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Trace element and isotopic evidence for Archean basement in the Lonar crater impact breccia, Deccan Volcanic Province

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Abstract

The Lonar impact crater in the Deccan Traps of the Indian peninsula provides unique opportunities to study physical and chemical processes of impact cratering on basaltic targets, because terrestrial impact craters on basalts are extremely rare. Such studies are needed for determining provenance and other parameters of the excavated rocks and the cratering phenomenon that may have implications for similar crater formations in Lunar, Martian and other basaltic targets in the solar system. Considering some of these objectives, we analyzed trace elements and Nd, Sr, Pb-isotopes of impact breccia rocks and target basalts collected from the Lonar crater.

Chondrite-normalized Rare Earth Element (REE) patterns in the target basalts and breccia rocks show similar light REE-enriched patterns, although in detail, the impact breccia are more fractionated in La/Sm compared to the target basalts. The target basalts also show much lower concentrations of Rb, Ba, Th, U and Pb compared to the breccia and are characterized by Rb, Ba and Pb depletions with respect to the primitive mantle-normalized Th, U, Nb, Ta and the REE contents. The breccia rocks are significantly enriched in Rb, Ba and Pb, and to a lesser extent in Th and U, compared to the target rocks. The Nd, Sr and Pb-isotopic compositions of the Lonar target basalts can be correlated with those of the Poladpur suite, one of the mid-section volcano-stratigraphic units of the Deccan traps. In contrast to the host basalts, the impact breccia rocks show more radiogenic Sr, less radiogenic Nd and higher Rb/Sr and lower Sm/Nd ratios, indicating an additional component, other than the target basalt, that must have been derived from beneath the basaltic target rocks at the impact site.

The Deccan traps in western India are underlain by Archean to mid-Proterozoic cratonic rocks. The overall geochemical signatures of the impact breccia rocks, specifically, the trace element concentrations, negative ε_{Nd} values, radiogenic Sr isotopic composition as well as the high $^{207}Pb/^{204}Pb$ at low $^{206}Pb/^{204}Pb$ indicate that a major component of the Lonar impact breccia was derived from melting of Archean basement rocks. We argue that the Archean component in the breccia cannot be from the incorporation of paleosols that are weathering products of the target basalts, or from the inter-trappean sediments that are most commonly cherts and limestones of Mesozoic age. Similarly, the possible role of eolian sediments in causing the Archean Pb-isotopic signature, identical to those of the Deccan basement, in the breccia rocks can be excluded.

The basement beneath the Lonar region is believed to be similar to the Dharwar craton of peninsular India. Based on their similar Pb-isotopic compositions with the breccia rocks, we suggest the Archean Chitradurga Group of rocks of this craton to be present in the basement beneath the Deccan lavas of the Lonar region. The thickness of the basaltic target rocks at the crater-site (~400 m) and the inferred crater depth (350 m–610 m), based on depth to diameter ratios in simple planetary craters (0.2–0.33), are consistent with our conclusion regarding melting and incorporation of these ancient basement rocks in the impact breccia of the Lonar crater. Using Pi-group scaling relations, the observed crater diameter, and density of the basaltic target rocks, we have

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estimated with reasonable approximation the diameter of the Lonar impactor to be either 70 m, 86 m or 120 m, assuming the bolide to be an iron meteorite, stony-iron meteorite, or an ordinary chondrite, respectively.

Keywords: meteorite impact crater; basaltic target rock; impact breccia; trace element geochemistry; Nd–Sr–Pb isotopes

1. Introduction

The Lonar impact crater [1], 1830 m in diameter (Fig. 1), formed on the 65 Ma old basaltic lava flows of the Deccan Traps in western India at 52 ± 6 kyr, [2]. A second crater, 300 m in diameter, located 700 m north of the main crater is considered to have formed by simultaneous impact of fragments of the same bolide [3]. The Lonar crater is one of the two known terrestrial impact craters on basaltic host rock and provides a key analog to impact craters on the Moon and Mars and other similar planetary bodies in the Solar System. The other terrestrial impact crater in basalts is in Logancha, Russia, but very little information is available for this crater [4]. With increasing interest in the study of impact cratering on Mars, precise geochemical and isotopic data from the Lonar impact crater may provide important geochemical information for future research on similar craters in our Solar System.

The formation of impact craters is a complex process, depending on the material properties of the target and projectile, parameters of impact, atmospheric effects and on gravity [5–8]. Simplistically, crater depth and diameter are functions of the energy of impact and the strength of the target material [9,10]. For the same energy of impact, the greater the height of the ejecta, smaller is the depth of the crater since a significant fraction of the impact energy goes into the generation of the ejecta [10]. The time of excavation of material from the crater may last for several minutes following the impact, while the amount of impact melt produced is dependent on the abundance of water in the target rocks [7]. Target material below the excavation depth is pushed downwards, whereas the strata above this depth may be pushed upwards [5] as seen in the Lonar crater (Fig. 1).

Trace element and isotope geochemical approaches have been successfully utilized in the study of other impact craters [11–17]. Specifically, geochemical and isotopic analyses of tektites have been used to determine age and provenance of the target materials and in correlating tektite fields with impact structures [18–22]. The earliest geochemical studies of the Lonar crater were aimed at understanding the mode of origin of this crater [23,24]. Major element and trace element concentrations of the Lonar impact melts and basalts have also been reported recently [1,25,26]. A more recent geochemical tracer study of this crater [27] has suggested impact-induced trace elemental fractionation of target material during formation of the impact melts from the Deccan host basalt.

We report Nd–Sr–Pb-isotopic data along with multiple trace element concentration data, in both the host basalts and the impact breccia of the Lonar crater. The purpose of this preliminary study is to characterize the host basaltic rocks by their isotopic and trace element geochemical signatures, in order to understand and document this unique cratering process on basaltic rocks. Our analytical results, particularly the isotopic data, should have implications for the suggestion made in the recent study [27] that trace element fractionation of target material accompanies the formation of impact breccia. Also, our new trace element and Nd, Sr and Pb isotope data should allow, as tracers, to identify reservoir-sources of the spherule-bearing impact breccia and the general geological provenance of the excavated rocks from this bolide impact. Using scaling relations, knowing the crater diameter and the density of the target rock basalts, it would be possible to estimate the size and nature of the impactor at the Lonar Crater. The results of this study should have implications for the cratering phenomenon in Lunar, Martian and other basaltic crust-bearing impact targets in the Solar System.

2. Geological setting and petrography of samples

The Lonar impact Crater [1,28], located in the Buldana district of Maharashtra, India (19°58′N, 76°31′E) (Fig. 1), is an almost circular depression in the ~65 Ma old basalt flows of the Deccan Traps. The impact origin of the Lonar Crater has been well established based on the evidence of shock-metamorphosed material. Coarse breccia with shatter cones and maskelynite-bearing microbreccia have been reported in drill core samples from the crater floor [1]. Glassy objects of varying sizes, up to 50 mm in diameter and resembling impact melts, have been recovered from the surrounding ejecta blanket [28]. However, no meteorite

