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The Lohawat howardite: Mineralogy, chemistry and cosmogenic effects

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Abstract–The Lohawat meteorite is a texturally heterogeneous breccia having a variety of mineral and lithic fragments. Among mineral fragments, pyroxenes show a wide range of composition ($Wo_{0.011-0.17}En_{0.37-0.78}Fs_{0.21-0.60}$) whereas plagioclase is anorthitic ($An_{0.92}Ab_{0.07}Or_{0.007}$). Abundant rounded "chondrule-like" objects ranging in size up to ~7 mm, some with concentric layering, have been observed. Petrographic features, trace element composition and rare earth element patterns show the presence of eucritic and diogenitic components confirming that it is a typical howardite. Cosmogenic tracks, rare gases (He, Ne, and Ar) and radionuclides (^{22}Na and ^{26}Al) were measured. Track density in olivine and plagioclase varies between 0.7 to 6 × 10^6/cm^2. ^{38}Ar exposure age is estimated to be ~110 Ma, being the highest among howardites. The track production rates correspond to ablation of 9 to 15 cm, implying a radius for its preatmospheric size of ~27 cm. ^{22}Na /^{26}Al ≈ 1, as expected from the production models and solar modulation of galactic cosmic-ray fluxes before its fall, suggesting that the meteoroid did not undergo any fragmentation during the past ~2 Ma in interplanetary space. The radiogenic age based on K-Ar method is 4.3 Ga while the U-Th-^{4}He age is 3.3 Ga indicating partial loss of He.

FALL AND MORPHOLOGY

On 1994 October 30 at 23:45 I.S.T., a stony meteorite fell at Sohan Ram Meghwal's house near Chandra Nagar School, 5 km east of Lohawat village (latitude 26°57'56", longitude 72°37'36") in Jodhpur district, Rajasthan, India (Fig. 1). According to the eyewitnesses, the meteorite fall was accompanied by an orange and bluish trail and sound of breaking and blistering for about a minute. The direction of the trail was from the southwest to the northeast. The meteorite appears to be very fragile since it broke into several pieces on impact. The Geological Survey of India collected 6.245 kg, but this must be only a part of the recovered mass since the person who dug out the meteorite fragment from the crater estimated that the size of the meteorite was about a foot in diameter corresponding to a mass of ~40 kg. A few small pieces of the meteorite were recovered by us from the site of the fall. It is noteworthy that five meteorites Didwana (H5), Piplia Kalan (eucrite), Lohawat (howardite), Devri-Khera (L6) and Itawa Bhopji (L3/5) fell in Rajasthan during a period of 9 years (1991 August to 2000 May) within a small distance from each other (Fig. 1) and two of them, Lohawat and Devri-Khera, fell on the same day within 3 h.

The first report and major element chemistry of Lohawat has been published by Chattopadhyay *et al.* (1998) who classified it as a howardite. Here, we present a detailed chemical and mineralogical analysis as well as its cosmic-ray history based on the study of tracks, radioactivity and rare gases. Preliminary results were reported by Singh *et al.* (1998) and Mahajan *et al.* (2000).

The Lohawat meteorite is a heterogeneous breccia consisting of ash-grey finely pulverized matrix containing grey and dark clasts (Fig. 2). Apart from the common ash-grey lithology, a dark lithology which occasionally occurs in sharp contact with the common lithology (Fig. 3a) was also observed. It is referred as LB in the following discussion. Macroscopically, various types of lithic clasts are found to be embedded in the meteorite mass. Chattopadhyay *et al.* (1998) reported clasts of chondrules, minerals and rocks with the matrix to clast ratio of 60:40. According to them, among the various types of clasts, mineral clasts are abundant (31% having 2% opaques) while rock clasts, lithic clasts (8%) and clast chondrules (2%) are rare. We have not observed any chondrule clasts as reported by Chattopadhyay *et al.* (1998), though some round "chondrule-like" objects ranging in size from 1 to 7 mm, similar to those reported by Olsen *et al.* (1990) in howardites,

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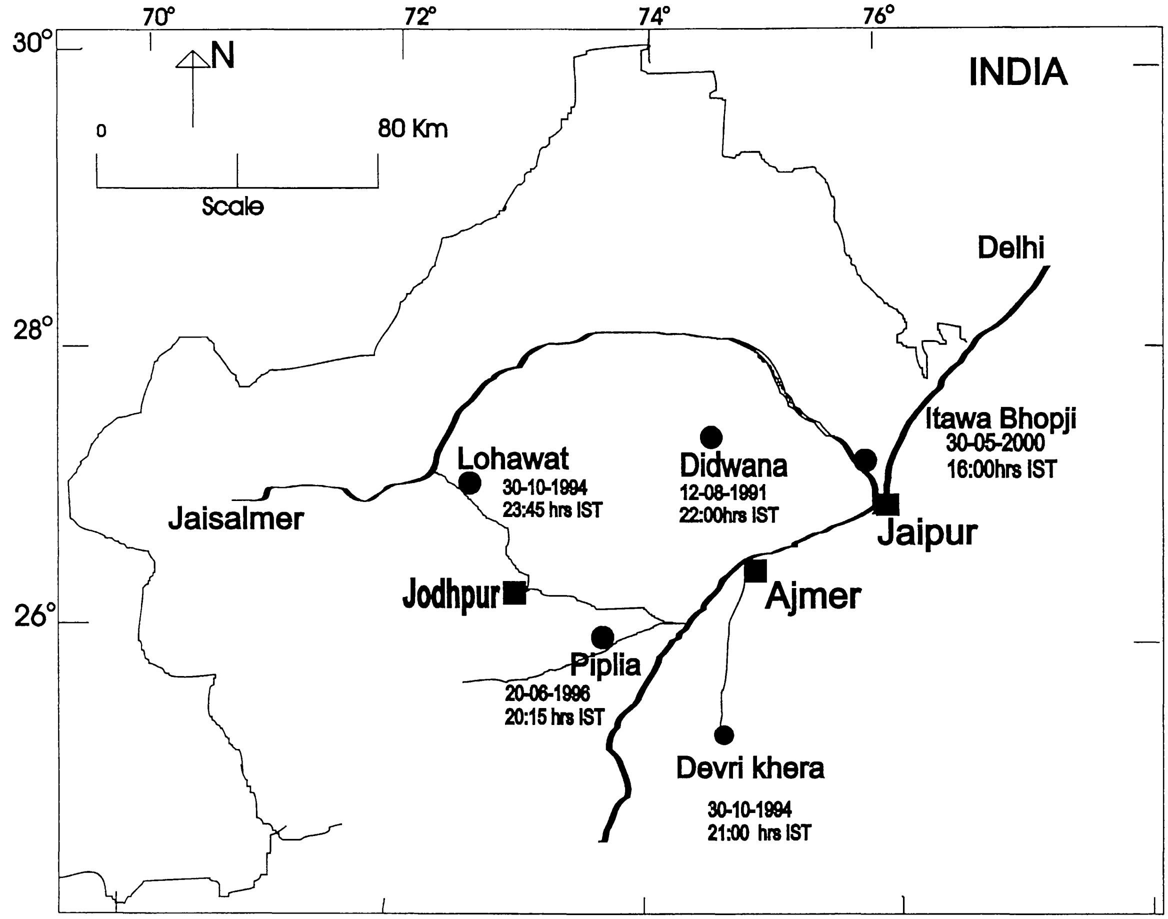

