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FIELD GUIDE

INPOST - 02

NATURE'S WONDERS AND ANCIENT MYSTERIES: LONAR, AJANTA-ELLORA, MAHARASHTRA







Mohammad Arif and Amar Agarwal

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Field Guide Book

INPOST-02
Nature's Wonders and Ancient Mysteries:
Lonar, Ajanta-Ellora, Maharashtra

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Table of Contents

1.	Team Leaders	1-2
2.	Abstract	3
3.	Preamble	4
4.	Research Problem and Global Context	5-7
5.	Regional Geology	7-9
6.	Flora, Fauna and Climate	9
7.	Literature Review and Open Research Problems	10-12
8.	Field Transect and Stop Descriptions	12-20
9.	Geoheritage, UNESCO Sites, and Archaeological Context	20-23
10.	Local Conveniences	23
11.	Conclusions	23-24
12.	Acknowledgements	24
13.	References	25-30
15.	Annexure	31-32

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Abstract

This field trip will give participants the chance to study three important features of the Deccan Traps, formed on basaltic lava flows either by natural geological processes or by human-made modifications during historic times. The excursion begins with the Lonar crater, a meteorite impact crater preserved within the basaltic lava flows of the Deccan Traps. The Lonar crater (N19°58'35", E76°30'30"), Buldhana district, Maharashtra, is the best-preserved hypervelocity impact crater in basaltic target rock on Earth. With a rim-to-rim diameter of 1.88 km and a present lake (saline) depth of ~150 m, the structure was excavated into tholeiitic Deccan flood basalts of ~65 Ma age (Maloof et al., 2010). Different studies have dated the Lonar impact event to between ~11.65 ka and ~570 ka, reflecting significant variation in reported ages (Jourdan et al., 2011; Maloof et al., 2010; Nakamura et al., 2014; Sengupta et al., 1997; Storzer & Koeberl, 2004). The first two days of the field excursion focus on the Lonar crater, including the outer ejecta blanket, the structurally deformed crater rim, basalt flow exposures along the inner wall, the lake shoreline, and the medieval temple complex within the crater basin. The field guide on the Lonar crater covers the shock metamorphism record, the contested geochronology, the incorporation of Archean basement rocks into the impact melt (Chakrabarti and Basu, 2006; Chandran et al., 2021), the sub-surface damage zone (Kumar and Rai, 2023), and the Quaternary paleoclimate archive preserved in the Lonar lake sediments (Anoop et al., 2013). The next two days includes visits to the UNESCO World Heritage sites of Ajanta and Ellora, where participants can observe the earliest human-made caves in the region, carved from pahoehoe lava flows and adorned with Hindu, Jain, and Buddhist art, while discussing the internal morphology of the cave-hosting lava and geotechnical aspects of their conservation.

Preamble

Lonar crater is exceptional among terrestrial impact structures because its morphology and ejecta blanket remain well preserved and readily accessible in the field. Many impact craters on Earth have been obscured by erosion, burial, or tectonic activity, making them recognizable mainly through geophysical anomalies or subtle circular shapes in remote sensing data. Lonar crater, however, has a clearly defined crater rim, an exposed crater lake, and well-preserved ejecta deposits. Visitors can descend into the crater via stairs and a short path. Exposed basaltic flow contacts are visible on the crater wall, and ejecta deposits can be observed along the road. The crater age estimates range from about 11,650 to 570,000 years, depending on the dating method used. The goal is to bring participants to the outcrop, present the evidence, and let the open questions speak for themselves.

The Lonar crater field excursion focuses on four main themes: (1) how layered basalt deforms during a hypervelocity impact; (2) the shock metamorphic and geochemical evidence preserved within the crater and its ejecta; (3) the environmental history (paleoclimate & paleoenvironment) recorded in the lake sediments after crater formation; and (4) the importance of Lonar for understanding impact cratering processes, its relevance to planetary science, and its value as a geoheritage site.

Research Problem and Global Context

Impact cratering is a key process in the evolution of planetary surfaces in the Solar System. On the Moon, Mars, and Mercury, it has shaped the surfaces, and the crater record is used to estimate the absolute ages of geological units and reconstruct impactor flux histories. To understand this properly, it is necessary to examine how impact cratering occurs in different rock types. Most impact craters on Earth are found in crystalline basement or sedimentary rocks, and only a few occur in basalt. In contrast, large areas of the Moon, Mars, and the asteroid Vesta are composed mainly of basalt.

Only five confirmed hypervelocity impact craters on Earth formed directly in basaltic provinces. Logancha (14 km, ~23-66 Ma) is in the Siberian Traps (Feldman et al., 1983; Masaitis, 1999); Vista Alegre (9.5 km), Vargeao Dome (12.4 km, 123 ± 1.4 Ma), and Cerro do Jarau (< 137 Ma) are in the Parana-Etendeka basalts of Brazil (Crósta et al., 2012; Crósta, Koeberl, et al., 2010; Crósta, Lourenço, et al., 2010); and Lonar (1.88 km, 11.65-570 ka) is in the Deccan Traps of India (Fredriksson et al., 1973; Fudali et al., 1980). The Brazilian impact structures are deeply eroded, and their shock metamorphic textures are degraded. Logancha is remote and poorly studied. Lonar is the only one that is geomorphically near-pristine, young enough to retain intact shock metamorphic assemblages, and equipped with a post-impact lake sediment record. This makes Lonar as essentially the entire reference dataset for small simple craters formed in basalt.

Besides, the Geological Survey of India (GSI) enlisted the Lonar crater as one of the National Geological Monuments (potentiality as a 'Geopark'). The interior of the Lonar crater is occupied by a shallow saline lake; below the lake water, a sequence of ~100 m thick unconsolidated sediment is reported that overlies the base of the crater, made up of highly weathered Deccan basalts. Lonar Lake is fed primarily by small streams and surface runoff, with no natural outflow. The lake is saline, alkaline, and eutrophic; below approximately 4 m of water depth, conditions are permanently suboxic to anoxic, a characteristic feature of closed-basin saline systems. Knowledge of the present-day conditions of Lonar Lake was required to enable the paleoclimate reconstruction on the basis of Lonar Lake sediments. Some properties of the modern Lonar lake, such as its endorheic nature, high pH, brackish water, severe eutrophication, and anoxic bottom water, make it a unique ecosystem and account for specific biogeochemical characteristics of its biota and sediments. Lonar lake is one of very few natural lakes located in the 'core monsoon zone' in central India, and it is fed exclusively by precipitation of the Indian Summer Monsoon and stream inflow that is closely linked to monsoon rainfall. The harsh chemical environment of the Lonar lake water and sediments is home to a diverse indigenous microbial community and several new bacterial species.

4.1 The Age Controversy

The age of the Lonar crater remains uncertain, as different dating methods applied to various materials have produced widely divergent results. Current estimates range from approximately 11,650 years to 570,000 years, reflecting the challenges of reconciling multiple techniques and datasets.

Thermoluminescence dating of three in situ impact-melt rock samples yields an age of 52.0 ± 6 ka, indicating that the Lonar impact event occurred during the Late Pleistocene (Sengupta et al., 1997). This age reflects the cooling period of the melt material formed during crater excavation following the impact. In contrast, fission-track dating of impact glass yielded an age of 15.3 ± 13.3 ka, but the significant uncertainty associated with this estimate limits its reliability and precision (Storzer and Koeberl, 2004). Radiocarbon (14C) dating of ejecta-derived material found in histosols surrounding the crater yielded an age of 11.65 ± 0.7 ka (Maloof et al., 2010). However, this age likely represents a minimum age for the impact event, as it dates organic-rich soils that contain reworked ejecta rather than the impact itself. Jourdan et al. (2011) proposed a significantly older isochron age of 570 ± 47 ka (MSWD = 1.5; P = 0.14) based on 40Ar/39Ar analyses of four impact melt rock samples. This result suggests a middle Pleistocene age for crater formation and remains the oldest published estimate for the Lonar impact event.

