MINERALOGICAL MAGAZINE, SEPTEMBER 1979, VOL. 43, PP. 423-7

The Rewari meteorite[1]

S. P. DAS GUPTA, P. R. SEN GUPTA, N. R. SEN GUPTA, D. R. DAS GUPTA, AND A. DUBE

Geological Survey of India, 27 Jawaharlal Nehru Road, Calcutta-700016, India

SUMMARY. The meteorite was an oriented polyhedron, which broke up into at least two parts after entry into the Earth's atmosphere. It has undergone some degree of terrestrial weathering. A cut surface of the meteorite shows light-grey interior with sporadic rusty-brown patches and a distinct brown alteration zone close to the fusion crust. Weathering has resulted in preferential replacement of NiFe by limonite, and veining of minerals by goethite.

Rewari is an equilibrated chondrite with rare ghosts of chondrules and at least one lithic fragment. Composition of olivine, as indicated by microprobe analysis is Fa_{23}, which agrees well with bulk wet chemical analysis; that indicated by d_{130} is Fa_{18-20}. From the outer surface inwards, four petrographic zones can be distinguished in the meteorite: a skin, about 0.01 mm thick, a troilite-poor zone slightly thicker than the skin, a troilite-rich 'soaking zone', about 0.5-0.6 mm thick, and a relatively coarse-grained interior. These are described in detail.

The interior of the meteorite is composed of relatively coarse-grained crystalline silicates with disseminated metallic minerals including plessitic and zoned intergrowths of kamacite and taenite. The matrix shows a high degree of integration with the chondrules. The coarse texture and zonation of taenite may be the result of protracted heat treatment responsible for recrystallization. The constituent grains show considerable shock effects such as fracturing, comminution, veins of shock-melted pseudotachylite, pressure twinning, and undulose extinction. Chemical composition (mean of two wet chemical analysis) of the meteorite is: metallic Fe 7.475, Ni 0.975, Co 0.045; as sulphide Fe 3.200, Ni 0.090, Co < 0.01; SiO_2 38.060, TiO_2 0.10, Al_2O_3 2.34, Fe_2O_3 0.175, Cr_2O_3 0.485, FeO 13.950, MnO 0.210, NiO trace, CaO 1.875, MgO 26.265, Na_2O 0.89, K_2O 0.115, P_2O_5 0.285, H_2O- 0.295, H_2O+ 0.81, CO_2 trace, S (total) 1.890, C (total) 0.19 per cent. The chemistry, mineralogy, and texture show that the Rewari meteorite is an L6 chondrite. Compared to average L-group chondrite it has a higher content of MgO and lower of SiO_2, a little lower oxidation state, and tends to be enriched in siderophilic elements.

THE Rewari meteorite was found by Edward A. Hopkins while he was in charge of the Indian Police of Gurgaon district, Haryana (then Punjab), India. To his recollection, the fall was in about July 1929, in a village about 96 km south of Delhi, near Rewari (28° 12′ N., 76° 40′ E.). The time gap between the dates of fall and collection is unknown.

Out of the complete meteorite weighing 3.332 kg, 1.658 kg and 1.277 kg were obtained by the University Museum, Oxford, and the British Museum (Natural History), respectively. In 1976, by courtesy of Mr Hopkins, the Geological Survey of India received 397 g of the meteorite and a fibre-glass replica of the stone before it was broken. It has been registered under number 410 of GSI.

Morphology. The original meteorite was polyhedral with a broad tetrahedral profile modified along one of the edges (fig. 1). The specimen studied, now in the GSI collection, is from the top of the tetrahedron. Barring the basal face all others show rounding of edges and rare shallow regmaglypts produced by ablation. The basal face if wavy and

