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The Dhajala meteorite[1]

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SUMMARY. The Dhajala meteorite shower, the latest recorded fall in India, comprises pieces fragmented near the lower limit of the break-up zone. The meteorite is a chondrite consisting of silica-rich chondrules making up to 34 vol.%, and fine-grained, Fe-Ni metal-rich groundmass admixed with a few irregular lithic fragments. Dhajala contains olivine of variable compositions, ortho- and clinopyroxenes, troilite, kamacite, taenite, chromite, and clear to opaque glass; magnetite occurs only in the fusion crust. The chondrules, which are of variable shape, mineral composition, and texture, represent different stages of quenching, leading to incomplete crystallization of minerals and some degree of disparity between norm and mode. Lithophile elements are less in Dhajala than in average chondrites. Two chemical analyses of Dhajala are presented and it has 27·10% total iron and 2·38% sulphur (maximum). Chemical and petrological data indicate that it is an H3 olivine-bronzite chondrite. Evidence for the crystallization of chondrules from melt is overwhelming. Some chondrules have been permeated by later troilite and NiFe from the groundmass, which might have crystallized directly from a gaseous environment.

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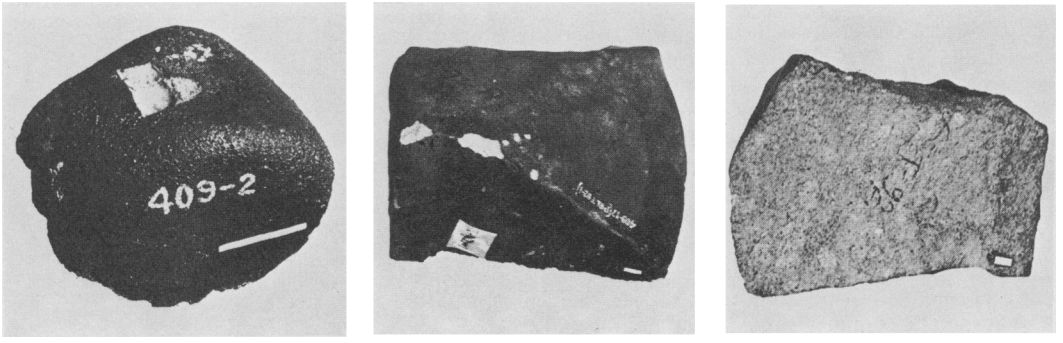
On 28 January 1976, a shower of meteorites, the latest recorded fall in India, took place around Dhajala (22° 22′ 40″ N.; 71° 25′ 38″ E.) in the Surendranagar district, Gujarat State, at about 20 hrs. 40 min. I.S.T. (15 hrs. 10 min. G.M.T.). The shower extended over an eccentric elliptical area having an 18 km-long major axis running NE.–SW., and comprised 300 fragments weighing 45 kg, with the single largest piece weighing about 12 kg. A piece of meteorite weighing 150 g. pierced through the clay channel roof of a hut hitting earthen vessels underneath. The circumstances of fall have been detailed by Bhandari *et al.* (1976).

Morphology. Of the 26 specimens examined, 8 are complete individuals, 4 small parts of individuals and powdery material; of the complete individuals, 5 are tetrahedral and 1 each cubic, pyramidal, and brick-shaped. Of the faces, 48 are complete, 49 incomplete; 2 faces are convex, the rest flat. Only 1 edge is sharp; 20 are slightly rounded and 5 much rounded. One specimen has a warty fusion crust, 9 a close-textured one, and 9 a knobby and ribbed crust. Regmaglypts are present on 5 specimens, and 2 are traversed by 1·5 to 4·5 mm wide bands.



FIGS. 1–3: FIG. 1 (*left*). Specimen No. 409-2. Shows rounded edges. Fusion crust is knobby, in places ribbed. Scale bar 1 cm. FIG. 2 (*centre*). Specimen No. 409-17. The largest specimen in the Geological Survey of India Collection (17 cm × 12·5 cm × 12 cm) shows prominent regmaglypts and faces of two generations. Scale bar 1 cm. FIG. 3 (*right*). Specimen No. 409-5. Fractured surface shows chondrules and specks of opaque minerals (dark-grey) and lithic fragments (light-grey). Scale bar 1 cm.