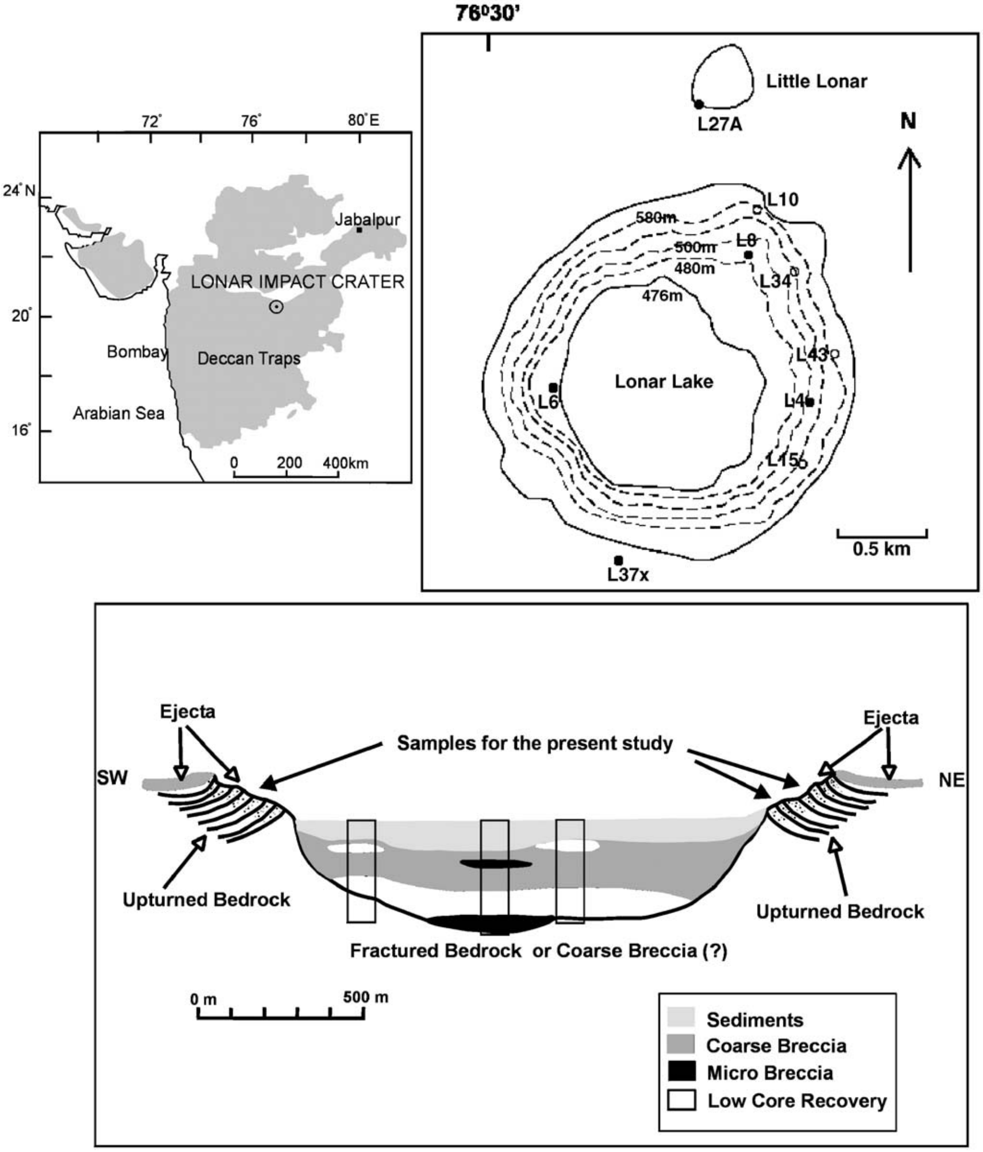

Fig. 1. Location of the impact breccia (filled circles) and host basalt samples (open circles) from the Lonar impact crater and the Little Lonar. Also shown in inset (top left) is the location of the Lonar impact crater in the Deccan volcanic province, India. Cross section of the Lonar crater (bottom) reconstructed after Fredriksson et al. [1] shows the layers of coarse and microbreccia along with the location of the drill-cores. The crater depth is tentatively determined from drilling [1] as the basement was not discernible from the drill-cores. Samples analyzed in this study are approximately indicated on the sides of the upturned bedrock.

fragments have yet been recovered. Thermoluminescence dating of selected impact spherule/melt samples suggests that this crater was possibly formed ~52± 6 kyr ago [2]. The crater is 1830 m in diameter and a shallow saline lake, ~7 m deep [29], occupies the crater floor. A 20 m high raised rim around the lake [1,28] formed by both the uplift of the target layers as well as deposition of impact breccia. Coarse as well as microbreccia have been recovered in drill cores from depths of ~350 m beneath the floor of the lake [1]. A smaller circular depression called Little Lonar, 300 m in diameter and located about 700 m north of the main crater, has been suggested to be a second impact crater (Fig. 1). The Little Lonar is thought to have formed either by impact of the throwout from the main crater or by direct impact of a smaller fragment of the main bolide [1,3].

The Lonar Crater is hosted by the Deccan basalts that erupted on cratonic rocks of the Indian peninsula (Fig. 1). The Deccan volcano-stratigraphy is best documented in its type area in the western parts of the traps, termed the ‘western ghats’, some 500 km southwest of Lonar around the Bombay region (Fig. 1) [30]. This volcanostratigraphy is not as well constrained in the eastern part where the Lonar crater is located. The maximum thickness of the Deccan traps in the Lonar crater region is estimated to be between 400 and 700 m [30,31]. In this region, there are six lava flows, ~8–40 m thick, exposed in and around the Lonar crater, of which the lower four flows are exposed along the crater wall [32]. The flows are separated from each other by marker horizons such as thin paleosols, chilled margins, and vugs with secondary mineralization [27,32]. Individual flows are often difficult to characterize because of vegetation and surface weathering features. The lava flows in the Lonar crater margin are upturned and dip away from the crater edge at inclinations of 14° to 27° [1,33] (Fig. 1). Fresh, dense basalts are exposed only in the upper 50 m of the crater wall below which the flows are weathered and friable [34].

The Deccan basaltic flows occasionally contain intertrappean sediments varying in thickness from a few centimeters to a few meters. They comprise cherts, impure limestones of Mesozoic age and are mostly fluvial and lacustrine in origin [35]. There are also reports of paleosols, termed ‘red bole beds’ [36,37], which were essentially formed by weathering of the basaltic flows.

The impact melts occur within the ejecta blanket found around the Lonar crater, which are seen to extend up to 1600 m from the crater rim [32]. The ejecta consist of two contrasting types of debris. The bulk of the ejecta is crudely stratified and shows no evidence of shock. The other type of debris in which clasts from different