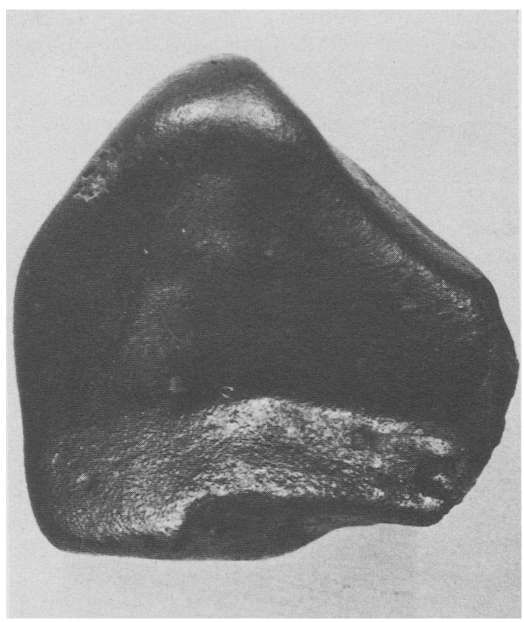


FIG. 1. Fibre-glass replica of the whole specimen of the Rewari meteorite showing morphology. Length of field 17.4 cm.

[1] Publication authorized by the Director General, Geological Survey of India.

shows flowage of fusion crust towards it indicating that it was the rear during the last stage of the flight of the meteorite; the smooth top of the meteorite was apparently the front. The morphological features suggest that the meteorite broke into at least two parts along what is now the basal face after its entry into the atmosphere of the Earth.

Mineral assemblage and texture. A cut surface of the meteorite shows light-grey interior with sporadic rusty-brown patches and a distinct brown alteration zone close to the fusion crust. The Rewari meteorite is holocrystalline and contains idiomorphic to xenomorphic grains of olivine, hypersthene, plagioclase, troilite, kamacite, taenite, plessite, and chromite. Composition of olivine as indicated by d_{130} is Fa_{18-20}. Microprobe analysis by F. B. Atkins (pers. comm.) gives a composition of Fa_{23} which is in good agreement with that obtained from the bulk chemical composition presented below. Well-defined chondrules and primary glass are absent, but rare areas of approximately circular outline with prominent boundary line in thin section, having grain size and texture different from that of the enclosing groundmass, testify to ghosts of pre-existing chondrules. Four petrographic zones can be distinguished in the meteorite, which are as described below.

A *skin* about 0.01 mm or so in thickness forms practically the outermost surface. The zone contains minute, twinned and untwinned discrete octahedra and dendritic crystals of magnetite embedded in glass. Whitish rim under reflected light around some of the crystals suggests further oxidation to hematite.

The next inner zone of about 0.5–0.6 mm thickness, is the *soaking zone* (Ramdohr, 1973, p. 67), which is characterized by first a troilite-poor zone and then a network of microveins of troilite filling fractures and silicate-grain interstices. Grain size of the groundmass here is finer than that of the interior. Veins of troilite pass uninterrupted through cracks in chromite. Roundish and irregular blebs of NiFe are commonly intergrown with troilite in the microveins. A similar intergrowth has been described by Vogel (1967, fig. 20) as 'texture on melting' and in the present case suggests eutectic crystallization of NiFe and troilite on melting. Within this zone there are also molten drops of troilite (fig. 2) embedded in glass, some of which have coalesced into a dumb-bell-shaped body. All these features indicate partial melting of troilite in the fusion crust and its invasion of the soaking zone. Coarse grains of troilite in this zone are free of pressure twins and undulose extinction common in grains of the interior. This is perhaps due to annealing at elevated temperature. The groundmass is made up of a xenomorphic granular aggregate of grain size finer than in the interior, indicating recrystallization. All these features, as well as the network of fractures, indicate heating of the soaking zone during atmospheric flight.

The soaking zone is followed inwards by a relatively coarse-grained interior composed of minutely fractured crystalline silicates with disseminated grains of NiFe, troilite, and chromite. Grains of chromite are particularly coarse (fig. 3). Grains of troilite and NiFe are of variable size and shape, and some are extremely irregular. These and clear plagioclase are interstitial to the larger olivine and pyroxene grains. The recrystallized matrix shows a high degree of integration with the chondrules. The chondrules contain olivine and pyroxene as major phases with relict barred or fan structure.