Recent cosmogenic nuclide dating of ejecta deposits using 10Be and 26Al has produced closely comparable ages of 37.5 ± 5.0 ka and 37.4 ± 3.4 ka, respectively (Nakamura et al., 2014). The strong agreement between these two independent cosmogenic dating methods supports a Late Pleistocene age for the crater. This finding has been considered by several researchers to be consistent with the relatively fresh appearance and limited erosional degradation of the crater rim and ejecta blanket.

Table 1: Geochronological estimates for the Lonar crater

Method	Age (ka)	Material	Key Caveat	Reference
Thermoluminescence	52.0 ± 6.0	In situ impact melt rock / impact glass	May reflect incomplete signal resetting or later thermal disturbance	Sengupta et al. (1997)
Fission-track dating	15.3 ± 13.3	Impact glass	Large analytical uncertainty due to low track counts	Storzer and Koeberl (2004)
Radiocarbon (^{14}C) dating	11.65 ± 0.7	Ejecta-derived material preserved in histosols	Represents a minimum age because the dated material is younger than the impact itself	Maloof et al. (2010)
Radiocarbon (^{14}C) dating	13.15 ± 0.09	Quarry histosol beneath ejecta blanket	Dates buried soil horizon, not direct impact melt	Maloof et al. (2010)
Radiocarbon (14C) dating	40.8 ± 1.1	Pit histosol beneath ejecta	May provide an older pre-impact soil age	Maloof et al. (2010)
^{40}Ar/^{39}Ar isochron dating	570 ± 47	Melt rock samples	Possibly affected by inherited radiogenic ^40Ar; much older than other estimates	Jourdan et al. (2011)
Cosmogenic ^{10}Be exposure dating	37.5 ± 5.0	Ejecta deposits	Gives minimum exposure age of ejecta surface	Nakamura et al. (2014)
Cosmogenic ^{26}Al exposure dating	37.4 ± 3.4	Ejecta deposits	Consistent with 10Be age; supports Late Pleistocene crater formation	Nakamura et al. (2014)

4.2 Projectile Composition

Early geochemical research by Venkatesh (1965) showed no increase in nickel (Ni) or cobalt

(Co) levels in lake sediments and soils beyond what is found in basalt. Initially, this suggested that these materials had no meteoritic origin. However, it later became clear that the signal from meteoritic materials often becomes too weak to detect in bulk analyses after an impact. Based on the mineralogical evidence, Fredriksson et al. (1973) proved the Lonar as an impact origin. Nickel (60–2500 ppm), chromium (27–618 ppm), and cobalt (38–196 ppm) measured in the spherules point to a chondritic composition (Chandran et al., 2023; Misra et al., 2009). In contrast, the abundance of highly siderophile elements and Re-Os isotope data suggest only a very small meteoritic contribution, with a chondritic component of up to about 0.03% in impact glasses and melt rocks (Schulz et al., 2016). Das Gupta et al. (2017) further showed that Lonar spherules contain elevated Ir and Cr concentrations consistent with the addition of about 1-8 wt% chondritic material to the basaltic target rocks, particularly in Group 1a and Group 2 spherules. Mougel et al. (2019) applied Cr isotopes to Lonar impact rocks and detected up to 3% chondritic material, possibly indicating a CM-type carbonaceous chondrite origin.

Regional Geology

5.1 Stratigraphy

The Deccan Volcanic Province (DVP) covers ~500,000 km2 of the western Deccan Plateau and was emplaced between 66 and 64 Ma predominantly during the Cretaceous-Palaeogene boundary (Renne et al., 2015). In the Buldhana region, the basalt sequence is part of the Wai Subgroup and consists of tholeiitic flows, usually about 10–25 m thick. These flows are separated by lateritic paleosols and vesicular flow-top zones formed during breaks between eruptions. The bulk chemistry of the target basalt is well documented, with SiO_2 around 49–50 wt%, TiO_2 2.0–2.8 wt%, Al_2O_3 13–14 wt%, total FeO 12–14 wt%, MgO 6–8 wt%, and CaO 9–11 wt% (Chandran et al., 2023). These values provide the geochemical baseline for identifying impact-related deviations in melt rock, breccia, and spherules.

Inside the crater's inner wall, Maloof et al. (2010) defined six lava flow units (Tf0-Tf5). The flows dip radially outward from the crater centre at 8–20° due to impact-induced structural uplift. In several rim sectors, the stratigraphy is inverted, with older flows above younger ones in an overturned flap produced by ballistic ejecta emplacement. This is one of the structural diagnostics of impact crater rim, documented also at Meteor Crater, Arizona, and the Ries Crater, Germany.

5.2 Structure

Lonar crater is a simple, bowl-shaped meteorite impact crater located in the Buldhana district of Maharashtra (19°58′ N, 76°31′ E). The rim-to-rim diameter is 1.88 km and stands about 40 m above the surrounding plains, made up of roughly 30 m of structural uplift and ~10 m of ejecta (Fudali et al., 1980). The exception is a low in the northeastern sector, where the rim is noticeably subdued (Fudali et al., 1980). The crater floor lies about 90 m below the pre-impact surface and is blanketed by 20 m of lacustrine sediments. The crater, having relatively pristine morphology, was formed by an oblique impact of a chondritic impactor that struck the pre-impact basaltic target of Deccan Traps (~65 Ma) from the east at an angle between 30 and 45° to the horizon (Misra et al., 2010). Six basaltic lava flows, each 5–20 m

thick, are exposed along the inner wall (Maloof et al., 2010). Around much of the rim, these flows are overturned and dip 10°–20° outward (Fudali et al., 1980; Kumar et al., 2014). Maloof et al. (2010) mapped fault systems at the rim: outward-dipping thrusts from radial compression during the shock phase, and steep normal faults that opened as the transient cavity rim collapsed.

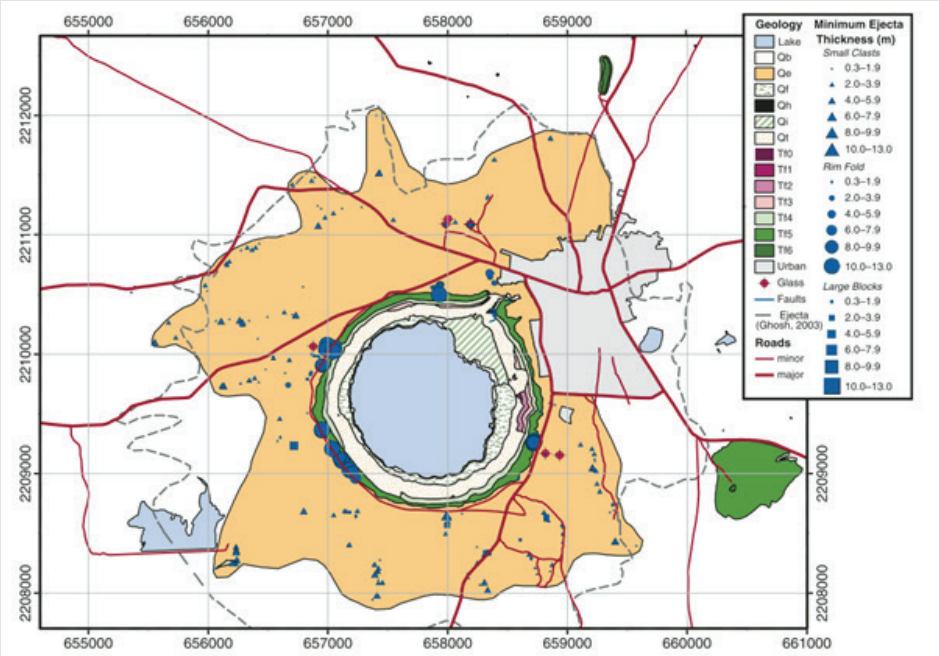


Figure 1: Geological map of Lonar Crater (UTM WGS84; Easting 655000–661000 m, Northing 2208000–2212000 m). Blue symbols mark ejecta outcrops, symbol shape indicates ejecta type and symbol size scales with thickness (m). Magenta circles indicate locations of impact glass spherules. The dashed gray line traces the continuous ejecta blanket boundary after Ghosh (2003). Quaternary units: Qb, beach; Qe, ejecta; Qf, forest; Qh, histosol; Qi, irrigated alluvial fan; Qt, talus (Maloof et al., 2010).

Sub-surface structure of the Lonar has been constrained by magnetic and gravity modelling (Rajasekhar & Mishra, 2005; Rao & Bhalla, 1984), electrical resistivity tomography (Sivaram et al., 2018), and ambient seismic noise tomography (Kumar and Rai, 2023).

5.3 Quaternary Geology

The Lonar crater formed during the Quaternary period, though its exact age remains uncertain. 40Ar/39Ar age dating of 570 ± 47 ka places the impact during Marine Isotope Stage (MIS) 15 (Jourdan et al., 2011). In contrast, a cosmogenic radionuclide (CRN) age of 37.5 ± 5.0 ka suggests it occurred during MIS 3 (Nakamura et al., 2014). Regardless of which age is preferred, the sediments that filled the crater post-impact are entirely from the Quaternary period. Since its formation, the crater has maintained a sedimentary record of varying ages from the lake that has developed within it. This lake is endorheic, meaning it has no outflow

channel. As a result, dissolved ions in the water become more concentrated over time due to evaporation. Changes in the balance between monsoon precipitation and evaporation are directly reflected in the lake's water chemistry and the types of evaporite minerals present. These variations form the basis for paleoclimatic reconstructions, such as those presented by Anoop et al. (2013).

Flora, Fauna and Climate

Lonar crater shows a unique vegetation cover within semi-arid basaltic terrain. The crater is covered by dry tropical forest and open woodland, with patches of denser vegetation near moisture zones and freshwater springs. A floristic study recorded about 237 plant species belonging to 153 genera and 70 families in the crater area (Jha, 2003). Later surveys describe the vegetation as including around 30 tree species, 10 shrubs, 13 climbers, 8 herbs, and 6 grasses. Common tree species include Saraca asoca, Acacia nilotica, Azadirachta indica, Ficus benghalensis, and Santalum album. Shrubs and herbs such as Mimosa hamata, Anisomeles indica, and Corallocarpus epigaeus are also widespread. Climbers like Tinospora cordifolia and grasses such as Dendrocalamus strictus and Heteropogon contortus occur throughout the crater. Overall, the vegetation is mostly open, with denser patches controlled by soil depth, slope, and local water availability (Hippalgaonkar, 2016). Additionally, several plant species are recognized for their medicinal uses within local communities (Rathod, 2014)

Lonar crater supports a range of animal life across its forested slopes and lake environment. Data compiled from the Zoological Survey of India (ZSI) and the Ministry of Environment, Forest and Climate Change list 7 amphibian species, 49 reptiles, 162 birds, 84 insects, 18 mammals, and 14 mollusks. Bird diversity is high, with more than 160 species recorded, including migratory waterfowl; species of concern include Ciconia episcopus and Aythya ferina. Mammals in the area include Canis lupus, langurs, mongooses, bats, and wild boar. Reptiles are also well represented, with several snake species, including venomous ones (Khobragade and Pawar, 2015).

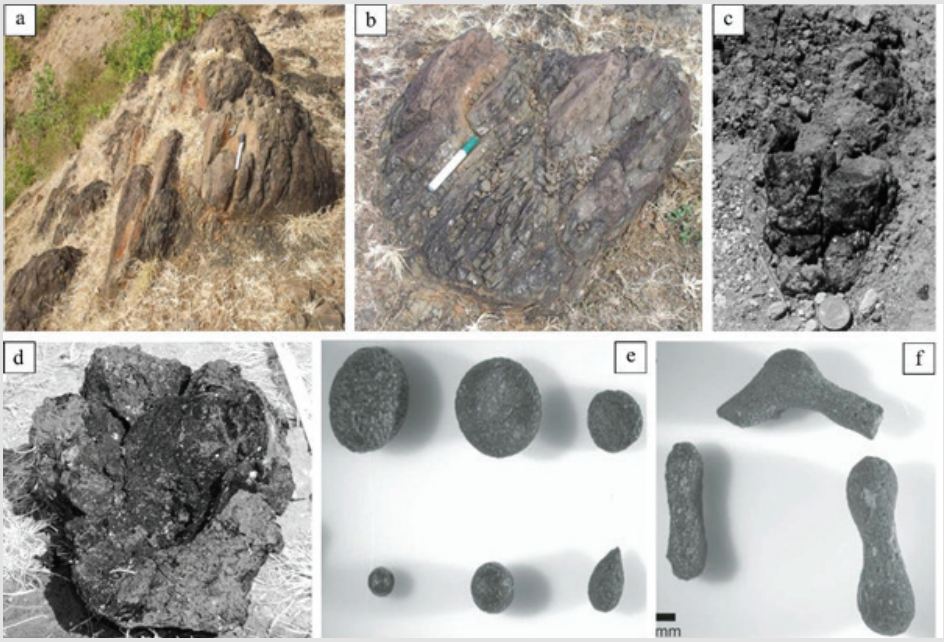
The lake itself, due to its high salinity and alkalinity, does not support fish, largely because of low oxygen levels and elevated salt content (Dabhade and Tandale, 2017). Instead, it is dominated by microbial life, including alkaliphilic and halophilic bacteria and archaea (Paul et al., 2016; Shivaji et al., 2017). Cyanobacteria and algae form the base of the lake's food system and are important for primary productivity.

The Lonar crater region has a semi-arid tropical climate, classified as BSh in the Köppen–Geiger system, which is typical of the Deccan basalt province. Rainfall is highly seasonal, with about 80–90% of the annual precipitation, approximately 700 mm, occurring during the Indian Summer Monsoon from June to September. High evaporation rates relative to precipitation levels characterize much of the year, leading to hypersaline and alkaline lake conditions. There are significant seasonal temperature variations, with moderate conditions in the post-monsoon period and high temperatures during the pre-monsoon months. These climatic factors greatly influence the hydrological balance, lake chemistry, and biological activity within the crater system.

Literature Review and Open Research Problems

7.1 Impact Origin and Shock Metamorphism

The origin of Lonar Crater has been debated for much of the 20th century, with various researchers initially showing it to be cryptovolcanic activity (Nandy and Deo, 1961; Subrahmanyam, 1985). However, the meteoritic origin was established by Fredriksson (1973), who discovered shatter-coned breccia and basalt fragments containing maskelynite from drill holes in the crater floor and rim trenches. Maskelynite is a type of diaplectic glass formed by the solid-state transformation of plagioclase under pressures exceeding approximately 24-35 GPa (Fritz et al., 2019). It is one of the diagnostic criteria for terrestrial impact structures (French, 1998) and cannot be produced by volcanic processes. Nayak (1972) also identified impact glass and maskelynite at the site. Kieffer (1976) described five progressive shock classes in the Lonar basalt, ranging from brittle fracture at low pressure to the complete transformation of plagioclase into maskelynite (approximately 25-45 GPa). They also noted the onset of feldspathic melt (approximately 45-60 GPa), vesicular flowed melt (approximately 60-80 GPa), and whole-rock melt at pressures exceeding 80 GPa.



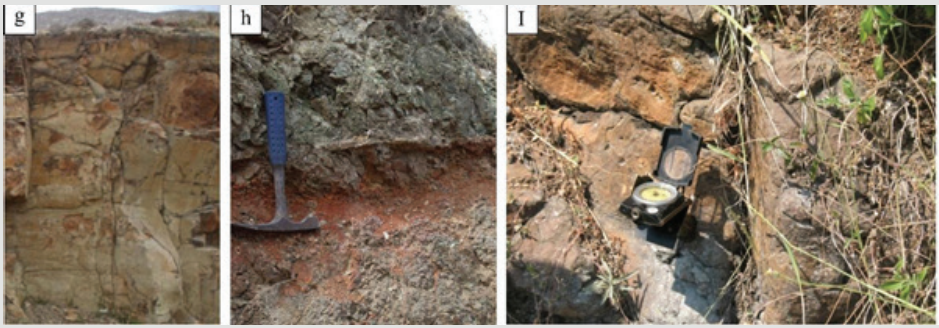


Figure 2: Field evidence of impact-related features at Lonar crater. (a) Dipping of basalt flow at western sector crater rim, (b) Cleavaged basaltic block within the ejecta at northern part, (c) Impact melt rock in the ejecta blanket outside the southeastern part of the crater rim, (d) brecciated impact melt rock with vesicular and glassy textures, (e & f) basaltic impact glass spherules with a variety of splash forms (spheres, pancake toroid, ellipsoids, teardrops, and dumbbells) recovered from undisturbed regions of crater rim and at Little Lonar, (g) the unshocked basalt flow exposed at ~2 km east of crater rim, (h) red bole horizon with calcite veins showing basalt flow separation, (i) paleomagnetic drill core orientation in the field (Photographs by Mohammad Arif)

7.2 Geophysics and Lake Paleoclimate

The sub-surface structure of the Lonar crater has been delineated through successive geophysical investigations. Fudali et al. (1980) used five to estimate an original crater depth of 230–245 m, now buried beneath roughly 100 m of sediment. However, four of these drill holes did not reach the base of the breccia, so the full depth of excavation remains uncertain. Rao and Bhalla (1984) conducted a palaeomagnetic study of samples from the inner crater walls and found systematic variations in parameters such as the Königsberger ratio and magnetic susceptibility. These patterns differ from the observed values in the surrounding unshocked Deccan basalt flows outside the crater. Their findings also indicated a secondary shock remanence, suggesting that impact-induced temperatures exceeded the Curie temperature point of magnetite (about 550 °C). Observations on circular/semi-circular gravity and magnetic anomalies (~2.5 mGal and 550 nT respectively) over the Lonar lake suggest that the meteoritic impact modified the magnetization vector and density of the target Deccan trap (Rajasekhar and Mishra, 2005). A 135-meter-thick brecciated layer underlies the crater floor, with a bulk density of 2.60 g/cm^3. Beneath it is a 150-meter-thick zone of fragmented basalt with a density of 2.70 g/cm^3. Kiik et al. (2020) documented a negative magnetic anomaly over the crater interior and attributed it to brecciation. The argument is straightforward: impact causes randomization of clast orientations, destroying the coherent remanent magnetization that characterizes the surrounding unshocked sequence.

Shear-wave velocities beneath the crater floor run 10–15% below those of the surrounding basalt, around 2.4 km/s, against a background that stays above 2.5 km/s in the pre-Deccan crystalline basement. The low-velocity zone is roughly circular in plan view and is read as a fractured region produced by the impact. Below it, basement velocities recover, placing a reasonably well-defined base on the impact-modified column. The depth of about 500 m

corresponds with global depth–diameter scaling for simple craters, underscoring the significance of their findings (Sivaram et al., 2018). Kumar and Rai (2023) reveal heterogeneous Deccan basalt flows, 500 to 900 meters thick, over an undulating Archean granite-gneiss basement. It identifies a 200-meter thick low-velocity lens beneath the crater floor, filled with impact breccia and lake sediments, extending into the southwestern ejecta blanket. This finding enhances our understanding of the geological landscape. The structural asymmetry of the damage zone and the breccia thickness in the southwestern quadrant supports an oblique impact trajectory from the northeast to the southwest (Rajasekhar and Mishra, 2005). This finding matches the ejecta asymmetry noted by Maloof et al. (2010). Kumari et al. (2024) identified an oval-shaped low-velocity zone beneath the southwestern rim (~400 m depth), indicating asymmetric damage from an oblique impact. Microfracture density indicates that deformation intensity is highest along the southern crater rim, suggesting a downrange direction toward the south and a corresponding impact trajectory from north to south (Tiwari et al., 2025).

The Lonar lake sediment sequence has been investigated as a Quaternary palaeoclimate archive. Mineralogical and isotope studies of a 10 m Holocene core show that the evaporite mineral gaylussite ($Na_2Ca(CO_3)_2{\cdot}5H_2O$) occurs only in two intervals, 4630–3890 and 2040–560 cal yr BP. These layers are linked to periods of high evaporation and a low precipitation–evaporation balance, indicating drier conditions and a drop in lake level (Anoop et al., 2013).

7.3 Outstanding Problems

Three problems stand out as tractable but unresolved. First, the crater age: the debate between the 40Ar/39Ar age of 570 ± 47 ka (Jourdan et al., 2011) and the CRN age of 37.5 ± 5.0 ka (Nakamura et al., 2014) remains unresolved after over a decade. A new 40Ar/39Ar study using isochron analysis with explicit screening for excess Ar, combined with OSL and 14C chronology of the lake sediment column, is the logical next step. Second, the lake sediment record: the age model for the entire sediment column is uncertain because it depends on the contested crater age; a sub-bottom profiling survey to determine total sediment thickness has not been done. Third, astrobiology: the unusual alkaliphilic microbial community of Lonar Lake has been widely recognized as scientifically interesting but has not been systematically characterized for planetary-analogue applications.

Field Transect and Stop Descriptions

The excursion spans four days, with one principal stop each day.

Day 1 focuses on the geology of Lonar crater, examining the ejecta blanket, rim structure, shock features, and the inner wall sequence.

Day 2 explores the later history of the crater, including lake sediments, the temple complex, and a discussion from the eastern crater rim.

Day 3 shifts to Ajanta, where the Waghora river gorge provides excellent exposures of Deccan basalt flows.

Day 4 concludes at Ellora in the Charanandri Hills, where the flow sequence andassociated structures are clearly visible

Excursion Plan:

While the visit to Lonar Crater (Day 1 & Day 2) includes five stops in and around the crater, the geology of the Ajanta and Ellora sites can be effectively understood by visiting on Day 3 and Day 4.

Lonar Crater Excursion Stops (Day 1 & Day 2):

The field visit begins at 8:30 AM from Aurangabad, following breakfast on 4 February 2027. The Lonar crater, situated about 142 km from Aurangabad, is accessible by bus in roughly two hours. The excursion covers the salient geological and geomorphological features of the Lonar crater area through five designated stops (Fig. 3), each highlighting key aspects of crater morphology, ejecta, breccia types, basalt flows, and lake sediments.

