

MÖSSBAUER STUDIES ON IMPACTITES FROM LONAR IMPACT CRATER

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Abstract

Iron mineralogy has been studied using Mössbauer spectroscopy on eight glassy impactite samples from different parts of the Lonar Crater Rim Region. Distinct changes are observed when compared to the host basaltic sample. Significant amount of Fe³⁺ phase is observed in the impactite samples whereas this phase is known to be almost absent in the basalt. Besides this we have a strong Fe²⁺ doublet showing up corresponding to the main iron-containing mineral. The Mössbauer results are very similar to those with glasses from Ries crater which is also believed to have formed from meteoritic impact but on nonbasaltic rock bed. Besides the glassy samples, we also study some spherules found in the crater region and some fine ejecta on the surface of melt impact bombs. These contain a good amount of magnetically ordered phase, most likely nanosize hematite. Interestingly, part of it is strongly attracted by a magnet and part of it is not. But both parts show a significantly strong six-line component corresponding to hematite.

1. Introduction

An estimated 50-60 thousand years old Lonar Crater in the Buldhana district of Maharashtra state in India, is the only known terrestrial meteoritic impact crater that was excavated on basaltic target rocks. It assumes great significance as many of the chemical analysis studies on Lonar crater samples and on Lunar samples brought by Apollo missions show similar results [1]. It is thus comparable to the impact structures on planets and planetary bodies of our inner Solar system having basaltic crusts [2-4]. The target-rock of this crater is the Deccan basalt that erupted in a very short interval of time at or near the Cretaceous-Tertiary (KT) boundary around 65 Ma [5, 6]. The crater is a bowl shaped simple impact structure with a diameter of ~1800 m, and a depth of ~150 m [7].

Though this crater has been known for more than 150 years, only in the later part of the 20th century evidences for its impact origin were found [2-3]. Because of the great volcanos in this region, it was natural for the early investigators to look for the volcanic origin of the crater. However presence of minerals like Maskelynites which form only in very high shock pressure conditions conclusively vote for the impact by a huge extraterrestrial body. The shape of the crater, its different slopes on the two sides, raised rim etc also support oblique impact. It is estimated that the impactor pumped an energy quantum of around 6 Mega Tonnes and the weight of the meteorite hitting the rock would be of the order 2 Million tones [8].

Such a large impact would have changed the temperature and pressure conditions significantly and the minerals present in the basalts would have cooked differently during the changed conditions. The basalt has essentially iron in the form of Fe^{2+} in the M1 and M2 sites of orthopyroxene as the minerals are formed in oxygen deficient conditions. However due to the heavy impact, the rocks melt and the minerals recrystallize. The characteristics of the recrystallized minerals will carry the signatures of the geochemical conditions like oxygen fugacity, cooling rate etc after the impact. As the impact is made in atmosphere it is likely that at least part of the mineral

will go in Fe^{3+} phase. The ratio of $\text{Fe}^{3+}/\text{Fe}^{2+}$ could be an important parameter to investigate the nature of the impact and the then prevailing redox condition. Though a large number of studies such as petrography and geochemistry have been reported on the melt rock samples from Lonar [9-11], Mössbauer studies on iron mineralogy of these samples are rare to see. We report the first detailed Mössbauer study on a number of samples (eight) collected from different places of the Lonar crater region in order to look at the iron mineralogy after the impact. Comparisons are made with the glassy samples from the 12-km diameter 15 Ma old Ries Crater in Germany which is also believed to have formed by meteoritic impact but on nonbasaltic rock [12].

2. Sample details and Experimental details

A total of eight samples collected from the Lonar lake region and one sample from the Ries crater are studied in this work using Mössbauer spectroscopy. The sample Codes and their short descriptions are given in Table 1. The samples GE1, GE2 and GE3 are ejecta material in the form of glasses or tektite-like glasses of few millimeter size from various regions of the crater. GEB is a glass bomb of size 17 cm length and 7 cm diameter. The two GS samples represent glassy spherules, magnetic and nonmagnetic, of submillimeter size whereas the two GF samples correspond to very fine material from the surface of some impact melt glass bombs.

The absorbers for Mössbauer spectroscopy were prepared by pressing finely ground powders in a 12 mm diameter copper ring and fixing the open ends with transparent tapes. The spectra were recorded using a conventional constant acceleration Mössbauer spectrometer with ^{57}Co in Rh matrix as the Mössbauer source. Data were analysed by fitting an appropriate number of discrete doublets and sextets with Lorentzian peaks using a least-squares code developed at IIT Kanpur. The typical uncertainty in the isomer shift (IS) and the quadrupole splitting (QS) are ~ 0.02 mm/s, whereas that for the hyperfine magnetic field (B_{hf}) is ~ 0.1 T. The relative areas under different component spectra have an uncertainty of $\sim 2\%$ obtained through repeated experiments.

3. Results and Discussion

The Mössbauer spectra of the Lonar impactites are displayed in Figure 1 and 2 and their Mössbauer parameters are displayed in Table 2. All the eight spectra show the common feature of having a strong quadrupole doublet corresponding to Fe^{2+} in pyroxene and another doublet of lesser intensity corresponding to Fe^{3+} phase. The ratio of the absorption areas, $\text{Fe}^{3+}/\text{Fe}^{2+}$ is about 0.4 to 0.5 in the five samples of glasses (GE series) and between 0.5 and 0.7 for the spherules (GS series) and the fine ejecta (GF series) sticking to glass bombs. This high ratio is another convincing evidence of impact origin of Lonar Crater. The craters formed due to subsidence after volcanic eruption show up glasses with much smaller $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio as it brings the hot iron minerals from within the crust that cools rapidly to form glass. In this process it contacts little with the oxygen and hence the ratio is quite small. The Deccan trap itself is formed from solidification of volcanic eruption of the material coming from inside the crust where no Fe^{3+} is expected because of oxygen deficiency. The basalts in all other regions including HED meteorites too show only Fe^{2+} . The occurrence of Fe^{3+} in the Lonar samples in such a high abundance is a signature of the impact where mineral chemistry was rewritten in the presence of atmospheric oxygen and high temperatures generated by the collision.

Apart from the variation in absorption area, the Mossbauer parameters of the doublets, like isomer shift, quadrupole splitting and linewidth, are almost the same for all the eight samples. The linewidths of the doublets are quite large which is expected from the disordered nature of glassy samples. The Mössbauer parameters of the glass ejecta from the Ries crater too show the same kind of Fe^{2+} and Fe^{3+} doublets. The Mossbauer parameters including the linewidth are almost the same as found in Lonar samples. The $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio of absorption areas is 0.4 in Ries glass sample which is also similar to what we found in Lonar glass ejecta samples. This comparison tells that once a strong impact occurs on a rock, the previous iron mineral signatures are largely washed out in the glassy material that forms due to melting and rapid cooling. Ries host rock is sandstone and shells

whereas Lonar is basalt. Still we find the same iron phases in the same abundance in Ries and Lonar glasses. It also shows that the geochemical conditions of the Ries impact and the Lonar impact were very similar so that the recrystallization goes in very similar fashion.

The quadrupole doublets fitted to the spectra have no asymmetry in the two line intensities (The visual asymmetry is because of presence of two doublets with different quadrupole splitting and different isomer shift). Fresh glass samples often show asymmetric quadrupole doublets. Mössbauer spectra thus indicate that the glasses are highly devitrified.

Apart from the two quadrupole doublets, we also find a magnetically split component in the spectra. In the GE series (Figure 3), this component is ill-defined as one can see visually. A free fit to a sextet gives huge linewidth of about 1-3 mm/s which shows that magnetic ordering is perhaps not because of a well defined chemical phase. However, the negative quadrupole splitting of the order of -0.10 mm/s and the isomer shift characteristic to Fe^{3+} , indicate that the magnetic portion is hematite ($\alpha\text{-Fe}_2\text{O}_3$), most likely embedded in glassy structure. This might have come from the vapourized plume resettling on the surface in due course. The hyperfine magnetic field B_{hf} of 43-45 T shows that this is in nanosize form where the small fluctuation of the particle magnetic moment about an easy axis of magnetization reduces effective hyperfine magnetic field. Different size hematite clusters embedded in the glassy structure will give a distribution in B_{hf} resulting in large linewidth. Such nanosize hematite has also been observed at other impact sites such as KT boundary samples in Gubbio [13].

The magnetic components in GS samples (spherules, Figure 4) show up in nearly the same way as in the GE samples (ejecta glass pieces). The portion that was attracted to a magnet shows magnetic lines with smaller linewidth (1.04 m/s) as compared to the case with the portion that was not attracted by the magnet (2.03 mm/s). Here also the parameters correspond to nanosize hematite. The variation in linewidth shows that the range of magnetic ordering is different in different

samples. The spherules as well as the glassy material have nearly the same abundance of fine nanosize hematite embedded but in some cases the ordering prevails to only very short range and in some cases it goes to somewhat longer range. The rapid cooling of the host material affects the magnetic ordering of the hematite particles trapped.

