



International Association of Geomorphologists  
Association Internationale des Géomorphologues



6 -11 November 2017 | Vigyan Bhawan, New Delhi, India

Organised by  
Indian Institute of Geomorphologists (IGI)

## A1: Geomorphological Field Guide Book on DECCAN INLAND

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New Delhi, 2017



**Published by:**

Indian Institute of Geomorphologists (IGI),  
Allahabad

**On the occasion of:**

9th International Conference on Geomorphology  
of the International Association of Geomorphologists (IAG),  
New Delhi (6-11 November, 2017)

**Citation:**

Joshi, Veena U. 2017. Geomorphological Field Guide Book on  
Deccan Inland (Edited by Amal Kar). Indian Institute of  
Geomorphologists, Allahabad.

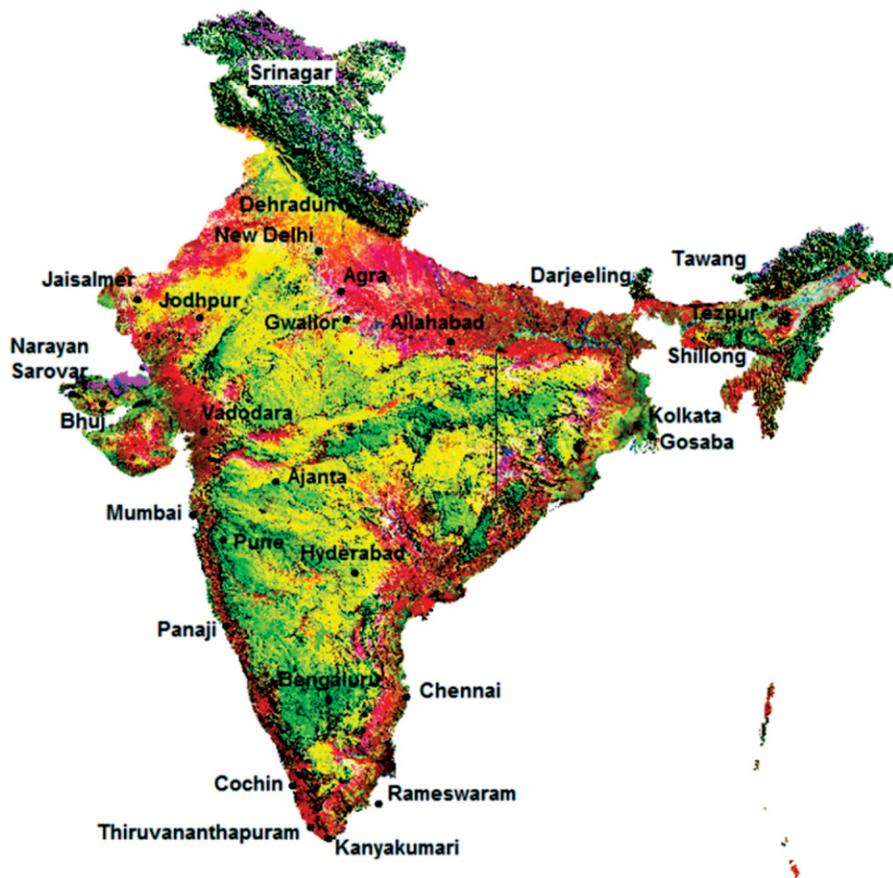


Fig. 1. Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the US Geological Survey site). Boundaries are approximate.

**Geomorphological Field Guide Book on  
Deccan Inland  
(30 October - 5 November, 2017)**

**Itinerary**

<b>Day</b>	<b>Date</b>	<b>Places from - to</b>	<b>Stay</b>
Day 1	30 October 2017	New Delhi to Pune by flight	Pune
Day 2	31 October 2017	Pune to Mahabaleshwar via Wai, Shendurjane & Panchgani Stop 1: Wai-Shendurjane Colluvial deposits Stop 2: Panchgani Tableland	Mahabaleshwar
Day 3	1 November 2017	Mahabaleshwar to Wilson Point, Pratapgarh and back Stop 3 & 4: Wilson Point, Western Ghats Escarpment Stop 5: Pratapgarh	Mahabaleshwar
Day 4	2 November 2017	Mahabaleshwar to Aurangabad via Morgaon Stop 6: Morgaon Alluvial Deposits	Aurangabad
Day 5	3 November 2017	Aurangabad to Lonar Crater and back Stop 7: Lonar Crater	Aurangabad
Day 6	4 November 2017	Aurangabad to Ajanta and back Stop 8: Ajanta Caves	Aurangabad
Day 7	5 November 2017	Aurangabad to New Delhi by morning flight	New Delhi