FIG. 1. Location of fall of the Lohawat howardite and four other meteorites which fell in Rajasthan, India in the span of 9 years (1991–2000).

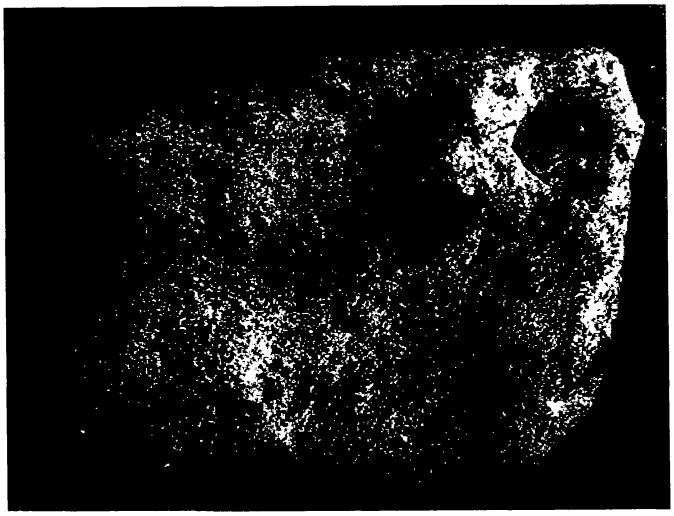

FIG. 2. Photograph of the Lohawat howardite showing brecciated texture and coarse pyroxenes. The angular to subrounded lithic clasts and mineral clasts embedded in fine ground grey matrix can be seen. The bar is 1 cm.

have been found. They are of two types: glassy balls (Fig. 3b) and round objects (Fig. 3c,d) with concentric layered structure. Figure 3c shows a round object with a crater-like feature, which might have been formed by an impact on this object that later got trapped inside the Lohawat meteorite. The crater morphology is however not similar to the micrometeorite craters observed by Brownlee and Rajan (1973). Most of these round objects are metal poor and pyroxenitic.

TEXTURAL AND MINERALOGICAL DESCRIPTION

Microscopic examination of Lohawat reveals three main lithologies. Based on their texture, colour and hardness they are classified as type I, II and III. Type I lithology is ash grey with fine-grained powdery texture containing angular fragments and forms the bulk of the meteorite (Fig. 4a). X-ray diffraction (XRD) studies made using a Philips x-ray diffractometer with a copper Kα source and Ni filter (at 35 kV and 25 mA current) on powdered bulk sample shows peaks of anorthite, clinopyroxenes and chromite in this lithology. Type II (LB) is a dark grey glassy lithology containing partially molten and recrystallised friable fragments which in thin section exhibit eucritic texture and mineralogy (Fig. 4b). The

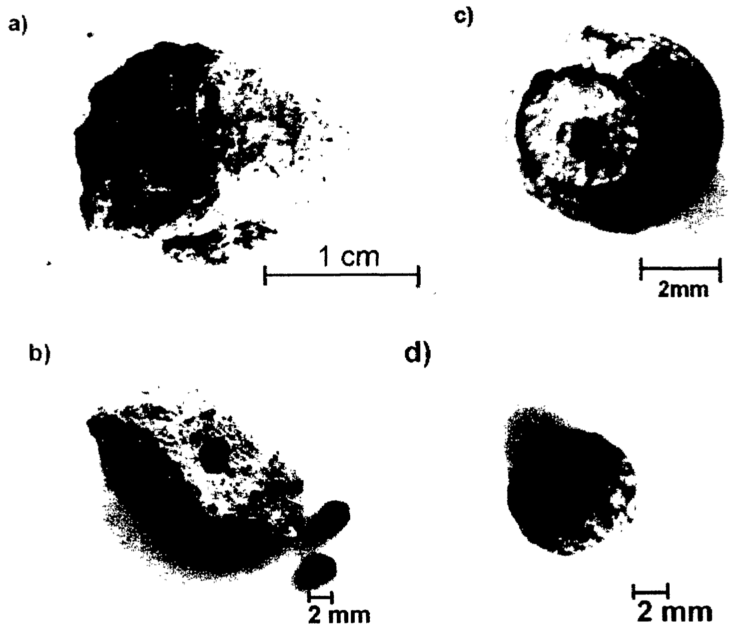

FIG. 3. (a) A fragment showing type I and II lithology in sharp contact. (b) A clast showing a dark glassy spherule. Two similar glass balls are also shown. (c) A pyroxenitic round chondrule-like object, showing a crater-like feature on its surface. (d) Another chondrule-like object.