The polyhedral forms are sharply defined. Other than in two specimens with curved faces and rounded edges indicating somewhat oriented flight, the faces are mostly flat and edges only slightly rounded. Features of flowage and accumulation of material are absent. The fusion crust is generally close-textured, knobby and ribbed, and rarely warty. These features suggest that fragmentation took place near the lower limit of the break-up zone, not long before landing on earth. The fragments did not maintain the same orientation after fragmentation.

Mineral assemblage and texture. The Dhajala meteorite is an agglomeration of big and small chondrules and angular pieces set in a fine-grained groundmass. The minerals so far include olivine (forsterite to fayalite), orthopyroxene (hypersthene, near bronzite), clinopyroxene, colourless, brown or opaque glass with variable degrees of devitrification, doubtful cristobalite (based on X-ray studies) in a chondrule in association with hypersthene, and magnetite in the fusion crust. Plagioclases (An_{82} and An_1), native copper, ilmenite, chlorapatite, and tridymite (?) have been reported by Noonan *et al.* (1976).

Composition. ($\pm 5\%$) of olivine, as indicated by d_{130}, in chondrule and groundmass, varies widely in some specimens, but agrees well in others. The range is not always as restricted as observed by Noonan *et al.* (1976). Specimen No. 409-11 shows widest variation in composition of olivine between chondrule (Fa_0) and contiguous groundmass (Fa_{10}). Two more samples from other parts of the groundmass gave olivine compositions of Fa_3 and Fa_{16}. Specimen No. 409-4 shows better agreement in composition between groundmass olivine (Fa_{14}), olivine (Fa_{14}) in bulk, and olivine (Fa_{16}) in fine (less than 1 mm in diameter) chondrules. Groundmass olivine of specimen No. 409-13 has the composition of $Fa_{19\ 20}$.

Chondrule. Generally spherical, some of the chondrules are also elliptical, tear-drop like, or segments of spheres or ellipsoids. Rarely, these are highly fractured; the fractures do not necessarily continue beyond the chondrules. The chondrules vary in diameter from 0·07 mm to about 2 mm, average diameter being about 0·3 mm; they constitute about 24% to 34%, by volume, of the meteorite. Several types of chondrules are present:

Monosomatic olivine chondrules.

Polysomatic chondrules, composed of grains of olivine, pyroxene, metals, etc., of three types: Microporphyritic or granular aggregates of olivine and pyroxene mainly; generally, a coarse phenocryst of olivine not less than ten times larger than the surrounding finer grains occupies the central or near-central position in thin section, and the rest of the grains have seriately decreasing grain diameter from core to the margin; others are granular aggregates of euhedra and subhedra of olivine with or without pyroxene; aggregates of euhedra of olivine and radiating crystals of pyroxene also occur. Excentroradial chondrules are commonly of pyroxene and rarely of olivine, with one or more centres. Skeletal chondrules may be grated-olivine girders alternating with glass occupying the core, with peripheral envelope of granular olivine, or skeletal crystals of olivine in herring-bone pattern (fig. 4) and of pyroxene of swallow-tail pattern.

Vitreous and cryptocrystalline chondrules are of isotropic glass or glass with variable degrees of devitrification charged with crystallites, microlites, and skeletal crystals; they are generally brown, often opaque, and rarely clear and transparent. Chondrules with a core of devitrified glass rimmed by crystals of olivine, and with pyroxene prisms with interestices filled by devitrified glass intersertally also occur. In one chondrule barred olivine occurs bounded by a sharp outline on two sides of devitrified glass; the outline of the chondrule is undistorted and circular. It is difficult to judge whether the texture has resulted from direct crystallization from the melt or from remelting of earlier crystallized olivine.

Groundmass. The groundmass is composed of the same mineral assemblage with a larger proportion of metallic minerals, which occupy interstices between chondrules, fill fractures in olivine, are disseminated in the groundmass, and rarely form microveins.

