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REVIEW ARTICLE

Lonar Impact Crater, India: the Best-Preserved Terrestrial Hypervelocity Impact Crater in a Basaltic Terrain as a Potential Global Geopark

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Abstract

Lonar Impact Crater is a simple meteorite impact crater carved out on the ~ 65 Ma old Deccan tholeiitic flood basalts. The crater, though scoured in a basaltic terrain, is still preserved in its most pristine form, with a central crater lake. The geomorphology, geochemistry, geochronology, hydrology, geophysical parameters, and structural aspects of Lonar Crater have been explored in detail, but still continue to contribute valid scientific insights into the geology of terrestrial impact craters. Lonar serves as a potential analog site for studying impact cratering on planetary surfaces with basaltic terrains such as the Moon and Mars. Besides being a highly recognizable impact crater in India, the Lonar crater and its hinterland stand out with its archeological relevance and spiritual influence among the people. The numerous temples in and around the crater premises uphold the cultural significance of the region. The crater and adjacent areas are rich in flora and fauna representing a diverse ecosystem in the vastness of the arid Deccan Flood Basalts. Hence, the astrobleme and its surrounding is declared a Ramsar site and is also a protected wildlife sanctuary. The Indian Government has also declared the crater a National Geological Monument as well as an archaeological monument. Furthermore, the astrobleme is a unique site with socio-cultural and economic significance. With these plethoras of importance, combined with the geological and socio-cultural aspects in its hinterland, together with the most acclaimed UNESCO world heritage centers Ajantha and Ellora caves in the neighborhood, it stands as the right candidate for a UNESCO Global Geopark. However, the crater and its ecosystem are not preserved well enough, and the uniqueness of the crater is diminishing. But after selection as a Ramsar site, the area shows increased vegetation growth. The SWOT analysis conducted in this study accounts for Lonar Crater and its adjoining areas as a potential global geopark. Thus, through this study, we try to propagate the vivid and myriad importance of the Lonar crater and the necessity of protecting this geological monument from both anthropogenic and natural processes and to appraise the necessity for nominating this area as a UNESCO Global Geopark.

Keywords Geopark · Geoheritage · Lonar · Impact crater · Deccan Basalt · Astrobleme

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Introduction

Brocx (2008) defined geoheritage sites as the global, national, and state-wide to local features of geology, inclusive of its igneous, metamorphic, sedimentary, stratigraphic, structural, geochemical, mineralogical, paleontological, geomorphic, pedological, and hydrological attributes at all scales that are intrinsically or culturally important sites. Such sites offer information or insights into the formation or evolution of Earth or into the history of science that can be used for research, teaching, or reference (Brocx, 2008). The development of the above concepts has resulted in evaluating the importance of the Earth's heritage and its conscious management for future generations (Brilha 2002; Stace and Larwood 2006; Zouros 2004, 2005, 2007, 2009; Zouros and McKeever 2009; Panizza 2009). Thus, geoheritage conservation is defined as the practice of conserving, enhancing, and promoting awareness of such features and underlying processes that have significant scientific, educational, cultural, aesthetic, or ecological value (Prosser 2013; Crofts and Gordon 2015). Keeping all these aspects, Global Geopark Network (GGN) was constituted under the auspices of UNESCO. Thus, the ultimate aim of a geoheritage site is its entry into UNESCO. Among the different sites of GGN, except for the recent entry of the Ries Crater of Germany, there are no meteorite impact craters, even though meteorite impact events were considered as one of the prime processes of planetary evolution.

Meteorite impact cratering events have been a fundamental geological process since planets evolved from the spinning nebula. The extra-terrestrial impactor constitutes asteroids and comets. Impact craters were known to humankind when the remotely sensed images of the Moon, dotted with tens of thousands of basin-like structures (called craters), were captured. This provided the impetus for studying craters on Earth, which not only led to the identification of several craters but also unraveled a plenitude of geological processes that were triggered or evolved through meteoritic impacts (Li et al., 2018; Keerthy et al., 2019; Chandran et al., 2021; James et al., 2021, 2022; Aneeshkumar et al., 2021, 2022; Indu et al., 2022). Impact events are linked to the possibility of the origin of life (McKay et al., 1996), mass extinction (Alvarez et al., 1980), the evolution of Moon (Daly 1946; Canup and Asphaug, 2001), and even the initiation of plate tectonics on Earth (Maruyama et al., 2018; Santosh et al., 2017; Maruyama and Santosh, 2017). With the scanty number of terrestrial impact craters identified to date (~210; Gottwald et al., 2020) and with the real possibility of the discovery of many more craters (Kenkmann 2021), these are the most sought-after features to further solve several conundrums in the geological history of our planet. The modest number of craters, which are the vestiges of collision between two celestial objects, is indeed a treasure house for geologists. Thus, the crater's surroundings became a window to probe both the interior of the planet and the nature of flying cosmic objects.

The typical morphology of an impact crater, comprising of a bowl-shaped depression that may or may not be filled with water, an edifice-like elevated rim, and a central elevated area (CEA, only for complex craters), has invoked curiosity and created socio-cultural footprints ever since human beings started a settled life. The intervention of early humans has also imparted an archaeological relevance to impact craters. The Ries crater in Germany is an excellent example of the same, since the central part of the crater is occupied by settlements. Furthermore, in developing countries like India, such features have also been loci for the religious commune. Lonar and Ramgarh, the two craters in India that preserve the typical morphology thus, became the important sites for religious gatherings and associated socio-cultural aspects. Thus, these structures have been in focus much before they were confirmed as impact craters. The younger Lonar Crater has been a focal point amongst Earth scientists as it is the best preserved terrestrial impact crater on basaltic terrain on Earth which thus, acts as an analog to Martian and Lunar craters (Fredriksson et al., 1973a; Chandran et al. 2021). Though, there are other craters carved in basaltic terrains such as Logancha (Russia), Vista Alegre, Vargeão Dome, and Cerro do Jarau (all three in Brazil), none retains a pristine morphology. Thus, Lonar Crater and its hinterland warrant bringing together of the vibrant and important geologic, social, cultural, and religious aspects in order to unveil Lonar's significance to the broader geoscientific community. Despite being surrounded by stunning natural beauty, rich biodiversity, and cultural significance, the Lonar Impact Crater is in poor condition. Though Lonar crater's preservation can provide an impetus for developing the crater and its hinterland as a potential UNESCO GGN member, the Geological Survey of India (GSI) and the Archaeological Survey of India (ASI) have already declared Lonar a geological and archaeological monument, respectively. In proximity to the Lonar crater, there are notable UNESCO World Heritage sites like the Ajanta and Ellora caves, which enhance the accessibility of the Lonar Impact Crater to the public. The transformation of the Lonar crater as a global geopark will uptick the geological significance of India, which is already acclaimed for the presence and sustenance of several biological and ecological sites like the Western Ghats and the Sundarbans.

Lonar Crater: An Overview

India hosts only three confirmed meteorite impact craters, viz., Dhala in the Bundelkhand Craton, Ramgarh in the Vindhyan Supergroup, and Lonar in the Deccan Volcanic Province. Additionally, India has a few suspected meteorite impact craters like Luna in the Rann of Kuchchh, Shiva in the western offshore basin, Kaveri in the southern granulite terrain, and Simlipal in the Singbhum Craton. Among all of the above, Lonar crater (19°58′N, 76°31′E) is one of the best-studied and well-preserved craters in India (Fig. 1). It is a simple, bowl-shaped, circular crater in the flat-lying Deccan tholeiitic flood basalts. The basaltic target rocks at Lonar make it more important as it can be considered as an analog for meteorite impact craters formed on other planetary bodies having basaltic target rocks such as the Moon and Mars (Fredriksson et al., 1973a; Kieffer et al., 1976; Hagerty and Newsom, 2003; Newsom et al., 2010).

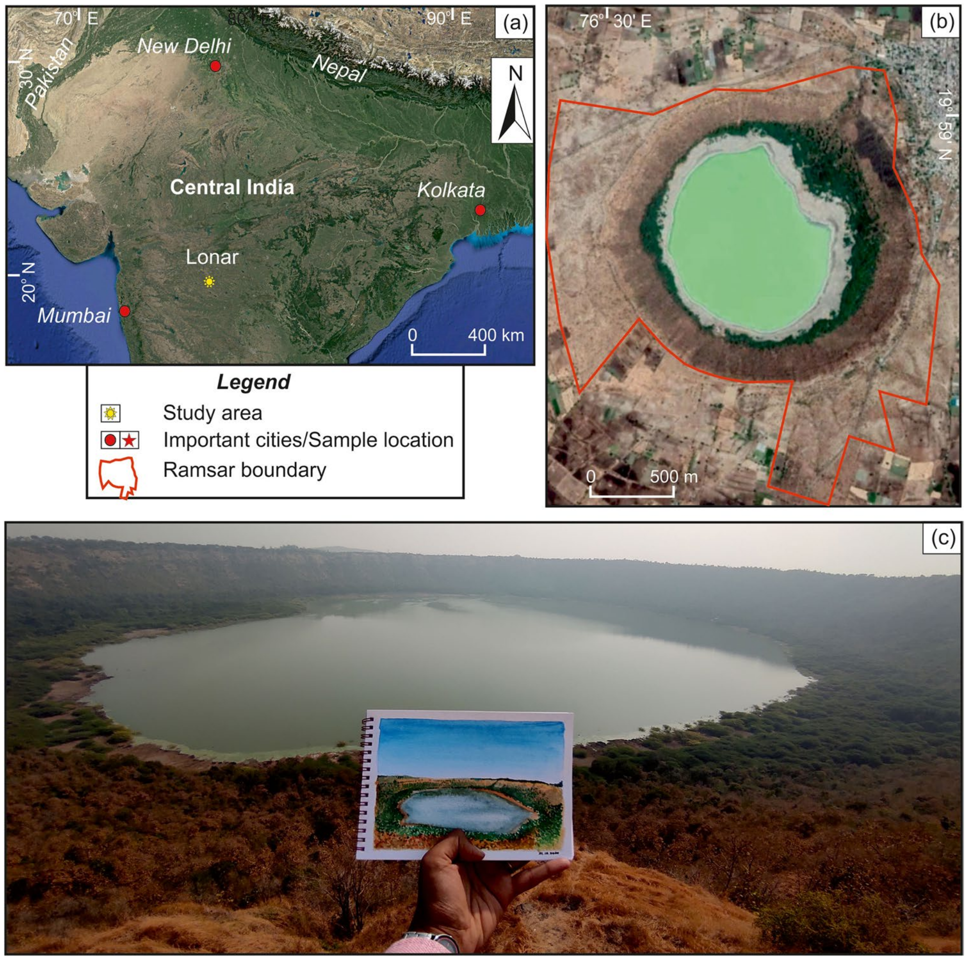


Fig. 1 Location map of the study area **a** Google Earth images of the location of the Lonar Impact Crater in India. **b** High-resolution Google Earth image of Lonar Crater showing the boundary of Ramsar site. **c** A hand-drawn image (by the first author) showing the panoramic view of the crater. Photo taken from the NW watch tower and facing towards the southeastern part of the crater

