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IV. METEORITIC BOMBARDMENT OF THE MOON

The contribution of major impact processes to lunar crustal evolution†

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[Plate 1]

Large terrestrial impact craters provide structural models for the interpretation of lunar craters and basins and petrological data for comparison with complex lunar breccias. The terrestrial examples illustrate the mixing processes operative in the production of impact melts and breccias and the considerable volumes of impact melt rocks in large impact craters. Three forms of craters are found on Earth, Moon, Mars and Mercury: Simple bowl-shaped craters (smallest), central uplift, and ring structures (largest). The variations in form are interpreted as different degrees of gravitational modification which immediately follow the initial excavation. On Earth the transient cavity excavated has diameter/depth (D/d) near 3/1 in non-porous, essentially homogeneous rocks. From Orbiter and Apollo photographic data transient cavities in the most competent lunar materials have D/d of approximately 4/1. Experiments indicate ejecta come from as deep as two-thirds rds the transient cavity depth: disturbed material from greater depths remains as the crater lining. Application to the Imbrium basin indicates a portion of the ejecta at the Apollo 15 site may have come from as deep as 100 km, and from somewhat shallower depths at the Apollo 14 site. Ultramafic green and howarditic glasses are possible candidates for these materials of deep origin. Uplift of upper mantle in the centre of the basin would contribute to the Imbrian mascon.

Introduction

Accompanying the extraordinary advances in our knowledge of the Moon and inner planets through spacecraft investigations, there has been a growing appreciation of the evidence for major impacts of extra-terrestrial bodies with the Earth. The number of large impact scars recognized has been growing steadily since systematic searches began about two decades ago (Beals, Ferguson & Landau 1956), the rate of recognition having accelerated since shock metamorphism has been used as the principal criterion (French 1968). On the geologically better known continents the census of impact structures with diameter of 20 km or more and residual topographic expression is substantially complete (Millman 1971; Dence 1972). For such stable continental regions the impact record shows a size *vs.* frequency distribution and a rate of formation, at least since early in the Phanerozoic, comparable with those of the post-mare crater population of the Moon (Robertson & Grieve 1975).

The preserved terrestrial craters are much more degraded by erosion, filling and, in a few cases, tectonic activity than those of the Moon, Mercury or Mars. There is, however, the advantage of having craters of similar size eroded to different degrees so that observations on the various levels exposed, combined with diamond drilling investigations (Dence, Innes & Robertson 1968), permit composite models of crater structure to be developed. Such models form the

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framework for ideas about impact cratering mechanics and the effects of bombardment on different planetary bodies.

In addition, samples from the terrestrial craters have been used in the interpretation of extra-terrestrial specimens, including a number of lunar samples (Grieve, Plant & Dence 1974). Use of these analogues has led to an appreciation of the manner in which crater materials are mixed and of the production of considerable volumes of melt rocks in major impacts. These insights can be applied, for example, to the structure of major lunar basins and to estimates of the depth to which the lunar crust may have been disturbed by the basin-forming events.

Terrestrial craters and their structure

Photographs from Earth-orbiting satellites have given a fresh view of some of the striking circular structures of impact origin on Earth. Three of the most prominent occur in the eastern Canadian Shield. The Mistastin Lake crater in northern Labrador (figure 1, plate 1) is an approximately circular bowl about 28 km across with a distinct central peak rising above the lake which partly fills the crater (Taylor & Dence 1969). Although only 38 ± 4 Ma old (Mak, York, Grieve & Dence 1976), the crater is deeply eroded. The relatively few remnants of the rocks which lined the crater floor commonly are in a remarkably fresh state of preservation. The country rocks comprise a Middle Proterozoic igneous complex of adamellite, mangerite and anorthosite, of which the latter forms the central peak. These rocks have been mixed in varying proportions to form the breccias and melt rocks of the crater floor (Grieve 1975). Most of the melt rocks are distinctly feldspathic in composition and contain 20–40 % of clasts of the country rock. In texture they are closely analogous to the poikilitic feldspathic basalts which are prominent in Apollo 16 breccias and soils (Grieve *et al.* 1975).

Similar rocks are found at the larger Manicouagan crater in central Quebec (figure 2, plate 1). Whereas the Mistastin Lake crater is a good example of the central uplift form, Manicouagan has a more evolved ring structure of which the most prominent feature is the 60 km diameter peripheral trough of down-dropped rim material (Murtaugh 1972; Dence 1976). There is a central cluster of peaks of moderately shocked anorthositic rocks, surrounded by a plateau underlain by impact melt rocks with a present thickness of as much as 200 m. Although more completely preserved than Mistastin Lake crater, Manicouagan is 210 ± 4 Ma old, the age being based on K/Ar dating of the melt rocks (Wolfe 1972).

The transition from central uplift to ring structure form is neatly bridged by the striking crater pair of Lac à l'Eau Claire (Clearwater Lake), northern Quebec (figure 3, plate 1).

Description of plate 1

Figure 1. Landsat photograph of ice-covered Mistastin Lake crater, Labrador, taken in winter. Crater age 38 ± 4 Ma. Present diameter of basin 28 km. Note the island forming a modest central peak.

Figure 2. Mosaic of Landsat photographs of Manicouagan crater, Quebec. Age 210 ± 4 Ma. Present diameter of crater depression 75 km, within which lies the reservoir filling the peripheral trough. The inner plateau of melt rocks is strongly scoured by glaciation moving from north to south. The anorthosite massifs forming the central peak cluster are 15 km across and rise 300 m above the mean inner plateau level. There is a weakly defined outer fracture zone with a diameter of 150 km.

Figure 3. The crater pair of Lac à l'Eau Claire (Clearwater Lake), Quebec, photographed from Landsat. Age 285 ± 30 Ma. The craters lie within depressions 37 and 25 km across. The island ring in the west crater is 15–18 km in diameter and small islands in the centre form a subdued central peak. Drilling in the east crater penetrated a central uplift 120 m below the lake surface.

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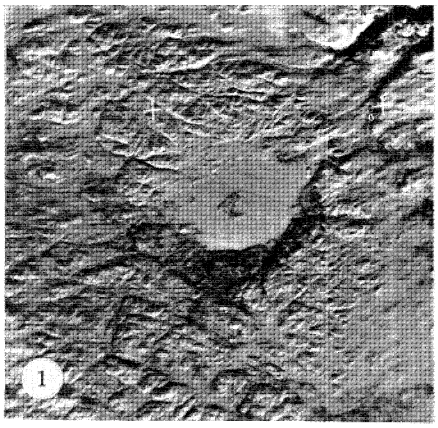

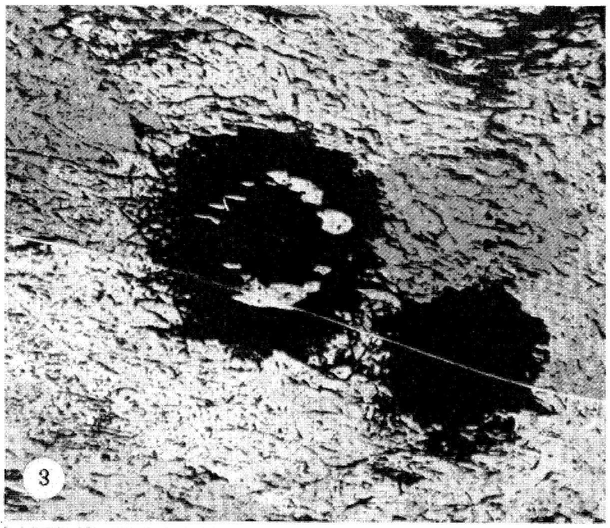

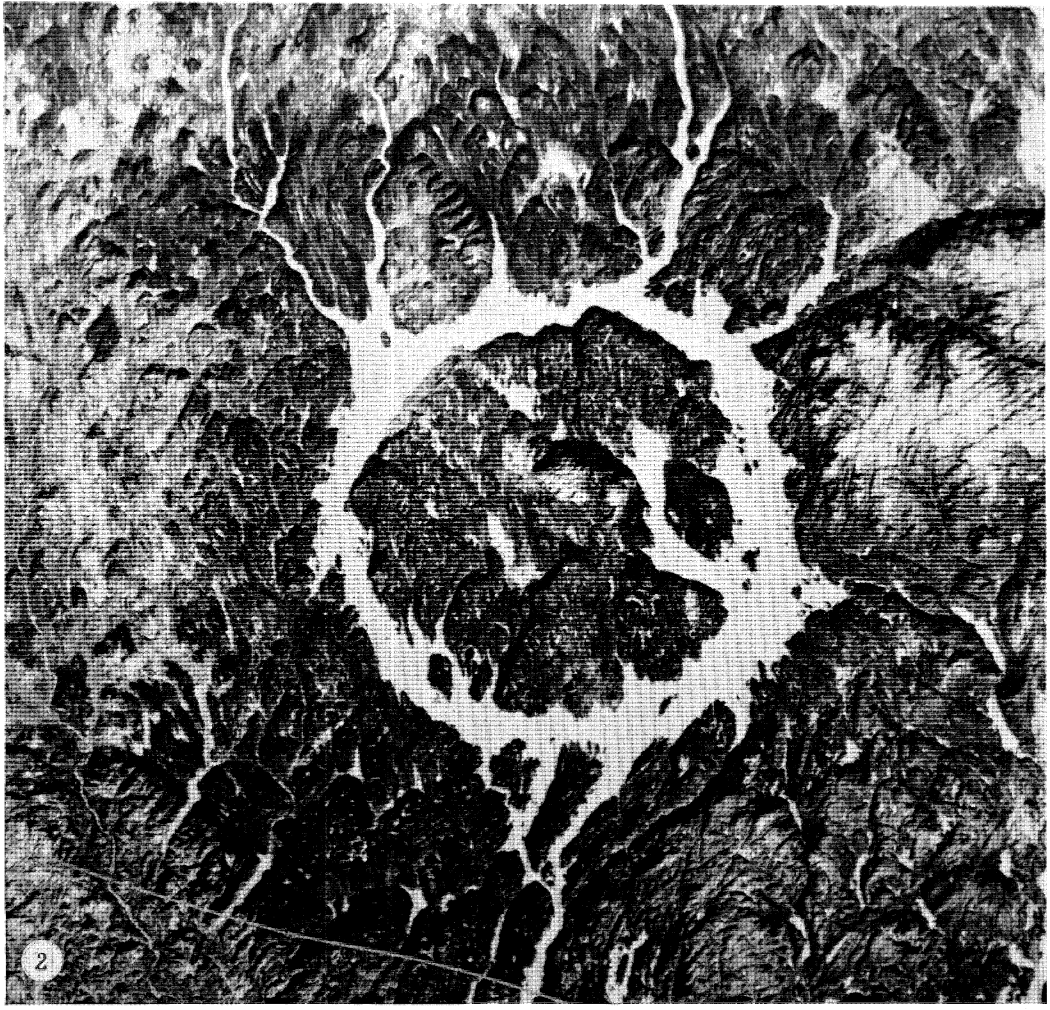

FIGURES 1–3. For description see opposite.

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Drilling has established that the smaller eastern crater has a submerged central peak and indeed is of the same crater type and almost the same size as Mistastin Lake (Dence 1968). The larger western crater has a ring structure similar to that of Manicouagan crater, though in this case the crater is more completely flooded, the central peak is almost submerged, and the impact melt rocks form the prominent inner ring. As there is little doubt that the craters were formed by simultaneous impacts into the same country rocks, Archean granites, gneisses and gabbros, it is clear that their difference in form must be largely a function of size.

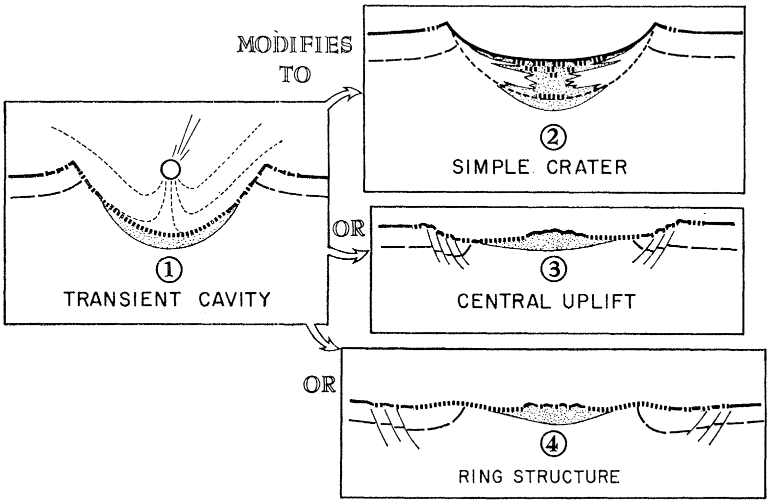

Figure 4. The main structural elements of the three alternative forms of hypervelocity impact craters formed in rocks of negligible porosity, and their relationship to the transient cavity or initial excavation crater. Rocks shocked to moderate pressures (5–30 GN m^{-2}) are stippled; more strongly shocked materials, predominantly glass-rich breccias and melt rocks, are represented by vertical bars. Dotted lines show typical trajectories followed by particles during excavation of the transient cavity. The dashed line represents an originally horizontal rock unit outlining the subsurface structure of each crater form.

As at Mistastin Lake, the melt rocks and associated breccias at Clearwater Lake and Manicouagan have compositions which can be closely matched by mixtures of the country rocks (Dence 1971). Except in the largest bodies of impact melt rocks mixing is incomplete. Processes of differentiation such as partial melting or crystal fractionation operate locally but are of negligible importance overall.

The consistent pattern of crater morphologies and structures found for these and other large terrestrial impact craters is summarized in figure 4. For craters formed in crystalline or non-porous sedimentary rocks the available evidence indicates that the transient cavity (initial excavation crater) which results from the direct action of the impact-generated stresses has a parabolic form in cross section with diameter/depth ratio near 3/1 (Dence 1973). Immediate modification under gravity results in one of three final forms: simple bowl-shaped craters similar to Barringer Meteor crater, central uplift structures and ring structures. The former have final diameters of 4 km or less, while the transition from central uplift to ring structures occurs at an apparent diameter of approximately 30 km. Note that in the craters with ring structure the final diameter is approximately twice that of the transient cavity and the layer of strongly shocked materials commonly laps over the collapsed rim and consolidates as a sheet of inclusion-bearing melt rock up to several hundred metres thick.

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At the laboratory scale late-stage modifications do not occur in hypervelocity impact craters (Gault, Quaide & Oberbeck 1968), so that the final forms of large natural craters cannot be duplicated in such experiments. Experimental craters also differ because spalling in hard rock targets and compaction in porous target materials produce relatively shallower profiles than those of the transient cavities of large natural craters. None the less, data on the depth of origin and distribution of ejecta can be applied to natural craters if differences in scale and in target properties are taken into consideration.

The depth of experimental craters produced in porous non-cohesive sand targets is half due to excavation and half to compaction (Gault *et al.* 1968). The deepest level from which ejecta originate is one-third of the total depth of craters formed in such materials (Stöffler, Dence, Graup & Abadian 1974). This is, however, actually two-thirds of the excavation depth and this 2/3 ratio is thus used for non-porous target materials for which compaction is negligible. Material from deeper levels together with that from the region directly below the point of impact, approximately 10 % of the volume ruptured and displaced during the excavation stage, remains within the crater to form a relatively thin lining of melted and brecciated materials. It is the remnants of this lining, for example, that underlie the inner plateau region at Manicouagan.

Lunar craters and basins

The three morphological varieties of terrestrial impact craters are immediately familiar to students of the Moon, who have long recognized simple bowl forms, craters with central peaks and terraced rims, and, in the large basins, concentric ring structures (Baldwin 1963; Pike 1967; Howard, Wilhelms & Scott 1974). These forms are also found on Mars and Mercury, and the characteristic diameters at which the transitions take place are scaled approximately in inverse proportion to the gravitational acceleration on each planet (Hartmann 1972; Gault *et al.* 1975). There is thus good reason to believe that the structural insights gained from terrestrial craters and from impact cratering experiments can be applied to craters on other planets.

In the absence of subsurface information, the shape of the transient cavity can best be inferred from simple craters with the smallest diameter/depth (D/d) ratio. With few exceptions these will be fresh craters formed in essentially homogeneous rocks of minimal porosity, as processes of degradation and factors such as inhomogeneity, porosity and lack of cohesion of target materials all tend to increase D/d. For the Moon the most recent data comes from the valuable compilation of measurements from Orbiter IV long-focus photographs by Arthur (1974) and from Apollo metric photographs by Pike (1974). As these authors point out, earlier measurements tended to underestimate lunar crater depths. The new data for simple craters less than 15 km across give an average D/d near 5/1, but in many cases D/d is approximately 4/1. A conservative view is that the latter group of craters has undergone little modification, so that $D/d = 4/1$ is a reasonable value for the transient cavities of craters formed in bedrock on the Moon.