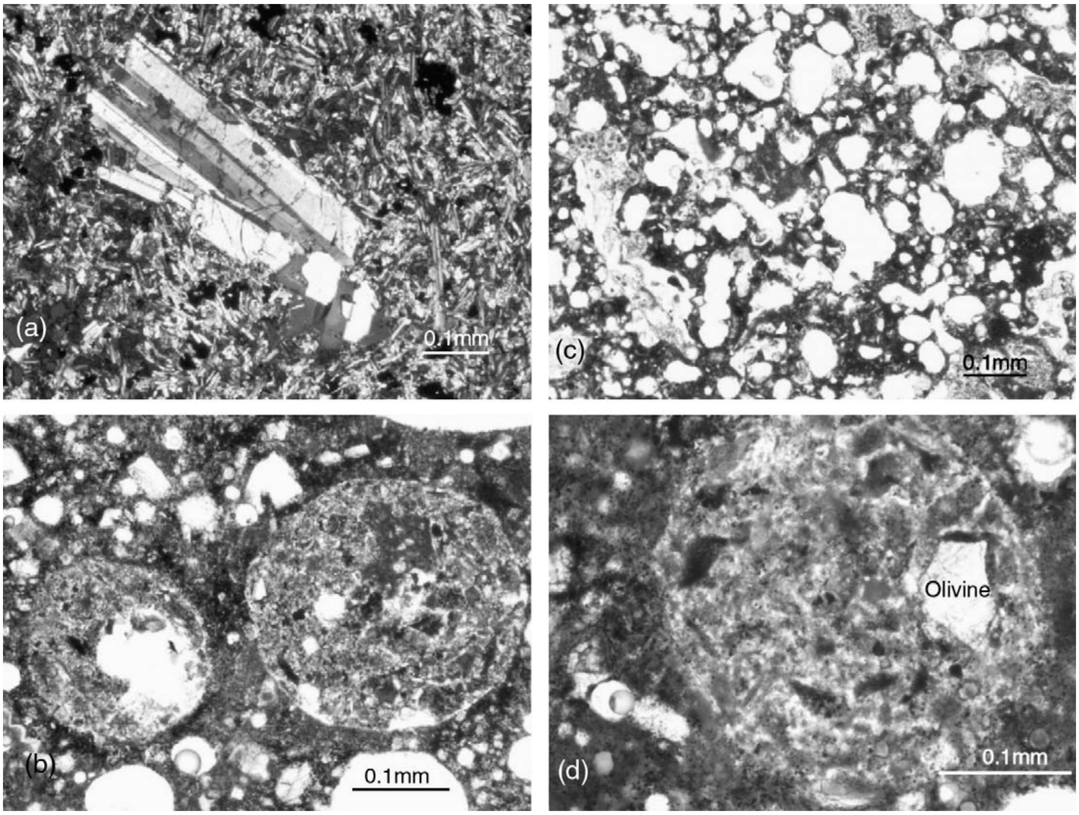

Fig. 2. (a) Photomicrograph of the Lonar target basalt (unshocked?) showing phenocrysts of plagioclase in an intergranular matrix comprising plagioclase, clino-pyroxene, magnetite and subordinate olivine. The host basalts do not show any effects of impact related shock metamorphism. (b) Photomicrograph of spherules in the Lonar impact breccia rocks. The spherules were produced as a result of impact and they were associated with a few clasts of the target rocks. The spherules were difficult to retain in the matrix of the breccia during preparation of the thin sections. (c) Photomicrograph of another typical Lonar impact breccia showing melted fragments of target rocks in various shapes and sizes that are characteristic of impact melt breccia. While bulk of the glassy material of the breccia is scooped out during preparation of the thin section, the varied tear-shaped, ovoid, spherical and bottle-shaped outlines of the melts are preserved. (d) Photomicrograph of one of the larger and preserved spherules in the thin section of the breccia. Note sub-angular olivine crystal derived from the target basalts embedded in the spherule.

bedrocks are mixed show evidence of varying degrees of shock [1]. These two units of the ejecta are similar to the so-called 'throwout' and 'fallout' units as identified in other simple craters [38]. Spherules of shock-melted glass have been recovered from the ejecta and were previously analyzed for major element chemistry [1].

The terminology of impact-related melts in the literature is diverse and its usage is not uniform. While impactite is a generic term used for glass produced by melting during an impact event, many impact glasses tend to include fragments of variably shocked, less homogeneous rocks. Tektites are another group of natural glass formed by impact and are airborne to locations far off from the site of the impact [39]. Target rocks comprise lithologies hosting the impact crater and rocks further below, all affected by the impact. In the present study, samples other than the host Deccan basalts or target rocks without obvious evidence of shock are best described as 'impact breccia rocks'. These breccia rocks contain airborne impact melts with circular cross-sections as well as clasts of the target rocks, including maskelynitized plagioclase. The host or the target basalts of our study do not show perceptible petrographic evidence of impact or shock features.

For the present study impact breccia rocks and target host basalts were collected from the upper crater wall of the Lonar crater (Fig. 1), which is raised about 20 m above the surrounding plains [34]. One impact breccia sample (L 27A) was collected from the edge of the Little Lonar crater (Fig. 1).

The host basalts are porphyritic with phenocrysts of plagioclase and rare olivine and have an intergranular matrix comprising plagioclase, clinopyroxene, magnetite and subordinate olivine (Fig. 2a). Effects of shock metamorphism due to impact are not obviously visible in these rocks under the polarizing light microscope.

The impact breccia are black in color and show flow structures on the surface with trapped angular rock fragments [27]. Under the microscope they are brown to opaque and contain melt spherules (Fig. 2b) of various sizes (0.02–0.3 mm diameter) and shapes. The shapes are mostly spherical, but tear-shaped, ovoid and bottle-shaped melts are also common (Fig. 2c). At least in part, these impact melts were generated by melting of the basaltic units as evidenced from sub-angular olivine crystals trapped inside these melts (Fig. 2c). The matrix, mostly dark, contains clasts of target rock fragments. Varying degrees of shocked and maskelynitized plagioclases [40,41] of different sizes are also common in the matrix of these impact breccias, which are otherwise dominated by the spherules. Spherules comprise ~20% of the impact breccia. The glassy matrix comprises ~65% while the remaining 15% is occupied by clasts of the target basalts including variably shocked and maskelynitized plagioclases. The impact breccia samples from the Lonar crater, including the adjacent Little Lonar, represent a mixture of airborne melt spherules, as seen from their circular and other aerodynamically shaped features in the cross-section, and clasts of the variably shocked target rocks.

3. Results: trace element and Nd–Sr–Pb isotopic geochemistry

3.1. Analytical methods

For this study, five impact breccia rocks and four basalt samples from the Lonar crater were analyzed for trace element concentrations and Sr, Nd and Pb isotope ratios. Whole rock samples were powdered in an alumina spex ball mill. Our attempts to separate the spherules by hand-picking were not successful due to small sample size available to us. Trace element concentrations were measured using an Inductively Coupled Plasma Mass Spectrometer (Thermo elemental X-7 series) while Nd-, Sr-, and Pb-isotopic ratios were measured with a Thermal Ionization Mass Spectrometer (TIMS, VG Sector). All the above analyses were performed at the University of Rochester.

For ICPMS analyses in our laboratory, 25 mg powder of the samples were digested and diluted to 100 ml in 2% HNO_3 solution with ~10 ppb internal standard of In, Cs, Re, and Bi. Table 1 shows the elemental concentrations of the samples obtained by using BCR-2 and BIR-2 (concentrations from USGS) as known external standards. The concentrations of the various elements, other than the rare earth elements, are within 5% error, as estimated from repeated measurements of AGV-2 (andesite-USGS) and BHVO-2 (basalt-USGS) rock standards which were run as unknowns. The rare earth elements, in particular Sm and Nd, are more precisely determined to within 2% error.

For Nd, Sr, Pb isotopic analyses, between 100 and 200 mg of powdered rock samples were digested in HF, HNO_3 and HCl acid mixtures. Nd and Sr-isotopes were measured with a VG Sector multi-collector TIMS using the procedures established for our laboratory at the University of Rochester [42].

Pb isotopes were measured using the silica-gel technique by TIMS [43]. Filament temperature during Pb-isotope ratio measurements was monitored continuously and raw ratios were calculated as weighted averages of the ratios measured at 1150 °C, 1200 °C and 1250 °C, respectively. The reported Pb-isotopic data

Table 1
Selected trace element concentrations in the Lonar host basalts and impact breccia rocks determined by ICPMS