Lonar crater with a saline lake in the vastness of the Deccan Trap basalts has caught the attention of scientists since the nineteenth century (Orlebar 1839; Malcolmson 1840). In the past, several speculations regarding the origin of Lonar crater were present; a volcanic origin was suggested as the structure being hosted in a thick pile of basaltic rocks (Orlebar 1839; Blanford 1870; La Touche and Christie 1912) with a few studies considering it as the source of Deccan basalts (Nandy and Deo, 1961). Blanford (1870), La Touche and Christie (1912), Krinov (1966), Crawford (1983), Subrahmanyam (1985), and Mishra (1987) suggested a cryptovolcanic or steam explosion based-origin of the crater owing to the presence of thin sediment fill in the lake, the immature level of river incision, and the slope diffusion of the crater wall, and with a suggestion of a younger age for the crater than the Deccan basalts. Since there was no trace of any recent volcanic activity, Cotton (1944) and Barringer (1967) supported the meteorite impact origin for the crater. Similarly, an impact origin for the physiographically young Lonar crater has also been proposed by Beals et al. (1960) and Lafond and Dietz (1964) after perceiving the impact origin of Barringer (Arizona). The high degree of circularity, depth-to-diameter ratio, drilled cores of brecciated rocks, quaquaversal dips in the surrounding country rocks, and debris mound surrounding the crater rim, combined with the regional uniqueness of the feature, have led Lafond and Dietz (1964) to support the impact origin of Lonar crater. The discovery of maskelynite and impact glasses from around the crater over the years is considered as one of the direct evidences of meteorite impact origin of Lonar (cf. Nayak 1972, 1993; Fredriksson et al., 1973a; Fudali et al., 1980; Sengupta et al., 1997; Ghosh 2003; Storzer and Koeberl, 2004; Chandran et al., 2021).

The confirmation of the impact origin of Lonar has led to the pursuit of diverse scientific studies. The occurrence of Lonar in a purely basaltic target and the exceptional preservation state of its morphology have attracted scientists worldwide. Fredriksson et al. (1973a) were the first to carry out a detailed study at Lonar describing the geochemistry of glassy fragments while drilling the Lonar crater floor. Lonar can be considered as one of the most extensively studied simple impact craters in the world, encompassing geochronology (Sengupta and Bhandari, 1988; Sengupta et al., 1997;

Storzer and Koeberl, 2004; Jourdan et al., 2011; Nakamura et al., 2014; Rao and Bhalla, 1984; Maloof et al. 2010), geomorphological characterisation (Fudali et al. 1980; Maloof et al., 2010; Indu et al., 2022), ejecta emplacement characterisation (Maloof et al., 2010; Kumar et al., 2014), mineralogy (Schaal et al. 1976; Kieffer et al., 1976), geochemical characterization of the target basalt rocks, and impact derivatives like melt rocks, glasses, and spherules (Nayak 1972; Fredriksson et al., 1973a, 1973b; Kieffer et al., 1976; Morgan 1978; Stroube et al., 1978; Osae et al., 2005; Son and Koeberl, 2007), projectile characterisation (Misra et al., 2009; Schulz et al., 2016; Gupta et al., 2017; Ray et al. 2017), involvement of basement rock (Chakrabarti and Basu 2006; Schulz et al., 2016; Chandran et al., 2021), geophysical studies (Fudali et al., 1980; Kumar et al., 2014; Sivaram et al., 2018), hydrological properties of surrounding rocks (Komatsu et al., 2014), structural characterisation (Kumar 2005; Misra et al., 2010), spectral studies of target rocks (Wright et al., 2004; 2011), and magnetic properties (Rao and Bhalla, 1984; Louzada et al., 2008; Weiss et al., 2010; Misra et al., 2010; Arif et al., 2012; Agarwal et al., 2016).

Geomorphology and Geology of Lonar Impact Crater

Morphologically, the Lonar crater is similar to the Barringer crater (Gilbert 1896). Lonar crater has a north–south diameter of ~ 1.83 km and an east–west diameter of ~ 1.79 km, with a circularity index of 0.95 (Fredriksson et al., 1973a) and covers an area of ~ 3.5 km^2. The crater has a depth of ~ 150 m from the rim crest, and the floor is occupied by a shallow hypersaline endorheic lake of pH 9.5–10. The rim has a height of 30 m above the pre-impact surface. The inner walls of the rim are steeply dipping with 15–18° in the east and ~ 30° in the west and south–west direction (Basavaiah et al., 2014). The basaltic flows around the crater show a quaquaversal dip except in the northeast section, where a prominent fracture runs across the rim (Kumar 2005; Maloof et al., 2010). In and around the crater, rich and varied hydrological processes are observed (Komatsu et al., 2014). The magnetization vector and density of the target rocks have been modified by the impact event to a certain distance in and out of the crater (Rajasekhar and Mishra, 2005). A circular to semi-circular shaped gravity and magnetic anomalies of 2.5 mGal and 550 nT, respectively, are observed in the target rocks and impactites (Rajasekhar and Mishra, 2005). At the crater premises, four types of fractures are observed viz: flow parallel fractures, radial fractures, concentric fractures, and conical fractures (Kumar et al., 2014; Kumar 2005).

The crater is emplaced on top of the Deccan basaltic flows, with seven different flow units recognized in the premises (Maloof et al., 2010). A detailed geological map of the crater with different flow units and the extent of the ejecta blanket, which is at present partially masked by the growing Lonar town in the northeastern part of the crater, is depicted in Fig. 2. Flow basalts of approximately 125 m thickness can be seen at crater walls. Here, only the upper ~ 50 m is composed of fresh, dense basalts, and below which are heavily weathered and friable basaltic flows. The weathered outcrops at the top of the basaltic flows are having an average slope of ~ 26° (Fudali et al., 1980) that is covered with thick overburden or talus. Ghosh and Bhaduri (2003) also noted the presence of pre-crater black, dense, sticky, and humus-rich soil with a thickness of ~ 0.05–0.9 m preserved at places between flows and ejecta. Six basaltic flows of around 8–40 m thickness form the crater walls (Ghosh and Bhaduri, 2003) wherein five of these flows are exposed with each layer separated by zones of weathering and one flow remains concealed. The first flow has an isolated occurrence within the crater while the last flow is exposed away from the crater and is not observed in the target area (Maloof et al., 2010). The horizontal basaltic flows are characterized by cooling associated columnar joints with columns ranging in average diameters of a few cm to over 1 m. The subvertical fractures are oriented mostly in NW–SE to NNW-SSE directions while a few are in the NE-SW direction (Kumar 2005), with the features depicting a trend similar to the major fracture systems seen across the Deccan Volcanic Province (Widdowson and Mitchell, 1999). Despite having variable thickness and weathering extents, different flows are separated by discontinuous marker horizons having red and green-colored palaeosols, chilled bottom and clinker breccias, and vesicular margins with vugs filled with secondary mineralization of chlorite, zeolite, quartz, and brown limonite (Misra et al., 2009; Ray et al., 2017). The flow tops consist of weathered basalts followed by red bole beds with soils of different colors, basaltic clasts, altered feldspars, friable vugs, and vesicles filled with secondary minerals.

Each flow is characterized by hard, massive, and aphyric to sparsely porphyritic basalt characterized by similar texture and mineralogy with minor petrographic differences in plagioclase phenocrysts, glass, and opaque minerals. The porphyritic basalts that contain phenocrysts of plagioclase and rare olivine in the groundmass are dominated by plagioclase, augite, pigeonite, titanomagnetite, palagonite, and secondary minerals like calcite, zeolite, chlorite, serpentine, and chlorophaeite (Ghosh and Bhaduri, 2003). The presence of olivine as phenocrysts is rare, and the rock contains abundant silica and calcite as secondary minerals. At places, the crystalline matrix of the basaltic rocks shows sub-ophitic texture wherein plagioclase phenocrysts exhibit glomeroporphyritic texture. Opaques are mostly ulvospinel that show well-developed exsolution textures. Figures 3a and b showcase the photomicrographs of a melt rock obtained from the crater whereas Fig. 3c and d is a massive unaffected

