Lonar Lake, India: An Impact Crater in Basalt

Abstract. *Discovery of shock-metamorphosed material establishes the impact origin of Lonar Crater. Coarse breccia with shatter coning and microbreccia with moderately shocked fragments containing maskelynite were found in drill holes through the crater floor. Trenches on the rim yield strongly shocked fragments in which plagioclase has melted and vesiculated, and bombs and spherules of homogeneous rock melt. As the only known terrestrial impact crater in basalt, Lonar Crater provides unique opportunities for comparison with lunar craters. In particular, microbreccias and glass spherules from Lonar Crater have close analogs among the Apollo specimens.*

Lonar Crater, in the Buldana District of Maharashtra, India (19°58′N, 76°31′E), is an almost circular depression in the basalt flows of the Deccan Traps (Fig. 1). It is 1830 m across and is nearly 150 m deep; a shallow saline lake occupies most of the floor. Around most of the circumference the rim is raised about 20 m above the surrounding plain. About 700 m north of the rim is a shallow depression outlined by a raised rim 300 m in diameter (Fig. 1); this may be a second crater.

Lonar Crater is a unique feature in the extensive Deccan Traps, and its origin has been a topic of controversy for a century and a half. Most early investigators (*1*) ascribed it to some form of volcanic explosion or subsidence, despite its evident geologic youthfulness and the cessation of Deccan volcanic activity in the early Tertiary. Although as long ago as 1896 Gilbert (*2*) pointed out the similarity of Lonar Crater to the feature now known as Meteor Crater, Arizona, an impact origin has been considered only in recent years, based on the gross morphology (*3*) and the uniqueness and youth (*4*) of the structure. Breccia encountered in a shallow drill hole just below the lake sediments (*5*) and glass fragments found on the rim (*6*) have also been adduced as evidence for an impact origin (*7*). A comprehensive investigation, including geologic mapping, drilling, trenching, and geochemical (*8*) and geophysical (*9*) studies, is being conducted by the Geological Survey of India. Although this study is still in progress, the results thus far offer definitive evidence that Lonar Crater is indeed an impact crater.

Lonar Crater was formed in a sequence of horizontal basalt flows, each 10 to 30 m thick and separated by zones of weathering. As exposed in the crater walls the flows are upturned toward the crater with no obvious major tears or faults. Dips are generally moderate, except near the rim crest, where they commonly reach 90° or are overturned.

Three diamond drill holes (Fig. 2) were drilled from a barge in the lake. After penetrating about 100 m of the lake sediments, each returned cores of breccia composed of coarse blocks up to meters in size which are unshocked or only slightly shocked. Microbreccia, which contrasts strongly with coarse breccia, consists of fragments ranging in size from a few centimeters to submicroscopic, many of which show moderate to strong shock metamorphism. Microbreccia occupies the interval from 301 to 335 m in LNR 2 as well as narrow intervals in the coarse breccia above and veins in the bedrock below. In addition, zones encountered in all three drill holes from which little or no core could be recovered may be occupied by an unconsolidated variety of microbreccia. Strongly shocked breccia beneath weakly shocked breccia has been reported from the floors of two somewhat larger impact craters in Canada, Brent (*10*) and West Hawk Lake (*11*), and interpreted as a result