Lithic fragments. Barring chondrules and the groundmass, the meteorite also contains lithic fragments and microliths of subangular outline and variable size. Some of these are chondritic. The

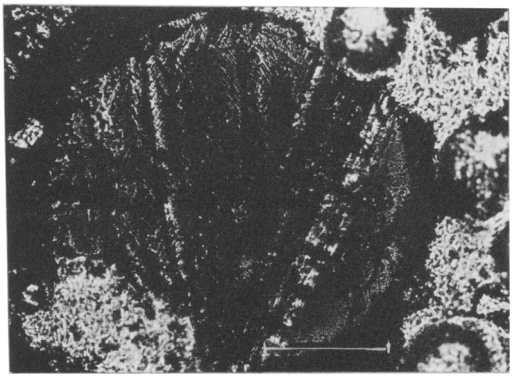


FIG. 4. Chondrule with skeletal, herring-bone-like crystals of silicate embedded in glass. Transmitted light. Scale bar 0·1 mm.

lithic fragments contain olivine, pyroxene, often polysynthetically twinned, opaque minerals, and glass, and are generally finer grained than the enclosing groundmass. In one lithic fragment of specimen No. 409-13, the composition of olivine in chondrules varies from Fa_{24} to Fa_{12}, whereas in the contiguous groundmass it is down to Fa_3. Some of the lithic fragments are holocrystalline; others contain fine crystals embedded in glass. Some have decidedly porphyritic texture with euhedral phenocrysts of olivine embedded in cryptocrystalline groundmass. Grain diameter is 0·3 mm at the maximum but generally less than 1 μm.

Impact features. Certain features of the meteorite indicate impact of component parts at different stages of its formation. These are: broken chondrules (some of the chondrules are apparently broken halves, with the other halves missing); fracturing, granulation, and melting of olivine to glass; and secondary twinning of pyroxene associated in places with the formation of glass.

The opaque minerals. These include kamacite, taenite and their intergrowth, troilite, and chromite, and are most abundant and coarsest in grain size in the general matrix. In NiFe grains, taenite commonly forms the outer rim with kamacite at the core. Troilite and NiFe occupy areas of irregular outline, at places extending up to chondrules, wrapping round and replacing them. In some specimens, microveins of troilite with maximum width of about 1 mm traverse the groundmass and, rarely, also fractured olivine chondrules. One or two troilite veins give place to NiFe veins at one end. Opaque minerals are much less abundant and finer in grain size in chondrules than in the groundmass. Fine dusty particles of troilite, with or without a little intergrown NiFe, are common; euhedral chromite is rare. In some chondrules, the opaque minerals are concentrated at the periphery. Larger areas and vein-like forms are rare. They also follow the cleavage planes of coarse crystals of pyroxene in the chondrules.

Characteristically, the opaque minerals in the chondrules occur embedded in glass (with or without skeletal crystals of silicates) occupying the interstices of coarse crystals of pyroxene and olivine. Where devitrified glass surrounds olivine crystals at the core, the opaque minerals are concentrated in the outer glassy zone.

In some chondrules in which skeletal crystals of silicates have been developed in glass as sheaves radiating in different directions, the grains of troilite and NiFe are concentrated along the line of contact of two sets of crystallites. 'Melting texture' (cf. Vogel, 1967, esp. fig. 20) of NiFe blebs in troilite testify to their separation as liquid soon after formation of the crystallites. In others, circular outline of NiFe embedded in hypidiomorphic granular aggregate of olivine indicates the presence of immiscible droplets of metal in the silicate melt of such chondrules.

In the 'soaking zone' (cf. Ramdohr, 1973, p. 67), troilite fills silicate-grain interstices and cracks forming a close network. Irregular blebs of NiFe in troilite, as in 'melting texture', are common and indicate eutectic crystallisation of troilite and NiFe from Fe–S melt. Part of the silicate-grain interstices is also filled by glass, in which roundish drop-like troilite indicates crystallization from immiscible sulphide liquid. Fractures in rare grains of chromite are also filled by troilite.

