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Authors: Harshal Pohekar, Raymond Duraiswami, Satadru Bhattacharya, A. S. Arya and Bhalchandra Pujari.

Numerical simulation of meteorite impact on basaltic lavas at Lonar Crater, India

Harshal Pohekar
Department of Scientific Computing, Modeling and Simulation,
Savitribai Phule Pune University, Ganeshkhind, Pune 411007 India.

Raymond Duraiswami
Department of Geology, Savitribai Phule Pune University, Ganeshkhind, Pune 411007 India.

Satadru Bhattacharya
Planetary Sciences Division, Satellite Application Center, Ahmedabad 380015, India

A. S. Arya
Planetary Sciences Division, Satellite Application Center, Ahmedabad 380015, India

Bhalchandra S. Pujari
Department of Scientific Computing, Modeling and Simulation,
Savitribai Phule Pune University, Ganeshkhind, Pune 411007 India.[*]

Lonar lake is a hypervelocity impact crater formed in a basaltic terrain of Deccan Traps in the state of Maharashtra, India. The crater has an approximate radius of 915 m and an average depth of about 137 m. Here we report the results of our numerical investigations aimed to elucidate the physical characteristics of incoming asteroid. For realistic simulation, we not only consider basalt but also basalt with granite basin as the surface of impact. Because most of the characteristics of impactors are unknown we sample the phase space of physics characters and determine the possible bounds of its properties. Among the handful of potential candidates, we believe the incoming asteroid was an iron-rich body of about 52m in radius hitting the surface at 60km/s. Our analysis also shows that the impact created a transient crater of 414m in depth leaving underlying granite basin more or less intact.

I. INTRODUCTION

Terrestrially impact craters in basalt are a rarity. Only four craters in basalt are known, none as prominent and well preserved as Lonar[1]. The Lonar crater is 1.83 km in diameter with an average depth of 137 m and a maximum depth of 150 m, formed in 65-million-year-old basaltic lavas of Deccan Traps. It provides a unique opportunity to study crater structures analogues to extraterrestrial craters on the bodies like Moon and the Mars [2–4]

Despite a few attempts, the nature of the impactor is still not clear. The field survey shows the presence of maskelynite fragments and deformational features which confirm hypervelocity impact as the cause of the formation of Lonar crater [2, 4, 5]. Lakshmi and Kumar [4] have investigated impact and deduced that the impactor was of radius (R) 35m and density (ρ) 2900 kg/m^3, with 20 km/s impact velocity (v). Two alternatives were reported by Louzada K. L. et al. [6] based on the density of incoming projectile, namely R=27.5m radius rocky asteroid with v=20 km/s and R=20m icy comet with v=50 km/s impact velocity based on crater scaling. Babar[7] has reported an impact of 30m radius impactor with 25 km/s impact velocity. A larger impactor was proposed by Taiwade with R=50m and v=18 km/s[8]. Finally, the radii of projectile materials such as iron with a density of 8000 kg/m^3, stony-iron with a density of 5000 kg/m^3 and ordinary chondrite with a density of 3400 kg/m^3 were predicted to be 35m, 43m, and 60m respectively using Pi-scaling relations[9]. In short, the physical dimensions of the impactor range from 20m to 50 m in radii with 18 to 50km/s as velocities. We note, however, that none of these studies involves explicit impact simulations, instead, they rely on empirical approaches. It is not only the dimensions but also the material of impactor that is shrouded in mystery. The enrichment of the basalt layer with Fe, Ni and Ca, and higher density than the basaltic target surface indicate Iron-rich projectile material[2]. On the other hand, some studies have indicated chondrites as possible impactors due to the presence of chondritic Cr and its affinity with a carbonaceous component similar to CM type[10]. However the impactor has not been discovered and considering that basalt has high uniaxial compressive strengths[11, 12] and is derived from upper mantle sources, the material of impactor remains ambiguous.

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[*] bspujari@scms.unipune.ac.in

FIG. 1. Panoramic view of Lonar lake, India. The lake has a diameter of about 1.8km and average depth of about 137m

At this stage, it is to be pointed out that none of the modelling studies so far take into account the granite gneiss basement underlying the basalt surface. Considering that during the impact the transient crater depth could have reached several times deeper than the final depth, it is reasonable to imagine that the subsurface, which is at a few hundred meters deep, would also have some role to play on the final crater dimensions.