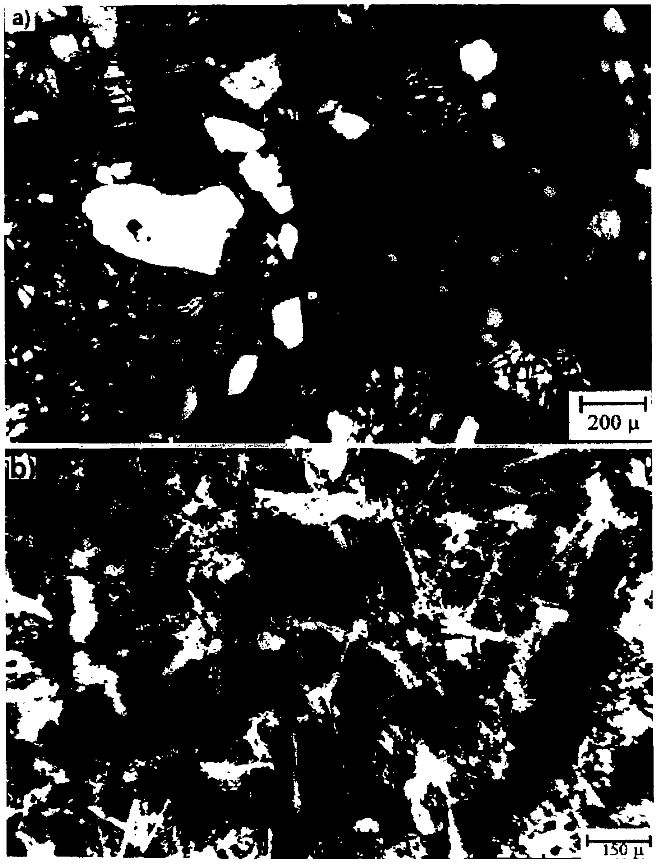

FIG. 4. Photomicrographs of thin sections showing (a) brecciated texture (type I), typical of the bulk meteorite; (b) type II (LB) lithology showing eucritic texture.

XRD analyses of this lithology shows dominant plagioclase and pyroxene, mostly augite in composition. Possible presence of a minor amount of quartz is indicated but this needs further confirmation since the fragments used for XRD analyses were lying in alluvium fields during rains, and quartz could be a contaminant. This type II lithology might be representing the eucritic component which together with the diogenitic component forms this meteorite. The diogenitic component is present in the form of mineral clasts of pyroxenes. Type III (LH) lithology is rare and consists of coarse-grained, well-developed cemented crystals of uniform size showing crystallization after melting, which are not as fragile as the bulk of the meteorite.

The lithic clasts are medium- to coarse-grained aggregates of different mineralogical assemblages such as olivine, olivine-pyroxene, pyroxene-plagioclase along with metallic opaques and accessories. Texturally Lohawat is a brecciated silicate-rich meteorite displaying a variety of textures such as ophitic, subophitic (Fig. 4b), intersertal (in which triangular and polygonal interspaces between plagioclase laths are filled with glassy and cryptocrystalline material), porphyritic and some not recognizably magmatic in origin. One such lithic fragment, enveloped in a glassy rim, showing mineral clasts and opaques embedded in a pulverized matrix with microvesicles, is shown in Fig. 5a. Some of the lithic fragments and single mineral grains are rounded and have a well-developed glassy rim. Figure 5b shows part of a typical rounded ball, composed of pyroxene, having abnormal textural properties such as weaker birefringence, brownish-black interference color and

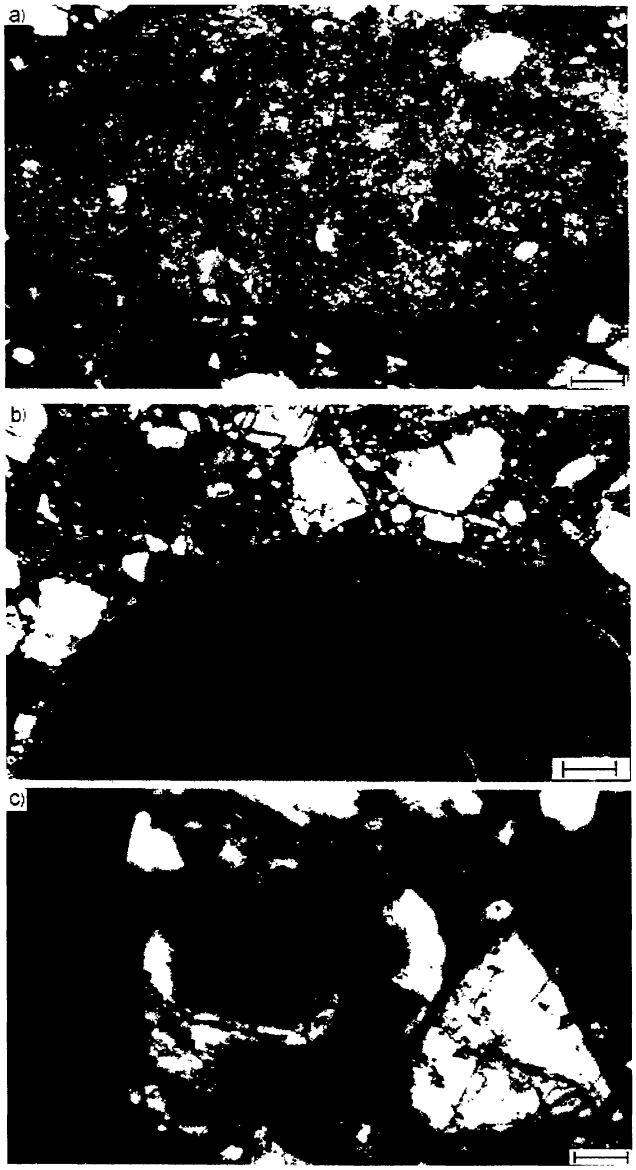

FIG. 5. (a) A fine-grained vesicular clast with glassy rim and numerous opaques, (b) a glassy spherule with rim, and (c) a fragmented olivine and pyroxene showing shock effects. The bar is 200 μm.

incomplete extinction. Reaction rims of clinopyroxene over orthopyroxene and olivines over orthopyroxene are commonly seen. Pyroxenes in the interstices, in some cases, show corroded boundaries (Fig. 5b).

