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Earth and Planetary Science Letters 247 (2006) 197 – 211

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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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Received 9 November 2005; received in revised form 29 April 2006; accepted 1 May 2006
Available online 16 June 2006
Editor: S. King

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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doi:10.1016/j.epsl.2006.05.003

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