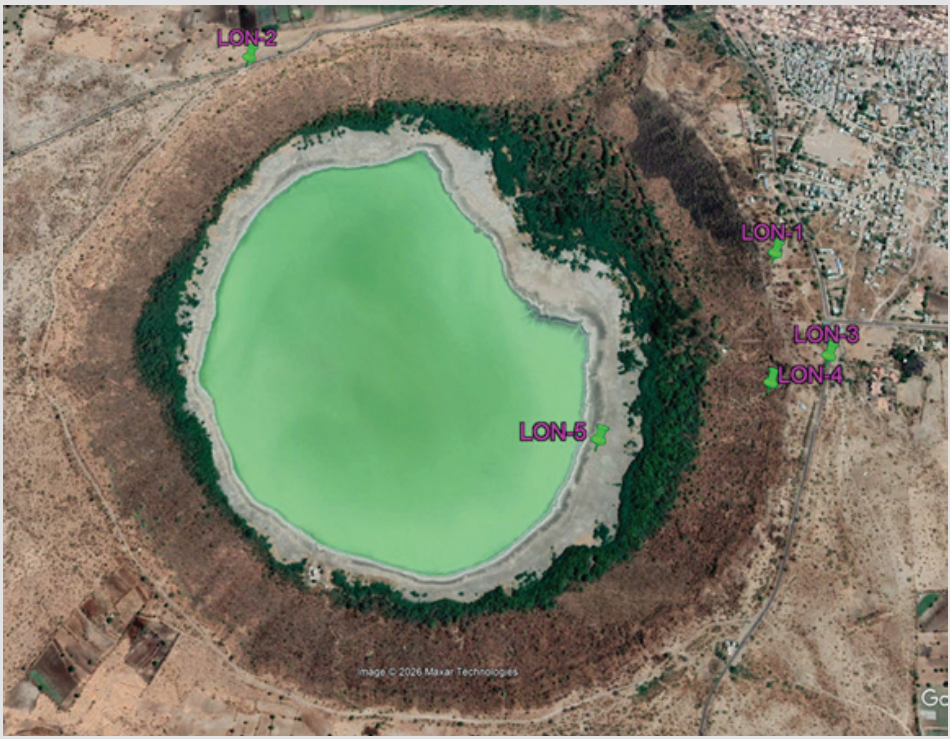


Figure 3: Google Earth Image of Lonar Crater showing crater with excursion stops LON-1 to LON-5.

Stop LON-1: PWD Guest House (Abandoned), ENE Rim of Lonar Crater

Location: N19°58′ 42.9″; E76°31′ 01.7″

Observations:

- Panoramic view of Lonar crater with its blue green saline lake (~5–7 m deep) at the base.
- Crater: circular depression, ~1,830 m in diameter, ~150 m deep, rim raised ~20 m above surrounding terrain; highest point ~610 m a.s.l.
- Inner slopes: upper moderate (30–40°), middle steep (~40°), lower gentle toe slope; covered with vegetation, gullies, and debris flows.
- Drainage: centripetal, seasonal streams; Dhar Valley notch with perennial springs forming a fan delta.
- Rim: breccia heaps of angular basalt blocks, underlain by the topmost lava flow.
- Geological significance: established as a meteorite impact crater by GSI–USGS–Smithsonian studies (1970s); commemorated by GSI plaque (1974).
- Recent U–Pb dating (~570 ka) of melt glass (Jourdan et al., 2011) confirms its young impact origin, distinct from Deccan volcanism (~62–68 Ma).

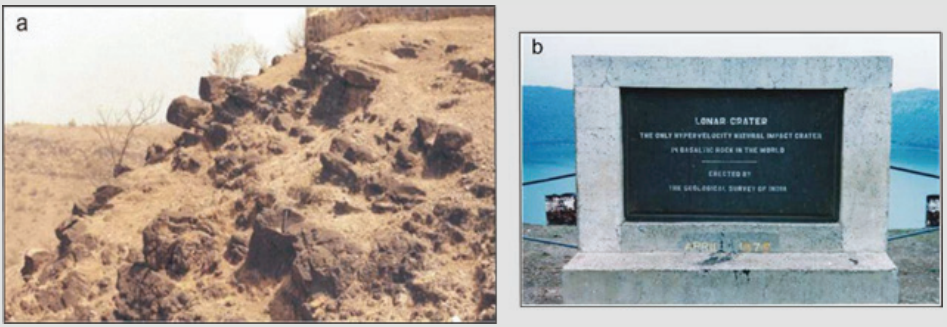


Figure 4: (a) Radially outward dips of contact-parallel joints in the topmost basalt flow, viewed northward from the PWD Guest House (Stop LON-1). (b) Plaque erected by the GSI in 1974, declaring Lonar as a meteorite impact crater.

Stop LON-2: Northwestern Gate of Lonar Wildlife Sanctuary

Location: N19°59′ 1.81″; E76°30′ 13.28″

Approach: Situated on the NW rim of Lonar crater; accessible within 15 minutes by bus. No hiking required.

Observations:

- Provides a distant view of the crater rim and reveals the undulating topography of the ejecta blanket.
- The ejecta blanket is well exposed along the rim and extends radially outward for ~2 km; Lonar town itself lies upon this blanket.
- It slopes gently (2–6°) away from the crater, preserving the original post-impact surface with minimal erosion (Osae et al., 2005).
- The ejecta, a few centimeters to ~8 m thick, rests over a palaeosol developed on weathered basaltic lava flows predating the impact.

- Field evidence suggests deposition by a debris surge mechanism, comparable to fluidized craters observed on Mars (Osae et al., 2005).
- The crater's youthful age (~570 ka) and well-preserved morphology indicate low denudation rates in this semi-arid Deccan Traps terrain.
- Based on crater circularity, the impactor's incidence angle was likely ~30° from the horizon, with ejecta extending farther west - implying an east-to-west impact trajectory (Misra et al., 2010).

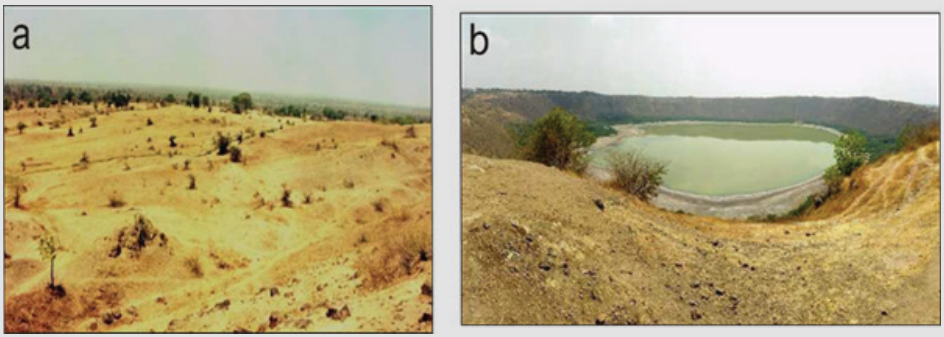


Figure 5: (a) Gently undulating surface of the ejecta blanket, viewed north-westerly from Stop LON-2. (b) Lonar crater, viewed south-easterly from the same location. The crater rim, composed of ejecta breccia, often contains loosely held basalt blocks and red bole with or without impact glass.

Stop LON-3: Southern Ejecta Blanket (Near MTDC Guesthouse Gate)

Location: N19°58′ 33.8″; E76°31′ 05.5″

Approach: Accessible within 15 minutes by bus from LON-2; no hiking required

Observations: Two types of ejecta breccia are exposed:

- Suevitic breccia (Fig. 6a) – polymictic, containing impact-derived melt fragments, cogenetic glass, basalt, and red bole in a clastic matrix. Occurs as pockets within fragmental breccia.
- Fragmental breccia (Fig. 6b) – more widespread, polymictic, with angular basalt clasts showing variable shock effects (unshocked to those with planar deformation features in plagioclase/pyroxene and maskelynite formation). Red bole fragments are common, set in a fine clastic matrix (Fig. 6d).