## A. THE DECCAN TRAP REGION: AN INTRODUCTION

The 'Deccan Inland' (also known as the Deccan Trap) is essentially a basaltic plateau within the Peninsular India, covering an area of about half a million square kilometres. The huge thickness of extruded basalt about 65 million years ago masked a pre-existing landscape, dominantly on granite-gneiss, and is intercalated with numerous ash beds. The western edge of this vast tract is marked by a ~1500-km long escarpment facing the Arabian Sea, called the Western Ghats, from where the plateau has a gentle eastward tilt, and is dissected by numerous streams of the Godavari and the Krishna River basins, which drain into the Bay of Bengal. The eastern edge of Deccan Trap is marked by a series of discontinuous hill ranges, called the Eastern Ghat. Occurring to the east of the Western Ghat escarpment, a large part of the Deccan Trap country falls within the rain-shadow zone of the South-west Monsoon (June to September), which is the main rainy season over most part of India. Deccan Trap area is dominated by a semi-arid climate, with a mean annual rainfall of 600-900 mm. The Western Ghat, though, receives copious rainfall of more than 2000 mm. The difference is reflected in the overall rugged topography of the plateau with a skeletal soil, sparse vegetation and a stony look vis-à-vis the lush green slopes of the Western Ghat. Deccan Trap occupies the whole of the state of Maharashtra and small parts of the neighboring states such as Saurashtra Region of Gujarat, Malwa and Mandla Region of Madhya Pradesh and small parts of Karnataka and Andhra Pradesh.

The tour will be entirely within the state of Maharashtra, where the mean summer temperature varies roughly from 30°C to 40°C, while the mean winter temperature varies from 10°C to 12°C, with wide spatio-temporal variation. Rainfall occurs between June and September and there is enormous variation in the amount across the state. The coastal areas receive above 7000 mm of rainfall annually at many stations, and on the plateau top, it is about 5500 mm annually. At Mahabaleshwar on the Western Ghat, the mean annual rainfall is 5761 mm. After one descends from the Ghat, Pune and Aurangabad receive about 700 mm rainfall annually. Further to the east, the central part of the state suffers from rain-shadow effect. A large part in the central Maharashtra has a semi-arid climate with a mean annual rainfall of 400 mm or less. As one proceeds eastward, the amount of rainfall increases again under the influence of Bay of Bengal. Nagpur receives about 1000 mm annually.

Basalt-derived soil, locally known as "Regur" or black cotton soil, characterizes the whole of Maharashtra state. In order to better appreciate the landscape of the Deccan Trap to be visited (Fig. 2), we first provide a brief geomorphological background of the terrain, as well as a short description of other aspects of the region, including people, their livelihood, major land uses, etc.

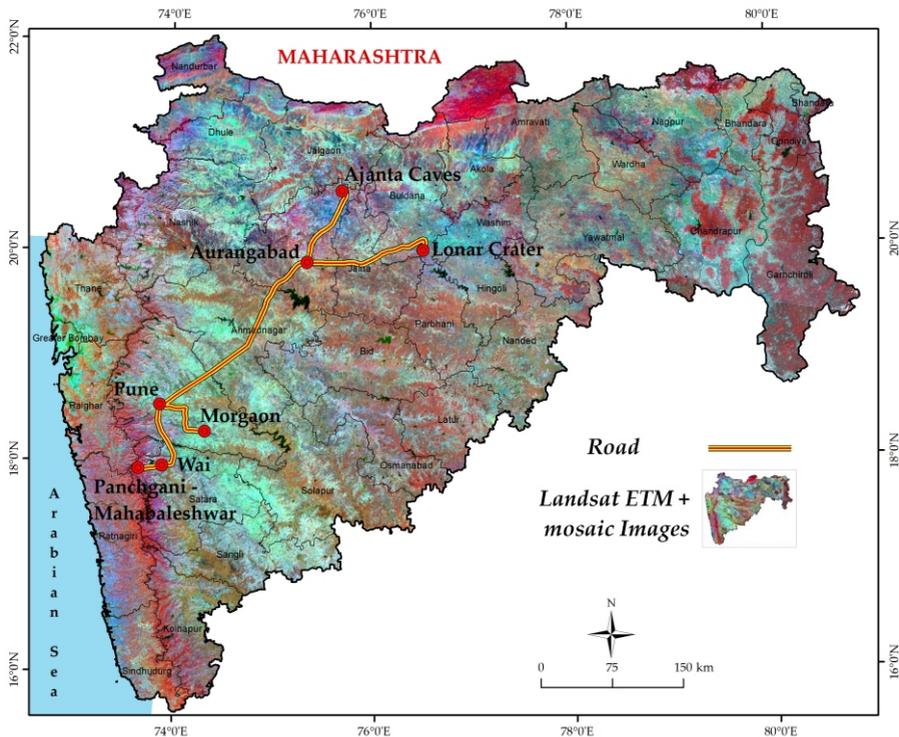


Fig. 2. Landsat ETM + Mosaic Images of the state of Maharashtra, showing the sites to be visited during the excursion and the routes to be taken.