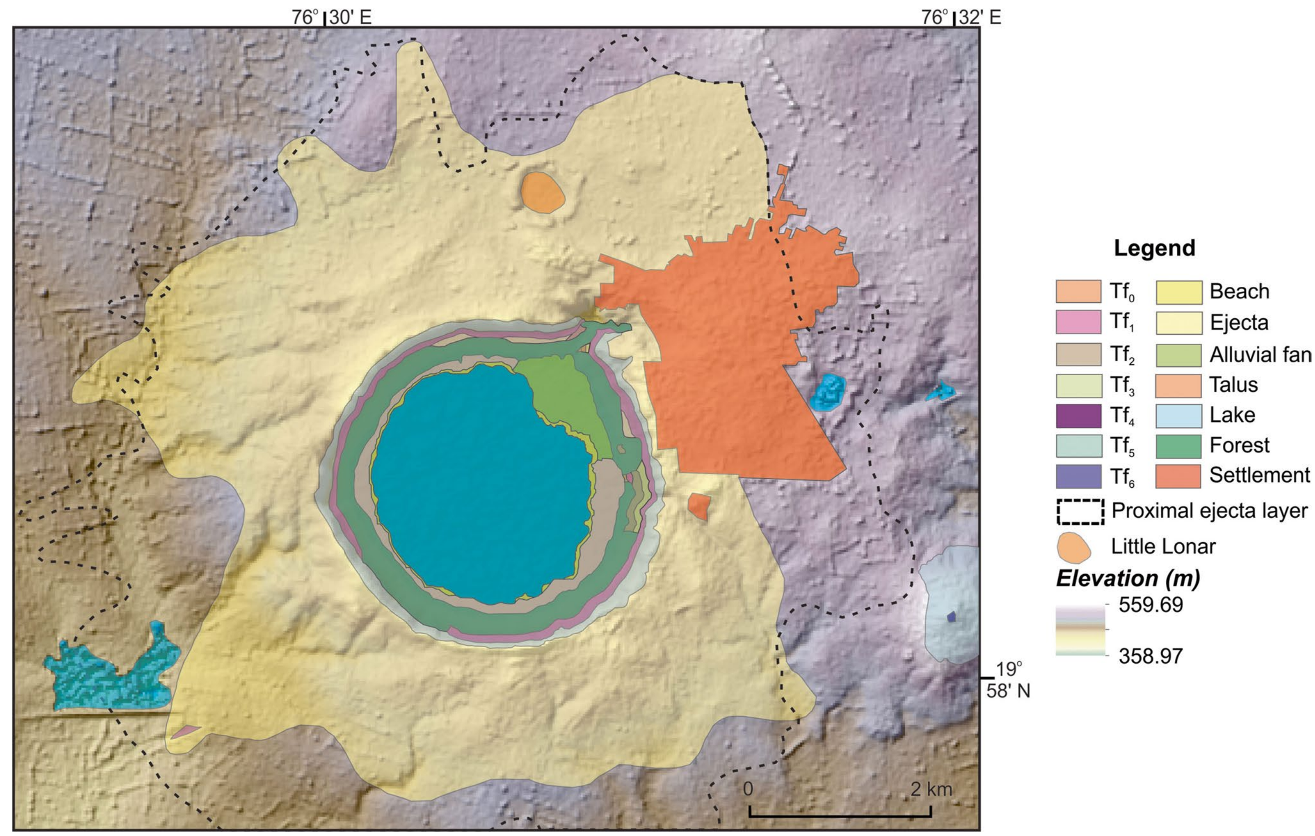


Fig. 2 The detailed geological map of the Lonar Impact Crater (modified after Maloof et al. 2010). TanDEM-X's elevation map draped over hillshade is the background image. The ejecta blanket is based on Ghosh (2003)

basalt. The melted rock is identified with numerous circular vesicles of different sizes and melt-like globules marked with texturally different components consisting of elongated plagioclase grains and fine-grained altered pyroxenes (Fig. 3a, b). The photomicrographs of massive basalt show typical sub-ophitic texture with laths of plagioclase partially enclosed in anhedral pyroxene grains (Fig. 3c). The plagioclase phenocrysts exhibit characteristic polysynthetic twinning and also show irregular fractures (Fig. 3d). When compared to the average tholeiites of Irvine and Baragar (1971), Lonar basalts are low-K tholeiitic within-plate basalt, that is marginally enriched in Fe and Ca and depleted in Mg and Al (Misra et al., 2009). An AFM diagram plotted using data from various sources shows the target basalt characteristics (Fig. 4). The target basalts show limited compositional variation except for Cr, Ba, and other volatile elements, which are more varied (Osea et al., 2005).

A continuous ejecta blanket can be seen all around the crater except in the northeast part for a distance of ~ 700 m whereas, it extends for more than 1 km in the western part (Misra et al., 2006). The ejecta blanket is very gently sloping at 2–6° away from the crater rim. According to Ghosh and Bhaduri (2003), the ejecta blocks form a continuous blanket around the crater for a distance of approximately 1.5 times the crater radius from the rim. The ejecta blanket consists of angular blocks of basalt of variable sizes within very fine ejecta. Moreover, Ghosh and Bhaduri (2003) identified three different components of the ejecta blanket exposed around the Lonar crater, namely unshocked throw-out ejecta, mixed-shocked ejecta, and shock-melted ejecta. The ejecta deposits are classified into two parts: (i) the upper part with shocked and melted target rocks with a fluidized appearance (Barlow et al., 2000) and (ii) the lower part with a dearth of shock evidences (Sivaram et al., 2018).

The age of the Lonar crater has been determined through different methods. Fredriksson et al. (1973a) and Fudali et al. (1980) suggested a younger age based on its well-preserved state and mild erosional features. Lafond and Dietz (1964) and Venkatesh (1965) have given the late Pliocene to Pleistocene age based on the stream incision. For Lonar crater, each of the different geochronological methods has yielded a range of ages viz. 52,000 (± 5000, ± 6000) as per thermoluminescence dating (Sengupta and Bhandari, 1988; Sengupta et al., 1997), 15 ± 13 ka in fission track dating (Storzer and Koeberl, 2004), 570 ± 47 ka in $^{40}Ar/^{39}Ar$ geochronology (Jourdan et al., 2011), ~ 37.5 ka through cosmogenic

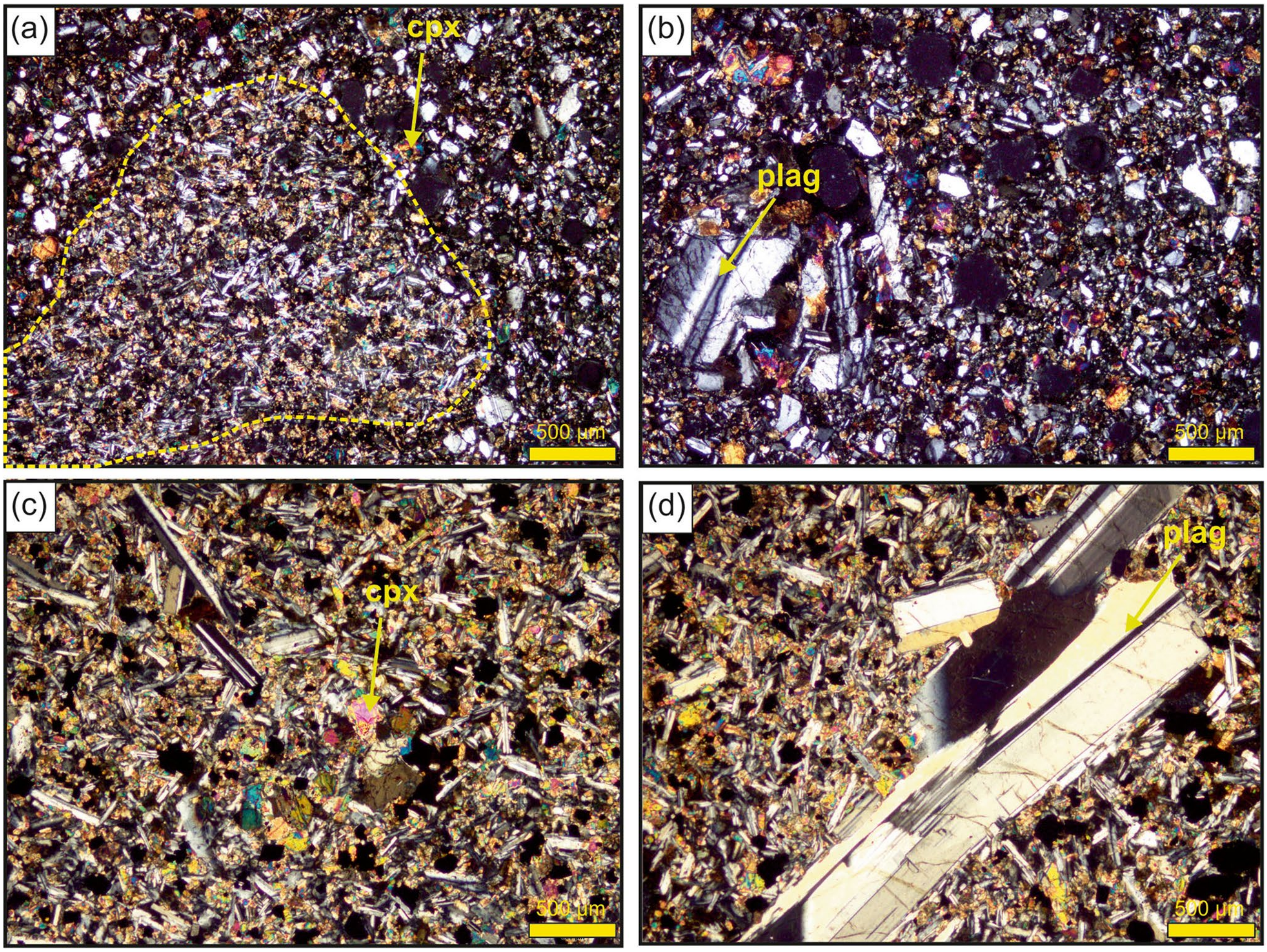
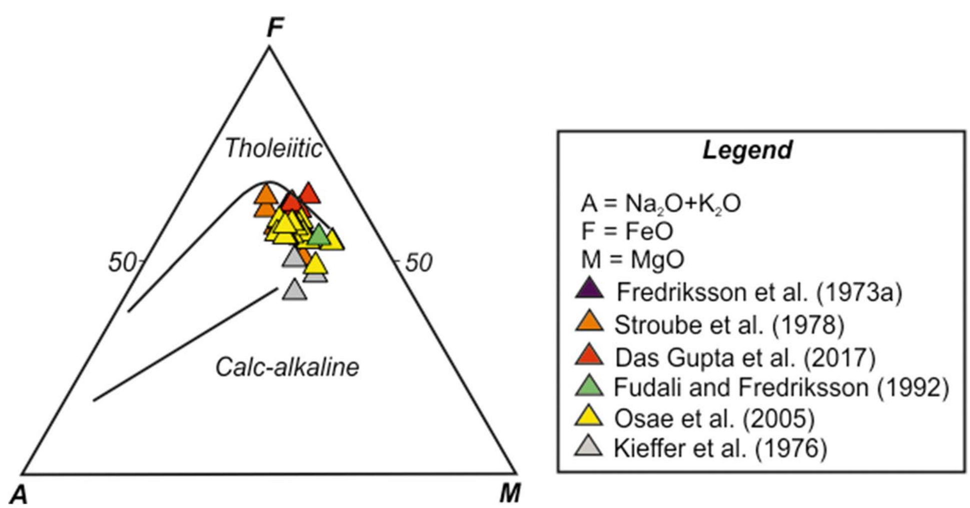