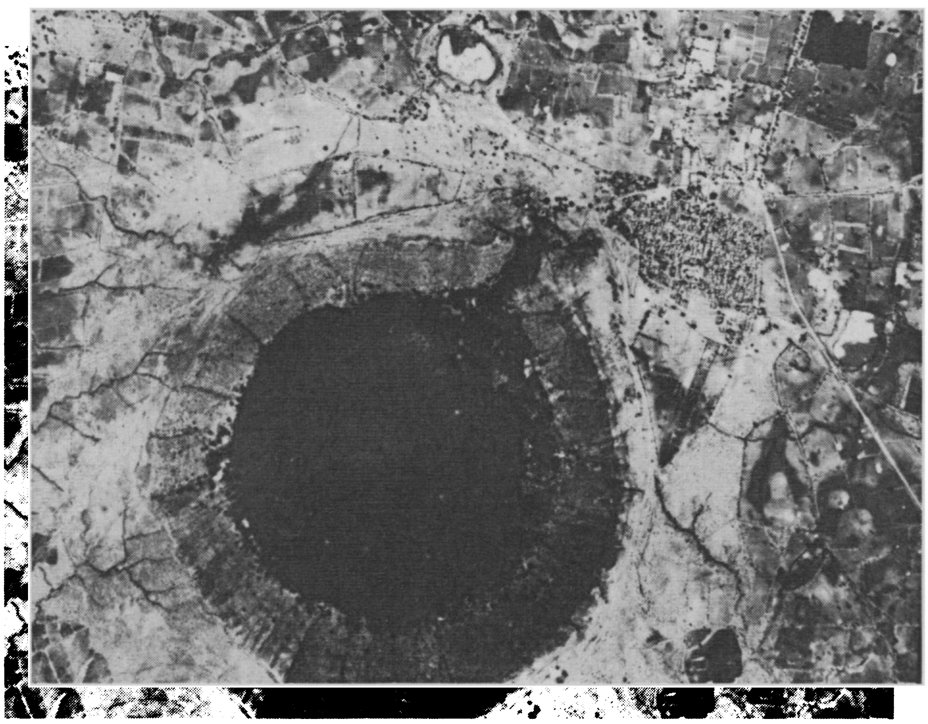

Fig. 1. Aerial view of Lonar Crater (diameter, 1830 m). The small (~ 300-m) depression to the north may be a second impact crater. Lonar village is on the northeast rim.

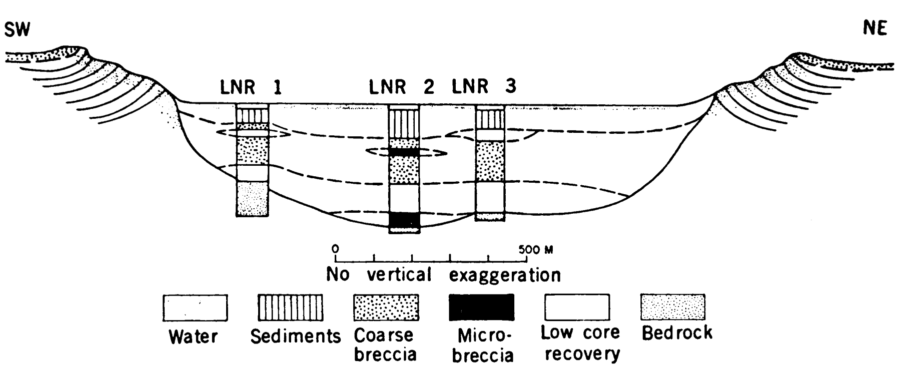

Fig. 2. Schematic section of Lonar Crater, geology based on surface exposures and diamond drill holes LNR 1, 2, and 3.

of slumping from the walls of the transient cavity. The three holes probably bottomed in bedrock, although it is difficult to distinguish coarse breccia from fractured bedrock.

The ejecta on the crater rim also consists of two contrasting types of debris. The great bulk is crudely stratified and shows no evidence of shock. Debris in which clasts from different bedrock units are mixed, and show all ranges of shock from none to intense, occurs as a discontinuous overlying layer reaching a thickness of more than a meter at some points and extending at least 550 m from the crater rim. The two units correspond to the "throwout" and "fallout" found on the rim of other well-preserved impact craters (*12*).

Coarse breccia shows little or no deformation on a microscopic scale, but the blocks exhibit crude shatter coning, a phenomenon diagnostic of impact structures. Individual fracture surfaces are only slightly curved, but where striations are present on several surfaces the assemblages describe cones. Fifteen striations on five surfaces measured on one 8-cm segment of core fit a cone with an apical angle of about 72°. Shatter coning of this type probably forms near the low end of the pressure range for shatter coning, about 30 kb (*13*).

Fragments in the microbreccia and in the mixed ejecta show microscopic deformation features characteristically developed by shock, as described from plutonic terrestrial rocks at impact structures (*14*) and basalts at nuclear explosion craters (*15*), as well as from lunar basalts (*16*). Shock metamorphism in clasts from the microbreccia ranges from none to moderately strong, whereas in the mixed ejecta it ranges up to intense (*17*).

Plagioclase grains in weakly shocked clasts (peak pressure, < 350 kb) show only irregular fracturing. In slightly more shocked clasts, plagioclase shows patches of reduced birefringence and occasional closely spaced "planar elements" (Fig. 3A). In moderately shocked clasts (350 to 450 kb), all the plagioclase has been transformed to maskelynite, completely isotropic glass (Fig. 3B). The perfect preservation of grain boundaries and of oscillatory zoning (marked by abrupt changes in the refractive index of the glass) indicates that transformation occurred in the solid state. Associated pyroxene grains are intensely fractured, and some show closely spaced twin lamellae, apparently shock induced. The most intensely shocked clasts (450 to 500 kb) in the microbreccia show moderately strong metamorphism. The rock texture is preserved, but oscillatory zoning has been erased and an incipient flow of plagioclase glass is indicated by the bending of laths (Fig. 3C).

Strong metamorphism (500 to 600 kb) is found only in clasts in the mixed

Table 1. Chemical composition (percentages by weight) of Deccan basalt and of Lonar and lunar impact glasses.

Oxide	Deccan basalt*	Lonar impact glasses		Lunar impact glasses	
		Fragment†	Spherules‡	Fragments§	Spherule ‖
SiO_2	50.56	51.6	47.7	51.1	50.0
TiO_2	2.78	2.9	2.3	1.7	1.9
Al_2O_3	12.79	13.7	13.3	15.9	15.9
Fe_2O_3	3.23				
FeO	11.28	13.8	16.0	10.5	14.2
MgO	5.40	5.4	6.8	4.5	7.6
CaO	10.29	9.7	9.5	10.1	10.6
Na_2O	2.55	2.2	1.8	1.2	0.3
K_2O	0.59	0.6	0.4	1.2	0.4
Sum	100.00	99.9	97.8	96.2	100.9

* Average of ten class A analyses (on a water-free basis; the sum includes 0.22 percent MnO and 0.31 percent P_2O_5) (*24*). † Average of the results for five spots ~20 μm in diameter. Electron probe analysis by C. E. Meyer, U.S. Geological Survey, Menlo Park, Calif. ‡ Average results for five spherules (Fig. 4). Electron probe analysis by N. Ware, Australian National University, Canberra. § Average of the results for six fragments, type 3b, Apollo 14 (*25*). ‖ Apollo 12 spherule [sample, table 2 in (*20*)].