Therefore here we aim at analyzing the effect of granite gneiss on basaltic lavas at Lonar and finding the size and impact velocity of the class of projectiles that was the cause of the formation of the impact crater. Because there are yet several unanswered questions from the field regarding the materials, we decide to scan the range from densities encompassing chondrites to iron with varying values of radii and velocities to come up with upper and lower limits on the characteristics of the impactor.

II. LOCATION

The great majority of currently known impact structures on Earth (about 190), have no preserved meteorites but have been identified by the discovery of shock metamorphic effects in their rocks[13, 14]. Lonar Crater from central India (Fig. 1) is a simple impact crater[15, 16] having a diameter of 1.8 km and a hypersaline lake lying about 137 m below the raised rim. Being a well preserved impact crater on Earth entirely formed in basalt, the Lonar Crater is a proxy to study similar craters on terrestrial planets and planetoids, and of interest to existing and upcoming missions like ‘Chandrayaan’. The geology of the crater and the ejecta blanket has been well studied [3, 17–19]along with products of shock metamorphism like impact glasses within the suevite breccia[20–22]. The discovery of maskelynite in the moderately shocked basalt and glassy objects in the ejecta clasts of the Lonar crater [23] was an important criterion for establishing the meteoritic impact origin of this crater. Detailed petrography, geochemical and spectroscopic analyses of the rocks also corroborated an impact origin [10, 17, 24, 25]. The occurrence of coesite, a high-pressure polymorph of quartz has also been reported from the crater [26, 27]. Recently, quenched morphologies in impact glass suggest rapid cooling rates in ejecta products [19].

III. COMPUTATIONAL DETAILS

All the simulations were carried out using iSALE2D shock physics code [28]. iSALE is an acronym for impact-Simplified Arbitrary Lagrangian Eulerian, of which we use EULER mode. Previously, the code was successfully used to model some other impact craters, like Chicxulub[29, 30]. Analytical Equation of State (ANEOS) is used for both projectile and target surface materials. ROCK, IVANOV and OHNAKA were used as strength, damage and thermal softening models respectively. We have selected 10 cells per projectile radius (default is 5) and the cylindrical coordinate system is used for meshing grid calculations.

In order to shortlist the potential candidates, we take two limiting cases for materials of the impactor, namely granite (ρ=2630 kg/m^3) and iron (ρ=7843 kg/m^3). For both cases, we sample a series of velocities ranging from