There are three textural types of NiFe grains, viz. zoned taenite (figs. 3, 4, and 5), plessite (figs. 3 and 6), and a combination of the two. In the zoned grains the outermost zone is of clear taenite, which is followed inwards by a sharp and narrow zone of dark-etched taenite. The interior, which forms the major part of the grain, is a more Fe-rich taenite. In some grains, the innermost part has broken down to plessite.

Shock and deformation features are particularly common in the interior. Grains of olivine are fractured and comminuted with the formation of veins of shock-melted pseudo-tachylite. Fracturing and pressure twinning of troilite are common with the development of undulose extinction (fig. 7) at places. The twin lamellae are of lanceolate shape and crowd in the area where fractures are more in number; undulose extinction is developed where fracture is absent. Elsewhere fractures extend from contact of chromite and olivine into the grains.

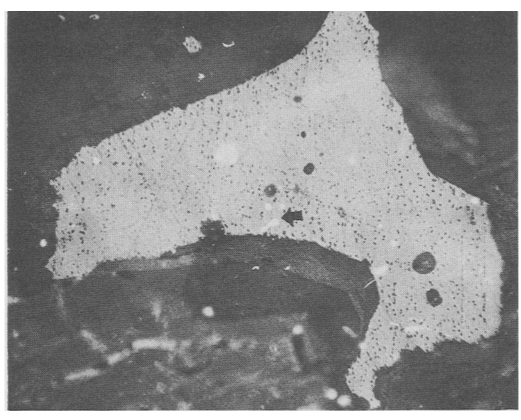
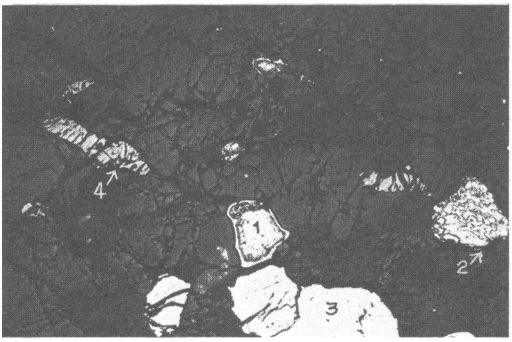
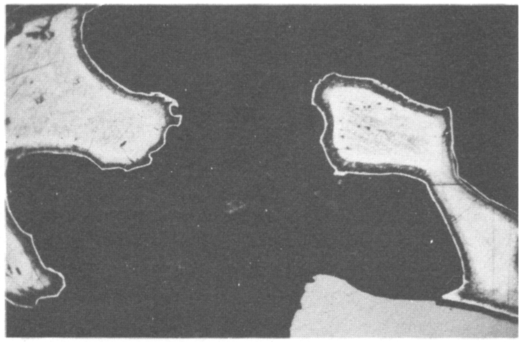
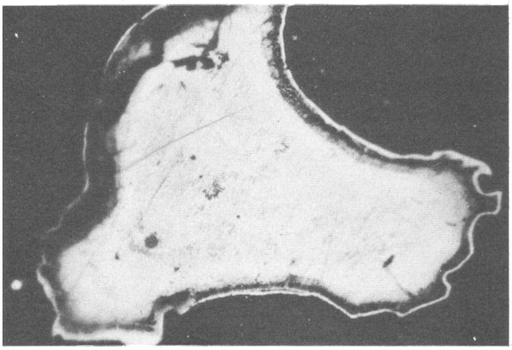
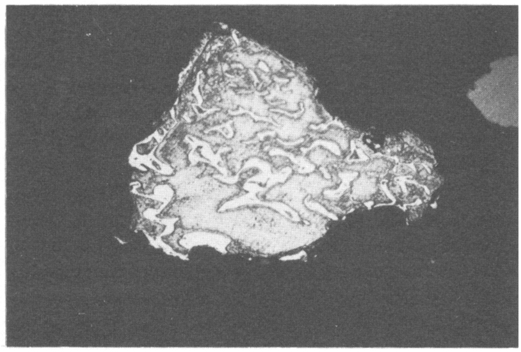


FIG. 2. Molten drops of troilite (white) in glass (light grey). Note coalescence of drops into a dumb-bell-shaped body (indicated by arrow). Length of field 0.2 mm. Reflected light.