Coarse single crystal fragments of olivine, pyroxene and plagioclase are seen embedded in fine- to medium-grained matrix. These fragments do not show any intergrowth relation with other minerals but intense shock effects are often present in them (Fig. 5c).

Electron microprobe analyses indicate a wide variety of pyroxenes. Two clusters having composition $Wo_{0.012}En_{0.78}Fs_{0.21}$ and $Wo_{0.05}En_{0.38}Fs_{0.57}$ can be clearly distinguished whereas many other pyroxenes show a range of composition $Wo_{0.1-0.17}En_{0.48-0.55}Fs_{0.45-0.52}$ (Fig. 6). Plagioclase composition was determined to be ($An_{0.92}Ab_{0.07}Or_{0.007}$).

CHEMICAL ANALYSIS

An interior chip (~4 g) representing the main lithology was taken from a fragment which was collected soon after the fall for chemical analysis. This sample was powdered using an agate mortar. Two aliquots ~190 mg each from this bulk powder together with the Dhajala meteorite and the U.S.G.S. diabase standard W-2 were sequentially digested with HF, HCl, $HClO_4$ and finally dissolved in dilute HNO_3 for inductively-coupled plasma atomic emission spectroscopy (ICPAES) and atomic absorption spectroscopy (AAS). Si was measured in another aliquot from the same powder after NaOH fusion using ICPAES. Two aliquots (about 90–100 mg) from the bulk powder and two samples belonging to different lithologies (LH, 76.59 mg and LB, 105.31 mg) together with standards (Allende meteorite and U.S.G.S. basalt standard BCR-1) were irradiated in the Dhruva reactor of BARC, Mumbai. The irradiated samples were counted on a high purity Ge detector (volume 148 cm^3) located in a 10 cm thick lead shield following standard

TABLE 1. Chemical composition of the Lohawat howardite.

Element	Bulk	LH	LB
Si (%)	23.8	NM	NM
Mg (%)	9.3	NM	NM
Al (%)	4.22	NM	NM
Ca (%)	4.75	7.15	7.57
Fe (%)	14.3	13.8	13.9
Ni (ppm)	217	NM	NM
Co (ppm)	12.4	7.5	23.6
Na (ppm)	2250	4100	4400
K (ppm)	317	NM	NM
Ti (ppm)	2850	NM	NM
Sc (ppm)	22.2	25.3	26.8
Hf (ppm)	0.93	1.82	1.23
Ta (ppm)	0.17	0.13	0.20
Cr (ppm)	5005	3070	2722
Mn (ppm)	4250	NM	NM
Zn (ppm)	21.8	19.10	22.5
V (ppm)	92	NM	NM
La (ppm)	2.18	4.50	2.95
Ce (ppm)	6.54	11.6	8.10
Nd (ppm)	4.1	7.83	4.65
Sm (ppm)	1.3	2.47	1.75
Eu (ppm)	0.4	0.66	0.56
Tb (ppm)	0.24	0.48	0.36
Yb (ppm)	1.2	2.15	1.72
Lu (ppm)	0.21	0.34	0.28

Errors for major elements are ≤2% except for Ca (5%). For trace elements, the errors are ≤10%. Abbreviations: NM = not measured; LH = hard clasts; LB = black clasts.

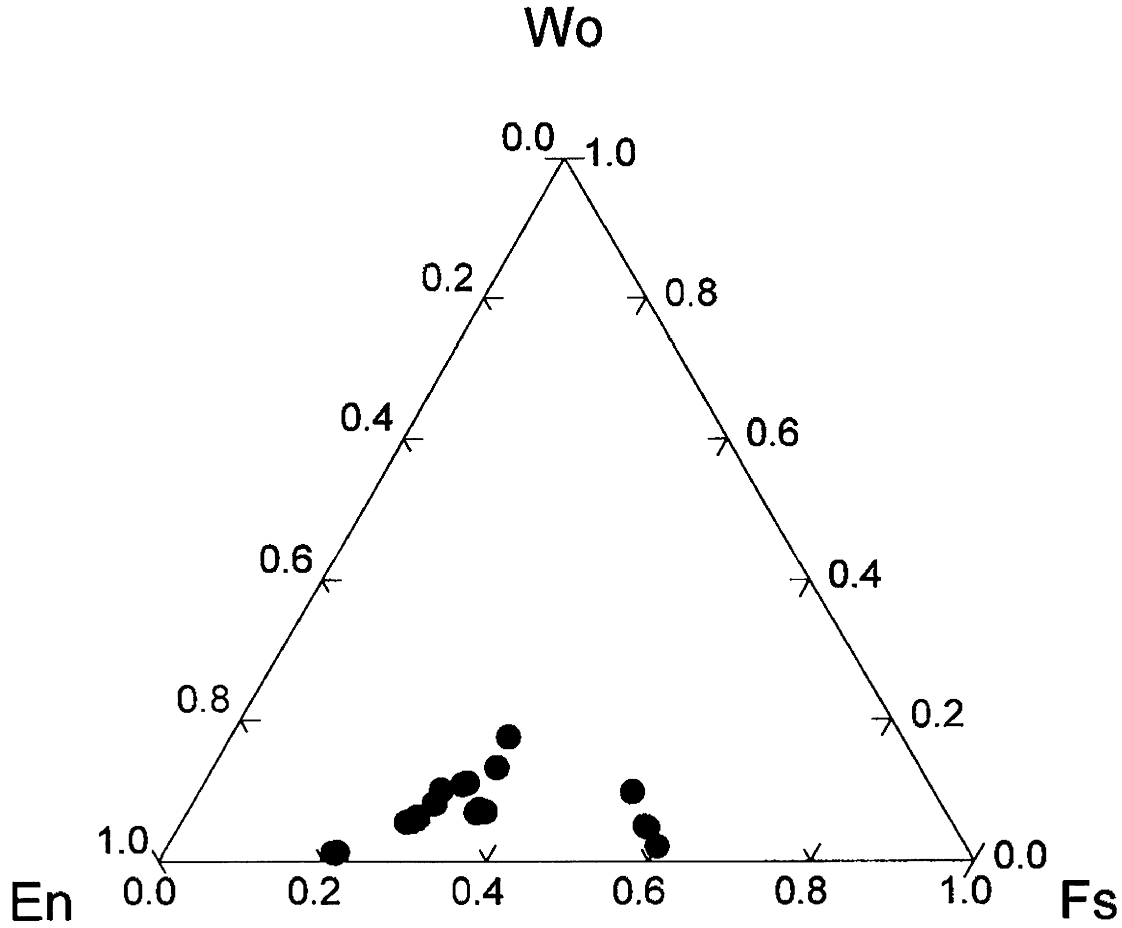

FIG. 6. Variation in composition of pyroxenes determined by electron probe microanalysis. Two clusters at En_{70} and En_{38} can be seen. The other pyroxenes show a gradational Wo content.

procedures (Laul, 1979). The concentrations of various major, minor and trace elements (*viz.*, Si, Al, Fe, Ca, Mg, Mn, Ti, Na, K, Ni and V) were determined using ICPAES and AAS. Several other elements (*viz.*, Fe, Ca, Co, Na, K, Sc, Hf, Ta, Cr, Zn and rare earth elements (REE): La, Ce, Nd, Sm, Eu, Gd, Tb, Yb and Lu) were determined using instrumental neutron activation analysis (INAA) procedures (Laul, 1979). We have obtained the bulk composition by taking weighted mean of several analyses of different aliquots. The results are given in Table 1. The errors quoted correspond to statistical (1σ) counting errors in case of INAA. For ICPAES/AAS measurements the errors are based on replicate analysis of standards. The composition of LH and LB clasts is based on INAA measurements of a single aliquot and may not be representative of these lithologies. Some elements show significant variation among different aliquots, for example, Fe concentration ranges between 13.3% to 15.8% in four aliquots and Ni concentration is found to be 125 and 309 ppm in two aliquots. This variation may be due to inherent inhomogeneities as expected in breccias. However, the average elemental concentrations are similar to those observed for howardites (Fukuoka *et al.*, 1977) and compare well with the composition reported earlier by Chattopadhyay *et al.* (1998) except that their Ni concentration (40 ppm) is lower and K concentration (415 ppm) is higher.

Compositionally, howardites occupy an intermediate position between the two end members, eucrites and diogenites (Duke and Silver, 1967; Fukuoka *et al.*, 1977), and resemble silicate portion of mesosiderites (Mittlefehldt *et al.*, 1979). These groups of meteorites form a cluster on the $\delta^{17}O$–$\delta^{18}O$ plot (Clayton and Mayeda, 1996) suggesting that they may have a common source material. Further, inclusions similar to eucrites, diogenites and the olivine portion of the main group pallasites have been recognized in howardites and mesosiderites (Mittlefehldt *et al.*, 1979, and references cited therein). Fukuoka *et al.* (1977) have shown that the composition of several howardites matches a mixture of eucrites and diogenites in different proportions except for siderophile elements. The excess siderophiles may be due to the addition of 0.5–3.3% of a carbonaceous chondrite-like component (Chou *et al.*, 1976), found to be present in howardites (Bunch, 1975). We find that a mixture of 57% Juvinas (eucrite) and 43% Johnstown (diogenite) type material (Fukuoka *et al.*, 1977) will reasonably

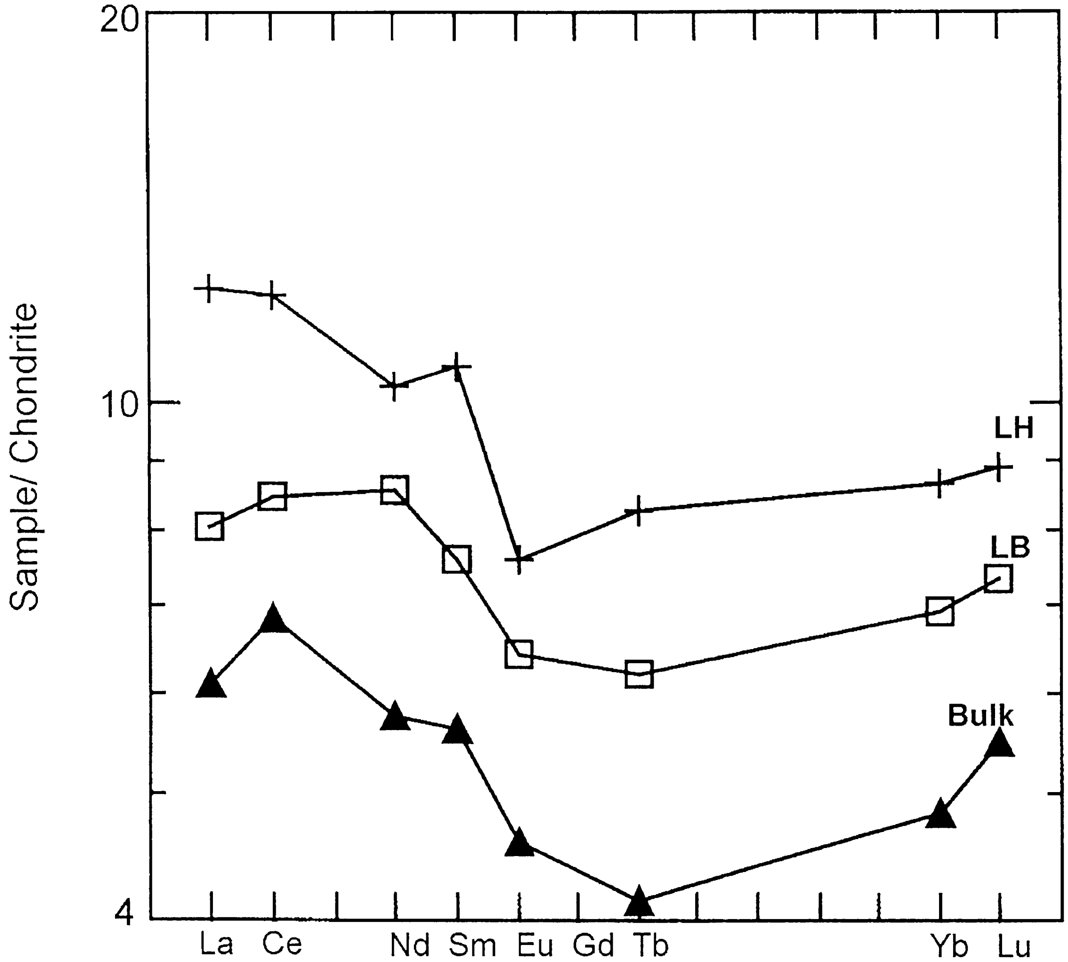

FIG. 7. Rare earth element (REE) patterns (normalized to chondrites) for various lithologies. REE patterns for bulk sample and lithologies LB and LH are shown. Abbreviations: LB = black clasts; LH = hard clasts.

reproduce the observed composition of Lohawat. However, it is not a unique combination as varying proportions of other eucrites and diogenites could also provide a similar match. For example, 59% of the eucrite Haraiya and 41% of the diogenite Tatahouine (Fukuoka *et al.*, 1977) also shows a reasonable match with the bulk composition of the Lohawat howardite. The lithologies LH and LB show higher concentrations of some lithophiles (especially REE) and lower concentration of Cr compared to bulk Lohawat, suggesting that these lithologies could possibly be eucritic. The Ca, Na and Cr values of these lithologies (LH and LB) lie well within the range observed for eucrites (Fukuoka *et al.*, 1977; Shukla *et al.*, 1997).

The chondrite-normalized REE patterns for the bulk and the two lithologies (LH and LB) are shown in Fig. 7. The bulk sample shows 4 to 6× enrichment for various REEs without any significant Eu anomaly as generally observed in howardites (Fukuoka *et al.*, 1977; Mittlefehldt *et al.*, 1979). A small positive Ce anomaly is discernible for the bulk sample. Higher Ce and Tb values have also been reported for some howardites (*e.g.*, Bholghati, Le Teilleul and Malvern) by Mittlefehldt *et al.* (1979). Confirmation of these small anomalies require more precise measurements. The REE pattern for lithology LB is almost similar to the bulk except that the enrichment factor varies between 6 and 9. The REE ratios such as La/Sm (1.7) and Sm/Lu (6.3) are the same as observed in the bulk sample (La/Sm = 1.7, Sm/Lu = 6.2). These ratios are affected by the addition or removal of an incompatible-poor component, such as olivine or orthopyroxene, as they have higher partition coefficients for heavier REEs having smaller ionic radii compared to light REEs with larger ionic radii. Thus, removal of pyroxene would result in a higher value for both these ratios, while a small addition may not alter La/Sm much, though the Sm/Lu ratio would be significantly reduced. This is clearly observed in the howardite–eucrite–diogenite (HED) family where the diogenites show the lowest Sm/Lu ratio (1 to 3.6) compared to eucrites and howardites where this ratio is higher (3.8 to 8.8; Fukuoka *et al.*, 1977). The REE pattern for lithology LH is about 8–12× enriched and show a Eu depletion unlike LB and bulk. The La/Sm (1.8) and Sm/Lu (7.3) are both higher than those observed in bulk and the lithology LB but identical to that observed in eucrite Nuevo Laredo (Fukuoka *et al.*, 1977). Although howardites are similar to the silicate portion of

TABLE 2. Track density in the Lohawat howardite.

Sample code	Mineral	Track density/cm^2 (number of tracks)
Lo-1	Olivine	7.2×10^5 (224)
Lo-2	Feldspar	2.27×10^6 (2477)
Lo-3	Olivine	1.8×10^6 (1722)
	Feldspar	2.2×10^6 (3327)
Lo-4	Feldspar	1.8×10^6 (346)
Lo-D-4'	Feldspar	3.0×10^6 (788)
Lo-9	Feldspar	2.1×10^6 (2179)
Lo-10	Feldspar	2.2×10^6 (581)
Lo-11	Feldspar	1.26×10^6 (404)
	Feldspar	4.34×10^6 (3735)*

*This crystal contains a large number of short tracks and the measured track density may not be reliable.

mesosiderites, their REE ratios La/Sm and Sm/Lu are quite different indicating different fractionation mechanism (Mittlefehldt *et al.*, 1979).

COSMOGENIC TRACKS AND RADIONUCLIDES

Track density was measured in plagioclase and olivine grains separated from a few fragments, using standard procedures (Bhandari *et al.*, 1980). The etching conditions for feldspars were boiling 1:2 NaOH for 20 min and for olivines boiling WN solution (40% EDTA + 1% oxalic acid and orthophosphoric acid, made to pH 8 by adding NaOH; Krishnaswami *et al.*, 1971). The measured track densities in plagioclase range between 1.26×10^6 cm^{-2} and 3.0×10^6 cm^{-2} (Table 2) . Compared to plagioclase, olivines show a lower density of about 7.2×10^5 cm^{-2} to 1.8×10^6 cm^{-2} as expected due to different sensitivity of these minerals (Bhandari *et al.*, 1980). Using an exposure age of 110 Ma, obtained from the cosmogenic components of rare gases (discussed below), and comparing the track production rates (per cm^2 Ma) with the calculated depth profiles of tracks in spherical meteoroids of various radii (Bhattacharya *et al.*, 1973), we obtain a value of 12 ± 3 cm for the average ablation suffered by Lohawat during its transit through the atmosphere. This yields a preatmospheric radius of 27 ± 3 cm for the Lohawat meteoroid, assuming a spherical shape. The mass ablation during its passage through the atmosphere, considering recovered mass of 40 kg is estimated to be 86%.

Cosmogenic radionuclides ^{26}Al and ^{22}Na were measured in 47.93 g of Lohawat by γ-ray spectrometry. The spectrometer consists of a 81.5 $\phi\times$ 77.5 mm long hyper-pure germanium detector, having volume of ~400 cm^3 and relative efficiency (compared to a 7.5 cm NaI (Tl) crystal) of ~115.4%, located in a 20 cm thick lead housing and is described in detail in Shukla *et al.* (2001). ^{26}Al and ^{22}Na activities are estimated to be 72 ± 2.4 and 72.4 ± 5.2, dpm/kg, respectively (Table 3). The solar cycle averaged activities expected for a meteoroid of Lohawat composition (Si = 23.66%, Mg = 9.3%, Al = 4.22% and Na = 2250 ppm; Table 1) having 30 cm radius and 12 cm shielding depth are ^{26}Al (74 dpm/kg) and ^{22}Na (87.3 dpm/kg) (Bhandari, 1981). Since Lohawat fell just before the solar activity reached the minimum level before the beginning of the solar cycle 23, it was irradiated by highly modulated galactic cosmic-ray fluxes for several years. The ^{22}Na is therefore calculated to be 20% lower than the average value based on the model of Bhandari *et al.* (1989). There are two eucrites that fell in India, Piplia Kalan (1996) and Vissannapeta (1997) immediately after Lohawat howardite, in which ^{26}Al, ^{22}Na and other radionuclides were measured (Bhandari *et al.*, 1998; Ghosh *et al.*, 2000). When corrected for their composition, size, shielding depths and the solar cycle modulation, the ^{22}Na/^{26}Al ratio in all the three meteorites seems to be close to the expected values. This result implies that during the past 2 Ma (comparable to the mean life of ^{26}Al) the Lohawat meteoroid had suffered no fragmentation in interplanetary space.

NOBLE GAS STUDIES

In order to investigate cosmogenic effects, we selected a single chip weighing 577.38 mg from the light lithology of Lohawat for noble gas analysis. It was packed in Al-foil and loaded in the extraction system of the VG-1200 noble gas mass spectrometer. Noble gases and nitrogen were analyzed by stepwise heating using standard procedures (Murty *et al.*, 1998).

TABLE 3. Cosmogenic radioactivities in various fragments of the Lohawat meteorite compared to recent eucrite falls*.

Isotope	Energy (keV)	Half-life (years)	Lohawat (1994 October 30)		Piplia Kalan† (1996 June 20)	Vissannapeta‡ (1997 December 13)
			(cpm)	(dpm/kg)	(dpm/kg)	(dpm/kg)
^{26}Al	1808.6	7.2×10^5	0.084 ± 0.003	72.0 ± 2.4	111	78.1 ± 3.0
^{22}Na	1274.5	2.60	0.132 ± 0.009	72.4 ± 5.2	52.8	42.4 ± 4.0
^{22}Na/^{26}Al	–	–	–	~1	0.48	0.51

*The date of fall is given within parenthesis.
†Bhandari *et al.* (1998).
‡Ghosh *et al.* (2000).

After a preliminary 400 °C combustion step in 2 torr O_2, the rest of the gases were extracted by pyrolysis at 1000 and 1600 °C, where the sample melted. A reextraction at 1600 °C gave almost blank levels, ensuring that the extraction of gases was complete at this temperature. In each temperature step nitrogen and all the noble gases (He, Ne, Ar, Kr and Xe) have been analyzed but here we report only the results of He, Ne and Ar analysis. Blanks were run before as well as after each sample analysis for all temperatures and were found to be <1% of the sample gas. The data reported here have been corrected for blanks and instrumental mass discrimination. In addition, the Ne data have been corrected for interferences at ^{20}Ne (from $^{40}Ar^{++}$) and ^{22}Ne (from CO_2^{++}), although such corrections are negligible (<<1%).

Data for He, Ne and Ar are given in Table 4. Cosmogenic and radiogenic components dominate the light noble gases although some trapped Ne and Ar are also present. We assume air composition for trapped Ne ($^{20}Ne/^{22}Ne = 9.8$, $^{21}Ne/^{22}Ne = 0.029$) while for He and Ar and the cosmogenic Ne, we use the values suggested by Eugster (1988) for estimating cosmogenic and radiogenic components. The measured value of $^{22}Ne/^{21}Ne$ has been corrected for contribution of trapped Ne to derive the cosmogenic $(^{22}Ne/^{21}Ne)_c = 1.137 \pm 0.010$. This high value of shielding parameter indicates that our sample comes from a shallow depth in agreement with the track data. The trapped, cosmogenic and radiogenic components derived for Lohawat are given in Table 5.