## Geomorphological Background

Deccan Trap region is the third geologically important huge continental basalt province in the world besides Parana Province of Brazil and the Karoo Province of South Africa. The Trap region covers an area of about half a million square km and forms a major geomorphic and morpho-tectonic unit of the Indian Subcontinent.

The Deccan Trap basalts were erupted about 60-65 Ma ago during the separation of the Seychelles micro-continent from India (Widdowson and Mitchell, 1999). This rifting occurred during the northward movement of the Indian subcontinent as it passed over the Reunion Hotspot. On a regional scale, the traps are 3000 m thick. Based on the chemo-stratigraphic and palaeomagnetic studies it is divided into three sub-groups, the Kalsubai (oldest), the Lonavala and the Wai (youngest) formations (Beane et al., 1986; Devey and Lightfoot, 1986; Subbarao and Hopper, 1988; Mitchell and Widdowson, 1991; Subbarao et al., 1994; Subbarao et al., 2000). The older flows (Kalsubai) occur in the northern part around Nashik and the younger flows progressively overstep southwards. The youngest flows (Wai) are the most extensive and widespread. Early Tertiary laterites are developed on these younger flows and are almost absent on the older flows occurring in the northern part.

The western part of the Trappean landscape is marked by a huge, impressive erosional escarpment known as the Western Ghats or Sahyadris in India. Many of the rivers are allocthonous and occupy unusually large, misfit valleys. The river channels are deeply entrenched in bedrock or alluvium, and flood plains are almost nonexistent. Many of the channels display channel-in-channel morphology.

Floods occur during the active monsoon season, and especially during the rainstorms originating over the Arabian Sea or the Bay of Bengal. Very rarely, these flood events are regionally synchronous due to the large geographical area.

The most striking features of the Trappean landscape over the plateau top are stepped hills and ranges, wide box-shaped valleys and large gently-sloping denudational surfaces occurring on the main divides (Kale and Gupte 1986). Hill slopes and valley bottoms are featured by weathered basalt (locally known as murum), regolith, colluvium and black soils (vertisols). Alluvium is confined to narrow belts close to the river channels.

## Laterites

Laterite is the only widespread post-Trap and Tertiary geological formation occurring in the region. Laterites have been the subject of study for about 200 years since Buchanan introduced the term laterite in 1807 to describe Fe-rich material that gets hardened on exposure to air. Genetically, Trap laterites have been classified as 'primary' (bedrock-derived and in situ) and 'secondary' (transported and reworked, or detrital) laterites. On the basis of altitude and geomorphic situation these are also classified as 'high-level' (on the Ghat crest) and 'low-level' laterites (coastal) (Fox, 1923). The high level laterites occur in the Western Ghat zone on the highest peaks and form the highest topography in the southern part of the Trap region. Laterites have a gentle slope towards the east and southeast. Patches of laterites are also present in the semi-arid region, such as Khanapur and Jath. During the excursion, it is proposed to stop at few sites to appreciate the laterite beds and the lateritic landforms.

Coastal or low level laterites are developed over the Deccan Traps (Cretaceous-Eocene) in the north and over Archaean and Proterozoic rocks in the south (south Konkan, Goa and Karwar). There is enough evidence to suggest that not all the laterites in south Konkan and Goa are developed on bedrock. Some of them have formed due to the laterisation of alluvium also.

Low-level laterites form coastal plateau dissected by the west-flowing short streams that have deeply entrenched the laterites. These laterites of the coastal zone occur along a wide zone at the foot of the Ghat, but the escarpment section is devoid of this formation. The coastal laterites have a gentle seaward slope (Widdowson and Gunnell, 1999). Unlaterised hills rise above the lateritic surfaces, indicating that the process of laterization was confined to the low-lying plains.

Based on the ages of laterites, Widdowson and Gunnell (1999) proposed that these laterites had been formed much before the onset of monsoon climate over the Indian subcontinent (ca. 8 Ma) and thus were formed under a totally different climatic and perhaps hydro-geomorphic condition.

## Quaternary Alluvial Record

The current Trapean landscape is essentially erosional in nature, with near-absence of Tertiary and early Quaternary sediment records (Kale and Rajaguru, 1988). Late Quaternary deposits however occur in many river valleys that include alluvial deposits along the main rivers (Kale and Rajaguru, 1987), colluvial deposits in the foothill zones of the divides (Joshi and Kale, 1997) and calc tufa deposits on the valley sides (Pawar et al., 1988).