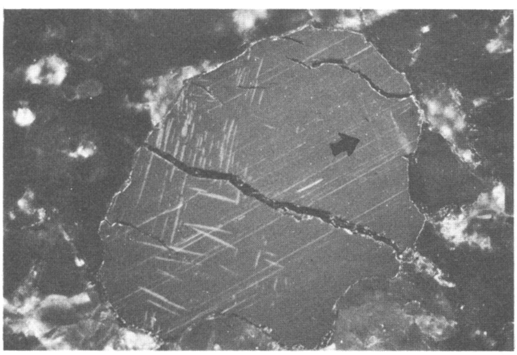


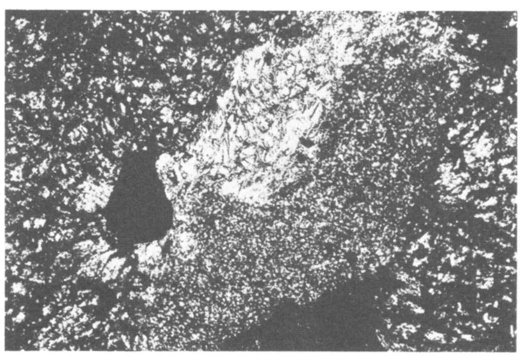


FIGS. 3–6: FIG. 3 (*top left*). Interior with zoned taenite (1), myrmekitic plessite (2), troilite (3) and chromite (4) in silicate groundmass (dark grey to black). Length of field 0.75 mm. Reflected light. FIG. 4 (*top right*). Zonation in taenite. The narrow, white rim is richest in Ni. The dark-grey background is of silicates. Length of field 0.48 mm. Reflected light. FIG. 5 (*bottom left*). Zoned taenite, further enlarged. Length of field 0.24 mm. Reflected light. FIG. 6 (*bottom right*). Cuneiform blebs of clear taenite (unetched white) in a base of iron-rich taenite (differentially etched grey to light grey); troilite (grey) at the corner. Length of field 0.24 mm. Reflected light.

An unusual lithic fragment in the meteorite (fig. 8) shows finely recrystallized pyroxene (?).

Weathering. The Rewari meteorite has undergone some terrestrial weathering. As a result, part of the NiFe has been preferentially replaced by limonite, and other minerals are veined and encircled by goethite. The alteration minerals include goethite and other oxides and hydroxides, indicated by associated rhythmic layers of various shades of grey and white under reflected light.





FIGS. 7 and 8: FIG. 7 (*left*). A grain of troilite (dark grey, central grain) with fractures, secondary pressure twins, and undulose extinction (marked by arrow). Surrounding grains (white to black) are of silicate minerals. Length of field 0.48 mm. Reflected light. X Nicols. FIG. 8 (*right*). Photomicrograph showing a recrystallized lithic fragment (?pyroxene). Length of field 1.03 mm. Transmitted light.

Transverse shrinkage cracks and rhythmic banding suggest colloidal precipitation of replacing limonite.

Chemistry. Samples from two different parts of the Rewari meteorite were subjected to wet chemical analysis for the major elements. For details of the analytical procedure followed, see Appendix, *Mineral. Mag.* 1978, **42,** M62. The results of analysis are presented in Table I. In comparison to average L-group chondrites (Mason, 1962, 1971), Rewari contains higher percentage of MgO and lower SiO_2, FeO, and sulphur.