Fig. 3 A comparison of photomicrographs of an impact melt-bearing rock (**a**,**b**) and unaffected massive basalt (**c**,**d**). **a** Depicting the globular melt-like domains having a different texture with fine-grained aggregates and elongated plagioclase grains compared to the general ophitic texture shown by the rest of the rock. The highlighted near circular feature is the extremely fine-grained domain, possibly representing recrystallized glass. **b** A melt rock showing a large number of bigger vesicles, mostly circular shapes, and fractured plagioclase (Plag) grains along with altered clinopyroxenes (cpx). **c** Typical sub-ophitic texture of the rock with laths of plagioclase embedded partially in a matrix of anhedral pyroxenes. **d** An elongated plagioclase (Plag) grain with polysynthetic twinning with minimal fractures

Fig. 4 AFM diagram depicting the tholeiitic trend shown by the Deccan target basalts reported in various sources



nuclide dating (Nakamura et al., 2014), and finally, an age between 15 and 30 ka by radiocarbon dating (Maloof et al., 2010).

Lonar Impact Crater has been drilled by Fredriksson et al. (1973a) along the NE-SW segment of the crater floor through five drill cores, for a depth range between 300 and 400 m below the floor. Brecciated zones were encountered beneath the sediment cover at the lake bottom. However, the drilled cores did not penetrate the entire thickness of the basaltic layers in the area. Chandran et al. (2021) stated that the transient crater depth has penetrated the Archean basement rocks (the Peninsular Gneiss exposed beneath basaltic flows), from the 3 to 3.1 Ga zircon grains incorporated within the melt rock. Most works on the geochemical characterization of target rocks and impactites have found similarities between them. Furthermore, the contributions from a chondritic impactor have been suggested at Lonar based on the presence of Cr, Ni, and Co in the impactites (Misra et al., 2009; Schulz et al., 2016; Gupta et al., 2017; Ray et al., 2017). The cumulative effects of rock magnetics, natural remanent magnetization (NRM), anisotropy of magnetic susceptibility (AMS), and microfractures have been applied for detailed estimation of the shock pressure characteristics of Lonar crater by a number of authors (Rao and Bhalla, 1984; Louzada et al., 2008; Weiss et al., 2010; Misra et al., 2010; Arif et al., 2012; Agarwal et al., 2016).

Another interesting aspect of the Lonar crater is that it is analogous to the craters formed on planets such as Mars and the Moon, where the crustal/target rocks are dominated by basalts (Fredriksson et al., 1973a). Several authors have widely discussed various attributes related to the cratering mechanism on Mars and the Moon in comparison to Lonar crater, with a focus on morphological parameters, ejecta emplacement, generation of impactites, hydrothermal alteration, the influence of water content, and hyperspectral characteristics (Fredriksson et al., 1973a; Fudali et al., 1980; Maloof et al., 2005, 2007, 2010; Hagerty and Newsom, 2003; Kumar et al., 2014; Wright et al., 2011, 2004; Lakshmi and Kumar, 2020).

Furthermore, there is a smaller, satellite crater-like structure located ~ 700 m to the NNE of the Lonar crater, conveniently called the Little Lonar or Amber Lake (Fredriksson et al., 1973a; Master 1999). The Little Lonar structure has a diameter of ~ 300 m with a raised rim of ~ 6 m from the surroundings. However, the absence of considerable evidence of an impact origin points to potentially different reasons associated with its formation (Maloof et al., 2010).

Socio-Cultural and Archeological Relevance of Lonar Impact Crater

The Lonar Lake, being an important pilgrimage spot, has an interesting mythology associated with its formation. The name Lonar is derived from the demon *Lonasura* (*Lawanasur*) (Apte and Joglekar, 2015; Hippalgaonkar 2016). Just like any other unique geomorphic feature in India, Lonar is also associated with a religious folklore behind its origin. The allegory says that a devil named *Lonasura* was settled in this region. The local people, devotees of *Lord Vishnu*, pleaded the god to help them tackle the limitless wickedness of *Lonasura*. Thus, the crater came into being when *Daitya Sudan* (the incarnation of *Lord Vishnu*) threw the lid of the subterranean cave under which *Lonasura* was hiding. The crater is considered as the remains of the cave of the *Lonasura* and the lake as the giant's blood, whereas the hill nearby as the thrown-away lid. Here, people consider the perennial springs emerging from the crater flanks as the holy waters of the River Ganges, which flow to wash off the blood-stained feet of *Lord Vishnu*.

Apart from being a proven meteorite impact crater, Lonar has its fair share of cultural and archaeological significance. The Lonar Lake, locally known as Lonar Sarowar, has been mentioned in ancient and medieval literature including the *Skanda Purāna* (a Hindu religious text), the *Padma Purāna* (a genre of texts in Hinduism), *Viraja-māhātmya* (text explaining the religious background and mythological stories of Lonar), *Līlācaritra* (a thirteenth-century biography of Sri Chakradhara Swami, the founder of Mahanubhava sect), *Sthāpnothi* (religious text of Mahanubhava sect), and the *Ain-e-Akbari* (detailed document recording the administration of Mughal Empire under Emperor Akbar). Lonar is considered as *Viraja Ksetra* (a natural sacred place) based on Hindu religious practice (Apte and Joglekar, 2015). All along the banks of the lake and around the rim of Lonar, a number of temples exist, dedicated to various Hindu deities like *Shiva*, *Vishnu*, and *Shakthi*. Most of the temples were constructed during the ancient and medieval periods, mostly between the twelfth and fourteenth centuries AD during the reign of various dynasties like the Yadavas of Deogiri, the Chalukyas of South India, and the Marathas of Central India (Vyas 2000; Basavaiah et al., 2014; Apte and Joglekar, 2015; Hippalgaonkar 2016; Jadhav and Mali, 2020). The temples are architectural marvels carved out of stones, especially in basalts, in the *Hemadpanti* style of the Yadava period (Apte and Joglekar, 2015; Hippalgaonkar 2016; Jadhav and Mali, 2020). Several temples are now in ruins, yet some unruined ones are currently open to pilgrims. The temples generally have plain exterior and interior forms. Therefore, one may find it difficult to spot dissimilarities between different temples. In the planar view, most temples have a general style consisting of the *ardhamandapa* (half-open hall), *mandapa* (pillared hall), *antarala* (foyer), the *garbhagriha* (sanctum sanctorum), and the *kunda* (tank for ablution) (Apte and Joglekar, 2015). The *dwarshakhas* (door jambs) of the temples are found to be more elaborate than the rest of the temple parts. It is noted that the sikharas (rising towers in Hindu temple architecture) of most temples are missing.

Since the temples are dissimilar from each other, some are having remarkable features than the rest. For example, Paphareshwar temple has a highly adorned *Nandi mandapa* (an entrance with an idol of a bull) and *Puskarini* (a temple tank). Among all the temples, Yajneshwar Mahadev Temple is the most decorated. The Wagh Mahadev *Mandir* (a mandir is a temple) has got a highly elaborate door for the *garbhagriha* with depictions of various *śākhās* (Hindu theological schools) like *vyalasakha*, *vallarisakha*, *stambhasakha*, *narasakha*, and *kumudasakha*. Besides Hindus, the Mahanubhava sect and Jains also consider Lonar as a sacred place.

Most temples in and around Lonar are frequently visited by pilgrims. The Lonar temples are truly the embodiment of spiritual, architectural, artistic, and aesthetic marvels. Based on the report of Chandra et al. (2021), there are 27 temples, three monuments, seven temple tanks, and three inscriptions inside the crater. In the following paragraphs, we highlight the significance of some famous temples.

Motha Maruthi or Sleeping Hanuman Temple

Motha Maruthi or sleeping *Hanuman* temple (Fig. 5a) is located ~ 3 km to the north of the main crater. The temple consists of a nine-foot-long *Hanuman* idol in sleeping position. The 9.3-foot-long *Hanuman* idol is carved in a magnetic rock. Locally, it is believed that the eighteenth-century idol in the sanctum sanctorum is made out of the splinter of the meteorite that fell upon the region resulting in the impact crater structure. The *Hanuman* idol is unique in its sleeping position, and the left foot of the main deity is resting on the small deity of *Shani Dev* (Lord Saturn). For years, the deity was covered in red *sindoor* (vermilion powder), which is now removed, and the original idol of the deity is clearly visible.

Daityasudan Temple

Daityasudan temple (Fig. 5b) is one of the most finely built temples in the Lonar region, but is currently in ruins. The temple is built to celebrate the victory of *Vishnu* over *Lonasur*. The temple is constructed at a distance of ~ 3.5 km away from the main crater. One has to move through the narrow streets of Lonar town to see this architectural marvel. The main deity of the temple is *Lord Vishnu* along with other deities such as *Goddess Durga*, *Lord Surya*, and *Narsimha*. The architecture around Daityasudan temple consists of many mythological sculptures similar to the ones depicted in the Khajuraho of Madhya Pradesh. Daityasudan temple is constructed in the *Hemadpanti* architecture, a remarkable building style prevalent in Maharashtra, by the Yadavas between the twelfth and fourteenth centuries AD (Apte and Joglekar 2015; Hippalgaonkar 2016). The construction style is named after its founder prime minister Hemadpant in the court of the Yadavas of Devagiri. Black basalts and lime are used for constructing the temple. The base of the Daityasudan temple has got seven layers, made of stone platforms. The temple was later demolished during the invasion of Aurangazeb, the sixth Mughal ruler of India.