  Impact glass: Homogeneous black glass fragments occur within suevite and as loose particles across the ejecta.
- Dimensions up to 50 cm, spheroidal to tear-drop shaped (Fig. 6c).
- Larger chunks are brittle, breaking easily when disturbed.
- Surfaces may be smooth and flow-like (indicating molten mobility) or fragmented (reflecting chilled crust disruption under shear stress).
- Vesicle-poor dark glass often annealed to vesicle-rich portions, showing complex cooling histories.

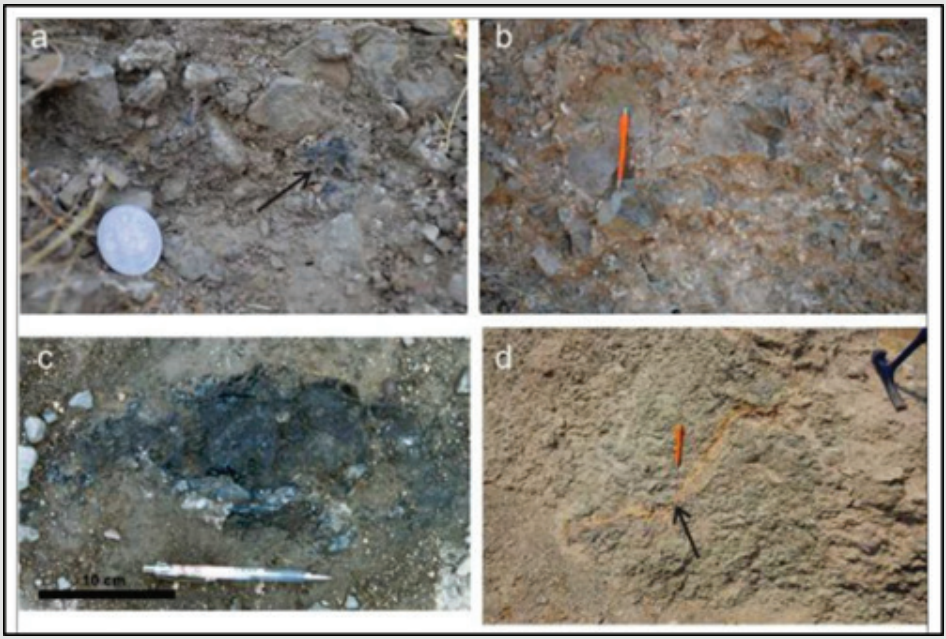


Figure6: Constituents of ejecta breccia at Lonar crater: (a) basaltic suevitic breccia with impact melt glass in clastic matrix; (b) fragmental breccia without glass; (c) spindle-shaped impact glass fragment; (d) pahoehoe-flow clast with chilled margin.

Stop LON-4: Foot Track from MTDC Resort Gate to Lonar Lake Shore

Location: N19°58′31.5″; E76°31′0.2″

Approach: Situated on the southeastern inner slope of Lonar crater; mild hiking (~100 m) required from LON-3.

Observations:

- Exposure of the topmost basalt flow (Flow 4) overlain by ejecta breccia containing clasts of impact glass.
- Flow-4 shows outwardly dipping, flow-contact parallel sheet/platy joints (Fig. 7a), with blocks displaying variable joint azimuths and dips.
- Breccia pockets occupy interspaces between basalt blocks (Fig. 7b).
- A few metres below, the Flow-4/Flow-3 contact is visible, marked by flow-top breccia composed of vesicle-rich basalt clasts, mildly oxidized and reddish in colour (Fig. 7c).
- This stop highlights the structural features of basalt flows and their relationship with impact-related breccia.
- Beyond this point, the trail descends steeply toward the lakeshore (Stop LON-5).

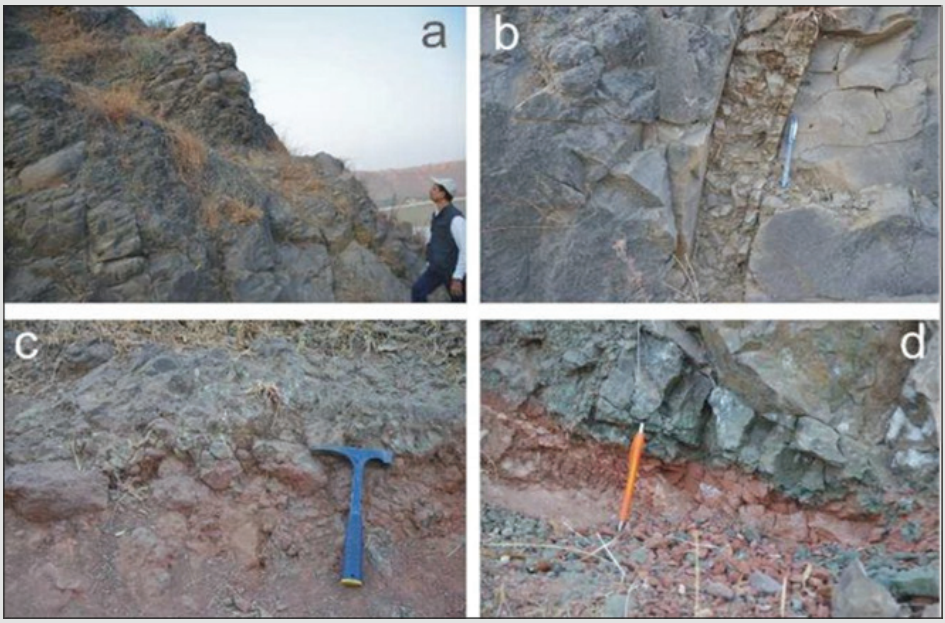


Figure 7: Structural and lithological features along the inner slope of Lonar crater: (a) outwardly dipping sheet joints in Flow-4 basalt; (b) fracture between basalt blocks infilled by breccia; (c) autobreccia at the Flow-4/Flow-3 contact with vesicular clasts; (d) red interflow horizon (red bole) marking the Flow-3/Flow-2 boundary.

Stop LON-5: Foot Track to Lonar Lakeshore

Location: N19°58-26.7″; E76°30′45.1″

Approach: Requires ~250 m hike from LON-4 along a steep inner slope; ~30 minutes total.

Observations:

- Exposures of Flows 3 and 2, separated by a red interflow horizon (bole-bed) (Fig. 7d).
- Morphology: rubbly pahoehoe type with smooth, continuous base; massive, vesicle-poor core; brecciated top.
- Flow 1 (lowermost) exposed along traverse; vesicular with small rounded vesicles, also pahoehoe type.
- Lower slope covered by a consistent horizon of rock debris fallen from upper flows.
- Crater floor: nearly flat, ~1200 m diameter, occupied by a saline lake (~5–7 m depth).
- Lake hydrology: level influenced by surface runoff (monsoon) and groundwater input.
- Dry season: salt incrustation visible over silt-clay lake sediments (Fig. 8).



Figure 8: Receding shoreline of Lonar lake during summer, showing silty-clayey sediments covered by salt incrustations. Dead tree trunks along the eastern shore suggest the presence of fresh water in the recent past (view looking north).

Day 3:

Ajanta Caves – Waghora River Gorge Section: The gorge at Ajanta cuts through stacked pāhoehoe basalt flows of the Deccan Traps. Individual flows exhibit a three-part structure: a vesicular top, a dense core, and a pipe-vesicle base (Sheth, 2023). Features such as lobe contacts, vesicle bands, ropy surfaces, and inflation structures are readily visible. The basalt contains plagioclase phenocrysts and amygdales filled with secondary minerals. Columnar joints and red bole layers mark pauses between eruptions (Duraiswami et al., 2003).