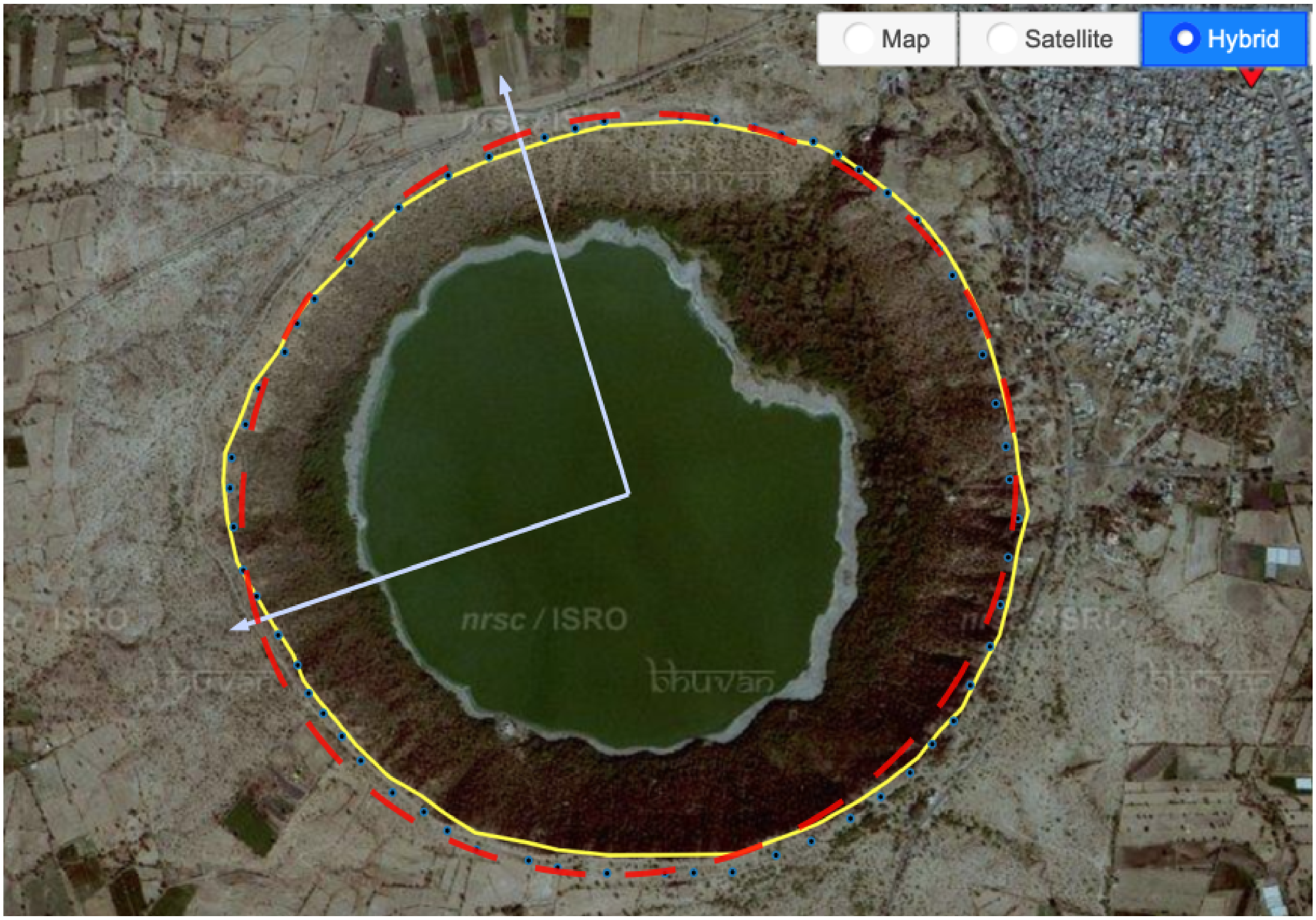

FIG. 2. Fitting an ellipse (red) to the traced rim (yellow) on a satellite image. The fitted ellipse has an eccentricity of 1.01 indicating a slight deviation from the vertical impact. The axes show orientation of the ellipse which is tilted to 17.9° from the north.

10km/s to 70km/s. We then look for the characteristics of the resultant crater to match it with the known dimensions of Lonar lake. The exercise is carried out with two target materials: basalt and bilayer of basalt and granite. The thickness of the basaltic lavas is taken as per known estimates of 500 m[5].

IV. RESULTS AND DISCUSSION

Before performing impact simulations it is worth investigating the angle of the projectile. We obtain it by fitting an ellipse to the rim of the observed lake. We trace contours along the rim of the crater using remote sensing data from the ISRO-Bhuvan web app[31]. As shown in Fig 2, the yellow coloured polygon is obtained by tracing crater rim using the satellite data, to which we fit a red coloured ellipse. We repeat this exercise 10 times and average the results. The fitted ellipse has a semi-major axis of 975 m and a semi-minor axis of 896 m. The resultant eccentricity is 1.09, which indicates the Lonar crater is nearly circular in shape and the incidence was nearly perpendicular to the target. The slight deviation from the vertical incidance results in the orientation of the ellipse along 17.9° East-West, indicating that the meteor approached at an azimuthal angle of 72.1°. This simple exercise assumes the target surface to be flat at the time of impact, which cannot be verified at this stage.

Because most of the things related to the impactor are unknown, we decide to focus on getting a range of dimensions rather than very specific values. Our strategy is to conduct a series of impact simulations and compare the resultant crater dimensions to those of Lonar lake. As mentioned before we consider two different materials for impactors: iron and granite. Iron represents the iron-rich meteorites that are the densest meteorites found, making it the upper bound of our potential candidates. On the other hand, some studies have claimed chondrite is an impactor. Chondrites in themselves are not possible to model due to the structural complexity involved and lack of specifics available. However,

