**First Order Reversal Curves (FORC) of Impact Products from Lonar Crater**  
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**Introduction:**
The Lonar crater (19°58’N, 76°31’E; Fig. 1) [1] is one of the few among 188 known terrestrial asteroid impact craters that are excavated in the basaltic target. It is a bowl-shaped, near circular, simple asteroid impact crater with an average diameter of ~1810 m, circularity of ~0.95 and depth of ~135 m, and relatively pristine in morphology [1, 2]. The crater was formed on a basaltic target (Deccan Traps) by an oblique impact of a chondritic impactor that struck the pre-impact target from the east at an angle between 30 and 45° to the horizon [2, 3]. The age of the crater is not clearly established and could be 570±47 ka [4] or ~52±6 ka [5]. Our previous studies on the Lonar crater show systematic variations in rock-magnetic, paleomagnetic and AMS properties of the target rocks from the crater rim and surrounding with reference to the direction of impact from the east [6]. In the present work, we report the first order reversal curves (FORC) analyses of the Lonar impact-melts and spherules and discuss their significance with the evolution of Lonar crater.

**Sample Description and Measurements:** mm-sized fragments of impact-melt and in-situ impact spherules from Lonar crater were recovered from trenches dug (~47 cm deep pit) on ejecta blanket close to the SE of the crater rim (19°58.356’N, 76°31.072’E). These impactites are characteristically black, have vitreous luster and highly vesicular surface. The impact-spherules have a variety of geometric shapes including rod, ellipsoidal, dumbbell and teardrop (Fig. 2). Secondary infillings of quartz are sometimes found in the vesicles. The FORC measurements of impact spherules, impact-melts and target rock chips (mass: ~5 to 20 mg) were performed using Princeton Measurements Alternating Field Gradient Magnetometer 2900 (AGM Micromag). The FORC distributions yield information about the microcoercivity distribution ($H_c$) and magnetic interactions ($H_u$) within a sample [7, 8]. The FORC data were processed into FORC diagrams using the VARIFORC protocol of [9] within the FORCinel software of [10]. All FORC data were processed with the following VARIFORC parameters: $S_c0=3.5$, $S_c1=7$, $S_b0=3$, $S_b1=7$, and $\lambda_{v,h}=0.1$. The FORC diagrams can enable discrimination between mixtures of grains with variable domain states and identification of the presence or absence of magnetostatic interactions because grains with different domain structures and interactions plot in different parts of the FORC diagram.

**FORC Results:**
The FORC diagram of impact-melt chip display closed concentric contours between ~10 and 60 mT with substantial vertical spread distributions (below ~20 mT) suggesting the presence of interacting finer SD magnetic grains (Fig. 3a). The degree of magnetic interactions decreases for larger $H_c$ values which probably reflects the increasing dominance of the intrinsic anisotropy over magnetic interactions with increasing coercivity [11]. In the case of impact spherules, the FORC diagrams show evidence of mixtures of SD and MD grains (i.e. PSD-type) but with higher $H_c$ values (Fig. 3b). Here, the SD-like moments progressively shifts to lower coercivities and that the MD-like magnetization diverges increasingly toward the $H_u$ axis [8, 12]. Most of the target basalt (both unshok & shock) display PSD grain-size distribution FORC (Fig. 3c, 3d, 3e). For some shock basalts, there is a disappearance of the closed-contour structure suggesting PSD-MD grain-size transition (Fig. 3f). The observed shock-induced magnetic hardening nature (with high $H_c$ values) for teardrop spherule and shocked ejecta (Fig. 3b, 3e) is consistent with the laboratory shock experimental studies [13].

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**Fig. 1:** Photograph of Lonar basaltic impact crater

**Fig. 2:** Impact-melt pieces and spherules (teardrop, rod, and spindle shape) recovered from Lonar ejecta

**Fig. 3:** (a) FORC diagram of impact-melt chip display closed concentric contours between ~10 and 60 mT with substantial vertical spread distributions (below ~20 mT) suggesting the presence of interacting finer SD magnetic grains. (b) The FORC diagram of impact spherules show evidence of mixtures of SD and MD grains (i.e. PSD-type) but with higher $H_c$ values. (c) Most of the target basalt display PSD grain-size distribution FORC. (d, e) For some shock basalts, there is a disappearance of the closed-contour structure suggesting PSD-MD grain-size transition. (f) The observed shock-induced magnetic hardening nature is consistent with the laboratory shock experimental studies.
Discussions and Conclusions:
High pressures and temperatures involved during impact cartering event results in melting and/or vaporization of target rock and projectile with a final opening of transient crater [14, 15]. The voluminous amount of material driven out of the transient crater is a mixture of shocked rock fragments and molten materials, which contrast in physical state, temperature and deformation. Impact-melts crystallized soon after the impact (but cool slowly) and eventually may contain finer SD magnetic grains whereas spherules undergone intense (superheated) melting followed by high-velocity ejection and chill rapidly in the impact-generated vapor plume atmosphere before landing at the impact site resulting in both finer and coarser magnetic grains with higher coercivity ($H_c$) values. This shock-hardening behavior is also evident for shocked ejecta rocks. The FORC analysis are thus a potential method for characterizing various aspects of impact melting and shock pressure suffered by target rocks during impact crater formation.

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References: