Bhawad L(LL)6 chondrite: Petrography and Mössbauer study

It is interesting to note that as many as five meteorite-falls, viz. Didwana[1], Lohawat[2], Devri Khera[3], Piplia Kalan[4] and Itawa Bhopji[5] have already been reported from Rajasthan within a short span of nine years[3]. We report here yet another meteorite fall that was observed on 6 June 2002 at village Bhawad (E 26°30′30″ : N 73°06′55″) in Jodhpur District, Rajasthan, India at 18.00 h IST (Figure 1). A lady from the Bhawad village witnessed the meteorite-fall. She did not notice any light, but saw a stone smashing onto the ground with roaring sound and raising dust. The direction from which the meteorite came, as shown by the lady, on measurement was found to be roughly 155°N. The meteorite initially weighed 678.10 g and measured 11 cm × 6 cm × 7 cm. The stone has well-marked thumb impressions with thin (1 to 2 mm) fusion-crust (Figure 2). A yellowish-grey inner surface is exposed on a portion of the stone due to removal of fusion-crust which gives the foetid smell of sulphur. One end of the stone shows a broken, rough surface covered with thinner fusion crust, indicating a probable breaking of the stone prior to its entry into the earth's atmosphere.

Microscopic examination of the Bhawad meteorite shows poorly discernible to discernible chondrules with ill-defined margins or ghost rims. The chondrules exhibit a variety of types and textures, the most common being barred, radial and porphyritic olivine and pyroxene (Figure 3). Most of the chondrules integrate with the matrix and at some places, are partially replaced by the matrix. Many of the chondrules are fragmented and fully crystallized; some are completely devitrified with virtually no glass.

Chondrules are set in an equigranular aggregate of equal amounts of olivine and orthopyroxene with minor amounts of troilite, other opaques, and twinned and untwinned plagioclase. The plagioclase is not lath-like, but granular in shape and sodic in composition (Figure 4). The opaque metal has concentrated along cracks or fractures and is seen flowing in the cracks, at places widening the cracks to a considerable degree (Figure 5). Limonite-staining is seen around metal grains.

Mössbauer analysis was done on a fraction of the Bhawad meteorite. The sample was ground to fine powder and about 70 mg was sandwiched between two transparent tapes to make the Mössbauer absorber. The Mössbauer spectrum of this powdered sample was recorded at 300 K using a conventional constant acceleration Mössbauer spectrometer with ^{57}Co in Rh matrix as the gamma-ray source. The spectrum was computer-fitted using a least squares routine and assuming it to be a sum of Lorentzian functions. During curve-fitting, the width and intensity of the two halves of a quadrupole doublet were constrained to be equal. The quality of fit was judged from the value of χ^2. The iterations were carried out till its minimum value was obtained. The isomer shift (IS) is reported with respect to α-iron. The reported values of IS and quadrupole moment (QS) have an accuracy of about 0.02 mm/s, whereas the hyperfine magnetic field *B* has an accuracy of about 0.2 T. The absorption areas have the accuracy of about 5%. The Mössbauer parameters

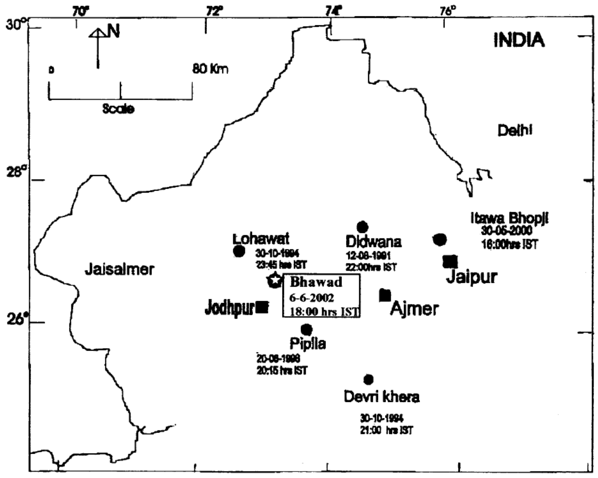

Figure 1. Location of the fall of Bhawad meteorite and five other meteorites which fell in Rajasthan during a span of 11 years (1991–2002).

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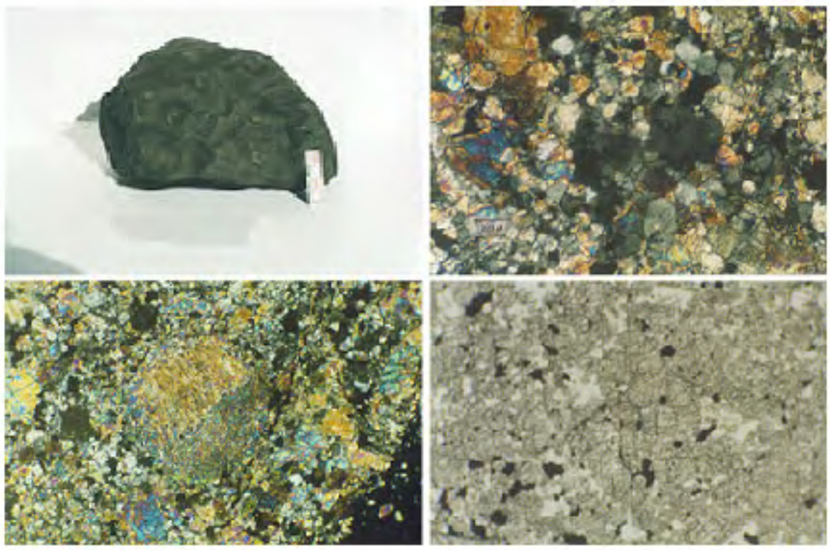