Using the chemical composition of Lohawat (Table 1) and the procedure suggested by Welten *et al.* (1997), we have calculated the production rates for ^{3}He, ^{21}Ne and ^{38}Ar at shielding depth corresponding to $(^{22}Ne/^{21}Ne) = 1.137$ and obtain 1.647, 0.257 and 0.087 (10^{-8} cc STP/g Ma), respectively. These production rates enable us to calculate the exposure ages given in Table 5. The exposure age based on $^{38}Ar_c$ seems to be higher, while values of T_3 and T_{21} are lower indicating partial loss of He and Ne (Mahajan *et al.*, 2000). The K-Ar age of 4.4 Ga shows that there is no significant loss of Ar from the sample indicating that the age $T_{38} = 110$ Ma can be taken as the correct cosmic-ray exposure age of Lohawat. The measured values of the cosmogenic ratios $(^3He/^{21}Ne) = 3.7$ and $(^{21}Ne/^{38}Ar) = 1.05$, as compared to the expected values of 6.4 and 2.9, respectively, for the composition of Lohawat at $(^{22}Ne/^{21}Ne) = 1.137$ (Eugster and Michel, 1995; Welten *et al.*, 1997) also indicate partial loss of cosmogenic ^{3}He and ^{21}Ne. The U-Th-^{4}He age has been calculated to be 3.3 Ga by assigning all ^{4}He (after subtracting the cosmogenic component) to be of radiogenic origin, and using average U, Th contents of howardites (Eugster and Michel, 1995). The lower U-Th-^{4}He age, compared to K-Ar age of 4.4 Ga, further corroborates loss of He. The exposure age of 110 Ma for Lohawat is the highest value so far reported for howardites and also one of the highest values among stone meteorites. Generally among the HED meteorites, only the howardites are found to have exposure ages >50 Ma (Welten *et al.*, 1997), the highest value, prior to Lohawat, being 81 ± 8 Ma for Luotolax (Eugster and Michel, 1995). At least two exposure age clusters around 20–25 Ma and 35–42 Ma are prominent among each of the individual members of the HED group (Eugster and Michel, 1995; Welton *et al.*, 1997), suggesting two major impacts on their probable parent asteroid, Vesta. The exceptionally high exposure ages of the two howardites (Lohawat and Luotolax) seem to suggest that the impact corresponding to their ejection must have occurred in a region containing howarditic material or we do not have in our collection the eucrite and diogenite counterparts corresponding to this ejection event. Alternatively, these two high exposure age howardites might have originated from a parent body other than Vesta. It is interesting to note that solar gases generally found in howardites (Wieler *et al.*, 2000; Swindle *et al.*, 1990) are not present in Lohawat nor in Luotolax, plausibly indicating that these two howardites belong to a different parent body.

TABLE 4. He, Ne and Ar data for the Lowahat howardite (577.38 mg).

Temp. (°C)	^{4}He (10^{-8} cc STP/g)	^{22}Ne	^{36}Ar	$^3He/^4He$ (× 10^4)	$^{20}Ne/^{22}Ne$	$^{21}Ne/^{22}Ne$	$^{38}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$
400	1329	0.69	0.18	56.11 ±4.75	0.8339 ±0.0024	0.7500 ±0.0067	1.314 ±0.002	607.0 ±6.1
1000	3763	6.34	6.62	77.71 ±6.58	1.567 ±0.001	0.8129 ±0.0072	0.6783 ±0.0010	213.2 ±2.1
1600	40	5.43	10.83	92.47 ±7.83	1.583 ±0.001	0.8142 ±0.0073	0.6415 ±0.0002	63.2 ±0.6
Total	5132	12.46	17.63	72.23 ±6.11	1.533 ±0.001	0.8100 ±0.0072	0.6622 ±0.0005	125.1 ±1.3

Errors in concentrations are ±10%. Errors in isotopic composition represent 95% C.L.

TABLE 5. Cosmogenic, radiogenic and trapped components (10^{-8} cc STP/g), and the estimated cosmic-ray exposure and radiogenic ages.

Cosmogenic			Radiogenic		Trapped		Cosmic-ray exposure age (Ma)			Radiogenic age (Ga)	
^{3}He	^{21}Ne	^{38}Ar	^{4}He	^{40}Ar	^{20}Ne	^{36}Ar	T_3	T_{21}	T_{38}	T_4	T_{40}
37.1	10.0	9.56	4939	2207	9.5	11.3	22.5	38.7	110	3.3	4.3

Recent discovery of a basaltic asteroid in the outer main belt (Lazzaro *et al.*, 2000) is of interest in this context. Thus it is possible that some howardites (particularly the ones with very high exposure ages) could belong to a different parent body.

Trapped Gases

A trapped Ne and Ar component is present in the sample analyzed here (Table 5). The trapped ratio $(^{20}\text{Ne}/^{36}\text{Ar})_T = 0.84$ is higher than the values expected for air (0.28) and primordial (0.52) components, but much smaller than the solar (37) value. However, within the uncertainties, the trapped component in Lohawat can be considered to be primordial. Presence of trapped Ne and Ar imply that some trapped He is also present and heavy loss (~80%) of cosmogenic ^{3}He implies that a significant amount of radiogenic ^{4}He is also lost. The U, Th-^{4}He age of 3.3 Ga calculated by attributing all non-cosmogenic ^{4}He to a radiogenic component therefore should be an overestimate if a part of the ^{4}He is in fact a trapped component. We can not unambiguously resolve the trapped and radiogenic ^{4}He, but part of the measured ^{4}He being trapped remains a possibility.

SUMMARY

Lohawat is a heterogeneous breccia with a variety of lithic fragments whose bulk composition corresponds to the howardite class of meteorites. The two lithic fragments studied appear to be eucritic in nature. The bulk composition of Lohawat appears to be a mixture of eucrites and diogenites (*e.g.*, 57% Juvinas and 43% Johnstown or 59% Haraiya and 41% Tatahouine). The results on cosmogenic tracks, radionuclides and rare gases indicate ablation of ~86% and small meteoroid size ($R \approx 27$ cm). The exposure age of Lohawat, estimated to be 110 Ma, is the highest for howardites and one of the longest for stony meteorites. The noble gas data show the presence of a trapped component and loss of ^{3}He and ^{4}He during the long exposure of this meteorite. The loss is also significant for neon, but negligible for argon and heavier noble gases.

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