Paphareshwar Temple

Paphareshwar temple (Fig. 5c), locally known as Paphareshwar *Mandir*, is dedicated to *Lord Shiva*. This temple is a group of many structures comprising a small temple dedicated to Shiva. It has a highly decorated *Nandimandapa* and *Puskarini*. The *Nandimandapa* is constructed on a high plinth with beautiful moldings led by a flight of steps having a lion balustrade on the western side. The pillars are depicting miniature *kirtimukha*, figures of *Vishnu* and *Shiva* in different forms, extensively carved out from top to bottom of the pillars.

Kumareshwar Temple

Kumareshwar temple or Vedshala is dedicated to *Lord Shiva* (Fig. 5d). The temple is enclosed within walls while having an entrance gate from the north. A circular raised ceiling can be seen in the center of the *mandapa*, built in trabeate style. The figures of *Shiva*, *Indra*, *Vamana*, and *Bhairava* are depicted in the brackets. The mutilated depictions from the *Saptamatrika* pantheon composed of *Indrani*, *Kaumari*, *Varahi*, and other goddesses are seen on the upper portion of the brackets. The center beam of the highly decorative door frame of the sanctum has a *Ganesha* figure.

Gomukh-Dhar Temple

Gomukh-Dhar Temple (Fig. 5e) is located near the northern entrance of the main crater. The temple is built on top of a one foot wide water stream, which falls into a stone pond constantly throughout the year. This temple is also called the Sita Nahani Temple or Dhara due to the perennial nature of the stream. This perennial stream is believed to generate from the aquifer system in the basaltic flows.

Kamalja Devi Temple

Kamalja Devi Temple (Fig. 5f) situated on the southern part of the Lonar crater is dedicated to Goddess *Kamalaja*. This is a temple frequently visited by pilgrims from various parts of Maharashtra. Every year, devotees celebrate temple festivals, and people from far-off places visit the temple.

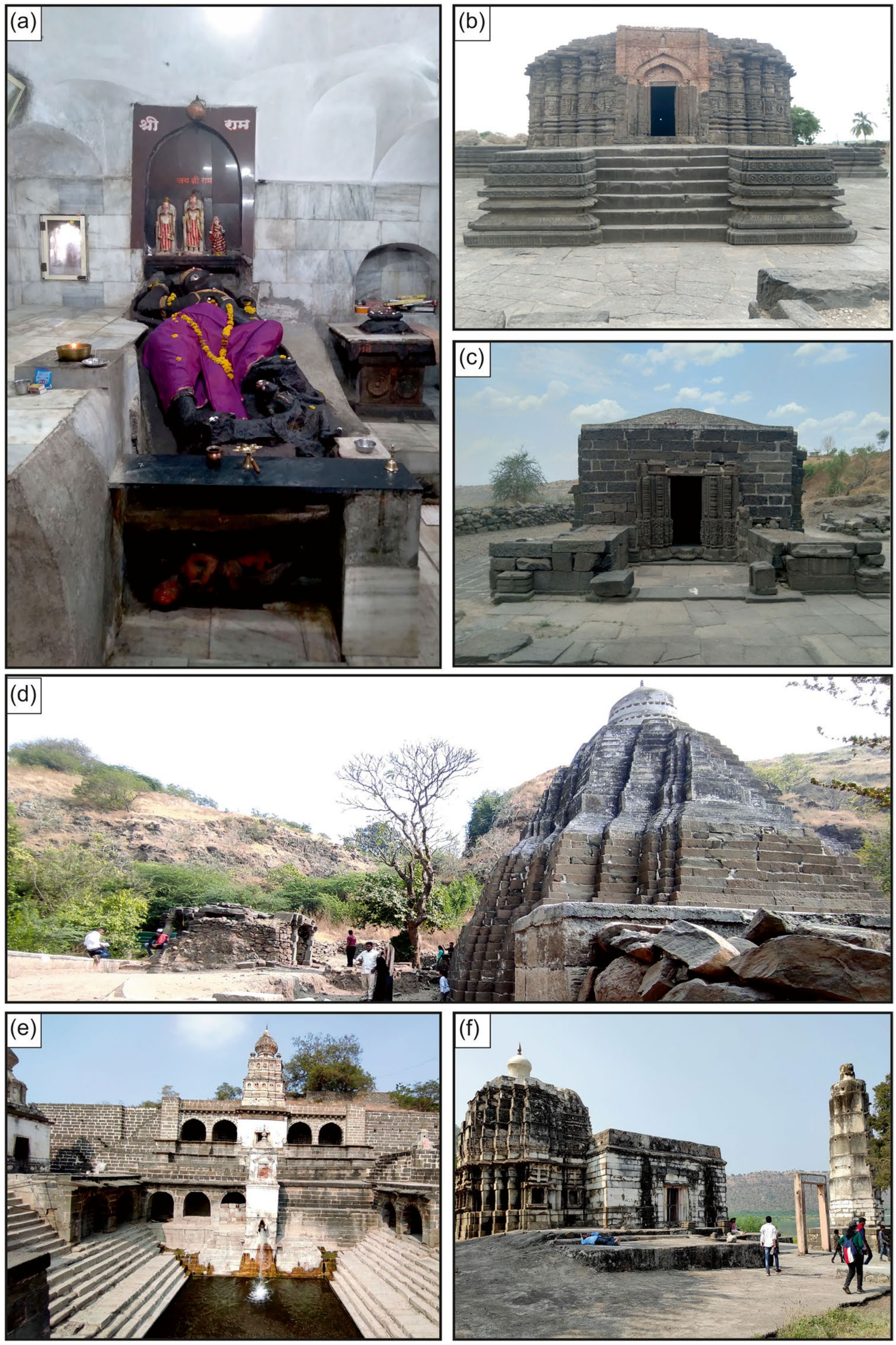


Fig. 5 Selected important temples in the premises of Lonar (**a**) Motha Maruthi or sleeping Hanuman temple near Little Lonar, (**b**) Daityasudan temple in the Lonar town, (**c**) Paphareshwar temple, (**d**) Kumareshwar temple near to the northeastern rim of the crater, (**e**) Gomukh-Dhar temple, and (**f**) Kamalja Devi temple on the southern banks of the Lonar Lake

The Ajanta and Ellora Caves: UNESCO World Heritage Sites

The Ajanta and Ellora caves are the two UNESCO World Heritage Centers that preserve the magnificent remnants of ancient rock-cut architecture in India. While the Lonar Impact Crater forms a spectacular natural wonder in the Deccan basaltic target rocks, Ajanta and Ellora caves uphold the cultural heredity and immaculate craftsmanship of the older generation carved out of the same rock units. Ajanta caves are nearly 150 km from the Lonar crater. The glory of Ajanta Caves dates back from the second century BC to the sixth century AD. Caves adorned with paintings and sculptures of Buddhist religious art are engraved on a horseshoe-shaped basaltic cliff on the left banks of the Waghora river in the Ajanta hills (Spink 2005). The geological setting of the Ajanta caves is identified as the compound flow of the Deccan tholeiitic flood basalts (Ansari et al., 2014a). It is composed of five flows with alternating "aa" and compound "pahoehoe" characters with varying thickness of up to 80 m (GSI 2001; Bondre et al., 2004; Gontareva et al., 2015). There are 29 caves among which five are *Chaityas* (commemorative prayer halls) and the rest are *viharas* (private prayer halls with resting cells) (Agrawal et al., 2016). The scenic beauty of Ajanta Caves remained hidden in the thick forests until it was discovered in 1819 by a British officer Captain John Smith. The serenity of the forest and the presence of a river might have attracted the Buddhist monks to establish a rock-cut architectural marvel in this calm and pleasant atmosphere. The Ellora caves are situated nearly 170 km from Lonar. With more than hundreds of caves carved out in the vertical basalt cliffs of Charanandri Hills, Ellora Caves form one of the largest rock-cut monastery temple cave complexes in the world. The caves are carved within several basaltic flows consisting of "aa" and more homogeneous "pahoehoe" flows in alternating sequence and quartz veins (Deshpande 1986; GSI 1986; Ansari et al., 2014b). The consistent coloration and strength of the vesicular basaltic rocks aided in carving out the caves and its durability. The caves are composed of artistic works that belong to Buddhism, Hinduism, and Jainism and date back from 600 to 1000 AD. All the Ellora monuments were constructed during the reign of the Rashtrakuta dynasty (Hindu and Buddhist caves) and the Yadava dynasty (Jain caves). Among the hundred caves, 34 are open to the public in which Kailasha Temple (cave 16) is the largest and most remarkable one (Ansari et al., 2014b). Being notable tourist hotspots, both nationally and internationally, Ajanta and Ellora caves being in close proximity to Lonar can enhance its tourism potential.

Ecological Importance of the Lonar Impact Crater

The premises of the Lonar Impact Crater form the Lonar Wildlife Sanctuary, a small sanctuary that is spread across 3.8 sq. km (including 2.66 sq. km reserve forest area) was established in the year 2000 by the Government of India. Lonar Lake forms a remarkable wetland site in the Deccan flood basalts. The addition of Lonar Lake in the Ramsar sites in 2020 marks its unique nature and makes it one of the 49 Ramsar sites declared in India (Fig. 1b). The Ramsar Convention, also known as the Convention on Wetlands, is an intergovernmental treaty that was established in 1971 to provide a framework for national action and international cooperation for the conservation and wise use of wetlands and their resources.

Soda lakes supporting saline and alkaline ecosystems are unique environments that are generally seen in terrestrial setups such as deserts and steppes and in geologically interesting locations like the East African Rift Valley (Paul Antony et al., 2013). The Lonar crater lake is completely enclosed from all sides without a single outlet away from the lake. The hypersaline nature of the lake water has attracted scientists from across the world. Table 1 is showing the compilation of physico-chemical characteristics of Lonar Lake water from various sources. The salinity of the lake water increases as the water loss is mainly through percolation to the underground and evapotranspiration coupled with less precipitation. The pale green to dark green color of the lake water is imparted from the highly dense algal population predominating Spirulina (Yannawar and Bhosle, 2013). Figure 6 shows a schematic diagram of the lake profile. The three freshwater springs at Lonar are Dhar, Sitanahani, and Ramgaya, which provide sweet and potable water from the aquifers beneath the basaltic flows. Dhar, meaning the continuously flowing water stream in Marathi (the local language), is the biggest one situated inside the northeast canyon. Sitanahani (the bathing place of Sita) is the second spring located beneath the top one. The third spring Ramgaya is located in the southeast slope of the crater close to the water level.