Normative and modal compositions of the Rewari meteorite and the silicate composition, after deducting metal, sulphide, and apatite, are included in Table I. The silicate composition may be compared to the average of eight L-group chondrites given by Dube *et al.* (1977). The SiO_2 content is lower and MgO content is higher in Rewari than average L-group, being even below and above, respectively, the range of these oxides obtained by them. Comparison of bulk silicate compositions of L- and H-chondrites with FeO content normalized to the same led Dube *et al.* (pp. 79–80) to conclude that the silicates are chemically identical in these groups. In the case of Rewari, however, the lower SiO_2 and higher MgO contents remain, even when this meteorite is compared to

TABLE I. *Chemical analysis, norm, and mode of the Rewari meteorite: and composition of the silicate fraction*

	410(A)	410(B)
Metal		
Fe	7.85	7.10
Ni	1.18	0.77
Co	0.06	0.03
	9.09	7.90
Sulphide		
Fe	3.67	2.73
Ni	0.11	0.07
Co	0.01	0.01
S	2.18	1.60
	5.96	4.40
Silicates, etc.		
SiO_2	37.41	38.71
TiO_2	0.10	0.10
Al_2O_3	2.30	2.38
Fe_2O_3	0.15	0.20
Cr_2O_3	0.52	0.45
FeO	13.86	14.04
MnO	0.22	0.20
NiO	tr.	tr.
CaO	1.90	1.85
MgO	25.96	26.57
Na_2O	0.89	0.89
K_2O	0.12	0.11
P_2O_5	0.25	0.32
H_2O+	0.70	0.92
H_2O-	0.30	0.29
CO_2	tr.	tr.
C*	0.18	0.20
	99.91	99.53

	Norm			Mode
	410(A)	410(B)	Mean	
Metal	9.1	7.9	8.5	9.1
Troilite	6.0	4.4	5.2	6.2
Apatite	0.6	0.7	0.65	—
Chromite	0.8	0.7	0.75	0.1
Ilmenite	0.2	0.2	0.2	—
Orthoclase	0.7	0.7	0.7	
Albite	7.6	7.6	7.6	
Anorthite	1.9	2.1	2.0	
Feldspar	10.2	10.4	10.3	7.2
Wollastonite	2.0	2.1	2.25	
Enstatite	11.7	13.9	12.8	
Ferrosilite	4.6	5.4	5.0	
Pyroxene	18.7	21.4	20.05	26.3
Forsterite	36.9	36.4	36.65	
Fayalite	16.0	15.6	15.8	
Olivine	52.9	52.0	52.45	50.4
Hematite	0.2	0.2	0.2	0.7†
H_2O+	0.7	0.9	0.8	—
H_2O-	0.3	0.3	0.3	—
C	0.2	0.2	0.2	—

Composition of the silicate fraction

	410(A)	410(B)	Mean	Ave.‡
SiO_2	45.6	46.0	45.8	47.2
Al_2O_3	2.8	2.8	2.8	2.6
FeO	16.8	16.6	16.7	17.5
MgO	31.6	31.6	31.6	29.4
CaO	2.0	1.8	1.9	2.0
Na_2O	1.1	1.1	1.1	1.2
K_2O	0.1	0.1	0.1	0.1

Analyst N. R. Sen Gupta.
* Total C.
† Goethite.
‡ Average of eight L-group chondrites (Dube *et al.*, 1977).

the Cranganore and Mirzapur meteorites containing equal amounts of FeO + MnO (16.7% and 16.9%, respectively), as cited by them.

Classification. Rewari with indistinct but definite indications of pre-existing chondrules, is a chondrite. Average of the two chemical analyses given in Table I gives the ratios total-Fe/SiO_2 and metallic-Fe/total-Fe 0.56 and 0.34 respectively for Rewari, characteristic of L-group meteorites. Average SiO_2/MgO is 1.44, characteristic of C-group meteorites and rare in ordinary chondrites. Probe analysis of olivine gives Fa_{23}, typical of L-group. Considered together, these chemical characters indicate that the Rewari meteorite belongs to L-group of Van Schmus and Wood (1967), or at least, nearest to it.