Alluvial deposits in the Deccan Trap region are modest in terms of lateral and vertical extent and are confined to a narrow belt along the river channels. A large number of radiometric dates indicate that for several thousand years, a succession of aggradational and excavational episodes followed one another in response to Quaternary climatic changes (Atkinson et al., 1990). Although spatially variable, the last major phase of aggradation was associated with the late Pleistocene aridity, and incision occurred in response to the early Holocene strengthening of the southwest monsoon (Kale and Rajaguru, 1987; Atkinson et al., 1990; Rajaguru et al., 1993). Alluvium and river terraces are less important elements of the Konkan landscape. Owing to their location, sea level changes have primarily determined the river behavior during the late Quaternary period (Kale and Rajaguru, 1988).

Archaeological and palaeontological studies indicate that during late Quaternary period, the upland region was characterized by tropical grasslands. Animals like cattle, horses, deer, elephants, ostrich, hippopotamus and rhinos roamed over the landscape. Stone Age artifacts are widespread in the upland region and indicate that the Early Man was present in the Deccan volcanic province since the Acheulian time.

### Socio-economic Aspects

As stated above, the field trip will be confined within the state of Maharashtra. Maharashtra occupies 307731 km<sup>2</sup> area, which is 9.84% of the total geographical area of the country. Its total population is about 112.4 million, with an average density of 365 persons per km<sup>2</sup>. It has a sex ratio of 925 females per 1000 males, which is lower than the national average, i.e., 940 females per 1000 males. Though the state reveals a lesser population density of 365 per km<sup>2</sup>, as compared to the national average of 382 per km<sup>2</sup>, there is wide disparity in its distribution across the state. There are 378 urban centers and 41000 villages within the state. Mumbai and Thane districts have densities of 20980 and 1157 persons per km<sup>2</sup>, respectively, while Ahamadnagar district has 266 persons per km<sup>2</sup>. Pune and Aurangabd districts, where most of the tour sites are located, have population density of 608 and 366 per km<sup>2</sup>, respectively. According to the 2011 census, literacy rate of the state is 83.2%. Female literacy is 75.48%, while male literacy is 89.82%.

Agriculture is the main occupation in the state in spite of it being the most industrialized state in the country. Like any other part of the country, agriculture is heavily dependent on the vagaries of the summer monsoon. The other major constraint is an overall shallowness of the soil. Since basalt-derived vertisol soil, locally known as "Regur" or black cotton soil, is dominant, the soil is clayey, rich in iron but poor in nitrogen.

It is suitable for cotton cultivation. Principal crops are rice, jowar (coarse millet) and bajra (pearl millet). Wheat, pulses, onions and vegetables also constitute main crops of the region. Sugarcane, cotton and turmeric are the main cash crops, while several oilseed crops, including sunflower, groundnut and soybean, are also grown extensively. The state is famous for Alphonso mango, which is exported in large quantities. Banana, grape and orange are also important fruits of the state, and fetch the state considerable revenue.

Large parts of Deccan Trap are characterized by a shallow rocky terrain, with poor natural vegetation cover. Consequently, open scrubs abound. Forests occupy only 17% area of Maharashtra state, confined mostly to the Western Ghats and the eastern hill ranges, while the plateau tops are dominated by open scrub jungle. Mumbai is the capital of the state which is the largest city and the financial capital of the nation. This is one of the most developed and the wealthiest of the states in India, contributing 25% of the country's industrial output and 23.2% of its GDP.

Maharashtra is India's leading industrial state. Nearly 46% of the Gross State Domestic Products is offered by the industrial sector. Mumbai Metropolitan Region (MMR) has historically been the most industrialized area in the state, followed by Pune Metropolitan Area, Nashik, Aurangabad and Nagpur. The state has had a long history in textiles, with the state capital Mumbai being one of the original homes of India's textile mills. The six important industries in the state are cotton textiles, chemicals, machinery, electrical appliances, transport and metallurgy. Pune is one of the largest automobile hubs in the country. Sugar industry has made considerable progress, especially in the co-operative sector.

Among the most populous first-level administrative country subdivisions in the world, Maharashtra stands second in the list. Within India, the level of urbanization is the highest in Maharashtra (45.23%), which is well above the nation's average (31.16%). Mumbai, with a population of 18.4 million, is the largest metropolis in India. Next to Mumbai, the other large cities in the state are Pune (5 million), Nagpur, Pimpri-Chinchwad, Nashik, Navi Mumbai, Dhule, Aurangabad, Parbhani, Akola, Kolhapur, Thane, Solapur, Amravati, Nanded and Latur.