A further factor influencing estimates of D/d arises from application of the fourth root gravity scaling relationship between crater size and kinetic energy of impact (Gault *et al.* 1975). The relationship gives good agreement when applied to comparisons between large fresh lunar craters such as Tycho, with terrestrial craters such as Manicouagan or the 95 km diameter Siberian crater, Popigay (Masaitis, Mikhaylov & Selivanovskaya 1971). If the fourth root

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relationship holds, then, for a given kinetic energy, approximately 2.5 times as much material would be ejected from a lunar crater as from a terrestrial counterpart. As the amounts of melt and moderately shocked rocks would be virtually the same, they would form a correspondingly smaller proportion of the total ejecta from the crater on the Moon than from the one on Earth.

These considerations may be illustrated by application to the Imbrium Basin. The model for the formation of Imbrium Basin depicted in figure 5 follows that of Dence, Grieve & Plant (1974) in most respects and, in final form, closely resembles the structure for Orientale of Howard *et al.* (1974). It differs principally from the former in the reduction of the size of the basin from the 1340 km diameter of Hartmann & Wood (1971) to 1140 km, following a reconsideration of its present morphology. None the less the transient cavity of the excavation stage is approximately 160 km deep and material following, for example, trajectory 3 could come from depths as great as 100 km. If the crust were 50 km thick at the time of impact, such material would be predominantly of lunar upper mantle composition. Moreover, at that time the lunar asthenosphere may have been at a depth of about 100 km. Thus with the addition of the heat deposited behind the shock wave, much of the ejecta from that level would be molten. As Dence *et al.* (1974) suggest, a possible candidate material for this ejecta is the green glass which is prominent in samples from some Apollo 15 stations.

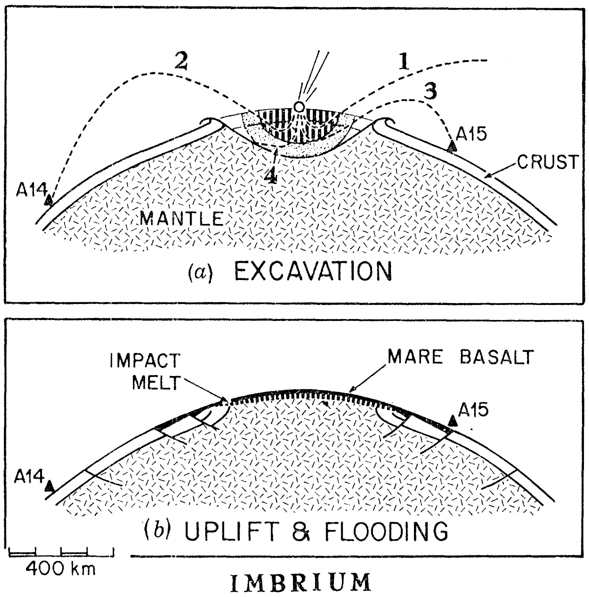

FIGURE 5. Model for excavation by hypervelocity impact and subsequent modification of the Imbrium Basin. The lunar crust is shown as 50 km thick. Shocked rocks and particle trajectories are as depicted in figure 4. Note the different proportions of crust to mantle materials for the different trajectories. Thicknesses of mare basalt and impact melt and lunar curvature are somewhat exaggerated.

They further suggested that the glasses of howarditic composition from the Apollo 14 site may also be Imbrium ejecta which, having followed a trajectory such as 2 (figure 5), would have a composition with a larger proportion of crust to upper mantle material than the material which followed trajectory 3. This idea is not supported by some of the age data for green glass clod 15426 (Podosek & Huneke 1973), although other age determinations appear compatible (Husain 1972; Lakatos, Heymann & Yaniv 1973). An alternative volcanic hypothesis places the depth of origin of the green glass at 250–300 km (Green & Ringwood 1973; Taylor &

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Jakeš 1974) but requires high levels of partial melting and presents certain mechanical difficulties for their ejection.