The crater and its surroundings stand out from the rest of the dry arid region by cradling a rich biodiversity in the vicinity circled by a forest cover entailing a habitat for wide range of plant and animal species. The harsh chemical environment of the Lonar Lake water and sediments is home to an indigenously diverse microbial community and several new species of bacteria (Paul et al., 2016; Sisinthy et al., 2017; Chandra et al., 2021). Lake water in the Lonar does not support fish life due to low dissolved oxygen and high salinity (Dabhade and Tandale, 2017). Diverse plant and animal species thrive in the freshwater spring emerging from the slopes of the crater (Chandra et al., 2021). In 2003, Jha (2003) reported the presence of about 237 plant species belonging to 153 genera and representing 70 families within the crater, in addition to rich faunal wealth. Recently, Chandra et al. (2021), based on the survey by the Zoological Survey of India (ZSI) and the Ministry of Environment, Forest, and Climate Change (MoEFCC), Government of India, on the faunal diversity in the Ramsar wetlands of India, presented an updated report on the ecosystem in Lonar crater. Based on that, the wetland is home to 30 species of trees, 10 species of shrubs, 13 species of climbers, 8 species of herbs, and 6 species of grass. The forest around the Lonar lake is open-type with some parts being wooded (Hippalgaonkar 2016). Major flora of the forested area includes trees such as Ashok (*Saracaasoca*), Babhul (*Acacia nilotica*), Chandan (*Santalum album*), Gulmohar (*Delonixregia*), Neem (*Azadirachtaindica*), and Wad (*Ficusbenghalensis*); herbs and shrubs like Chilati (*Mimosa hamate*), Ranmirchi

Table 1 The physico-chemical characteristics of Lonar Lake water compiled from various sources

Parameter	1	2	3	4	5	6	7	8	9	10	11	12
Ph	-	-	-	10	9.8	10	10.3	9.92	8.13	9.83	10.03	9.8
Temperature (˚C)	-	-	-	35	28	28	28		24.6	24		24.05
TDS (mg/L)	-	-	-	15,500	N.D	N.D	9060	11,752	770	12,389	11,143	10,657
Alkalinity (mg/L)	-	-	-	3600	2750	3200	3751.25		3660	3407		3689.8
Chloride (mg/L)	40,780	31,520	30,870	3000	2468.4	5600	3492.08	4139	2128.8	3968	4050.5	1682
Salinity (mg/L)	74,872.08	57,870.72	56,677.35	5508	4532	10,281.6	6391.36		2326.6	7488		
DO (mg/L)	-	-	-	N.D	N.D	N.D	0.0034	0.05	1.64	0.622		0.0275
Total hardness (mg/L)	-	-	-	N.D	N.D	N.D	480.08		130	245.4		
Ca hardness (mg/L)	-	-	-	N.D	N.D	N.D	118.5		40	151.4		
Mg hardness (mg/L)	-	-	-	N.D	N.D	N.D	361.58		90	95		
Sulfate (mg/L)	1480	300	670	N.D	N.D	N.D	21.55	139.4	195	137.3	113.25	51.5
Phosphate (mg/L)	N.D	N.D	N.D	0.2		22	0.44		1.076	0.458		3.75
Nitrate (mg/L)	N.D	N.D	N.D	N.D	N.D	N.D	3.7		N.D		1.55	

(1) Christie (1910), (2) Jhingran and Rao (1958), (3) TISCO (1960), (4) Thakker and Ranade (2002), (5) Joshi et al. (2008), (6) Surakasi et al. (2007), (7) Tambekar et al. (2010), (8) Babar (2010), (9) Yannawar and Bhosle (2013), (10) Borul (2012), (11) Reddy et al. (2015), (12) Khobragade and Pawar (2016)

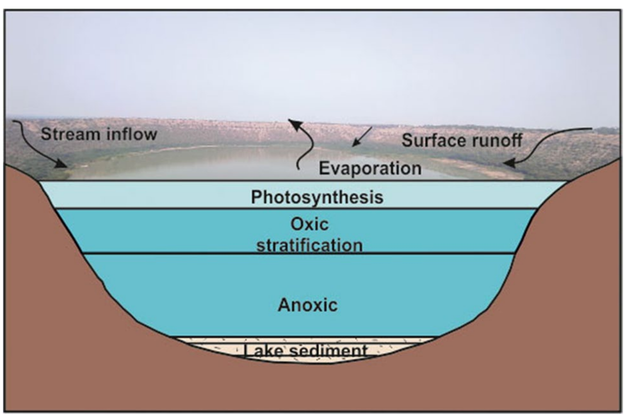


Fig. 6 A schematic diagram of the Lonar Lake profile is shown. Sketch not to scale. Modified after Anoop et al. (2013)

(*Corallocarpusepigaeus*), and Rantulas (*Anisomelesindica*); climbers such as Adulsa (*Adhatodazeylanica*), Gulvel (*Tinosporacordifolia*), Vasan-vel (*Cocculashirsutus*), grasses and bamboos dominated by Bamboo (*Dendrocalamusstrictus*), Kusali (*Heteropogoncontortus*), and Marvel (*Dichanthiumannulatum*). Plants such as *Justiciaadhatoda* (Adulsa or Malabar nut) and *Calotropisgigantea* (Rui) from the Lonar forest area are used as medicinal plants for various local ailments such as nasal infection, cough, throat infection, boils, elephantiasis, and wounds (Rathod 2014).

The lake surroundings are known to have ~ 160 species of birds including the vulnerable Asian woollyneck (*Ciconiaepiscopus*) and common pochard (*Aythyaferina*), 46 species of reptiles, 12 species of mammals, including the iconic grey wolf (*CanisIupus*), and 14 species of mollusks (Chandra et al., 2021). They also give a report of animal groups around the crater, that include seven species of amphibians, 27 species of arachnids, 162 species of birds, 84 species of insects, 18 species of mammals, 14 species of mollusks, and 49 species of reptiles. The Lonar crater premises are known to have 16 species of snakes belonging to five families including poisonous snakes (Khobragade and Pawar, 2015). Some of the other wild inhabitants of the thick forest at the crater premises include a leopard, a wild cat, a hyaena, a wolf, a languor, a mongoose, a bat, and a wild boar. The perennial hypersaline lake is rich in blue-green algae that attracts a large number of winter migratory birds between November and March. The surroundings of Lonar Lake and the crater premises are inhabited by a large number of resident birds and migratory waterfowls (Palot 2006; Dabhade and Tandale, 2017). Flamingos visit the crater occasionally. Palot and Soniya (2003) reported the presence of 48 species of butterflies under five families in the crater region.

The Lonar Lake water had turned pink during June 2020 due to the presence of *Haloarchaea* microbes (Fig. 7) (Bhattacharjee et al., 2021; Ali and Ali, 2021). Several media reported this event of 11th June 2020; however, a similar color change of water from green to brown was observed in June 2019 also. In 2020, it was prominent owing to the color change from green to brown to pinkish red (Mishra et al., 2021). Bhattacharjee et al. (2021) used Sentinel-2 datasets from January 2020 to June 2020 and found out that the microbial bloom might have occurred between May 31 and June 5 with the help of several calculated indices. The red–orange carotenoids produced by the microbes give the water a pink tint that was even detectable from outer space. *Haloarchaea* survives in high salinity and has flourished due

Fig. 7 High-resolution (3 m) freely available Planet Lab image of the Lonar Lake showing the pink-colored water of the lake during June 2020, which is due to the presence of *Haloarchaea* microbes

to less rainfall, high regional temperatures and less human interaction during COVID-19 lockdown (Bhattacharjee et al., 2021).

Threats to Lonar

Depletion and Deterioration of Water Resources

The crater is exposed to regular human intervention and hence, possesses a threat to the indigenous resources of the crater, if not well maintained. One of the main threats to the sustainable growth of Lonar is its depleting water conditions. The extensive afforestation practice using *Acacia nilotica* and the agricultural practices of using dug wells and borewells have deepened the groundwater resource. The crater lake with seasonal fluctuation of water levels and high water levels contributed by sewage flow has led to the destruction of the tree species *Acacia nilotica* and the corroding of the ancient temples on the shores (Babar 2010; Basavaiah et al., 2014). In a study conducted by Mahto and Kushwaha (2018) on the fluctuating inter-seasonal surface water level and volumetric change of Lonar Lake over the years 2009, 2010, 2011, 2015, 2016, and 2017 using Landsat satellite imageries, it is seen that in the years 2015–2017 there is a faster rate of removal of water from the lake than the rate of addition of water to the lake. Currently, the alkalinity, salinity, and pH of the lake water are decreasing (Shinde and More 2013; Surve et al., 2021), which continue to deteriorate the uniqueness of the Lonar lake. The lake water has an offensive odor that comes out of hydrogen sulfide. According to Surve et al. (2021), the decrease in salinity and alkalinity of the lake is mainly due to the sedimentation of the salt at the bottom of the lake. The eutrophication process, if continued unchecked, will result in low oxygen level followed by the reduction of macrophytes, macroinvertebrates, and phytoplankton diversity and an increase in the growth of algal blooms and pathogenic organisms (Dabhade 2013; Dabhade and Tandale, 2017). This has led to the dying of the lake. Cultural (man-made) eutrophication in the Lonar lake is increasing at an alarming rate due to the discharge of untreated domestic sewage and garbage from the Lonar town, as well as inorganic fertilizers, insecticides, and pesticides that were used in the past years for agricultural practices on the alluvium deposits of the lake shore (Yannawar and Bhosle, 2013; Dhabade 2013; Babar 2010). Water from the springs, especially from Dhar and Sitanahani, is widely used by pilgrims and Lonar villagers for various domestic purposes including drinking, washing, and bathing, and it is pumped out for drinking purposes.