Iron		Basalt			Basalt+Granite		
R	v	Transition crater(m)	Final crater radius (m)	Final crater deapth (m)	Transition crater(m)	Final crater radius (m)	Final crater deapth (m)
52.5	60	378.00	955	152	400.29	917	141
52.5	70	383.23	953	162	420.07	922	155
55	60	384.58	930	165	413.06	928	154
60	50	384.25	952	162	415.38	940	156
60	60	395.86	931	174	445.84	934	174
80	25	369.59	915	137	408.10	924	136
82.5	25	364.39	925	145	424.96	921	142
85	25	387.08	918	152	418.70	932	160

Granite		Basalt			Basal+Granite		
R	v	Transition crater(m)	Final crater radius (m)	Final crater deapth (m)	Transition crater(m)	Final crater radius (m)	Final crater deapth (m)
70	60	371.66	932	147	400.48	914	139
70	70	386.07	918	167	423.26	934	161
75	60	382.50	938	159	413.97	919	156
80	50	376.25	920	143	415.67	913	151
90	40	387.00	935	152	414.60	925	144
105	30	388.50	918	141	421.29	908	157

TABLE I. Some of the best suited results that reproduce radius equivalent to that of Lonar lake. Here R and v are the radius (in meters) and velocity (km/s) of the impactor at the time of impact.

granite's density falls within 10% of CM-type chondrite and hence it is reasonable to select Granite as a projectile material to model chondrite impactor[32]. Such attempts have been made successfully for Chicxulub crater [29]. The granite forms the expected lower bound on the density of the projectile.

The velocities of impactors range from 11 km/s to 72 km/s in our study. The lower bound corresponds to the escape velocity of the Earth and the upper bound represents the maximum possible velocity of the incoming impactor[9]. We consider both the single layer (basalt) and bilayer (basalt+granite gneiss) as targets[33, 34]. This is important as the heterogeneous compressive strength is expected to alter the results (as will be evident later). Also, the basaltic layer is not too deep and granite gneiss may have a role to play in the final dimensions of the crater.

We carried out a total of 313 simulations using various possible combinations of modelling parameters, and only a few of them - which are close to the required crater dimensions - are presented in Table 3. As expected, the crater radius increases with the projectile radius. As pointed out before using two extreme material types we can now establish a bound of possible values for the dimension of the meteor. Using the data points from the Table we plot the select points on velocity-radius phase space in Fig 3. We find that they follow an exponential fit which is plotted as solid lines. We believe that irrespective of actual material, the dimension of the incoming projectile must represent a point in the shaded area. As mentioned before the typical range for velocity of incoming impactor is between 11 km/s to 72 km/s therefore it inappropriate to extend the shaded area outside the boundaries of the plot. Clearly, the higher the density, the lower the required velocity.

Next, we investigate the nature of ejecta via the snapshots of simulations. We show three snapshots of four representative simulations in Fig 4. The snapshots are acquired roughly at the beginning, middle and end of the simulation. The colours in the plots indicate the pressure (on the left half of the image) and temperature (on the right half) and are shown with the colour bars. The ejecta appears as a thin blue line at the top. Although all the four simulations create the crater with similar dimensions the ejecta produced by the granite impactor appears to have spread in a much larger area - in fact beyond the simulation frame - while that due to iron impactor is limited to about 1.5 km in radius from the center. We wish to ascertain here that the simulations can only capture coarser ejecta due to the inherent limitation of the resolution, and as a result, the actual ejecta produced by the impact would spread further than it appears in the picture. Therefore, it is reasonable to assume that the ejecta produced by the iron impactor produces the ejecta with a spread limited to about 2 km in radius, while that of the granite impactor can be significantly more. The field measurements by Fudali et al.[35] have determined the value of continuous ejecta blanket as an average of 1.35 km outside the rim, which is in good agreement with our simulations with iron impactors. At this stage we note that no meteorite fragments were found at Lonar, thereby increasing the likelihood of a smaller impactor. Thus although it is difficult to conclude we believe the incoming impactor must have the constitution of iron-rich material.