This generalized model for the Imbrium basin impact may be compared with other recent studies. O'Keefe & Ahrens (1975) have modelled the excavation stage by computer. Their model is in general agreement with that given here at the excavation stage, although the kinetic energy they infer appears to be low. On the other hand, there are substantial differences with the interpretation of Head, Settle & Stein (1975) who advocate shallower depths of excavation over a much wider area. However their model and the present one yield comparable volumes for ejecta deposited beyond the basin edge.

Conclusion

The basic similarities between shock metamorphosed structures on Earth and lunar craters and basins, as well as craters on other planets, find common explanation in the hypervelocity impact hypothesis. The model of crater formation favoured here involves relatively deep excavation where the target materials are coherent rocks, even for the large, basin-forming impacts. Immediate modification under gravity is responsible for structural modifications which result in central uplift or ring structures, the latter having twice the diameter of the initial transient cavity. The largest basins formed in areas with crustal thicknesses of approximately 50 km will have central uplifts of mantle material which would contribute to central positive gravity anomalies (mascons). Ejecta, and melt rocks lining the interior of the basin would be mixtures with a major component of upper mantle composition. Identifying such materials and unravelling impact mixing processes to identify possible primary components of the lunar highlands remains a task to which terrestrial crater studies can make a major contribution.

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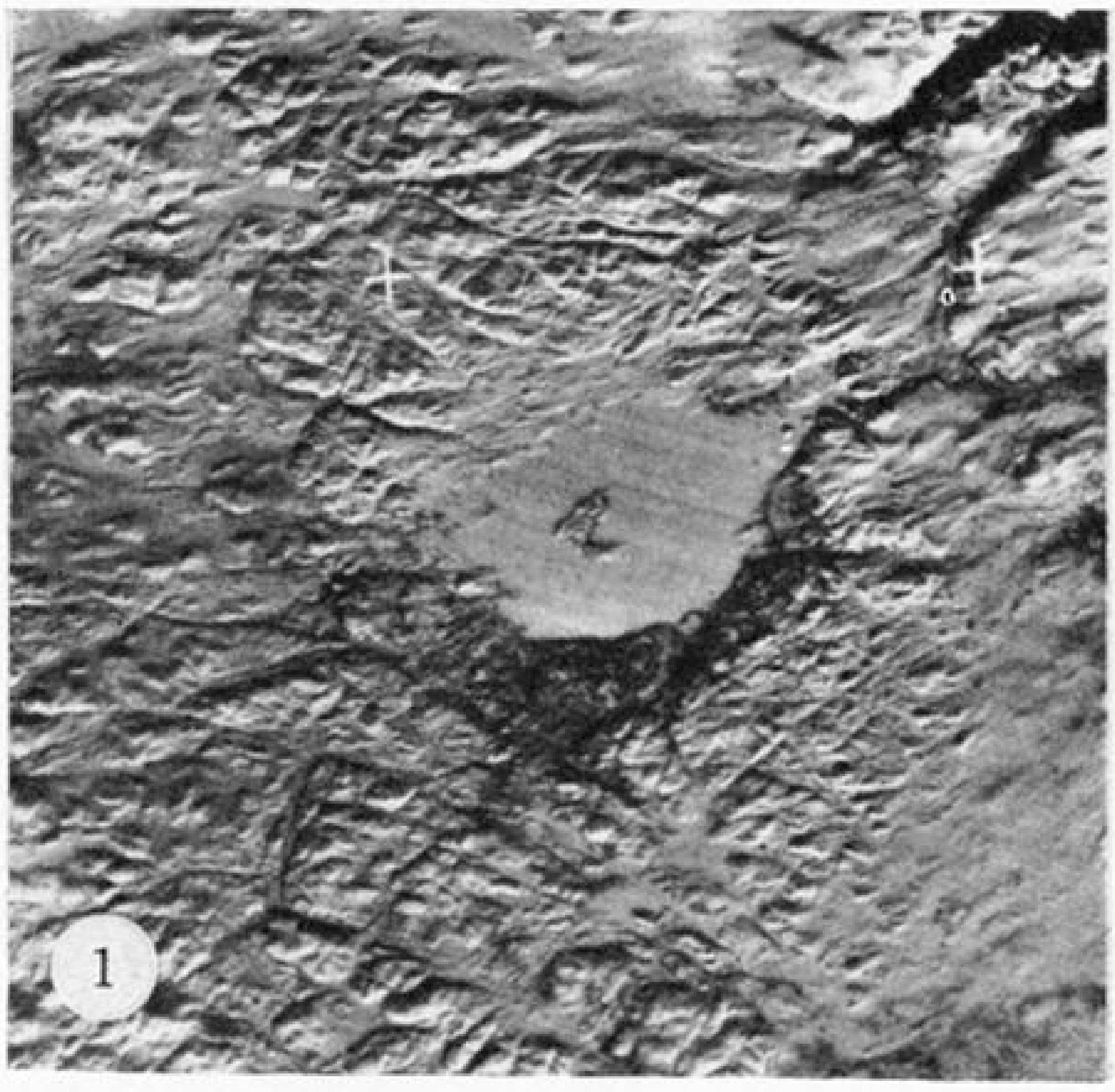