Rewari has been affected by terrestrial weathering and part of its NiFe has been preferentially replaced by iron hydroxides. As such, its present metallic-Fe/total-Fe ratio does not reflect the original ratio. However, as the Fe_2O_3 and H_2O+ contents are not high, the degree of terrestrial oxidation-hydration is taken to be negligible. Lower C, S, and H_2O content of Rewari than even type III carbonaceous chondrites and presence of significant amounts of free nickel-iron and FeS preclude the possibility of its being a carbonaceous chondrite (Mason, 1962, pp. 96–8). Furthermore, Rewari is characterized by the following petrological features: composition of olivine is uniform; low-Ca pyroxene is orthorhombic; clear interstitial grains of polysynthetically twinned plagioclase feldspar are present; primary glass is absent; both kamacite and taenite are present; low content of Ni is present in sulphide; chondrules are poorly defined; matrix is recrystallized; bulk carbon content is less than 0.2% and bulk water content is less than 2%. Considered together, these features indicate that Rewari belongs to petrologic grade 6.

The mineral assemblage, FeO content of about 14% and total iron content of about 22%, relation of iron in metal + FeS and oxidized iron place Rewari among the olivine-hypersthene chondrites (Mason, 1962, pp. 78, 91). Mason (1962, p. 79) pointed out that all olivine-hypersthene chondrites are L type.

Discussion. In the Rewari meteorite, well-defined fusion crust, soaking zone, and core make the process of troilite veination understandable. The molten material produced at the fusion crust during atmospheric flight will be subject to oxidation at the contact with the Earth's atmosphere, as evinced by the formation of magnetite at places. The oxidation, by increasing the P_{O_2}, will tend to saturate the melt with respect to sulphur and precipitate iron sulphide, in this case, in liquid form with appropriate saturation temperature, P_{S_2} and P_{O_2}. The sulphide melt formed as immiscible liquid as is evident from the textural features described. The separating sulphide melt took also a little Ni and Fe in excess of S for FeS, which crystallized as NiFe blebs in troilite veins, perhaps eutectically. The separated FeS melt might fill the cracks already formed in the periphery of the meteorite by differential heating of the contiguous solid matrix, especially if the heavier FeS liquid could move centripetally with facility.

Rewari is characterized by higher content of MgO and lower contents of SiO_2, FeO and S compared to average L-chondrites, by coarse grain size of chromite, and by considerable shock effects in the core. The contents of Mg and S in Rewari lie between those of olivine-hypersthene chondrite and hypersthene achondrite. Compared to L-chondrite, it has a lower oxidation state and it tends to be enriched in siderophilic elements. The chromite grains are decidedly coarser than unequilibrated ordinary chondrites; the myrmekitic plessite (individual taenite blebs about 0.003 mm wide) is also coarser than plessite of other stones (taenite blebs about 1 μm or less in width, e.g. in Dhajala (H3), Estacado (H6), Mezo-Madaras (L3), etc., see figs. A16 and A17 of Ramdohr, 1973). The coarse texture, including that of the myrmekitic intergrowths, especially those involving troilite and plessite, may well be the effects of recrystallization. The protracted heat treatment responsible for recrystallization might have favoured the zonation of taenite so common in Rewari.

Acknowledgements. The authors' sincerest thanks are due to Dr F. B. Atkins, University Museum, Oxford, for making the result of electron microprobe analysis of olivine available.

REFERENCES

Dube (A.), Fredriksson (B. J.), Jarosewich (E.), Nelen (J. A.), Noonan (A. F.), O'Keefe (J.), and Fredriksson (K.), 1977. *Smithsonian Contrib. Earth Sci.* **19**, 71–82.

Mason (B.), 1962. *Meteorites.* John Wiley & Sons, New York.

—— 1971. *Handbook of Elemental Abundances in Meteorites.* Gordon & Breach Sc. Pub., New York.

Ramdohr (P.), 1973. *The Opaque Minerals in Stony Meteorites.* Elsevier Pub. Co., Amsterdam.

Van Schmus (W. R.) and Wood (J. A.), 1967. *Geochim. Cosmochim. Acta,* **31**, 747–65.

Vogel (R.), 1967. Ibid. 1181–99.

[*Manuscript received 31 May 1978; revised 23 November 1978*]