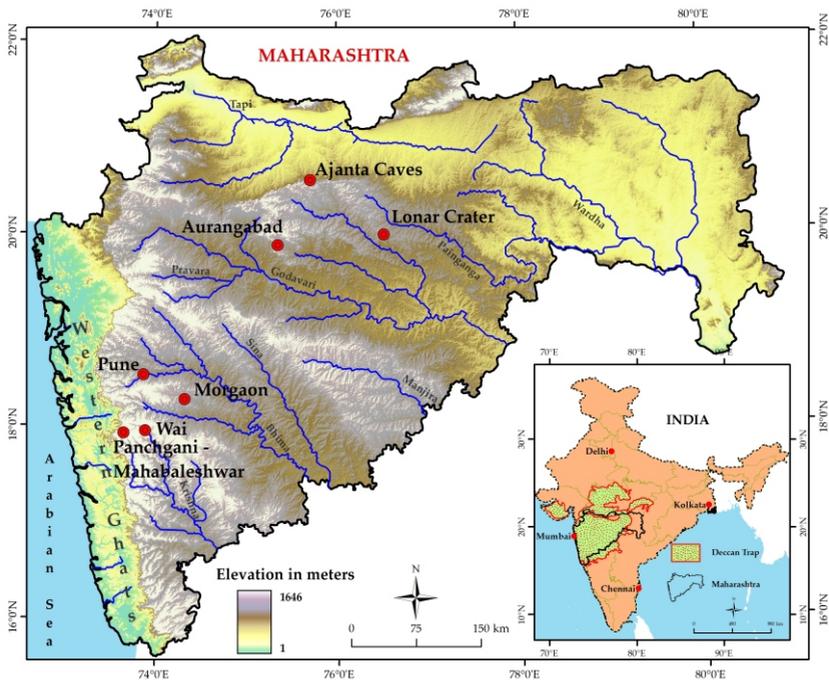
## B. DESCRIPTION OF THE FIELD SITES

**Day 1: 30/10/2017**

**Delhi to Pune by Flight**

**Stay at Pune.**

The first day of the tour will be spent on discussing the routes of the field trip, the logistics, and the general characteristics of the area. The field trip will begin from Pune, and will conclude at Aurangabad (near Ajanta caves), spanning a distance of 875 km. During this period it is proposed to take several transects across the DeccanTrap to observe some of the major landforms as well as some typical geomorphic features on basaltic terrain, and discuss their salient characteristics. An idea of the broad topographic variability in the region and the major streams flowing through it could be had from Fig. 3.



*Fig. 3.*

*A DEM of Maharashtra state, showing the broad landscape variability in Deccan Trap Region, as well as the major stops during the excursion (Inset Map of India with the state boundary and the current Deccan Trap boundary).*

**Day 2: 31/10/2017****Pune to Panchgani and Mahabaleshwar via Wai and Sendurjane (125 km; all distances are from Pune, unless specified)****Stay at Mahabaleshwar.**

It is proposed to begin the excursion with a visit to the south-western part of the Deccan Trap terrain, especially to appreciate landscape evolution along the Western Ghat area within the Krishna River basin. The road from Pune to Wai passes through a rugged and almost desolate basaltic tableland with shallow soils, and dissected by numerous ephemeral streams that join the Bhima River, a major tributary of the Krishna River.

**Stop 1: Wai-Sendurjane Colluvial Deposits (88 km)**

This site provides the view of a typical colluvial deposit occurring along the foot of the hill slopes in this upland area, and forming the interfluves of the numerous stream catchments. The site is located near Sendurjane village on the northern side of the Surul-Wai-Mahabaleshwar road. Currently the deposits are deeply disturbed by various activities of human that includes stone quarrying, agriculture and construction.

Geographically, the site falls in the source region of the Krishna River which is a major river of Deccan Peninsula. The colluvial deposits drape the foothills of one of the offshoots of the northern divide of the Krishna River. Although the site is close to the Western Ghat Escarpment, it falls in the rain shadow zone and receives about 800 m rainfall as compared to 6000 m in the adjacent Ghat Zone.

The hill range behind the deposit has an average elevation of 1000 m above msl, with the highest elevation reaching 1184 m above msl. The colluvium-draped pediment extends for a distance of about one km. The average elevation of the pediment is about 750 m above msl. The local relief ranges from a few tens of meters to more than 425 m. The deposits overlie the rocky pediment on basalt, and are thinner near the foot of the hills. The thickness reaches a maximum of >5 m in the middle part, and becomes thinner again downslope within a distance of less than one km to merge with the black soil/alluvium. The areal extent of the deposits at this site is approximately 6 km<sup>2</sup>.

A dense network of gullies has dissected the deposits. These gullies are sinuous and generally v-shaped. Inter-gully areas are large, flat and smooth. Many gullies are incised through the colluvium and into the underlying basalt bedrock, which is highly weathered. Active gully-head erosion is witnessed in the form of knicks. The higher order gullies/streams meet the main river Krishna after traversing a distance of approximately 4 km.

Texturally, the colluvial sediments are dominated by coarse silts (4-5  $\Phi$ ) and the mean phi value is 4.2 (Joshi and Kale, 1997). Skewness is positive and indicates excess amount of finer fractions. Sorting is poor. SEM studies of a few grains indicate v-notches, chatter marks, high surface relief, considerable etching and precipitation on the grains. All these features provide evidence for the role of fluvial activity, short-distance sediment transport and diagenesis. Smectite is the dominant clay mineral in these sediments (Joshi and Kale, 1997).