Pumping out water from the freshwater springs for drinking purposes will reduce the inflow of water toward the lake. All these anthropogenic activities led to the increasing nutrient content in the lake.

Land Use Changes

Over the years, the land use pattern in the crater premises has changed owing to larger human intervention and the growth of the Lonar town. Figure 8 shows the Google Earth images of the Lonar crater from 2005 to 2022, which clearly show the change of land use pattern and growth of the Lonar town over a span of seventeen years. Sewage, hunting, firewood collection and cattle grazing, bathing and washing activities, and religious fairs and rituals inside the crater have had a negative impact on the Lonar ecosystem. Currently, many of these practices are under control except the religious affairs. However, the effects of encroachment over the years have severely affected the status of the crater. But, after declaring the area as a Ramsar site, a positive shift in the land use changes has been noticed (the year 2016–2022 with 2-year interval has been selected to identify noticeable changes prior and after selection as a Ramsar site. Images were selected for the same season so that seasonal changes in land use are not reflected). The land use is shown as the normalized difference vegetation index (NDVI) maps (Fig. 9a, b, c, and d) generated using Landsat 8 imageries, classified based on Holben (1986). The change in land use pattern with regard to five different classes viz. dense vegetation, moderate vegetation, less vegetation, barren land, and waterbody is shown in Fig. 9e. The most noteworthy feature is the increased moderate vegetation in lieu of less vegetation (shrubs) post 2020. This could be due to the afforestation practices adopted after declaring Lonar as a Ramsar site. Waterbody also shows a slight uptick after 2020. Barren land has been diminishing since 2016, probably due to agricultural practices until 2020 and afforestation thereafter.

Dilapidated Condition of Infrastructures

A stone board, engraved to show the importance of this crater, was erected by GSI in 1975, which can be seen on the Lonarkar Garden in the eastern rim of the crater (Fig. 10a). From the garden, one can get a serene view of the crater. However, the garden is in a dilapidated condition. The watch towers erected on the south and west parts of the crater rim offer magnificent views of the entire crater but are only poorly maintained (Fig. 10b). Moreover, quick, unscientific renovations made on some of the temples in and around the crater by authorities are only deteriorating its aesthetic, cultural, religious, and tourism significance (Malu et al., 2007). Constructions on the slope of the crater aided the instability of the crater.

SWOT Analysis

The qualitative analysis of the proposed site is carried out by using the methodology proposed by Reynard et al. (2016). Furthermore, for testing the reliability of the Lonar area as a prospective geopark with the potential to achieve geo-touristic goals, a strength, weakness, opportunity, and threat (SWOT) analysis has been performed. The tourism sector routinely uses SWOT analysis as a basis for

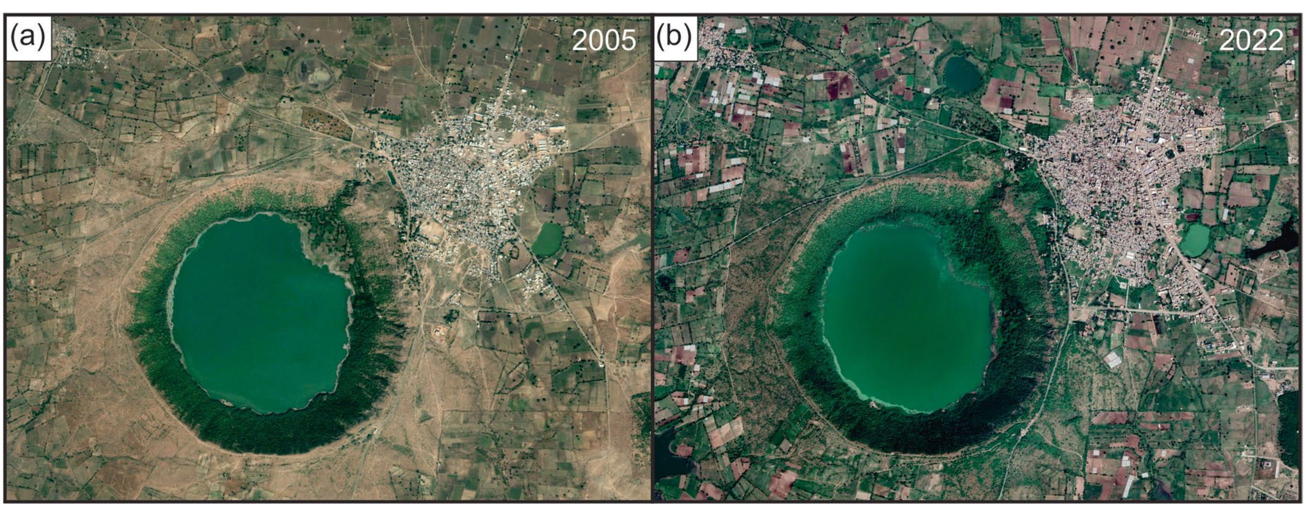


Fig. 8 Google Earth images of the Lonar Crater showing the differences in the vegetation pattern observed around the Lonar Crater and the growth of the Lonar town in a span of 17 years from 2005 to 2022. The cultivation that prevailed in the northeastern delta lobe of the lake is evident from the Google Earth image of 2005. However, a ban on agriculture resulted in the growth of natural vegetation, which is seen as a canopy in the latest image taken in 2022. The advancement of the Lonar town is also visible in these two images

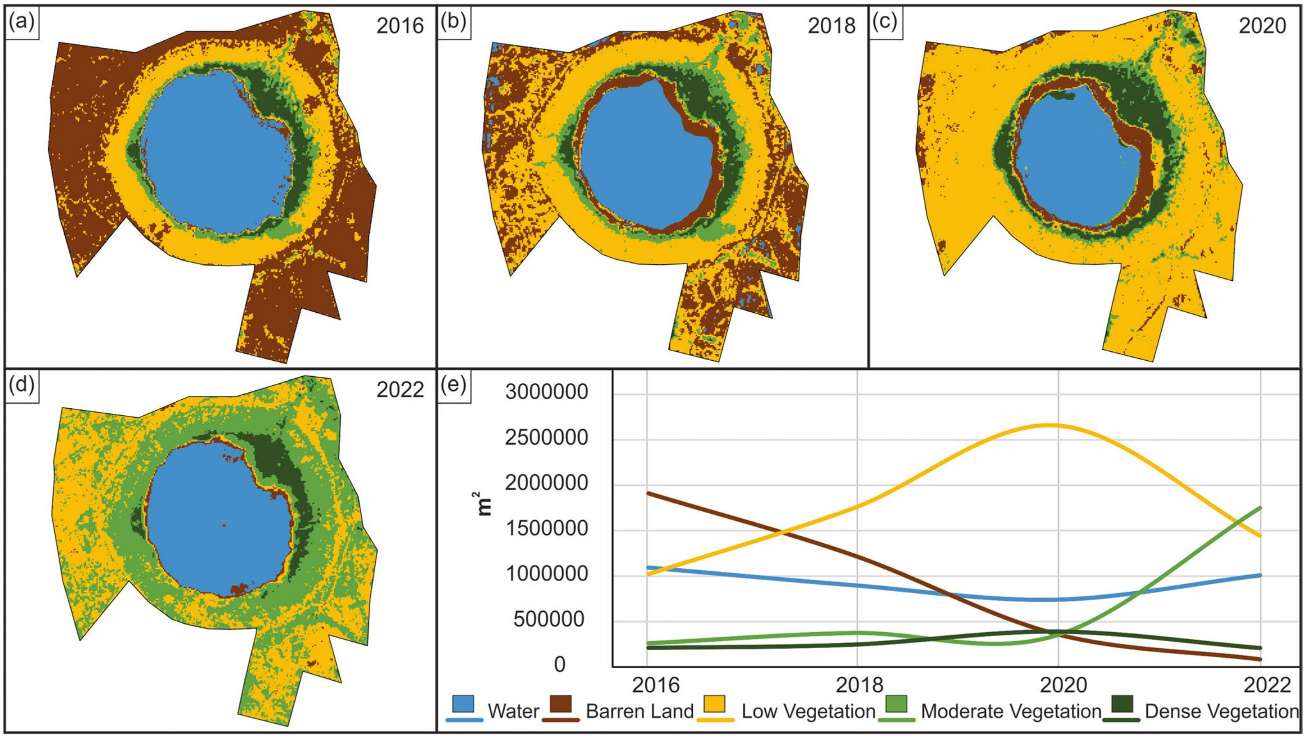


Fig. 9 Normalized Difference Vegetation Index (NDVI) maps of the Lonar Impact Crater obtained using the Landsat 8 imagery of the crater downloaded from https://earthexplorer.usgs.gov/ for the years **a** 2016, **b** 2018, **c** 2020, and **d** 2022. Images are mostly from the months of March, April, and May, which clearly drew out the difference in the extent of vegetation cover, barren land, and water body in the premises of the crater. NDVI is classified based on Holben (1986). **e** Graph showing the relative change in land use pattern with respect to five classes in the observed years