The outermost skin of the fusion crust is crowded with extremely fine skeletal crystals and octahedra of magnetite embedded in glass.

Chemistry. Two representative samples of the meteorite, one including fusion crust and the other excluding it, were subjected to wet chemical and spectrographic analysis (Table I); the methods used are described in the Appendix, p. M62.

The results of the chemical analyses agree well with each other, showing that the fusion crust does not make any appreciable difference in this respect.

Compared to average chondrites (cf. Krinov, 1960, p. 293; Mason, 1962, pp. 76, 148–82), the Dhajala meteorite contains more Fe, Ni, Co, S, and Cu and less SiO_2, Cr_2O_3, FeO, CaO, P, V, and Zr and slightly less of MgO and perhaps Ti; K_2O content is exactly the same as for H-group chondrites (Mason, 1962, p. 161). Lithophile elements are thus impoverished in this meteorite compared to average chondrites. Its FeO content of 10·30% is characteristic of olivine-bronzite chondrites (Mason, 1962, p. 89).

In calculating the mode some inaccuracy in the results is possible as the fine and cryptocrystalline phases could not be resolved enough for micrometric analysis. The disagreement between norm and mode (Table I) is likely to be due to crystallization of the minerals not proceeding to completion before quenching of part of the melt to glass, and part of the normative feldspar may be distributed otherwise, e.g. CaO, Na_2O, and Al_2O_3 in 'Ca-Al-Na rich inclusions' described by Noonan *et al.* (1976), Al_2O_3 in chromite and SiO_2 in cristobalite etc.

Classification. Dhajala is a chondritic meteorite, containing up to 34% by volume of chondrules and about 16% by volume of metallic minerals. Its chemical characteristics (total $Fe/SiO_2 = 0·74$; $SiO_2/MgO = 1·61$, sample 409-4, 1·60, sample 409-13; metallic Fe/total Fe = 0·55; $FeO/(FeO + MgO) = 20$ mol.%) place the meteorite in the H-group of Van Schmus and Wood (1967).

TABLE I. *Chemical composition, norm, and mode of the Dhajala meteorite*

	1	2
Metal		
Fe	14·92	14·80
Ni	1·65	1·65
Co	0·09	0·09
Sulphide		
Fe	4·10	4·20
Ni	0·06	0·06
S	2·38	2·37
Silicates and oxides		
SiO_2	36·60	36·40
TiO_2	0·11	0·11
Al_2O_3	2·82	2·80
Fe_2O_3	tr.	tr.
Cr_2O_3	0·25	0·25
FeO	10·30	10·30
MnO	0·20	0·20
NiO	tr.	tr.
MgO	22·75	22·88
CaO	1·90	1·70
Na_2O	0·97	0·97
K_2O	0·17	0·17
H_2O+	0·38	0·38
H_2O-	0·30	0·30
P_2O_5	0·19	0·19
C	0·23	0·17
CO_2	Nil	Nil
Sum	100·37	99·99

Norm	1	2
Nickel-iron	16·66	16·54
Troilite	6·54	6·63
Apatite	0·44	0·44
Chromite	0·36	0·36
Ilmenite	0·20	0·20
Forsterite	27·17	27·52
Fayalite	10·05	10·13
Wollastonite	2·25	1·83
Enstatite	17·62	17·44
Ferrosilite	5·91	5·81
Orthoclase	1·00	1·00
Albite	8·23	8·23
Anorthite	2·84	2·84
H_2O+	0·30	0·30
H_2O-	0·38	0·38

	1	2
Total Fe	27·10	27·10
Total Ni	1·70	1·70
Total Co	0·09	0·09
Total Cu	0·014	0·014

Mode	1	2
Metal	21·08	18·02
Troilite	8·08	10·61
Chromite	—	0·26
Glass	17·95	16·22
Olivine	33·41	29·42
Pyroxene	18·43	21·02
Others	1·05	4·45

Spectrographic data (p.p.m.) (anal. J. C. Pal and B. B. Dey).