All through the deposits, calcrete occurs profusely ( $\text{CaCO}_3$  range: 12-70%). The Si/Sesquioxide ratio ranges from 1.0 to 1.5 as compared to 2.1 for fresh basalt rock, and suggests weathering of the deposit (Joshi and Kale, 1997).

As could be observed, the surrounding landscape is rarely in pristine, natural state, and is disturbed by human activities in varying degrees. The impacts of these activities can be seen in the form of numerous cuts and fills, as well as over-burdens. We shall, however, stop at one or two naturally cut exposures in a gully to observe a few litho-sections. The sections reveal that calcrete-rich fissured clays occur at the base. Several gravelly units of varying thickness overlie this unit. Evidence of scour and fill are present in the middle level. Finer but gravelly units occur at the top. Mud balls could be seen at some places. Upward fining sequence can be detected within some units. Calcium carbonate is conspicuously present in all the units.

The presence of clays at the base suggests deposition of fines in a shallow basin environment or in a wetland condition under semi-arid climate. The overlying gravels suggest that the deposition of the fines was followed by a sudden flux of coarse gravel by short ephemeral streams. Frequent alterations of sandy/silty facies with coarse gravel suggest the erratic nature of the depositing medium. The scour and fills are clear indications of dominant fluvial activities bringing the sediments down the hill slopes. The unsorted nature of the gravels and rapid changes in the facies indicate highly variable runoff and discharge conditions at the time of deposition. The presence of mud balls suggests that the deposition was not continuous but was interrupted by short periods of erosion and cutting. Calcrete formation post-dates the deposits. A single U/Th date on a calcium carbonate nodule from a gully yielded an age of 75 ka, indicating that these are relict deposits and that the bodies of colluvial silts can persist for tens of thousands of years in this area (Atkinson et al., 1990). This and a few more dates from other colluvial sites imply that the deposits might have been laid down during a major glacial aridity. Evidently, the materials had to be formed through weathering of hill slopes under a wetter climate (perhaps last interglacial). Strengthening of the southwest monsoon during the early Holocene period (Kale and Rajaguru, 1987) perhaps stopped any further addition to the deposits.

Increased runoff and consequent gully formation led to erosion and remobilization of the sediments. Although currently in a disturbed state, the flat and large inter-gully areas suggest that the deposits are being removed very slowly.

From this stop, we proceed towards Panchgani-Mahabaleshwar via Wai town. We cross the Krishna River near Wai, and then start ascending the Pasarni Ghat, which offers a breathtaking view of the Krishna Valley. The scenery begins to change dramatically from a tree-less, dry rocky terrain to greener lateritic terrain. We reach the next stop, Panchgani (102 km from Pune).

### **Stop 2: Panchgani Tableland (102 km)**

Panchgani is one of the most visited tourist destinations in Maharashtra state. The settlement here was founded by the British in the mid-19th Century, and developed as a popular health resort. The most prominent geomorphic features here are the isolated, laterite-capped tablelands and the mesas, which rise abruptly from the surrounding plains. The special identity of Panchgani laterite is its flatness, vastness and simplicity (Kale, 2014). Thick laterite crust (ferricreted duricrust) acts as the cap rock and protects the underlying Deccan Trap basalt flows from surface erosion. The elevation of the mesas varies between 1300 m and 1350 m above msl. The edges are sharp, with vertical cliffs of 5 to 25 m height. Five such mesas can be noticed at Panchgani, and hence the name “Panchgani” (i.e., five entities). The mesas are separated by valleys of the Bavdhan River and the Kudali River. The local relief is generally less than 550 m. Panchgani falls in the rain shadow zone of the Western Ghats, but receives an average annual rainfall of 1700 mm. At Mahabaleshwar, the rainfall exceeds 6200 mm.

The mesa tops have negligible relief and have a general slope toward the south and southeast. A number of pseudo-karstic features, such as large depressions that are filled with wind-blown sediments, sinkholes, natural bridges and caves, are associated with the indurated laterite crust (Kale, 2000). Their development is favoured by the occurrence of an impervious, clay-rich lithomargic horizon below the vesicular and porous laterite crust. All along the cliff margins, large blocks have been peeled off from the main tableland, providing an example of mechanical disintegration of the hard indurated crust on the top. The disintegration is caused by undermining at the base of the indurated layer, followed by caving. Consequently, as soon as the laterite cap is stripped, the saprolite horizon gets eroded, giving rise to smoother and gentler slopes (Kale, 2014).

### Duricrust distribution: Dissected high plain or inversion of relief?

The present distribution of high-level duricrust on Western Ghats has been under speculation for quite some time. The views can be grouped under two schools of thought: (1) a 'high-level model', and (b) an 'inversion of relief model' (Fig. 4).