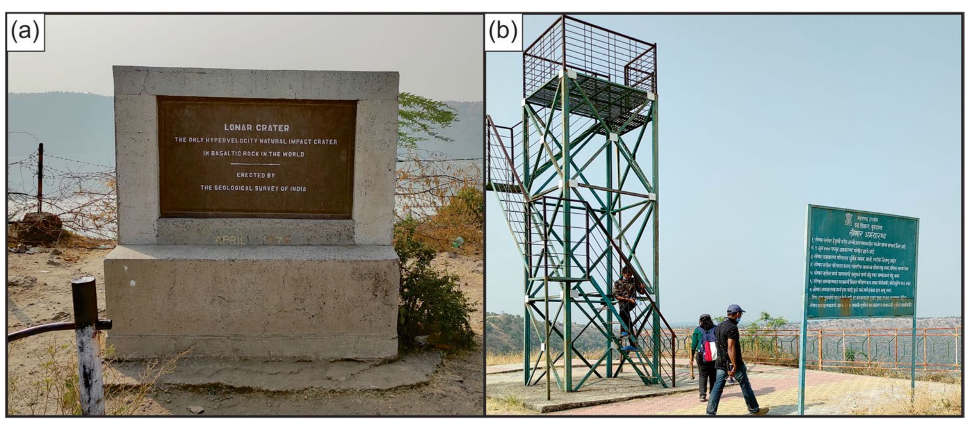


Fig. 10 **a** The stone board erected by the Geological Survey of India in 1975 in the premises of the Lonarkar Garden in the eastern rim of the crater showing the geological importance of the Lonar Crater. **b** A watch tower on the southern part of the rim

understanding and framing development plans in a region (Reihanian et al., 2012; Zhang 2012). It is also being used to develop geosites as potential tourist destinations across the world (Kalantari et al., 2011; Antić and Tomić, 2017; Chavan et al., 2022; Sajinkumar et al., 2022). The strengths and weaknesses of a site are listed along with the potential opportunities to capitalize on the strengths of a particular site and to mitigate threats using the weaknesses. The strengths and weaknesses are provided in Table 2 and belong to the internal factor evaluation matrix (IFEM), whereas the opportunities and threats fall under the external factor evaluation matrix (EFEM) (Table 3). The strengths of the crater are its unique representation of diversified fields such as geology, biology, planetary science, and archaeology, but the opportunity to explore the local culture is only limited (Table 2). Weaknesses primarily points to the lack of awareness of the society on the economic and cultural benefits a recognized geotourism spot can offer and the annual climatic extremities of the terrain (Table 2). The establishment of geotourism in the

Table 2 Strengths and weaknesses of internal factor evaluation matrix (IFEM)

Strengths	Weight	Score	Weighted score
Presence of culturally significant sites near the geosite locations (Aesthetic and historical value)	0.2	4	0.8
Potentiality of the area based on the diversified field of scientific/educational value such as geological, biological, and planetary sciences	0.2	4	0.8
Presence of already existing infrastructure like motorable roads, banks, ATMs, means of communication, boarding and lodging, etc. in most locations (Infrastructural values)	0.1	3	0.4
Opportunity to understand the local culture due to the sites being very culturally unique	0.05	3	0.15
Weaknesses			
Lack of government-imposed laws in favor of the conservation and protection of geosites	0.05	4	0.3
Lack of awareness among locals about the geological significance of the site	0.1	2	0.3
Lack of participation of local governing bodies in the protection of geologically significant sites	0.15	3	0.2
Tourist season restricted to winters and rainy seasons due to dry and warm weather during summers	0.05	2	0.1
Lack of awareness on the economic opportunities created by geotourism	0.1	2	0.4
	1		**3.45**

crater creates more opportunities for flourishing local businesses and employment (Table 3). However, the threats of contamination of the lake, destruction of the environment, and poor maintenance of the archaeological sites are fatal in preserving this geological wonder. It is essential that both matrices must have a total weighted score (TWS) greater than 2.5 to indicate that strengths and opportunities outweigh the weaknesses and threats. To calculate the TWS, the stakeholder's weight is used, which ranges from 0 (least significant) to 1 (very significant). The scores are allotted in the range from 1 to 4 (1-poor, 2-average, 3-good, 4-excellent). The stakeholder's weight is multiplied by the score resulting in the weighted score. The weighted score, when summed up for each matrix, results in the TWS. The TWS for both the matrices is graphically represented in Fig. 11 to review the viability of the Lonar site as a potential tourist destination. Furthermore, the SWOT analysis indicates a good prospective future (Tables 2 and 3) for geotourism in the Lonar area in terms of the multi-aspect importance of the Lonar impact crater.

Potentiality of Lonar Impact Crater as a Geopark

The variability of terrestrial surface and physical processes form an integral part of nature and is highly significant for sustaining ecosystems (Gray 2004). The International Congress on Geotourism defined geotourism as the tourism that sustains and enhances the identity of a territory, taking into consideration its geology, environment, culture, aesthetics, heritage, and the wellbeing of its residents (Newsome and Dowling, 2018). Geotourism especially focuses on the participation of the general public in geoconservation by imparting ambient knowledge on the concerned sites. The geological element in the geotourism is considered as a

Table 3 Opportunities and threats of external factor evaluation matrix (EFEM)

Opportunities	Weight	Score	Weighted Score
Showcase of indigenous culture by the locals in the form of traditional performances	0.2	4	0.8
Economic opportunities for the locals by selling traditional clothing, beverages, and food products	0.2	4	0.8
Creating and selling impact-related souvenirs like badges, caps, T-shirts, and mugs at the sites to further enhance economic growth in the regions	0.1	3	0.3
Establishment of exhibition centers in the form of a museum with animated models of impact cratering processes to provide educational value to the visiting tourists	0.1	3	0.3
Training and implementation of locals as tour guides	0.1	2	0.3
Threats			
Intense contamination of natural water of the lake by sewage water from the Lonar town	0.2	3	0.6
The temples and pilgrim places are in dilapidated conditions from natural processes as well as people engraving their names on the pillars of temples (Graffiti vandalism)	0.1	3	0.3
	1		**3.4**

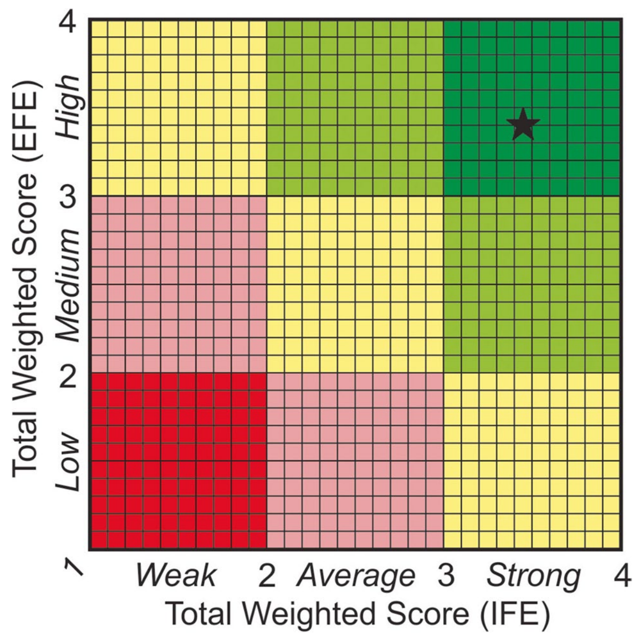


Fig. 11 The graphical representation of the Total Weighted Score (TWS) of the Lonar Crater based on the SWOT analysis done for determining its tourist potential using the internal factor evaluation matrix (IFEM) for strength and weaknesses and the external factor evaluation matrix (EFEM) for opportunities and threats

provision for providing interpretive and service facilities to enable tourists to acquire knowledge and understanding of the geology and geomorphology of a site beyond the level of mere aesthetic appreciation (Hose 1995). The underlying motive of the approach lies in fostering geoconservation and understanding geological heritage (Newsome and Dowling, 2018). The above objectives can only be achieved through visits to geological features, use of geological trails and viewpoints, guided tours, geo-activities, and patronage of visitor centers (Newsome and Dowling, 2018). Moreover, nowadays, many governmental programs aim at conserving important geological sites (geoconservation) and spreading awareness to the general public regarding the importance of geological processes and its role in the sustenance of ecosystems (Newsome and Dowling, 2018). The geological perspectives of the natural world aid in imparting the substrates, landform mosaics, and dynamic physical properties for habitat development and maintenance (Hjort et al., 2015).

In this scenario, protecting and conserving the wrecked remains of precious geological landmarks is highly important. In India, GSI is the chief authority in framing policies and implementing the same in geological conservation. According to GSI, National Geological Monuments are geographical areas of national importance and heritage established for the maintenance, protection, promotion, and enhancement of geotourism. The Lonar crater is one of the 34 National Geological Monuments designated in India by GSI. Even though Lonar crater has been a National Geological Monument for years, it has not been preserved in a manner conducive for future studies or visits.

This first identified crater in India is indeed a natural wonderland considering its geological, geographical, socio-cultural, archeological, and ecological significance. Geologically, Lonar is highly notable with its perfect, simple bowl-shaped morphology in a basaltic target rock similar to the crustal rocks observed on Mars, the Moon, Venus, and Mercury. Lonar crater's link to the socio-cultural and archeological significance is very well established through the numerous temples seen in and around the crater. The forest and wildlife wealth in such a small aerial extent and its nomination in the Ramsar list make Lonar noteworthy. A combination of so many virtues with regard to an impact crater is a unique sight in the world.

Malu et al. (2007) implemented conservation methods for Lonar crater in five different geomorphic zones, viz., the outermost ejecta blanket, the crater rim, the slopes of the crater, the crater basin excluding the lake, and the crater lake. Government authorities including the Lonar Municipal Council, Forest Department, Revenue Department, Public Works Department (PWD), Irrigation Department, and ASI are in charge of respective aspects of the Lonar crater. The Indian Constitution and several international treaties have well-defined agendas for the conservation and protection of nature and wildlife. The proper implementation of laws and rules will protect Lonar to a great extent.

Lonar crater is easily accessible from major cities like Mumbai, Aurangabad, and Jalna through air, rail, and road transportation. Thus, it can be an interesting destination for a large number of domestic and foreign tourists. Therefore, Lonar Crater has a significant influence on different fields of human interest. A mutual collaboration of all these different fields will help in bringing out the true potential of the Lonar crater, which will be a great asset for future generations. The crater, if converted into an established Global Geopark, will benefit students, the general public, nature enthusiasts, researchers, historians, and pilgrims, apart from geoscientists. The crater with its scientific potential and mesmerizing ecosystem is a common destination for satisfying a myriad of interests. The establishment of the Lonar Crater Geopark Park will be a huge testament to science and impact crater studies in the country. An UNESCO Geopark tag for Lonar will bring great laurels for India. Above all, the Lonar crater will be retained as a landmark geological wonder for generations of people and researchers to marvel at.

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Declarations

Conflict of Interest The authors declare no competing interests.

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