The case with the fine ejecta sticking to glass bombs is different. The two GF samples show hematite components with linewidth around 0.6 – 0.7 mm/s. These hematite particles seem to be free and not embedded in the glass formed. It is possible that some hematite is formed in the vapour plume that has settled down on the ejecta at a somewhat later stage and hence the fine particles collected from the surface of the glass samples show better crystallized hematite.

The chemical analysis of the two GF samples shows similar total iron abundance. Yet one is strongly attracted by a magnet while the other is not. Mossbauer spectra of the samples show only hematite as the magnetically ordered component. The relative area of the magnetically split sextet is only marginally larger in the magnetic portion GFM than that in the nonmagnetic portion GFNM of the fine ejecta sample. Hematite being weakly antiferromagnetic is not expected to help much in getting the sample attracted towards a magnet. The magnetic character that helped in separating the two portions with a magnet might have come from Ni, Co, Cr etc whose presence is more in the magnetic fraction GFM than in the non-magnetic fraction GFNM.

4. Conclusions

A variety of samples, such as small and large glass pieces, spherules and fine ejecta particles, collected from Lonar Crater region were analyzed using Mössbauer Spectroscopy. All the samples show significant presence of Fe^{3+} phase confirming the meteoritic impact as the host rock of Deccan trap is basaltic and has no Fe^{3+} in it. The Mössbauer parameters of the two doublets match very well with those recorded with Ries glass sample which is another known crater of meteoritic impact origin but on non-basaltic host rock. This shows that in a strong impact, the signatures of the original

mineralogy is largely lost and the rapid melting/vaporization and cooling dictates the new composition.

All the samples show nanosize hematite. However the crystallinity and range of ordering of this component varies from sample to sample resulting in wide variation in linewidths. It appears that at least a part of the nanosize hematite was formed in the vapour plume and settled in due course of time. The fine powder from the surface of a glass bomb showed much sharper and well defined six-line component of nanosize hematite leading to this speculation.

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Table-1 : Sample codes and short descriptions of the samples studied

SAMPLE CODE	DESCRIPTION	SOURCE
GE1	Glassy ejecta material of size ~1cm from the northern side of the Rim	Prof N Bhandari, Physical Research Laboratory, India,
GE2	Glassy ejecta material from some distance away from the crater	-do-
GE3	Tecktite-like glass	-do-
GEB	Glass Bomb 17 cm long, 8 cm dia, 35 cm below the ejecta surface, east of the rim	-do-
GSM	Glassy spherules of sub-millimeter size from south-eastern part, attracted to a magnet	Saumitra Misra, IIT Kharagpur
GSNM	Glassy spherules of sub-millimeter size from south-eastern part, not attracted to a magnet	-do-
GFM	Glassy spherules fine ejecta particles from the surface of a glass bomb, attracted to a magnet	-do-
GFNM	Glassy spherules fine ejecta particles from the surface of a glass bomb, not attracted to a magnet	-do-
RIES	Glass from Ries crater	Prof N Bhandari, Physical Research Laboratory, India

Table-2A Mössbauer parameters of the Glass samples of GE series. Mössbauer parameters for the glass samples from Ries crater are included for comparison

Sample	IS (mms ⁻¹)	QS (mms ⁻¹)	HMF (kOe)	LW (mms ⁻¹)	Area (%)	Assignment	Fe ³⁺ /Fe ²⁺
GE1	1.00	2.13		0.77	41	Fe ²⁺	0.54
	0.38	0.86		0.73	22	Fe ³⁺	
	0.40	-0.10	433	3.23	37	α -Fe ₂ O ₃	
GE2	1.05	2.11		0.69	52	Fe ²⁺	0.40
	0.37	0.87		0.71	21	Fe ³⁺	
	0.53	-0.08	441	1.28	27	α -Fe ₂ O ₃	
GE3	1.00	2.12			41	Fe ²⁺	0.54
	0.37	0.86			22	Fe ³⁺	
	0.41	-0.10	432		37	α -Fe ₂ O ₃	
GEB	1.05	2.02		0.70	49	Fe ²⁺	0.47
	0.34	1.06		0.77	23	Fe ³⁺	
	0.60	-0.07	454	1.99	28	α -Fe ₂ O ₃	
Ries Glass	1.06	2.17		0.6987	50.6	Fe ²⁺	0.44
	0.33	0.91		0.8511	22.1	Fe ³⁺	
	0.40	-0.14	438	1.11	27.3	α -Fe ₂ O ₃	