Sample #	L-10	L-43	L-15	L-34	L-8	L-6	L-37X	L-4	L-27A
Rock type	Basalt	Basalt	Basalt	Basalt	Breccia	Breccia	Breccia	Breccia	Breccia
Ba	61.8	99.7	105.0	101.2	137.6	173.7	164.8	165.7	150.5
Rb	2.03	2.15	16.12	3.94	21.78	38.52	36.59	36.26	22.96
Sr	200.6	211.9	204.0	213.3	229.6	218.8	213.7	194.2	191.2
Pb	1.50	1.98	2.07	2.04	1.40	6.73	18.30	12.98	18.58
La	9.38	12.93	12.70	12.30	14.84	12.10	12.46	13.23	12.16
Ce	22.87	30.55	30.08	29.20	34.65	28.27	28.72	31.19	27.88
Pr	3.47	4.49	4.43	4.32	4.68	3.69	3.76	4.07	3.94
Nd	16.08	20.58	20.26	19.72	20.67	16.00	16.32	17.74	17.50
Sm	4.68	5.86	5.78	5.60	5.57	4.28	4.33	4.78	4.85
Eu	1.65	1.98	1.94	1.92	1.86	1.34	1.33	1.53	1.60
Gd	5.36	6.55	6.53	6.29	6.06	4.69	4.64	5.24	5.43
Tb	0.87	1.06	1.05	1.02	0.98	0.75	0.75	0.83	0.87
Dy	5.13	6.20	6.13	5.97	5.65	4.37	4.36	4.89	5.11
Ho	1.05	1.27	1.26	1.23	1.16	0.90	0.89	1.00	1.06
Er	2.71	3.29	3.24	3.18	2.99	2.32	2.34	2.60	2.74
Tm	0.39	0.47	0.46	0.46	0.43	0.33	0.34	0.38	0.39
Yb	2.41	2.92	2.90	2.87	2.72	2.11	2.11	2.36	2.48
Lu	0.33	0.41	0.40	0.40	0.38	0.30	0.29	0.33	0.34
Y	27.30	33.07	33.65	32.21	30.78	24.00	23.81	26.82	27.82
Th	1.30	1.85	1.86	1.77	2.71	2.76	2.78	2.94	2.38
U	0.27	0.41	0.46	0.43	0.59	0.51	0.51	0.55	0.48
Zr	120.6	148.5	152.0	149.0	146.5	107.3	105.6	130.3	136.6
Hf	3.17	3.89	3.96	3.90	3.81	2.82	2.77	3.40	3.61
Nb	9.32	11.27	12.26	12.43	10.92	9.80	9.37	11.14	12.48
Ta	0.66	0.72	0.76	0.76	0.77	0.64	0.59	0.70	0.76
Sc	34.4	33.4	33.8	33.4	29.2	24.1	23.3	27.6	32.6
V	377.8	346.1	394.9	446.6	288.5	241.6	236.4	273.9	375.0

The concentrations are shown in μg/g (ppm). Analytical uncertainties are less than 5%, commonly at 2% for the REEs.

are corrected for mass fractionation of 0.12±0.03% per amu based on replicate analyses of the NBS-981 Equal Atom Pb Standard measured in the same fashion. Our laboratory procedural blanks were less than 400 pg for Sr and less than 200 pg for both Nd and Pb. No blank correction was necessary for the isotope ratios measured.

3.2. Trace element geochemistry

Trace element concentrations of four Lonar Crater host basalts and five impact breccia rocks are shown in Table 1. Chondrite-normalized Rare Earth Element (REE) patterns for these basalts and breccia are shown in Fig. 3. The REE plots show an overall uniform and light REE-enriched pattern for both the impact breccia and the host basalts with La concentrations varying from 10 to 13 times chondrite values. The impact breccia rocks are more fractionated ($La_N/Sm_N = 1.58–1.81$, average 1.72) compared to the host basalts ($La_N/Sm_N = 1.26–1.39$, average 1.35). There is a slight enrichment of the light rare earth elements from La to Pr in one breccia sample compared to the other breccia rocks, while one basalt sample is depleted in the same elements compared to the others. These results are consistent with previously published REE data of the Deccan host basalts and also with some preliminary REE data of the Lonar impact breccia rocks [25–27,30,44–46]. Also shown for comparison is the range of chondrite-normalized REE concentrations of the Poladpur suite of lavas [46], which are in the mid-section of the Deccan volcano-stratigraphy in the Western Ghats region. It is interesting to note that both the impact breccia and the target basalts fall essentially within the range shown by this suite of lavas of the Deccan.

The primitive mantle-normalized “spider” plots for a wide range of compatible and incompatible elements are shown in Fig. 4; the more incompatible elements are plotted on the left that become progressively more compatible on the right. In contrast to the more uniform REE concentration patterns, the impact breccia rocks and host basalts show distinctly different patterns in the spider diagram with respect to the elements Rb, Ba, Th, U and Pb

(Fig. 4). The host-basalts have lower concentrations of Rb, Ba, Th, U and Pb compared to the impact breccia. For example, Rb is enriched in the impact breccia by as much as 20 times, Ba by 3 times, Th by 2 and Pb by as much as 13 times. The basalts also show Rb and Pb depletion while most of the breccia rocks are strikingly enriched in these elements. These results are consistent with previously reported geochemical analyses of the Lonar host basalts [27]. It is interesting to note that the host basalts show higher concentrations of Sc (33.4–34.4 ppm; average = 33.74 ppm) and V (346.1–446.6 ppm; average = 391.4 ppm) compared to the impact breccia (Sc = 23.3–32.6 ppm; average = 27.35 ppm and V = 236.4–375.0 ppm; average = 283.1 ppm). The average composition of the Poladpur suite of lavas is indicated by the shaded region for comparison (Fig. 4).

3.3. Nd–Sr–Pb isotopic geochemistry

Sr, Nd, and Pb isotopic composition of the host basalts and impact breccia rocks are shown in Table 2. Compared to the host basalts ($^{87}Sr/^{86}Sr = 0.70552$–$0.70624$; $\varepsilon_{Nd} = +0.39$ to $+2.75$), the impact breccia ($^{87}Sr/^{86}Sr = 0.70729$–$0.70824$; $\varepsilon_{Nd} = -3.8$ to -0.86), have more radiogenic Sr-isotopic composition and more negative ε_{Nd} values (Fig. 5). The Nd–Sr isotopic composition of the four uppermost volcano-straigraphic units of the Deccan is also shown in Fig. 5 for comparison. The breccia rocks have a higher Rb/Sr (0.09–0.19) and a lower Sm/Nd ratio (0.265–0.277) compared to the host basalts (Rb/Sr = 0.01–0.08; Sm/Nd = 0.284–0.291) (Fig. 6).

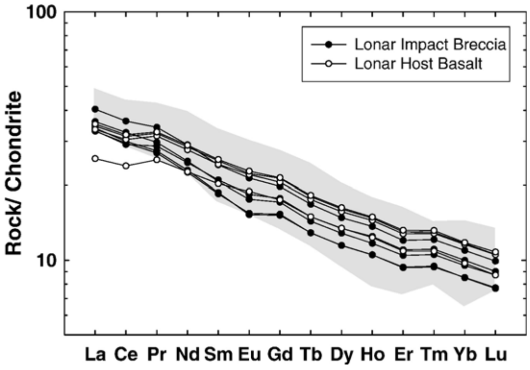

Fig. 3. Chondrite-normalized Rare Earth Element plot for the Lonar impact breccia and the host Deccan basalts. Also shown for comparison is the composition of the Poladpur suite of lavas [44–46] (shaded portion), the inferred host basalts of the crater (see text). Note overall similarity of the REE patterns between the impact breccia and the host basalts, although distinct differences are revealed between the two suites when for example La_N/Sm_N ratios are considered. The impact breccias are more fractionated ($La_N/Sm_N = 1.58$–1.81, average 1.72) compared to the host basalts ($La_N/Sm_N = 1.26$–1.39, average 1.35).

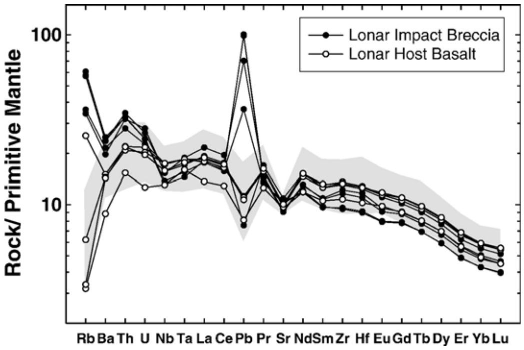

Fig. 4. Primitive mantle-normalized multiple trace element concentration patterns for the Lonar impact breccia and the host Deccan basalts. Note, that the Poladpur suite of rocks [44–46] have negative Rb and Pb anomalies, which is also seen in the Lonar target basalts. The conspicuous enrichment of Rb, Ba, Th, U, and Pb in the impact breccia, compared with the target basalts is noteworthy.