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Figures 2–5. **2**, Bhawad meteorite showing well-developed thumb impressions and broken rough surface covered with fusion-crust at the one end, indicating breaking prior to its entry into the earth's atmosphere. **3**, Photomicrograph showing barred, pyroxene chondrule. **4**, Photomicrograph showing twinned and untwinned grains of plagioclase feldspar along with olivine, polysynthetically twinned pyroxene and opaques. **5**, Photomicrograph showing flow of metal (the metal is devoid of iron) along linear cracks.

Table 1. Mössbauer parameters of Bhawad meteorite

Doublet/sextet	IS (mm s^{-1})	QS (mm s^{-1})	B_{heff} (kOe)	Relative intensity (%)	Assignment of iron in
Doublet	1.14	3.0	0	64	Olivine
Doublet	1.15	2.13	0	21	Pyroxene
Sextet	0.70	– 0.15	314	15	Troilite

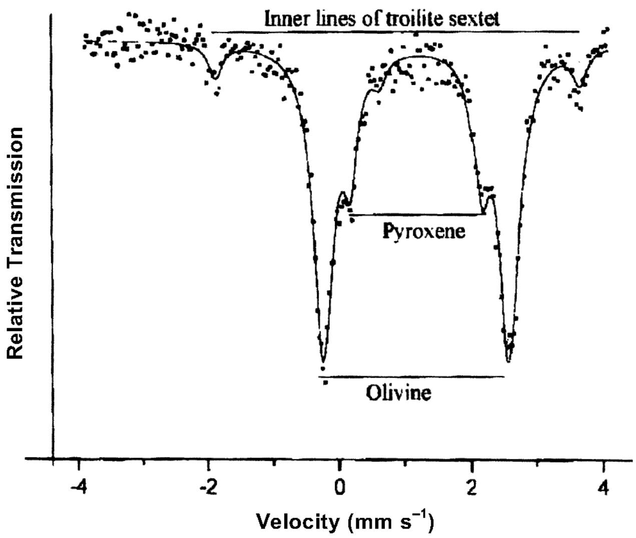

Figure 6. Mössbauer spectrum (low velocity) of Bhawad meteorite.

along with their assignments are given in Table 1. Mössbauer spectrum of the meteorite collected at room temperature is shown in Figure 6. We have displayed low-velocity spectrum for better resolution of pyroxene and olivine doublets. The outer peaks in Figure 6 correspond to the second and fifth peaks of troilite sextet. Note that the peaks corresponding to kamacite/metallic iron are absent.

The thin section and Mössbauer study show that the Bhawad meteorite contains chondrules and is composed of olivine and pyroxene, with minor amounts of troilite and plagioclase. These are essential constituents of L chondrites[6]. The poorly defined margins of chondrules, the absence of glass, their integration with the matrix, their fragmentation; the granular plagioclase; the exsolution lamellae in pyroxenes and flow of opaque constituents reveal that the Bhawad meteorite has suffered fracturing as well as metamorphism. At the same time, one interesting observation made from this study (Table 1) is the high olivine-iron to pyroxene-iron ratio in the Bhawad meteorite. The ratio of the absorption areas corresponding to these silicate phases is 3.0. For all other ordinary chondrites, this ratio is in the range of 1.4–2.3 (see refs 7 and 8 and also references therein).

While the pyroxene area in the Bhawad meteorite is comparable with several other chondrites, for instance, Dhajala[7], the olivine area is significantly higher than all other chondrites. The absence of metallic phase (metallic iron and kamacite) and unusually large amount of olivine shows that the Bhawad meteorite underwent severe oxidation converting the metallic phase (Fe^0) to ferrous phase (Fe^{2+}), which got incorporated in the silicate–olivine matrix. Rubin[9] made a similar interpretation for the presence of lesser amount of iron in ordinary chondrites. It is important to note that the Mössbauer study shows complete absence of metallic phase. However, under the microscope this meteorite shows a good amount of opaque metal. It is therefore, interpreted that iron has differentiated very early from the pre-planetary material. Secondly, this meteorite provides important information regarding primordial variation and fractionation mechanism of alkali elements. It seems that fractionation of alkali metals was almost simultaneous with that of iron. Formation of granular sodic-plagioclase further suggests that sodium fractionated before potassium.

Bhawad meteorite is L(LL)6 chondrite, as revealed by petrography and Mössbauer study. It is an unusual meteorite because of the following reasons.

(1) Absence of kamacite and iron in metallic phase. The metal visible in thin sections seems to be iron-deficient, undifferentiated metal.
(2) It shows fractionation of alkali elements.

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