As evident from the Table IV, the maximum depth of the crater just reaches the granite basin. We do not believe

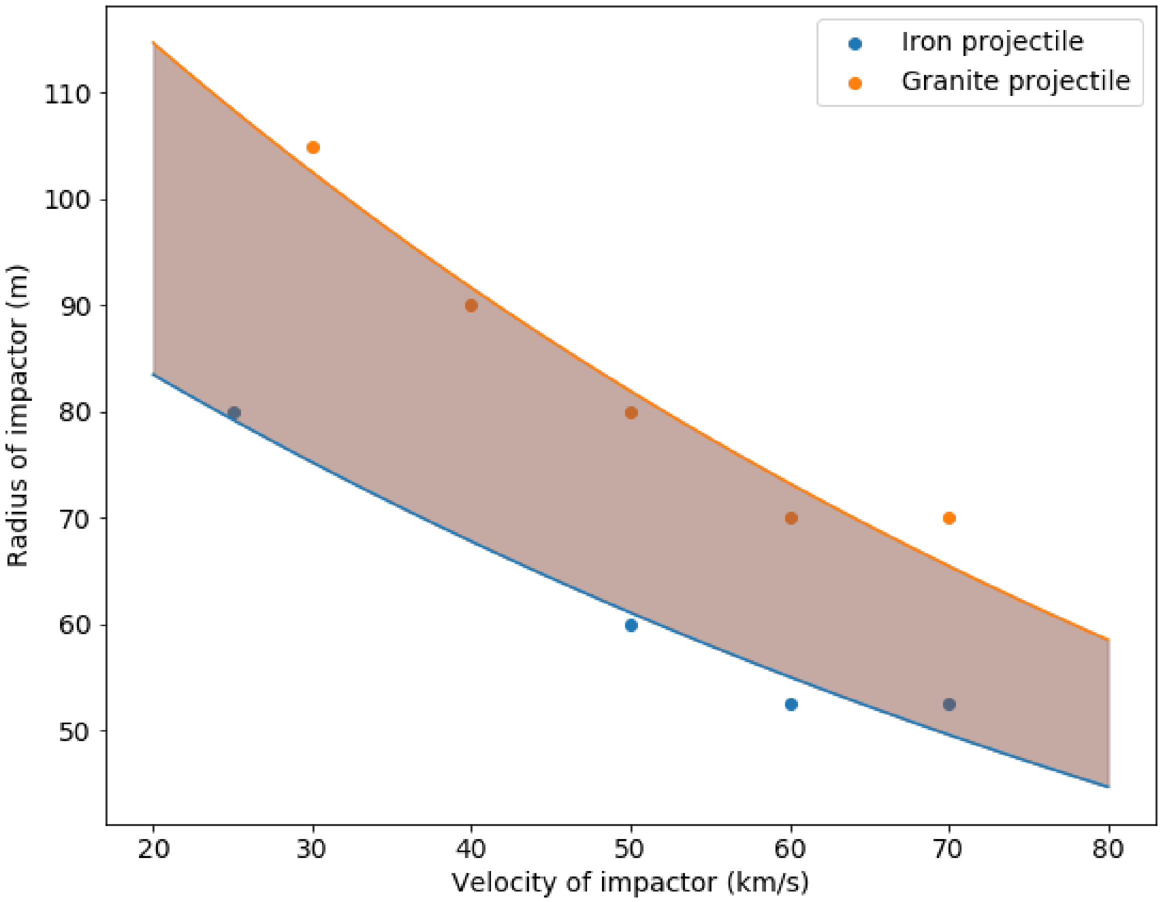

FIG. 3. Phase space of possible radius and velocity of impacting projectile. The velocity and radius of any arbitrary meteorite is likely to belong to the shaded area. In principle the shaded area can be extended beyond what is shown here, however such extremely low and high velocities are highly unlikely.

this would have been sufficient to expel the granite into ejecta material in detectable amount. Additionally, we also look for damages that might have occurred to the granite basin by inspecting pressure profiles during the simulations. We observe that right after the impact the granite basin experiences maximum pressure of less than 6×10^7 Pa. We note that the compressive strength of a typical granite is $\sim 2 \times 10^8$ Pa [3]. Considering an order magnitude difference, it is reasonable to speculate that the granite bed would have remained more or less intact. Moreover the temperatures go as high has 1000K at the site of impact but is largely constrained in basaltic region, leaving granite basin unheated. However more specific effects on the granite basin due to the combinations of pressure, temperature, shock and specific geography may not be ruled out, but is beyond the scope of this study.