The impact breccia also have lower $^{206}Pb/^{204}Pb$ (17.67–18.69) and $^{208}Pb/^{204}Pb$ (37.67–39.02) but higher $^{207}Pb/^{204}Pb$ (15.63–15.80) ratios compared to the host basalts ($^{206}Pb/^{204}Pb = 18.86$–$19.34$; $^{207}Pb/^{204}Pb = 15.64$–$15.71$; $^{208}Pb/^{204}Pb = 39.20$–$39.57$) (Fig. 7). The entire range of the Deccan lavas [46] along with the field of the Poladpur suite of lavas [46] and Archean basements rocks from peninsular India [47,48] are shown in Fig. 7 for comparison.

4. Discussion

Trace element and isotope geochemistry has been successfully utilized in the study of several impact craters, specifically in deciphering the impact melt origin and the source components in the impact ejecta [11–17]. Geochemical and isotopic studies of tektites have been traditionally used to study the age and provenance of the target materials and for correlating tektite fields with impact structures [18–22]. The earliest geochemical studies of the Lonar Crater were aimed at understanding the nature of origin of this crater [23,24]. Electron probe analysis of Lonar impact glasses (fragments and spherules) and the host basalts indicated that the impact glasses, particularly the spherules were depleted in the alkalis [1]. Stroube et al. [26] analyzed several compatible and incompatible elements, including the Rare Earth Elements (REE), in the host basalts and the impact glasses of the Lonar Crater. They found the glasses to be geochemically similar to the basalts and suggested that impact-induced chemical fractionation was minimal for most of the major rock and mineral

Table 2
Sr, Nd and Pb isotopic data for the Lonar impact breccia rocks and the host basalts

Sample	Rock type	Rb/Sr[a]	^{87}Sr/^{86}Sr (0)[b]	Sm/Nd[a]	^{143}Nd/^{144}Nd (0)[c]	ε_{Nd} (0)[d]	U/Pb[a]	Th/Pb[a]	^{206}Pb/^{204}Pb[e]	^{207}Pb/^{204}Pb[e]	^{208}Pb/^{204}Pb[e]
L-10	Basalt	0.01	0.705516	0.291	0.512739	1.97	0.18	0.87	18.856	15.641	39.202
L-43	Basalt	0.01	0.706090	0.285	0.512732	1.83	0.21	0.94	19.319	15.705	39.530
L-15	Basalt	0.08	0.706237	0.285	0.512779	2.75	0.22	0.90	19.337	15.713	39.566
L-34	Basalt	0.02	0.706110	0.284	0.512658	0.39	0.21	0.87	19.320	15.697	39.508
L-8	Breccia	0.09	0.707319	0.270	0.512443	−3.80	0.42	1.94	18.692	15.652	39.020
L-6	Breccia	0.18	0.708243	0.267	0.512515	−2.40	0.08	0.41	17.673	15.754	37.673
L-37x	Breccia	0.17	0.707954	0.265	0.512480	−3.08	0.03	0.15	17.844	15.800	37.783
L-4	Breccia	0.19	0.707999	0.269	0.512550	−1.72	0.04	0.23	17.866	15.742	37.914
L-27A	Breccia	0.12	0.707290	0.277	0.512594	−0.86	0.03	0.13	18.063	15.632	38.097

[a] Rb/Sr, Sm/Nd, U/Pb and Th/Pb ratios are estimated from the ICPMS trace element concentration data in Table 1.

[b] ^{87}Sr/^{86}Sr ratios were normalized to ^{86}Sr/^{88}Sr = 0.1194. Uncertainties for the measured ^{87}Sr/^{86}Sr were less than 4 in the 5th decimal place, corresponding to 2σ of the mean. The NBS-987 Sr standard analyzed during the course of this study yielded ^{87}Sr/^{86}Sr = 0.710245 ± 23 ($n = 4$).

[c] Measured ^{143}Nd/^{144}Nd ratios were normalized to ^{146}Nd/^{144}Nd = 0.7219. Uncertainties for the ^{143}Nd/^{144}Nd ratios in the samples correspond to 2 in the fifth decimal place, representing 2σ of the mean. La Jolla Nd-standard analyzed during the course of this study yielded ^{143}Nd/^{144}Nd = 0.511852 ± 24 ($n = 3$).

[d] $\varepsilon_{Nd}(0)$ was calculated using the present day bulk earth (CHUR) value of ^{143}Nd/^{144}Nd = 0.512638 and ^{147}Sm/^{144}Nd = 0.1967. The $\varepsilon_{Nd}(0)$ values represent the deviation of ^{143}Nd/^{144}Nd in parts per 10^4 from the present day CHUR value.

[e] Pb data corrected for mass fractionation. Estimated errors are less than ±0.06%.

forming elements. These authors, however, did not analyze any volatile elements, such as Pb and the halogens. Ehmann et al. [49] came to a similar conclusion from their study of the Zhamanshin impact crater in Russia. More recently, enrichments of Al_2O_3, Fe_2O_3 and K_2O (wt.%), Co and Sr (ppm) and depletions of TiO_2 and MgO (wt.%), Cr and Sc (ppm) in the impact breccia rocks compared to the target basalts of the Lonar crater have been reported [32]. Another study on the Lonar Crater [27] reported greater concentrations of SiO_2 and K_2O (wt.%) in the impact melt rock with Fe_2O_3, MgO, MnO and Na_2O concentrations decreasing from the target rock to the melt rock. The higher concentrations of Rb, Sr, Ba, La, Ta, Th, Cs and Ce in the impact melts were interpreted in these studies to be due to plagioclase dominated melting of the host basalt upon impact. In addition, higher abundance of Co and marginal enrichment of Cr in the impact melts are considered by these authors [27] to be derived from the impactor. A similar conclusion was made by Taylor [50] from the study of impact glasses from the Henbury crater in Australia.

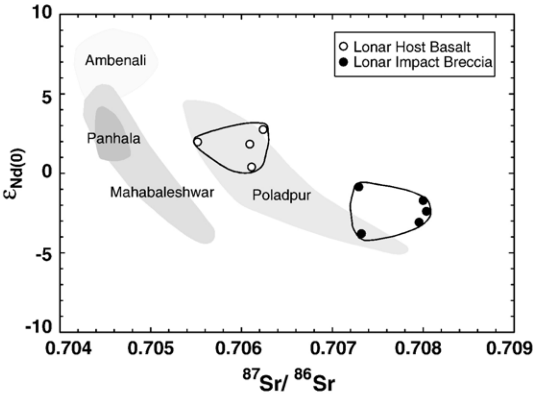

Fig. 5. Nd–Sr isotopic composition of the Lonar host basalts and the impact breccia. Also shown for comparison are the Nd–Sr isotopic compositions of the four uppermost volcanostratigraphic units (Panhala-Desur, Ambenali, Mahabaleshwar and Poladpur) of the Deccan [46,51–53]. The Lonar host basalts have a similar isotopic composition to the Poladpur suite of rocks, but the impact breccia indicate a different source, perhaps components from the Archean crust beneath the Deccan traps.