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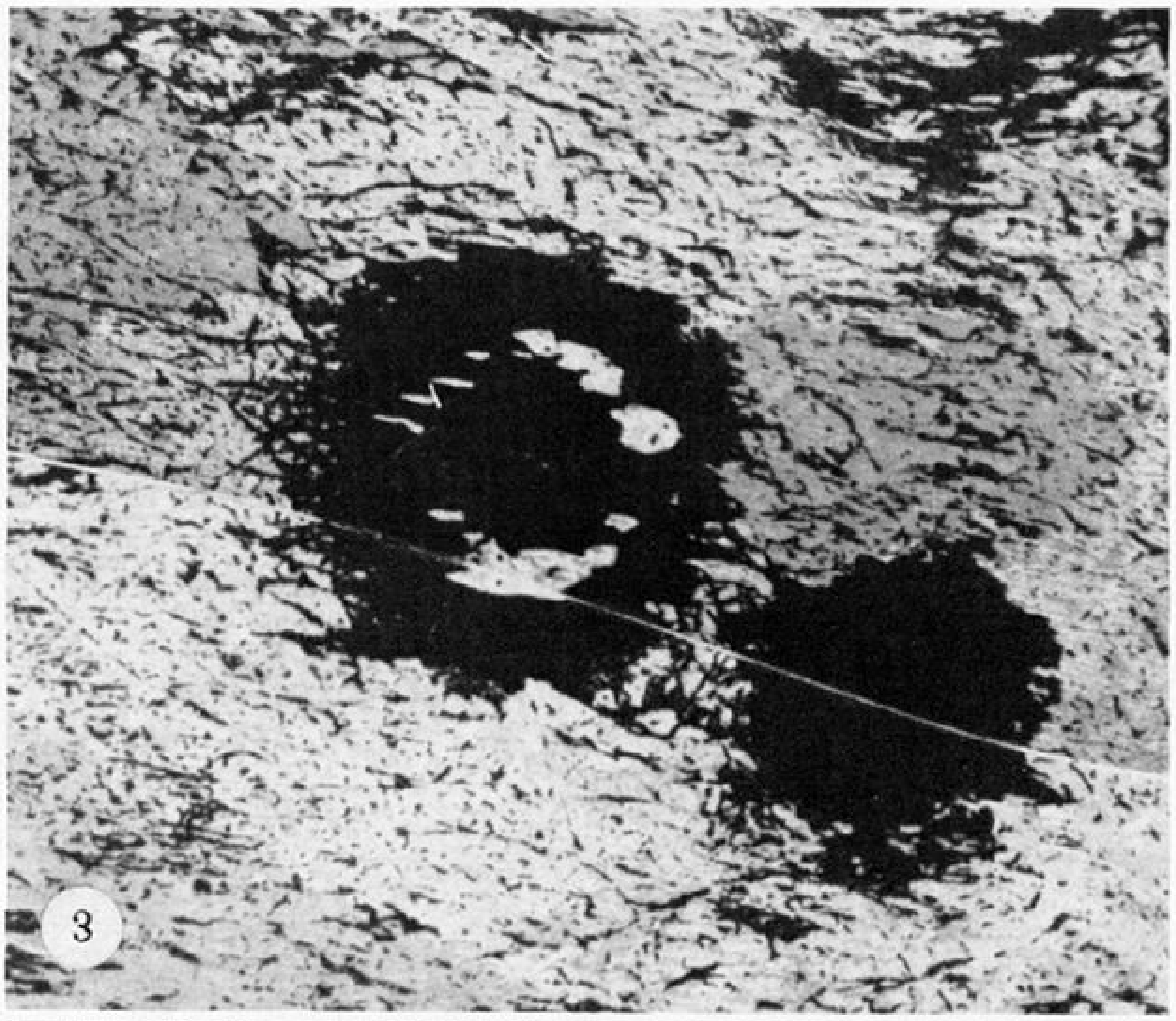