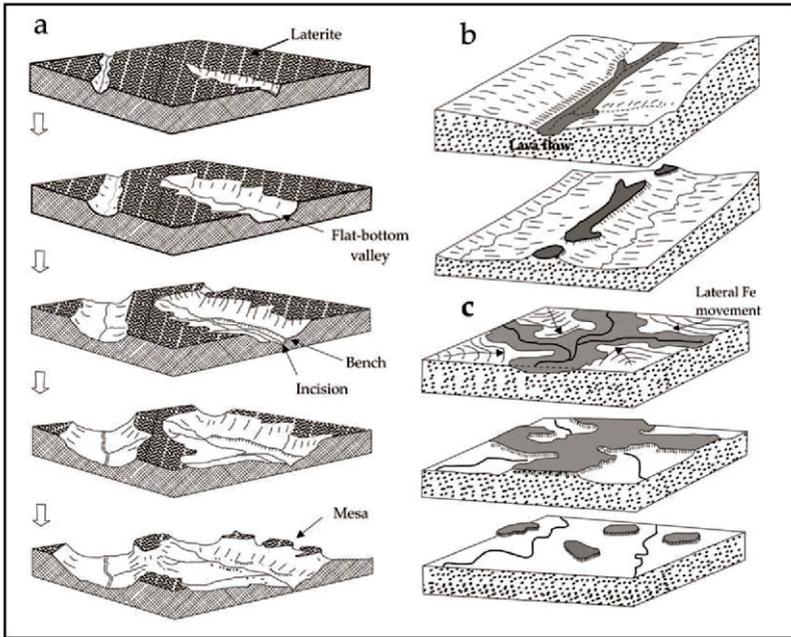


Fig. 4.

(a) *High-level model: Formation of a vast and continuous blanket of laterite, and then erosional destruction of most of it to leave the ferricretes at mesa tops (Kale, 2000). The author suggested that the roughly-accordant ferricrete mesas around Mahabaleshwar were the remnants of a once-continuous (but now largely destroyed) ferricrete blanket on the lava pile.*

(b) *Inversion of relief model-1: A lava flow fills a valley; original streams are shown as dashed lines. New lateral streams form on each side of the lava flow, and down-cutting and valley widening by them leave a lava mesa (Ollier, 1988).*

(c) *Inversion of relief model-2: The floor and lower slopes of a river valley are partly covered with alluvium and colluvium, which are cemented to form ferricrete. Later, erosion attacks neighbouring weathered rock and the resistant ferricrete forms mesas (Pain and Ollier, 1995; Ollier and Sheth, 2008).*

It has long been suggested that these laterites have developed from the topmost exposed flows of the Deccan Trap across a vast plain (Widdowson and Cox, 1996; Widdowson, 1997; Kale, 2002). This acted as a continuous blanket over the basalt topography, but subaerial denudation since then has left the remnants of the laterite-capped plains as the ferricreted mesa tops. The above authors suggested that the roughly accordant ferricrete mesas around Mahabaleshwar were the remnants of a once-continuous (but now largely destroyed) ferricrete blanket on the lava pile. Palaeo-magnetic considerations suggest the late Cretaceous – early Palaeogene as the most likely age of these laterites (Schmidt et al., 1983). In Panchgani area, the laterite-capped mesas are found on interfluves and occur on both sides of the river valley almost at the same elevation. The present-day laterite distribution and the broadly accordant heights of the hills suggest that the mesas are erosional remnants of an earlier vast laterized surface over a large part of Deccan Trap – several tens of kilometres from Mahabaleshwar (which is located at a higher level in the west) in all directions. Subsequently the laterized surface was breached, first by headward erosion of the streams and then by vertical incision, followed by lateral extension of valleys. This created an uneven surface where laterite-capped outliers stood higher above the surrounding areas as mesas and tablelands.

Pain and Ollier (1995) and Ollier and Sheth (2008) suggested the formation of duricrusts along drainage lines, followed by inversion of relief. They suggest that the ferricrete caps forming the present summits of the duricrusted mesas today were formed in a river valley system, and these original valleys have since been inverted as the surrounding softer weathered basalts have been eroded to a greater extent. The chief line of evidence in support of this relief inversion hypothesis is the thin shoe-strings-like appearance of the outcrop mesas, occurring in a dendritic fashion that does not resemble the pattern of a dissected plateau surface. The ‘strings’ appear to have a branching pattern, like the dendritic pattern of a simple river system. On this basis, Ollier and Sheth (2008) suggested that these mesas represent an inverted palaeo-river valley system. They further suggested that the ferricretes never formed a continuous blanket but were formed in a palaeo-river system, with interfluves of the basalts. Subsequent erosion and relief inversion produced the present landscape. In this scenario, the duricrusts no longer marks the original top of the Deccan basalt pile, but the duricrusted floor of a palaeo-river, named by the authors as the Bamnoli palaeo-river (Ollier and Sheth, 2008).