4.1. Geochemical tracers for the external component in the impact breccia

Chondrite-normalized Rare Earth Element (REE) patterns of this study show a uniform and overall light REE-enriched pattern for both the impact breccia rocks and the host basalts of the Lonar Crater (Fig. 3). These results are generally consistent with previously published REE data of Lonar impact glasses [25–27] and the Deccan host basalts [44–46] from the crater. A closer inspection of the present data of our study, however, indicates that the impact breccia have a more fractionated REE pattern (average La_N/Sm_N ratio of 1.72) compared to the host target basalts (average La_N/Sm_N ratio of 1.35) (Fig. 3), suggesting that the target rock at the Lonar impact site may not entirely be the Deccan basalts exposed on the surface. These observed differences in the La/Sm ratios are significantly outside the analytical error of the REE data reported in Table 1. In addition, the impact breccia and host basalts show

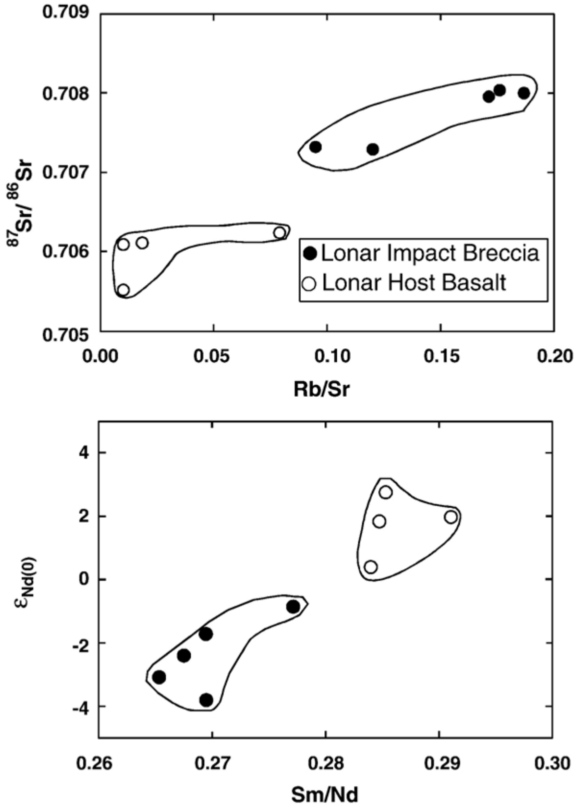

Fig. 6. Sr and Nd isotopic variation of the Lonar impact breccia and the host basalts and their correlation with their Rb/Sr and Sm/Nd ratios (determined by ICPMS), respectively. The impact breccias have more radiogenic Sr-isotopic composition and higher Rb/Sr ratios; however, as expected, the Sm/Nd ratios for the impact breccias and their present day ε_{Nd} values are significantly lower than the Lonar host basalts.

strikingly different patterns in the primitive mantle-normalized multiple trace element plots (Spider plots) (Fig. 4). The host-basalts show negative Rb and Pb anomalies while the impact breccia are strikingly enriched in Rb, Ba, Th, U and Pb compared to the host basalts. For example, Rb is enriched in the impact breccia by as much as 20 times, Ba by 3 times, Th by 2 and Pb by as much as 13 times. The degree of Rb and Pb enrichment in the impact breccia rocks relative to the host basalts is much greater than Ba, Th and U. It has been suggested by earlier workers that mobile elements like Rb and Pb are fractionated due to the impact event that produced the Lonar crater on Deccan host basalts [27]. In basaltic rocks, Rb and Pb are hosted mainly in plagioclase. Partial melting of plagioclase upon impact could cause the removal of these elements from the host rock and their redistribution in shock melted glass or spherules, which were then incorporated into the impact breccia [27].

We compare the Sr, Nd-isotopic compositions of the Lonar host basalts with those of the uppermost four volcano-stratigraphic units of the Deccan basalts [46,51–53] (Fig. 5). While the Deccan volcano-stratigraphy is best documented in the Western Ghats region [31,54], it is not as well characterized in the eastern part of the Deccan province where the Lonar crater is situated. Based on the Nd and Sr-isotopic compositions of the Lonar host basalts of this study and the unpublished data of two other host basalts (Mahoney, personal communication, 2006), we suggest that the host basalts for the Lonar impact crater must have had compositions very similar to the Poladpur suite of lavas, which are in the mid-section of the Deccan volcano-stratigraphic province (Fig. 5).

We also compare the multiple trace element concentrations of the Lonar host basalts with those of the Poladpur suite of rocks. The chondrite-normalized REE

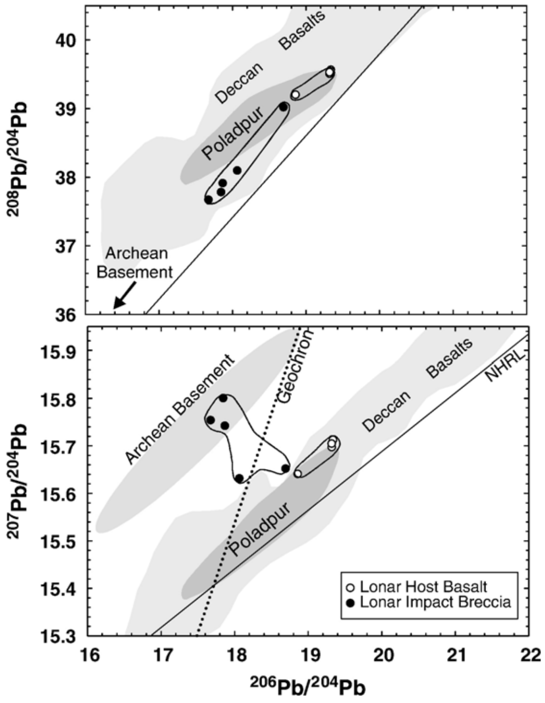

Fig. 7. Pb isotopic composition of the Lonar impact breccia and the host basalts. Also shown for comparison are the Pb isotopic compositions of the Deccan lavas, the Poladpur suite of rocks [46] and those of potential Archean basement rocks of the Dharwar craton of peninsular India [47,48]. The host basalts have Pb-isotopic compositions similar to the Poladpur suite of rocks. It is clear that the impact breccia and the host basalts have distinctly different Pb-isotopic signatures, specifically with respect to ^{207}Pb/^{204}Pb values. These differences indicate Pb-sources from another reservoir, the Archean basement rocks from beneath the ~350 m thick basaltic floor of the crater. The Pb-data clearly show a mixing trend between the Deccan Trap basalt and Archean basement Pb.

patterns of the Lonar host basalts and the breccia rocks fall within the range of the Poladpur suite of rocks (Fig. 3). The primitive mantle-normalized multiple trace element plots of the host basalts is strikingly similar to the patterns observed in the Poladpur suite of rocks [44–46] including the negative Pb and Sr anomaly and the lower Rb contents observed in the target basalts (Fig. 4). This observation indicates that the depletions of these mobile elements are characteristic of the target basaltic rocks and need not be produced by impact related melting of plagioclase in the host basalts as suggested previously [27] and mentioned above.

Compared to the host basalts, the impact breccia rocks have more radiogenic Sr-isotopic composition and more negative ε_{Nd} values (Fig. 5). The breccia rocks also have higher Rb/Sr ratios and lower Sm/Nd ratios compared to the host basalts (Fig. 6).

Plagioclase and pyroxenes have characteristically different Sm/Nd and Rb/Sr ratios, which can produce different time-integrated Nd and Sr-isotopic ratios respectively, if allowed to evolve over long periods of time. Preferential impact-induced melting of plagioclase in very old basalts can therefore give rise to Sr and Nd-isotopic compositions in the plagioclase-dominated melt different from the residual rock. However, given that the Deccan basalts are only 65 Ma old, different Rb/Sr and Sm/Nd ratios in plagioclase and pyroxenes could not have resulted in discernible differences in isotopic ratios between the plagioclases and pyroxenes of the host basalts of the Lonar crater. Therefore, preferential, impact-induced plagioclase-dominated melting of the Deccan basalts could not have caused the observed differences between the Lonar host basalts and the impact breccia rocks.