Table-2B Mössbauer parameters of the Spherules and fine ejecta particles

Sample	IS (mms ⁻¹)	QS (mms ⁻¹)	HMF (kOe)	LW (mms ⁻¹)	Area (%)	Assignment	Fe ³⁺ / Fe ²⁺
GSM	1.09	2.11		0.59	49.7	Fe ²⁺	0.49
	0.36	0.87		0.80	24.5	Fe ³⁺	
	0.44	-0.11	448	1.04	25.7	α-Fe ₂ O ₃	
GSNM	1.05	2.04		0.69	44.5	Fe ²⁺	0.69
	0.34	0.86		0.83	30.9	Fe ³⁺	
	0.35	-0.08	472	2.03	24.6	α-Fe ₂ O ₃	
GFM	1.11	2.10		0.56	37.6	Fe ²⁺	0.72
	0.38	0.70		0.63	27.1	Fe ³⁺	
	0.33	-0.05	495	0.68	35.3	α-Fe ₂ O ₃	
GFNM	1.11	2.10		0.55	46.5	Fe ²⁺	0.60
	0.35	0.70		0.63	27.9	Fe ³⁺	
	0.35	-0.10	499	0.59	25.5	α-Fe ₂ O ₃	

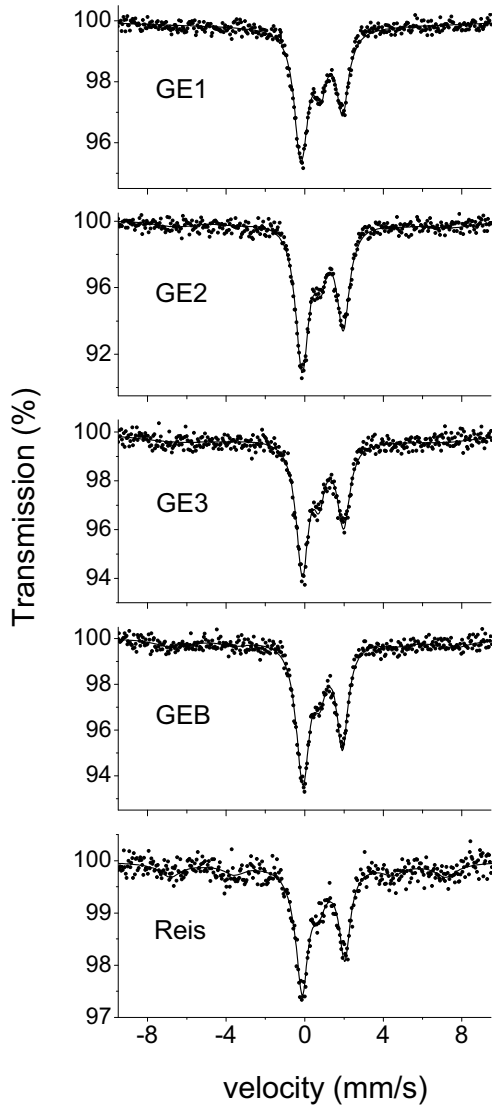


Figure-1 Mössbauer Spectra of the glass samples from Lunar Crater region. See Table-1 for interpretations of the Sample Codes.

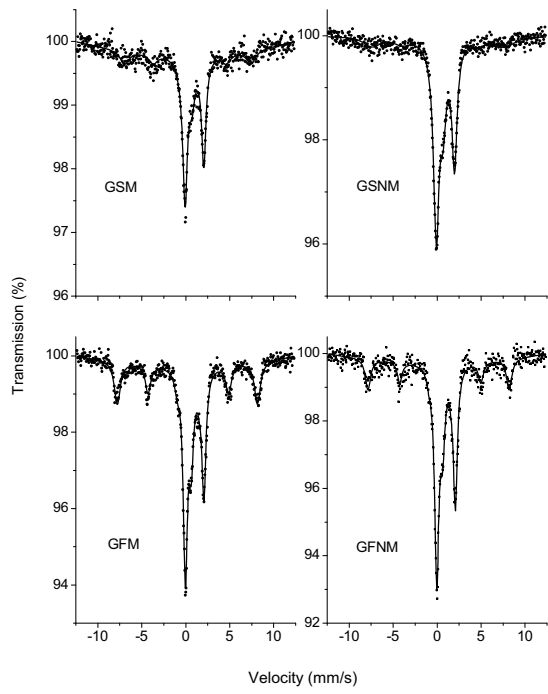


Figure 2 Mössbauer Spectra of the spherules and fine ejecta particles from Lunar Crater region. See Table-1 for interpretations of the Sample Codes.