V. CONCLUSION

For Lonar crater - for which nature of impactor is completely unknown -we investigated a phase space of impactor's configurations including density, velocity and radius, using state-of-the-art numerical techniques. The results provide us a range of values for the dimensions and momenta of incoming impactor. Our study suggest that depending on the material the impactor could be as small as 52m or as large as 105m in radius. However the simulations indicate that the smaller size impactors best reproduce relatively smaller extent of the ejecta. Thus we believe the incoming

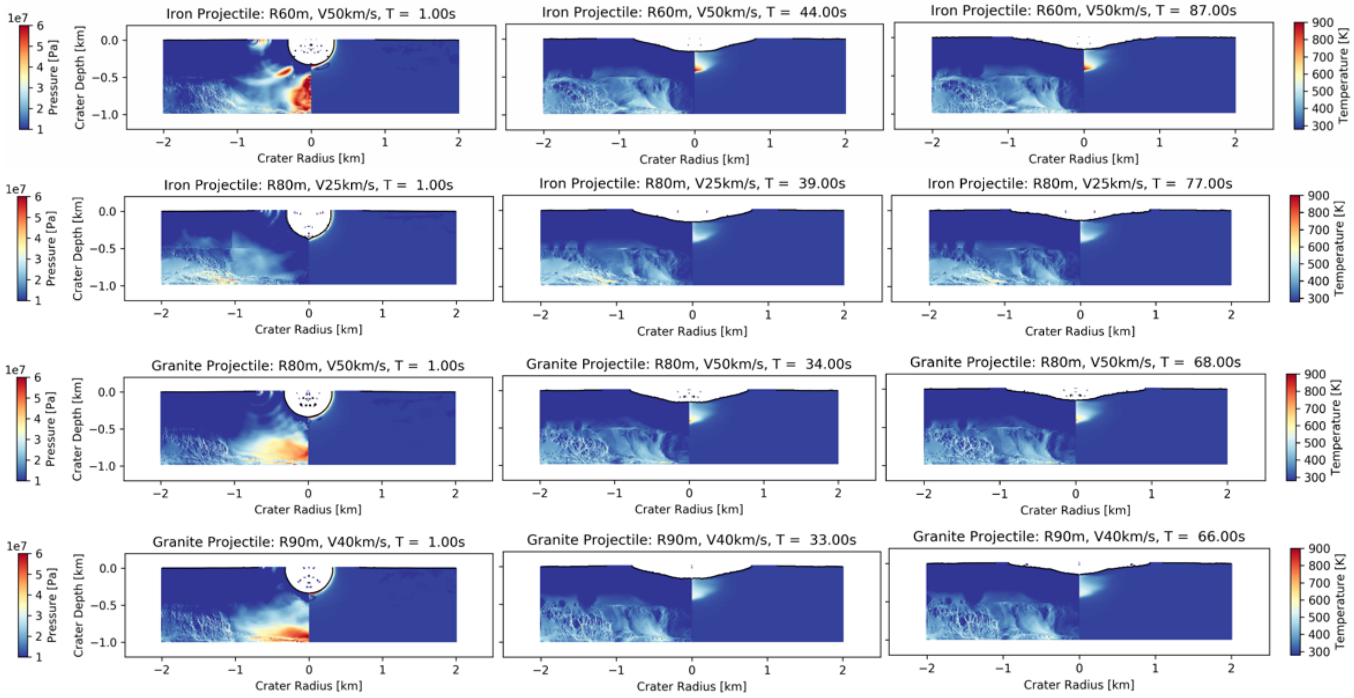

FIG. 4. Simulation snapshots at different time of impact with a) iron projectile with R =60m and v=50km/s, b) iron projectile with R=80m, v=25km/s, c) granite projectile with R=80m, v=50km/s and d) granite projectile with R=90m and v=40km/s.

asteroid was iron-rich material with radius about 52m and velocity at the impact around 60km/s. The resultant weight of the asteroid would be around 4.5 million tons, which is comparable to Great Pyramid of Giza (5 million tons). The impact would have released about 8×10^{12}J or 2 kilo-ton-of-TNT energy which is significantly smaller than that was released during Hiroshima atomic explosion (15 kilo-ton-of-TNT). Our simulations highlight the importance of underlying granite basin. We found out that in absence of granite basin the volume of the resultant crater is generally overestimated. In presence of granite, a transient crater of depth just around 400m would have been formed momentarily before reaching to existing depth within first 90 seconds of impact. This also means the underlying granite basin would have remain largely intact and no fragments would have been expelled in the ejecta. This is consistent with the field observations.

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