Nd and Sr isotopes are not known to fractionate during an impact event. Even if we allow that the higher Rb/Sr and lower Sm/Nd ratios in the impact breccia compared to the host basalts are due to impact-related elemental fractionation, this fractionation cannot produce the contrasting present day Sr and Nd isotopic compositions, in only 52,000 yrs since the Lonar impact, which is a very short time for measurable growth of radiogenic Sr and Nd. The Sr and Nd isotopic composition of the impact breccia hence indicates incorporation of components derived from the continental crustal material of the basement Archean complex beneath the Deccan lava flows of the crater. This interpretation is consistent with the higher Rb/Sr, lower Sm/Nd and lower concentrations of Sc and V of the impact breccias compared to their host basalts.

The Pb-isotopic composition of the Lonar host basalts lies in the field of the Deccan basalts and overlaps with the Pb-isotopic composition of the Poladpur suite of lavas [46] (Fig. 7). The impact breccia rocks have lower $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios but higher $^{207}Pb/^{204}Pb$ ratios compared to the host basalts (Fig. 7). High $^{207}Pb/^{204}Pb$ ratios at low $^{206}Pb/^{204}Pb$ values must indicate the presence of an ancient crustal component in the source of the impact breccia. This is consistent with the Nd, Sr-isotopic evidence as mentioned above. Higher concentration of Pb in the impact breccia is a result of the incorporation of the crustal component that resulted in low U/Pb and Th/Pb ratios as observed in the impact breccia.

Can incorporation of paleosols cause the observed anomalies in the impact breccia? The Deccan basalt flows contain paleosols, termed ‘red bole beds’, which are weathering products of the basaltic flows formed between successive eruptions and also since the cessation of the Deccan volcanism [36,37]. Major element data for the host basalts and the impact melts from the Lonar crater indicate that SiO_2 and K_2O concentrations are higher while Fe_2O_3, MgO and Na_2O concentrations are lower in the basalts compared to the impact melts [27]. The major element chemical data of the impact melts do not show any increasing Al_2O_3 concentrations with accompanying decrease in CaO [27], and this observation rules out the incorporation of paleosols into the impact breccias. A few reported REE patterns, available from the literature [37], of the red boles are broadly similar to those of the local basalts. However, unlike the basalts and also the impact breccia (Fig. 3), these paleosols show strong negative cerium anomalies, which are attributed to acid rain occurring at the time of red bole formation [37]. The strikingly different REE pattern of the red boles and the Lonar impact breccia further rules out the incorporation of paleosols into the impact breccia. Moreover, since the paleosols are weathered products of the Deccan basalts, their Nd–Sr–Pb isotopic composition, unlike the impact breccias, should not be too different from the basalts.

Diagenesis does not fractionate Sm and Nd and hence Nd-isotopes are not affected by surficial alteration. Given the coherent behavior of the trace element as well as Sr and Pb-isotopic signatures with the Nd-isotopic data, it can be concluded that the trace element and Nd, Sr, Pb-isotopic compositions are primary characteristics of the impact breccia.

The Deccan volcanic province is also known to have inter-trappean sediments varying in thickness from a few centimeters to a few meters [35]. The inter-trappeans comprise cherts, impure limestones and are mostly fluvial and lacustrine in origin with well-preserved Mesozoic animal fossil remains [35]. Incorporation of inter-trappean sediments into the impact breccia would result in increased concentrations of CaO and SiO_2 in the breccia compared to the host basalts, which is not observed [27]. In addition, incorporation of these Mesozoic-age sediments in the impact breccia cannot explain the Archean Pb-isotopic signatures. Therefore, we conclude that these sediments did not contribute to the observed geochemical signature of the impact breccia.

Unlike either Rb or Pb, only a few elements, such as the REEs, Th and Sc in fine-grained terrigenous clastic sediments preserve a direct relationship of their abundance in upper crustal source rocks and in the derived sediments [55]. Therefore, the positive anomalies of Rb and Pb as seen in the spider plots (Fig. 4) of the Lonar impact breccia cannot be due to the incorporation of eolian detritus from upper crustal sources. Moreover, eolian sediments show REE patterns that are identical to upper crustal compositions with a characteristic negative Eu-anomaly [55]. Had the impact breccia incorporated eolian sediments, they would show prominent negative Eu-anomalies and much higher La/Yb ratios (~10) as seen in average upper crustal rocks. This is, however, not observed in the Lonar impact breccia rocks (Fig. 3). Hence, incorporation of eolian sediments into the impact breccia cannot explain the observed geochemical signatures of the breccia.

Consideration of surface geology of the Indian subcontinent as well as the geochemical and isotopic signatures of the lowermost flows of the Deccan indicates the presence of Archean to mid-Proterozoic crustal layers below the Deccan lava flows. Some of this ancient crust was assimilated by the ascending Deccan lavas [46,54]. It has been suggested that this crust was composed of amphibolites or granulites [54] or metasediments derived from them. The negative ε_{Nd} values and radiogenic Sr isotopic composition of the impact breccia can be explained by melting of Archean basement rocks similar to those exposed in the Dharwar craton of peninsular India [47]. The high $^{207}Pb/^{204}Pb$ ratios at low $^{206}Pb/^{204}Pb$ values observed in the impact breccia (Fig. 7) can be derived from the late Archean lithologies, similar to the Chitradurga Group [48] by impact melting. Rocks of similar age and lithology may be part of the basement sequence below the Deccan traps in the Lonar region.

The thickness of the Deccan traps is at its maximum in the western 'ghat' region where it is greater than 3 km thick. However, the thickness of the lavas is considerably less near the southeastern and eastern part of the Deccan Province, where the lava flows are, in general, about 100 m thick [31]. Maximum estimated thickness of the Deccan traps near the Lonar region ranges from 400 to 700 m [27,31]. Diamond drilling in the Lonar Crater has retrieved cores comprising 100 m of lake sediments on the top followed by coarse and microbreccia down to depths of ~350 m beneath the floor of the Lonar lake [1] (Fig. 1). The drill holes were terminated at the bedrock but it was considered difficult to distinguish coarse breccia from fractured bedrock [1]. Simple craters on planetary bodies have similar depth to diameter ratios ranging between 0.2 and 0.33 [7]. Based on the above information, the depth of the Lonar impact crater, which is also a simple crater [56], should be between 350 m and 610 m as the diameter of the crater measures 1830 m. This depth is in the range of the estimated thickness of the Deccan traps in this region, and it also implies that the Archean basement rocks would melt upon impact and be incorporated into the impact breccia. This conclusion is strongly supported by the trace element and Nd, Sr and Pb isotopic composition of the impact breccia as presented in this study.

It is suggested here that during the excavation stage of an impact event, unmelted clastic debris from inside the transient crater is incorporated into the melt, ultimately to be either digested by the superheated melt or frozen in the melt sheet inside the crater. The degree of assimilation of the clasts depends largely on the initial temperature and the cooling rate [57]. This in turn depends on the initial clast-to-melt ratio and the volume of the melt. Large impacts like the one in Sudbury result in the rapid formation of a 'superheated magmatic emulsion' [58] comprising chemically miscible but physically discrete melt blobs, which is the high-temperature equivalent of a breccia. With time the emulsion components separate out based on their relative densities to form layered structures with similar isotopic and trace elemental compositions. However, for a smaller sized impact as in the Lonar, this is not seen. The impact breccia samples from the Lonar crater represent a mixture of airborne melts, as seen from their circular cross-section and clasts of the target rock. The melts are derived from melting of the upper basaltic layers as well as the Archean basement rocks while the clasts are derived mostly from the basaltic target rocks. Although the "crystalline" clasts of the Archean basement have not yet been found in the Lonar breccia rock, further efforts are needed in this search.