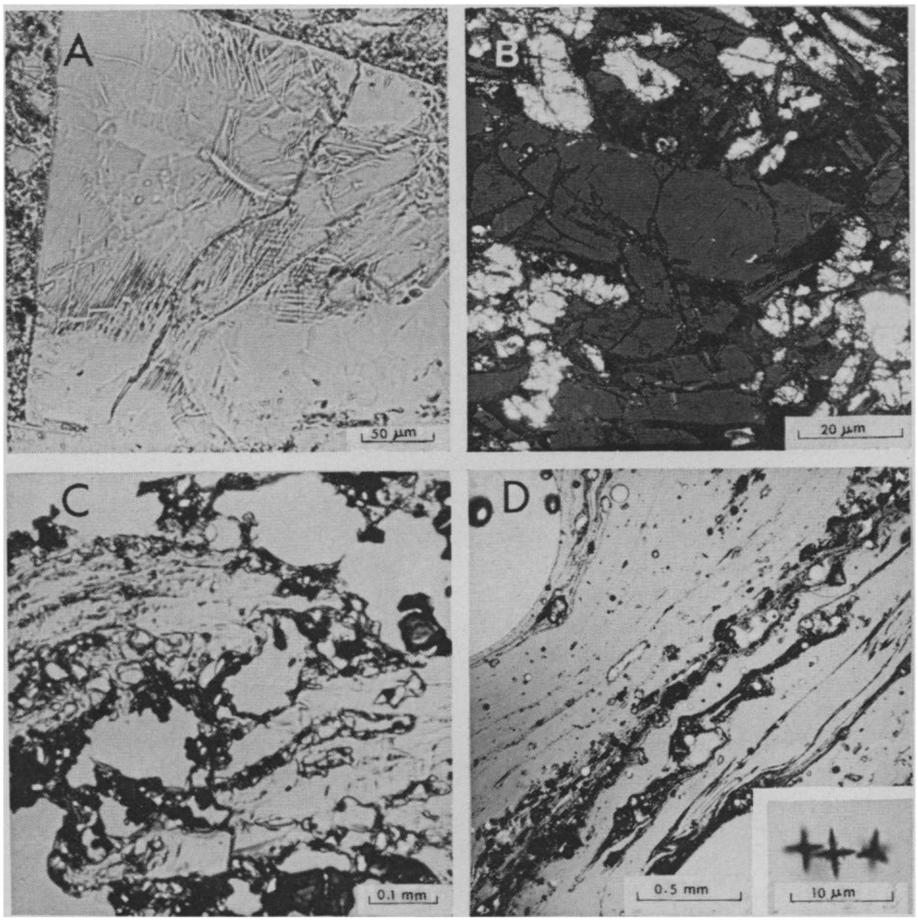

Fig. 3. Basalt from Lonar Crater showing the effects of increasing shock metamorphism. (A) Plagioclase grain in microbreccia showing planar elements. The birefringence is anomalously low and variable, but the entire grain is at least slightly anisotropic. (B) Moderately shocked basalt from ejecta clast. The pyroxene is white, maskelynite is gray (note zoning bands), opaques are black. Slightly uncrossed polarizers. (C) Strongly metamorphosed basalt from ejecta clast. Plagioclase laths are isotropic and show incipient flow, the pyroxene is partially decomposed, and some vesiculation has occurred. (D) Homogeneous glass with schlieren and trains of titaniferous magnetite crystallites (inset).

ejecta. In these, plagioclase glass is vesicular and shows definite flowage and some of the associated pyroxene has been altered to a fine-grained opaque mass. Such clasts are very friable and have a low density and a light gray color, apparently a result of intense fracturing as well as vesiculation.

Completely melted homogeneous black basalt glasses in the mixed ejecta are the product of intense shock metamorphism (> 600 kb). The larger pieces of glass, 10 or 15 cm in diameter, are flattened and wrap around underlying clasts like the Flädle of the Ries (*18*), an indication that they were soft when they landed. They invariably break when disturbed, perhaps a result of stresses induced by rapid cooling. The abundance of vesicles in the glass varies widely; commonly a dense outer zone encloses a vesicular core. Among the smaller particles, millimeters to micrometers in diameter, are spheres and droplets (Fig. 4) similar in appearance to lunar spherules and to microtektites (*19*). In thin section, the bulk of the glass appears a uniform brown, although some colorless and darker brown schlieren and partially melted mineral inclusions occur (Figs. 3D and 4). Flow-banding is indicated by contorted schlieren and by trains of minute cross-shaped crystallites, apparently titaniferous magnetite (Fig. 3D). Otherwise, crystals of new formation are restricted to unidentified microlites surrounding relict grains and to plagioclase inclusions which have recrystallized with a feathery texture. In Table 1 the composition of the Lonar impact glasses is compared with that of Deccan basalt. Analyses of two lunar glasses are also given (the parent materials for which may have been similar in composition to the Deccan basalt). Alkalies appear to have been depleted, particularly in the spherules. It has been suggested (*20*) that alkalies were lost by volatilization during the formation of some lunar spherules.

As the only known terrestrial impact in basalt, Lonar Crater provides unique opportunities for comparison with craters in the lunar maria and lunar samples of shocked basalt. All the petrographic features described above have analogs among the Apollo samples. The formation of spherules, apparently depleted in alkalies, is particularly significant. Lonar microbreccia, although entirely derived from ordinary, somewhat porphyritic basalt, contains apparently multigranular aggregates of more or less shocked plagioclase and plagioclase-pyroxene. This result suggests that one should exercise caution in accepting similar aggregates in lunar microbreccias as "anorthosite" or "norite" clasts (*21*). Likewise, the strong induration, the rounding of clasts, and flow texture in the fine matrix in microbreccia from a crater floor indicate that one should be cautious in interpreting similar textures in lunar microbreccia as evidence for transport by "base surge."

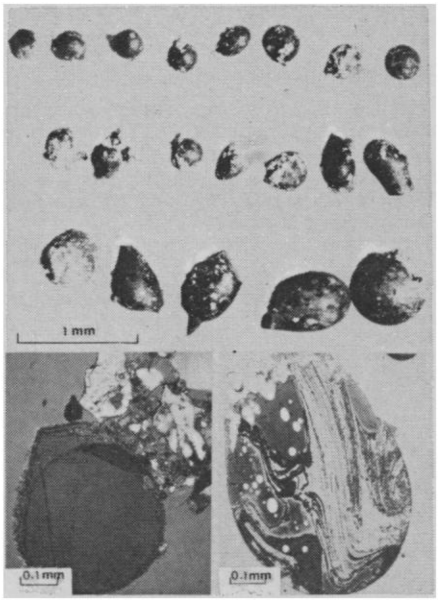

Fig. 4. Spherules of shock-melted glass from a trench east of the crater. (Top) Whole spherules; (bottom) thin sections of a homogeneous spherule attached to microbreccia containing both shocked and undamaged plagioclase (left) and a drop-like spherule with flow-banding (right). Note the similarity to lunar glass and microtektites.

Preliminary results of fission-track dating of shock-melted glass (*22*) indicate an age less than 50,000 years. The state of preservation is in accord with such comparative youthfulness and makes Lonar Crater a particularly rewarding site for studies of impact structure, petrography, and geochemistry (*23*).