	1	2
Cu	140	150
V	50	40
Zr	25	25
Ti	150	100

Zn and As < 200, Sb and Cd < 30, Ba < 20, Pb, Sn, Ga, Bi, Nb, and Sr < 10, Mo < 5, B < 2, Ag < 1 p.p.m. in both specimens.

1. No. 409-4, with fusion crust. Sp. gr. 3·65.
2. No. 409-13, without fusion crust. Sp. gr. 3·69.
Analyst: N. R. Sen Gupta.

The meteorite is further characterized by the following petrological features: Composition of olivine shows large variability with greater than 5% mean deviation. Low-calcium pyroxene includes both orthorhombic and monoclinic types. Coarse plagioclase is not discernible. Both clear and isotropic, and turbid glasses are present. Constituent metallic minerals include both kamacite and taenite. Chondrules are very sharply defined.

Some of these features are characteristic of more than one type, but taken together they place the meteorite in type-3 of Van Schmus and Wood (1967). Thus the Dhajala meteorite comes under H3 olivine-bronzite chondrite group.

Petrogenetic consideration. Varied shape, fabric, and mineral assemblage of the chondrules indicate their differing formation, cooling history, and composition. The fragmental nature of some indicates that they were broken before accretion. Spherical, ellipsoidal, and even tear-drop like shapes indicate that they had been molten drops before solidification and accretion. Existence of glass, melting texture of troilite-NiFe intergrowth, and globules of immiscible NiFe also testify the molten nature of the chondrules, at least at the last stage of their development.

Chondrules containing coarse euhedral and subhedral crystals of olivine and pyroxene appear to be products of a slower cooling rate than those with parallel and radiating crystallites. Those composed of glass and skeletal crystals are evidently quench products of pre-existing drops. The feathery and herring-bone-like crystals are similar to the quench crystals obtained in laboratory experiments, e.g. by Kushiro *et al.* (1968). In some chondrules, gradually decreasing grainsize from core to margin indicates gradually increasing cooling rate in the same direction. In others, made of glass, a darker ring

near the periphery suggests some amount of differentiation before quenching.

Crystallization of olivine started earliest as indicated by coarse phenocrysts of this mineral, by replacement of olivine by pyroxene, and by corona of pyroxene around olivine against fine-grained groundmass, suggestive of peritetic reaction between olivine and melt. Feldspar, perhaps, remained in embryonic or cryptocrystalline state in turbid glass, as coarse crystals of this mineral are absent. The metal and sulphide are confined to the residual glass and must have crystallized after the silicates.

It has been observed that olivine within chondrules and lithic fragments is richer in fayalite than olivine of contiguous groundmass. This is possibly derived by partially melting the groundmass of lithic fragments; the liquid of olivine composition will always be richer in fayalite content than the coexisting crystals of olivine. A fractionation of this molten liquid will give rise on crystallization to olivine richer in fayalite than the olivine remaining in the lithic fragment and the meteorite. Euhedral olivine and pyroxene with droplets of NiFe in a glassy groundmass have also been explained by Wlotzka (1969) as a product of partial shock melting of meteorites.

The fluidity of the Fe–Ni–S system is evinced in the groundmass by microveins of troilite and NiFe. The groundmass troilite and NiFe do not show melting textures, though they do within the chondrules and the soaking zone. It is possible that the troilite and NiFe of the groundmass have crystallized directly from gas, perhaps acquired from a S-rich atmosphere. Replacement of chondrules by troilite–NiFe and passage of NiFe vein to troilite vein support this view. Carter (1971) described mounds of Ni and P-rich Fe and FeS on glass silicate spheres from lunar soil samples and interpreted them as due to vapour deposition and subsequent growth. Theoretical studies by Vogel (1967) also suggest this as a possibility.

Melting of troilite and NiFe at the fusion crust is indicated by the features of the soaking zone, and oxidation of the metals in the outermost surface is indicated by the existence of magnetite.