4.2. Origin of the little Lonar crater

The Little Lonar is a smaller, 300 m diameter, circular depression about 700 m north of the Lonar crater and is a satellite crater (Fig. 1). The mode of origin of this smaller impact crater has been debated. Fredriksson et al. [1] argued that the Little Lonar was formed when the throwout from the main crater landed. Debris ejected from an impact crater follows ballistic trajectories from its launch position within the main crater. Ejecta originating farther from the crater center are launched later and more slowly, falling near the crater rim while the innermost ejecta have the steepest trajectories and are deposited farthest from the crater [7]. Large impact craters are often surrounded by numerous secondary craters occurring either in loops, clusters or lines. The largest secondary crater diameter is approximately 4% of the primary crater diameter, as observed on the moon [7]. Given the 300 m diameter of the Little Lonar compared to the 1830 m diameter of the Lonar crater, it is therefore reasonable to assert that the Lonar crater and the Little Lonar have formed by near-simultaneous double impacts of fragments of the same bolide as suggested by Master [3]. We also suggest that the impact breccia sample collected from the rim of the Little Lonar was probably formed from the ejecta of the main Lonar crater as the energy associated with the formation of Little Lonar was not sufficient enough to excavate the overlying basaltic rocks and incorporate the isotopic and trace element signatures from the Archean basement rocks as seen in the breccia rocks.

4.3. Size and nature of the impactor

The formation of impact craters is a complex process, depending on the material properties of the target and projectile, atmospheric effects, angles of impact and on gravity [5,7,8]. The crater depth and diameter as well as the volume of melt produced are functions of the energy of impact and the nature of the target material [9,10]. Possibility of impactor break-up in the atmosphere prior to impact depends on the strength of the impactor, which indirectly affects the size of the crater. Simple crater dimensions are dominated by the strength of the target while complex crater dimensions are primarily controlled by the gravity of the planet [9].

The impact and subsequent growth of a crater can be modeled using a set of classical differential equations known as the Navier–Stokes equations, which express the conservation of mass, energy and momentum along with a set of equations describing the thermodynamic properties and strength of materials [7,59]. The main problem encountered in modeling is that the equation of state and material model are not well known for most natural materials. However, many of these equations possess ‘invariances’ i.e. change in some variable leaves the overall equation unchanged. One such invariance, though not strictly true with increasing impact angles and projectile sizes, arises from the fact that final crater size is much larger than the size of the projectile. Hence, none of the projectile specific properties other than its total energy and momentum affects the size and shape of the final crater [60]. Under such circumstances, ‘scaling relations’ can be derived; such scaling relations take the form of power laws linking combinations of dimensionless quantities describing the projectile and the final crater. We have used Pi-group scaling relations [7,59,61] to estimate with reasonable approximation the size and nature of the Lonar impactor.

$$\pi_D = C_D \pi_2^{-\beta} = D\ (\rho_t/m)^{1/3}$$

where π_D is a dimensionless measure of the crater diameter, D is the transient crater diameter, ρ_t is the target rock density (2.9 g/cm^3 for basalts) and m is the projectile mass. C_D and β are constants that are determined empirically [61] and depend on the nature of the target material, in particular on its porosity or coefficient of internal friction. π_2 is the inverse of the Froude number and is expressed as:

$$\pi_2 = (1.61gL)/\ v_i^2$$

where g is the surface gravity, L is the projectile diameter, and v_i is the impact velocity.

Based on the above equations and assuming a spherical impactor, we have estimated the size of the impactor that resulted in the formation of the 1830 m-diameter Lonar crater on basaltic target rocks. The densities of iron, stony-iron and ordinary chondritic meteorites used for this calculation are 8.0, 5.0 and 3.4 g/cm^3, respectively [38,62]. Using these parameters, the diameter of an iron meteorite impactor would be ~70 m while those of a stony-iron meteorite and an ordinary chondrite would be ~86 m and ~120 m, respectively.

The best terrestrial example of an iron meteorite impactor is the Canyon Diablo meteorite, which resulted in the formation of the 1190 m diameter Meteor Crater in Arizona [63]. Pieces of iron meteorite impactors are usually preserved at the site of impact as observed in the ~49,000 yr old Meteor Crater. Based on C-isotopic studies, an iron meteorite impactor has been suggested for the Lonar crater [27]. However, no traces of the impactor have yet been found in and around the Lonar crater. Given the lack of any iron meteorite fragment in the Lonar crater despite the relatively young ~50,000 yr age, similar to the Meteor crater in Arizona, we suspect that Lonar impactor might not have been an iron meteorite. Using the same set of equations and assumptions as described above, we determined that the diameter of the bolide which formed the Little Lonar is ~12 m for an ordinary chondrite or ~10.5 m for a stony-iron meteorite. This small impactor excavated only the upper basaltic crust and could not have affected the basement rocks of the Deccan. Impact breccia fragments located around the Little Lonar are therefore mostly derived from the main impact crater including the impact breccia of sample L-27A (Fig. 1, Table 1).

5. Conclusions

(1) Nd–Sr–Pb isotopic composition and trace element concentration patterns of the target basalts at Lonar uniquely match the Poladpur suite of lavas of the Deccan Traps. The negative Rb and Pb anomalies seen in the target basalts are characteristic of the Poladpur suite of the Deccan volcanics, which is one of the mid-level suites of the Deccan lavas. These anomalies cannot be due to plagioclase-dominated melting of the target basalts upon impact as previously suggested.

(2) The impact breccia rocks and the target basalts from the Lonar impact crater are distinctly different in trace element compositions. The impact breccia show more fractionated chondrite-normalized REE patterns compared to the target Deccan basalts. The breccia rocks are more enriched in Rb, Ba, Th, U and Pb compared to the target basalts. The impact breccia rocks also show characteristically lower Sc and V concentrations relative to the target basalts.

(3) The enrichment of certain incompatible elements, Rb, Ba, Th, U and Pb in the impact breccia is due to mixing with continental crustal material from beneath the target basalts of the Deccan Traps. The incorporation of paleosols, which are weathering products of the basalts, into the impact breccia are ruled out based on non-conformity of major element and REE data for the paleosols and the impact breccia. Incorporation of paleosols as well as post-depositional alteration also cannot explain the systematic difference in the Nd-isotopic composition of the Lonar impact breccia rocks and the host basalts. The incorporation of inter-trappean sediments, mostly cherts and limestones with Mesozoic animal fossils, into the impact breccia cannot account for the Archean Pb-isotopic signatures observed in the impact breccia. Thus, these sediments are also ruled out as potential components of the impact breccia. Eolian sediments have REE patterns that are identical to upper crustal rocks with a characteristic negative Eu-anomaly. The impact breccia rocks do not show these characteristics. Therefore, eolian sediments were not incorporated in the breccia during the impact process.

(4) The impact breccia rocks show more negative $\varepsilon_{\mathrm{Nd}}$ values and more radiogenic Sr-isotopic compositions compared to the target basalts. The breccia are also characterized by elevated Rb/Sr and low Sm/Nd ratios, indicating the contribution of continental crustal material in the formation of these rocks. The high $^{207}\mathrm{Pb}/^{204}\mathrm{Pb}$ ratios at low $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$ ratios of the impact breccia indicate contribution from ancient continental crustal material.

(5) The Precambrian crustal basement beneath the Deccan traps is composed of amphibolites, granulites or sediments derived from them. The high $^{207}\mathrm{Pb}/^{204}\mathrm{Pb}$ ratios at low $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$ values observed in the impact breccias are similar to late Archean lithologies of the Chitradurga Group of peninsular India, considered in this study as part of the basement rocks below the traps in the Lonar region. The trace element and isotopic data presented here demonstrate that the impact breccia of the Lonar crater formed by impact-mixing of melts and clasts derived from the Deccan basalts and the Archean basement. For a simple crater such as Lonar, the incorporation of Archean basement from beneath the Deccan in the breccia rocks provides new insights for crater formation in basalts underlain by granites.

(6) Although the exact nature of the impactor is not known, using Pi-scaling relations, we predict that the diameter of an iron meteorite impactor would be ~70 m while those of a stony-iron meteorite and an ordinary chondrite would be ~86 m and ~120 m, respectively.

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