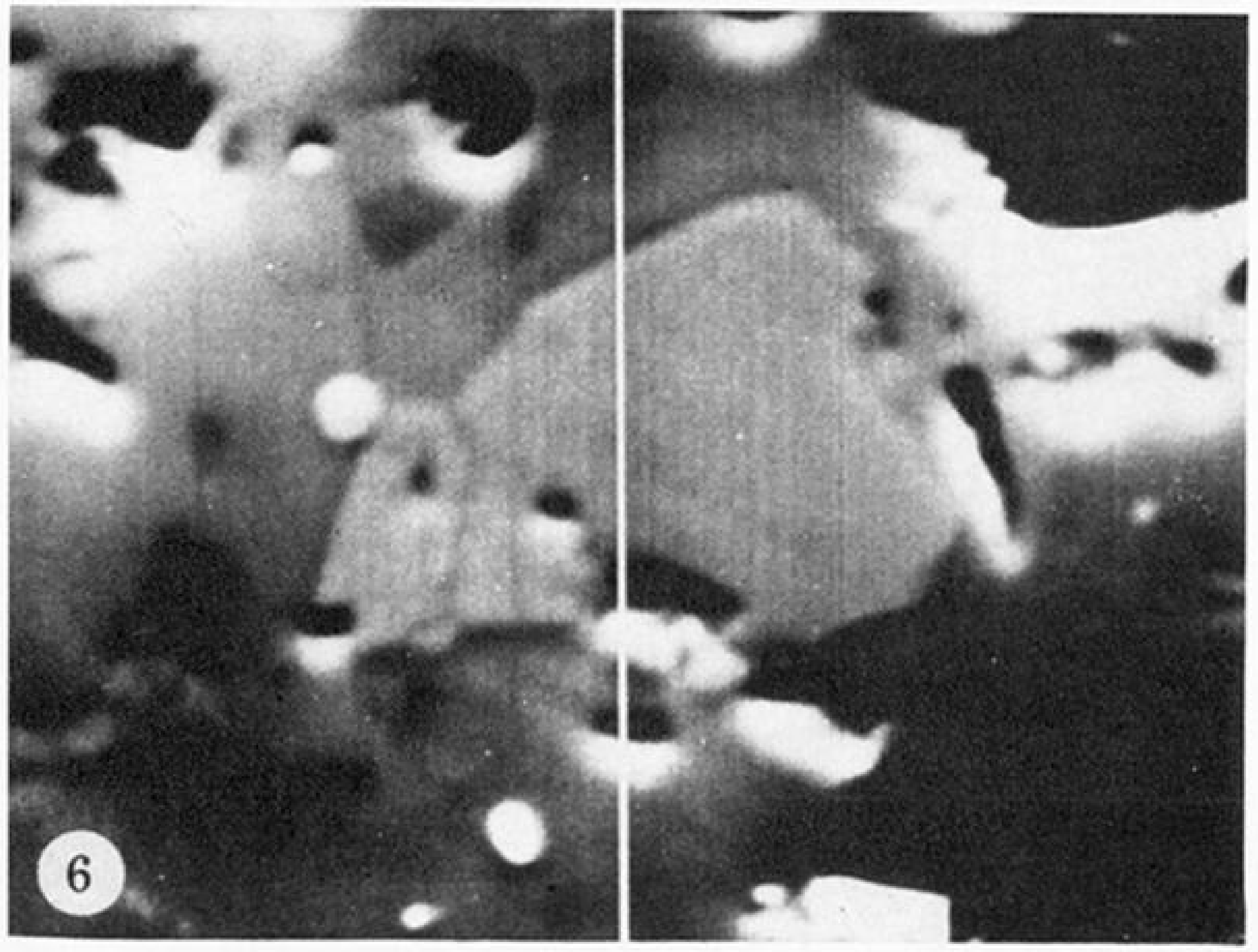

4(*a*)


4(*b*)


4(*c*)


4(*d*)


5


6

FIGURES 2–6. For description see opposite.