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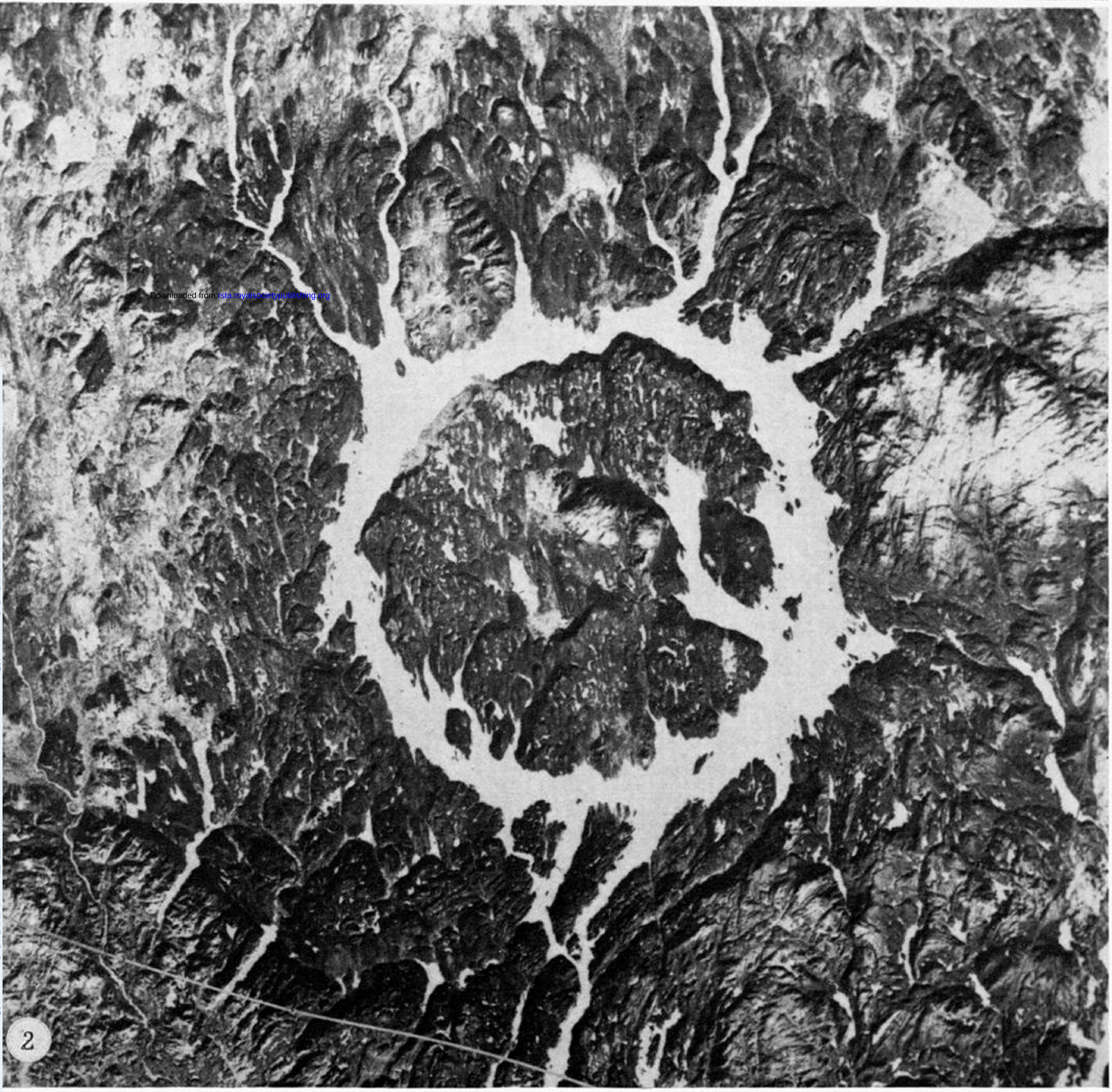

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