Day 4:

Ellora Caves – Charanandri Hills Section: The Ellora section shows a vertical stack of basalt flows cut into by the cave excavations. Both pāhoehoe and ‘a’ā flows are present, with differences in flow texture and structure. The internal layering of flows is clear, along with joint patterns such as vertical cooling joints and horizontal fractures. Quartz veins cutting through the basalt are also visible, helping to understand the structure of the flow sequence.

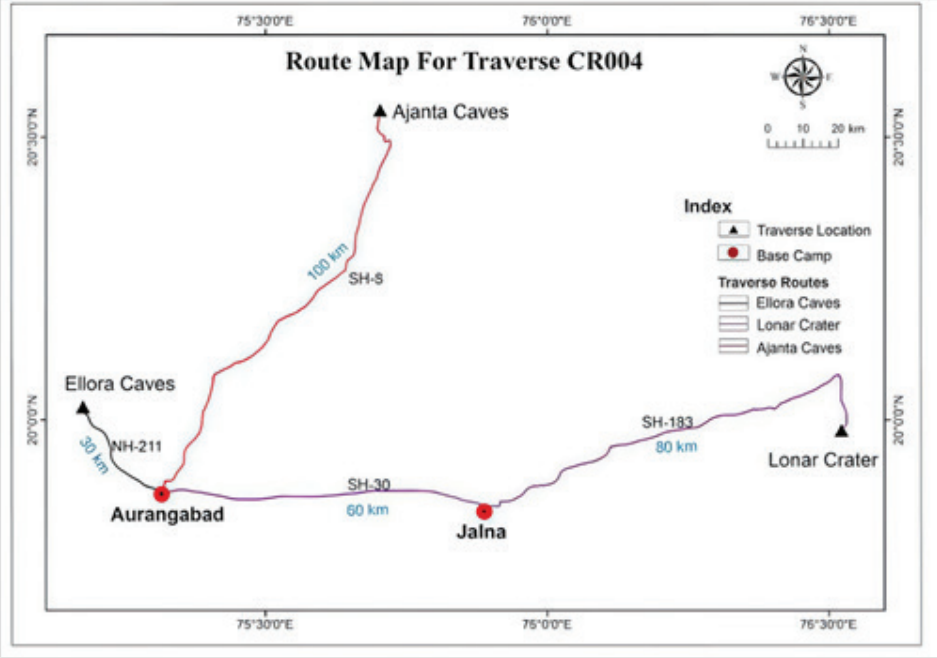


Figure 9: Route map to Lonar, Ajanta and Ellora from the base camps of Aurangabad and Jalna. Visitors will assemble and disperse from the Aurangabad airport, Maharashtra, India.

Date	Location	Activities	Scientific/Cultural Focus	Notes
Feb 4, 2027 (Thu)	Aurangabad Lonar	- Morning: Drive (~2–3 hrs, 140 km) to Lonar Crater - Afternoon: Orientation at crater rim - Evening: Walk around rim, initial mapping	**Geology of Lonar Crater:** ejecta blanket, rim structure, shock features, inner wall sequence	Stay at MTDC resort/ guesthouse in Lonar
Feb 5, 2027 (Fri)	Lonar Crater	- Morning: Geological survey - Afternoon: Ecological study of saline lake - Evening: Group discussion	**Later history of crater:** lake sediments, temple complex, discussion from eastern crater rim	Field gear essential: field notebooks, Topographic maps, sampling kits
Feb 6, 2027 (Sat)	Aurangabad Ajanta	- Morning: Drive (~2.5 hrs) to Ajanta - Afternoon: Fieldwork in Waghora river gorge - Evening: Return to Aurangabad	**Ajanta focus:** Deccan basalt flows exposed in Waghora gorge, study of cave geology and frescoes	Stay in Aurangabad

Feb 7, 2027 (Sun)	Aurangabad Ellora	- Morning: Visit Ellora Caves (Charanandri Hills) - Afternoon: Study flow sequence and structures - Evening: Wrap-up session & departure	**Ellora Focus:** Charanandri Hills basalt flow sequence and associated structures	Departure flights via Aurangabad

Travel Plan

Onward Flight: Lucknow - Aurangabad (via Delhi/Mumbai) on 03 February 2027 (Late Night) or 04 February 2027 (Early Morning)

Return Note: No return flight will be provided. Field trip concludes on 7 February 2027 at 5:00 PM in Aurangabad.

Geoheritage, UNESCO Sites, and Archaeological Context

The Lonar crater has several official recognitions. The Archaeological Survey of India (ASI) lists it as a National Monument under the Ancient Monuments and Archaeological Sites and Remains Act. The Geological Survey of India (GSI) has also declared it a National Geological Monument. In 1999, the Maharashtra government notified the area as a Wildlife Sanctuary under the Wildlife Protection Act. Later, in November 2020, Lonar Lake was included in the Ramsar list as a Wetland of International Importance (site no. 2453). Chandran et al. (2022) carried out a SWOT analysis. They suggested that the site has strong potential for nomination as a UNESCO Global Geopark, noting its proximity to the Ajanta and Ellora World Heritage Sites.

The Ajanta Caves lie about 100 km southwest of Lonar and were inscribed as a UNESCO World Heritage Site in 1983. They consist of 30 rock-cut Buddhist caves carved into a horseshoe-shaped basalt cliff along the Waghora River. The caves date from around the 2nd century BCE to the 6th century CE and are known for their early Indian mural paintings. The painted ceilings and walls depict Jataka tales, images of Buddhas, and courtly scenes in a naturalistic style that has influenced Buddhist art throughout Asia. The physical setting of the caves is significant for this excursion; the cliff face reveals individual basalt flow units of the Deccan Volcanic Province (DVP) in cross-section. This exposure allows visitors to see the same layered basalt stratigraphy at a natural scale, as evidenced by the tilted and deformed walls of the Lonar crater.

The Ellora Caves, located approximately 130 km southwest of Lonar, have been designated a UNESCO World Heritage Site since 1983. The site includes a group of 34 rock-cut caves belonging to three religious traditions: Buddhist (Caves 1–12), Hindu (Caves 13–29), and Jain (Caves 30–34). These were excavated in the Deccan basalt between the 6th and 11th

centuries CE. Among them, the Kailasa Temple (Cave 16) is especially notable as a large monolithic structure carved directly from the rock. It was carved entirely from a single mass of basalt by excavating downward and inward from the top of the cliff. This temple is particularly relevant to the field excursion as it illustrates the mechanical properties of Deccan basalt, including its hardness, fracture patterns, columnar jointing, and how different vesicularity levels within the rock respond to chiselling. The site offers both a visually stunning experience and valuable scientific insights.



Figure 10: (a) Panoramic view of the Ajanta Caves carved into the Waghora River gorge, showing the arcuate arrangement of rock-cut caves within horizontally layered Deccan basalt flows (Photo: Archaeological Survey of India). (b) The Ellora Caves, featuring the monolithic Kailasa Temple (Cave 16), were excavated from basaltic lava flows of the Deccan Traps (Photo: Leonid Andronov).

Several Hindu temples dating from the 11th to 13th century CE occupy the crater basin, built in the Hemadpanthi tradition using locally quarried Deccan basalt, assembled without mortar. The Daitya Sudan Temple, dedicated to Vishnu, is partly submerged when the lake level rises, providing a useful indicator of past water-level changes. The stone used in its construction also reflects the mechanical properties, fracture patterns, and weathering behaviour of Deccan basalt over several centuries. The crater was first scientifically identified by Newbold (1848) and received its first systematic geological description from Gilbert (1896). The lake is referenced in the Skanda Purana and Padma Purana, and the Ain-i-Akbari (c. 1600 CE) records commercial saltpetre production from the lake brine.