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M62 Das Gupta *et al.*: The Dhajala meteorite (Appendix)

THE DHAJALA METEORITE

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Appendix: Procedure followed for the chemical analyses.

The determinations were carried out on eight portions out of 4 g of powdered material (-200mesh).

H_2O-, H_2O+, CO_2, and total C were determined by standard conventional methods on four separate portions.

Na_2O and K_2O were determined by atomic absorption after decomposing a portion with hydrofluoric and sulphuric acids.

For the determination of FeO, a portion was treated with bromine in anhydrous methanol for about ½hr at about 25°C, filtered, and washed free of bromine with anhydrous methanol, then washed with water. The residue was transferred to a quartz flask and treated with hydrofluoric and sulphuric acids in a CO_2-atmosphere; FeO was then estimated by dichromate titration.

Total sulphur, iron, nickel, and cobalt were determined in one portion. This was fused with sodium peroxide in a zirconium crucible, and the cooled melt leached with water and filtered. In the filtrate sulphur was determined as $BaSO_4$ after reducing chromate with alcohol and HCl. A correction for co-precipitated silica was made. The residue from the extraction of the melt was dissolved in dilute sulphuric acid and bulked to a definite volume. From this total iron, total nickel, and total cobalt were determined following the conventional procedure.

For the separation of the metallic, sulphide, and silicate plus oxide plus phosphate phases, one portion was first treated with ammonium mercuric chloride solution for about an hour at the boil in a carbon dioxide atmosphere, filtered, and the residue washed with water. The filtrate was bulked to a definite volume and served for determination of Fe, Ni, and Co in the metallic phases.

The residue from the mercuric chloride extraction was dried and treated with bromine in anhydrous methanol for about ½ hr at about 25°C, filtered, and washed with anhydrous methanol till free from bromine. The filtrates were evaporated to fumes after addition of 5 ml of 1:1 H_2SO_4, cooled, dissolved with water, and bulked to a definite volume. This solution served for the determination of Fe, Ni, and Co in the sulphide phase.

The determinations of Fe, Ni, and Co in both the above solutions were made by the methods of N.R.Sen Supta and A.N.Chowdhury (1974, 1976), which employ atomic absorption.

The final residue after the mercuric chloride and bromine-methanol extractions was ignited in a platinum crucible, then fused with sodium carbonate. The fusion cake was transferred to a platinum basin, dissolved in 1:1 HCl plus a little alcohol, and the solution evaporated to dryness and baked to render the silica insoluble; silica was then estimated as in silicate rocks.

Fe, Al, Ti, Cr, and P were precipitated with ammonia, using methyl red as indicator; a double precipitation was made. In the filtrate, manganese was precipitaed with ammonia and bromine, using ferric chloride as a carrier; the precipitate was dissolved in hydrochloric acid and the solution evaporated to fumes with sulphuric acid; Mn was then determined by the periodate method.

Calcium was determined in the filtrate obtained after removing Mn by double precipitation, as calcium oxalate, followed by permanganate titration. Magnesium was determined in the above filtrate by double precipitation as magnesium ammonium phosphate and weighed as magnesium pyrophosphate. The filtrate after removing manganese was used for Ni by the usual dimethyl glyoxime procedure.

The ammonia precipitate was fused with sodium carbonate, leached with water, and filtered to separate Fe and Ti from Al, Cr, and P. The residue from the leaching was dissolved in sulphuric acid and divided into two portions: in one iron was estimated with potassium dichromate after reduction with a silver reductor (total iron in the silicate-oxide-phosphate phases), in the other titanium was estimated colorimetrically with hydrogen peroxide.

The leachings from the sodium carbonate fusion of the ammonia precipitate were divided into three portions: in one Al was determined with 8-hydroxy quinoline, in a second Cr by redox titration with ferrous salt, and in the third phosphorous was determined by precipitation as ammonium phosphomolybdate and colorimetric determination.

The Fe_2O_3 of the silicate-oxide-phosphate phase was determined as the difference between the total Fe_2O_3 of this fraction and the Fe_2O_3 equivalent of the FeO determined as above.

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