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References and Notes

1. T. H. D. LaTouche and W. A. K. Christie, *Indian Geol. Surv. Rec.* **41**, 266 (1912).
2. G. K. Gilbert, *Science* (new ser.) **3**, 1 (1896).
3. C. A. Cotton, *Volcanoes as Landscape Forms* (Whitcombe and Tombs, Christchurch, New Zealand, 1944), p. 274; E. C. LaFond and R. S. Dietz, *Meteoritics* **2**, 111 (1964); T. P. Kohman, unpublished report, Carnegie-Mellon University, Pittsburgh, 1964.
4. K. Fredriksson and A. Dube, unpublished report, Geological Survey of India, Calcutta, 1968.
5. N. C. Nandy and V. B. Deo, *TISCO* **8**, 144 (1961).
6. G. P. L. Walker, unpublished report, Sagar Symposium, University of Sagar, Sagar, India, 1969.
7. The widespread distribution of glass fragments shown by V. K. Nayak [*Earth Planet. Sci. Lett.* **14**, 1 (1972)] was not confirmed by our investigations. Fragments of ancient artificial glass are abundant and may have been mistaken for natural glass. Electron probe analysis gave ~10 percent Na_2O, ~0.2 percent K_2O, and high concentrations of CaO and Al_2O_3, clearly indicating an artificial origin.
8. V. Venkatesh, *Geol. Soc. Amer. Bull.* **76**, 1315 (1965).
9. L. N. Kailasam, D. Gupta Saram, Y. R. Ghanumurthy, P. C. Das, unpublished report, Geological Survey of India, Calcutta, 1964.
10. M. R. Dence, in *Shock Metamorphism of Natural Materials*, B. M. French and N. M. Short, Eds. (Mono, Baltimore, 1968), p. 169.
11. N. M. Short, *Geol. Soc. Amer. Bull.* **81**, 109 (1970).
12. E. M. Shoemaker, in *The Solar System: The Moon, Meteorites, and Comets*, B. Middlehurst and G. P. Kuiper, Eds. (Univ. of Chicago Press, Chicago, 1963), vol. 4, p. 301.
13. D. J. Roddy and L. K. Davis, *Trans. Amer. Geophys. Union* **50**, 220 (1969)
14. E. C. T. Chao, in *Shock Metamorphism of Natural Materials*, B. M. French and N. M. Short, Eds. (Mono, Baltimore, 1968), p. 135; W. v. Engelhardt and D. Stöffler, *ibid.*, p. 159.
15. O. B. James, *Science* **166**, 1615 (1969).
16. E. C. T. Chao, O. B. James, J. A. Minkin, J. A. Boreman, E. D. Jackson, C. B. Raleigh, in *Proceedings of the Apollo 11 Lunar Science Conference*, A. A. Levinson, Ed. (Pergamon, New York, 1970), vol. 1, p. 287.
17. Stages of progressive shock metamorphism are those defined by James at the Danny Boy nuclear crater in basalt (*15*). Approximate ranges of peak pressure are based on the findings of D. Stöffler [*J. Geophys. Res.* **76**, 5541 (1971)].
18. F. Hörz, *Beit. Mineral. Petrogr.* **11**, 621 (1965).
19. B. P. Glass, *Nature* **214**, 372 (1967).
20. K. Fredriksson, J. Nelen, A. Noonan, C. A. Anderson, J. R. Hinthorne, in *Proceedings of the Second Lunar Science Conference*, A. A. Levinson, Ed. (M.I.T. Press, Cambridge, Mass., 1971), vol. 1, p. 727.
21. K. Fredriksson, J. Nelen, B. Melson, in *Proceedings of the Apollo 11 Lunar Science Conference*, A. A. Levinson, Ed. (Pergamon, New York, 1970), vol. 1, p. 419.
22. D. Lal, D. MacDougall, L. Wilkening, personal communication.
23. Core and trench samples are preserved by the Geological Survey of India, and requests for samples may be made to M.S.B. with appropriate statements of samples required and work proposed.
24. R. N. Sukheswala and A. Poldervaart, *Geol. Soc. Amer. Bull.* **69**, 1475 (1958).
25. J. Nelen, A. Noonan, K. Fredriksson, in *Proceedings of the Third Lunar Science Conference*, E. A. King, Jr., Ed. (M.I.T. Press, Cambridge, Mass., 1972), vol. 1, p. 726.
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