Figure 11: photographs of Lonar impact crater, Buldhana district, Maharashtra, India. (a) Panoramic view from the eastern crater rim showing the bowl-shaped morphology and the saline–alkaline crater lake occupying the crater floor. (b–e) Ancient temple structures were constructed within and along the crater rim. (Photographs by Gourab Dey)

Cuisine and Culture of Aurangabad

Maharashtra Aurangabad's cuisine is a rich fusion of Mughlai, Hyderabadi, and Maharashtrian traditions, while its culture reflects centuries of dynastic rule, architectural marvels, and vibrant festivals. Signature dishes like Naan Qalia and Aurangabadi Biryani embody its royal culinary heritage, and the city's cultural identity is deeply tied to monuments like Ajanta-Ellora caves and Bibi Ka Maqbara

Local Conveniences

The Civil Hospital in Lonar town (approximately 4 km from the crater entrance) handles routine emergencies. For surgery or intensive care, the District Civil Hospital, Buldhana city (approximately 70 km, 1-1.5 hours) is better equipped. For tertiary care, Nagpur is approximately 230 km (3.5-4 hours). Government ambulance: dial 108. Emergency contact cards will be distributed before Day 1.

If a passport is lost or stolen, file a First Information Report (FIR) at Lonar police station (approximately 3 km from the crater entrance) immediately; the FIR is required by all embassies for emergency travel documents. The organizing committee holds digital copies of registered participants' passport photographs; individuals should also store personal copies on a secure cloud service before departure. Embassy emergency contacts for all nationalities represented on the excursion will be in the participant information sheet.

Lonar town has a daily bazaar (6-10 AM) selling fresh produce and cooked food. Food is predominantly vegetarian Maharashtrian; non-vegetarian options are limited. Mobile network coverage (Jio, Airtel, BSNL) is adequate on the rim and in town, but patchy inside the crater. Group transport from Aurangabad Airport (IATA: IXU) to Lonar and back will be arranged by the organizing committee for all registered participants.

Conclusions

Lonar occupies a unique position in planetary geology. It is the only geomorphically intact, well-studied, simple impact crater in basaltic target rock on Earth, and the only one with an accessible post-impact lake sediment record. Those two properties, together, make the site worth protecting and studying. Five decades of research have produced a detailed picture of the shock metamorphic record, the ejecta stratigraphy, and the structural geology, while leaving four major problems unresolved: the crater age, the projectile identity, the completeness and chronology of the lake sediment record, and the systematic

characterization of the microbial community for astrobiology applications. None of these is intractable with the right combination of methods and fieldwork.

Lonar, Ajanta, and Ellora are geoheritage sites of global significance. Geotourism is central to this traverse: Lonar impresses with its circular crater and lake, while Ajanta and Ellora showcase India's archaeological marvels. At Ajanta and Ellora, participants will be accompanied by English-speaking ASI guides who explain the importance of these World Heritage Sites.

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The authors would like to thank the Maharashtra Forest Department and the management of the Lonar Wildlife Sanctuary for allowing access. They also appreciate the help from the Archaeological Survey of India, Aurangabad Circle, with the monument protection zone, and the Geological Survey of India, Nagpur, for logistical support and geological mapping data. This study synthesises published research on the Lonar impact crater spanning more than five decades and draws on contributions across geochronology (Jourdan et al., 2011; Maloof et al., 2010; Nakamura et al., 2014; Sengupta et al., 1997; Storzer & Koeberl, 2004), geomorphological characterisation (Fudali et al., 1980; Maloof et al., 2010), impact origin and shock metamorphism (Fredriksson et al., 1973; Kieffer et al., 1976; Nayak, 1972), geochemistry of target rocks and impactites (Morgan, 1978; Osae et al., 2005; Ray et al., 2017; Son & Koeberl, 2007; Stroube Jr et al., 1978), projectile characterisation (Das Gupta et al., 2017; Misra et al., 2009; Schulz et al., 2016), basement rock involvement (Chakrabarti & Basu, 2006; Chandran et al., 2021), ejecta characterisation (P. S. Kumar et al., 2014; Lakshmi & Kumar, 2020), structural geology (P. S. Kumar, 2005; Misra et al., 2010), magnetic and palaeomagnetic properties (Agarwal et al., 2016; Arif et al., 2012; Louzada et al., 2008; Rao & Bhalla, 1984; Weiss et al., 2010) geophysical sub-surface imaging (Kiik et al., 2020; V. Kumar & Rai, 2023; Kumari et al., 2024; Rajasekhar & Mishra, 2005; Sivaram et al., 2018), spectral studies (Wright et al., 2011), and geoheritage assessment (Chandran et al., 2022, 2023). We also thank the XXII INQUA Congress Local Organizing Committee for including this excursion in the program.

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Annexure

Field Excursion Guidelines: Do's and Don'ts

To ensure the safety of all participants and to promote responsible scientific field practices, all participants are requested to adhere to the following guidelines throughout the field excursions.

Keep a valid passport (for international participants) or a government-issued photo ID (for Indian participants) with you at all times during the field excursion.

Do's	Don'ts
1. Follow the instructions of the excursion leaders, coordinators, and local authorities at all times.	1. Do not collect rocks, fossils, archaeological artefacts, biological specimens, or any other materials without prior authorization.
2. Remain with the group and inform the excursion leader before leaving the designated route.	2. Do not damage, deface, or remove material from geological outcrops, caves, monuments, heritage structures, or other natural features.
3. Wear appropriate field attire, including sturdy closed-toe footwear, full-length trousers, a hat or cap, and weather-appropriate clothing.	3. Do not wander alone or separate from the excursion group without informing the field leaders.
4. Carry sufficient drinking water, personal medications, sunscreen, insect repellent, and other essential field supplies.	4. Do not climb unstable slopes, cliffs, rock formations, or enter hazardous areas unless specifically instructed or supervised.
5. Keep a valid photo identification and your excursion registration details with you during travel.	5. Do not swim or enter rivers, lakes, lagoons, or coastal waters unless expressly authorized by the excursion leaders.
6. Respect local customs, religious sites, cultural heritage, and private property.	6. Do not consume alcohol, recreational drugs, or engage in unsafe or irresponsible behaviour during the excursion.
7. Follow the Leave No Trace principles by carrying back all waste and helping to keep field sites clean.	7. Do not operate drones or other restricted equipment without obtaining the necessary permissions.
8. Use designated trails and approved observation areas to minimise environmental disturbance.	

9. Observe geological, ecological, archaeological, and cultural features carefully without causing any damage.

10. Record field observations systematically and collect samples only with prior permission from the excursion leaders and the relevant authorities.

11. Exercise caution near cliffs, riverbanks, caves, unstable slopes, road cuts, and other potentially hazardous terrain.

12. Respect wildlife by maintaining a safe distance from animals, birds, reptiles, insects, and their habitats.

13. Immediately report any illness, injury, emergency, or hazardous situation to the excursion organizers.

14. Be prepared for changing weather conditions and comply with all safety advisories issued by the excursion leaders.

8. Do not photograph restricted installations, sensitive locations, or local residents without prior permission.

9. Do not create excessive noise or disturb local communities, religious activities, wildlife, or natural habitats.

10. Do not leave valuables unattended or rely solely on mobile phone connectivity in remote areas.

11. Do not undertake any activity that may compromise your safety, the safety of fellow participants, or the conservation of the area's geological, ecological, archaeological, or cultural heritage.

Disclaimer

Participation in the field excursions is entirely at the participant's own risk. While the Organising Committee and excursion leaders will make every reasonable effort to ensure participant safety and provide appropriate guidance, they shall not be held responsible for any personal injury, illness, loss of personal belongings, property damage, delays, or unforeseen incidents arising during travel or field activities. Participants are expected to act responsibly, follow all instructions issued by the excursion leaders, and comply with applicable local laws and regulations throughout the excursion.













Scan for
Field Guide Book

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