It is proposed to observe various stages of plateau consumption along the cliff margins over the main Panchgani Tableland. Some of the pseudo-karstic forms, like the large shallow depressions filled with wind-blown sediments, and with overhangs (alcoves), as well as the caves and natural bridges will also be visited.

**Day 3: 01/11/2017****Field visit to Mahabaleshwar Plateau (125 km) and back  
Stay at Mahabaleshwar.**

Mahabaleshwar area is one of the best-studied areas in the Deccan Trap region, especially for flow-by-flow chemical stratigraphy of more than 2000 m thick lava flows (Subbarao, et al., 2000). The volcanic pile in the area belongs to the Wai Sub-group. The flows are dominated by simple flows and are characterized by multiple reddish weathered layers, known as the red boles.

Large, dissected laterite-capped mesas characterize the plateau. Geochemical fingerprinting of the Mahabaleshwar and Panchgani laterites and other laterites capping the adjacent isolated mesas strongly suggest that the laterites have developed on the topmost sequence of the Wai sub-group (Subbarao et al., 2000). This also implies that the laterites might have developed over the lava surface immediately after the end of the Deccan Trap volcanic activity during late Cretaceous-Early Tertiary times (Widdowson and Cox, 1996). Palaeo-magnetic ages on these laterites (Schmidt et al., 1983) also support this inference.

**Stop 3: Wilson Point (1 km from Mahabaleshwar Town)**

Wilson Point (1438 m above msl) is the highest point in southwest Deccan. It provides an excellent view of the Mahabaleshwar Plateau, one of the few high-plateaus perched on the Sahyadri (Western Ghats). The average monsoon rainfall in the area is about 6000 mm.

The octopus-shaped plateau, with an elevation of 1220 to 1430 m above msl, occurs at the highest elevation in the southern Deccan Trap region (Kale, 2000), and has patches of thick indurated laterites. The largest patch is observed at Wilson Point where the elevation rises to 1400 m above msl. Elsewhere the plateau reveals stripped surfaces (Dikshit and Wirthmann, 1992), underlain by weathered basalt. Unlike the Panchgani laterites, the laterites in Mahabaleshwar do not form mesas or tablelands because the area surrounding the laterite patches has not been deeply dissected and lowered by fluvial erosion (Kale, 2000).

The Mahabaleshwar Plateau has a radial drainage pattern. In the north, the wide, box-shaped Krishna Valley, drained by misfit Krishna River, borders the plateau. The southwestward draining Venna River originates on the plateau and crosses the Lingmala Falls (40 m) before descending down into a narrow v-shaped valley. Other rivers, like the Koyna and the Solshi, rise on the margins of the plateau and flow in a southeasterly direction. The Koyna valley marks the western limit of the plateau. A major fort, the Pratapgarh Fort, is located on an outlier on the western divide of the

Koyna valley and overlooks the coastal lowland of Konkan. River Savitri takes off from an area close to Arthur's Seat and flows westward to the Arabian Sea.

The octopus-like shape of the plateau suggests that it has undergone extensive dissection by headward erosion of the rivers and broadening of the valleys. The tentacle-like ridges are narrow, with elongated spurs or interfluves between the river valleys.

Table 1 shows the chemical composition of the Mahabaleshwar basalts, red boles and laterites at Wilson Point. It reveals a higher concentration of the major elements, such as Fe and Al, and concomitant decrease in silica. The data also indicates a depletion of mobile elements like Ca, Na, Mg, K, Sr, etc.

Patches of laterites also occur to the north of Krishna valley, more or less at the same elevation. This concordance suggests that the Mahabaleshwar Plateau surface with a thick laterite cover was originally much more extensive, and has been subsequently dissected by stream erosion from all the sides. It represents a post-eruptive palaeo-surface that certainly extended beyond Panchgani. The present valleys of the Krishna, the Venna, the Koyna and the Solshi are younger than the laterites as well as the laterised surface that formed on the top of the Mahabaleshwar Plateau.

*Table 1: Chemical composition of the Mahabaleshwar basalts, laterites and red boles*

Element (wt %)	Basalts	MAP 059/ MAP 060	Red boles
SiO <sub>2</sub>	45.9-50.6	30.83 /19.55	43.86
Al <sub>2</sub> O <sub>3</sub>	13.0-15.22	27.1 /16.02	12.70
TiO <sub>2</sub>	1.04-3.02	4.493 /1.27	1.97
FeO / Fe <sub>2</sub> O <sub>3</sub>	4.23-8.24	27.81 /58.44	15.11
MnO	0.09-0.3	0.226 /0.02	0.15
CaO	8.3-10.6	0.34 /0.28	4.57
MgO	4.65-6.74	1.05 /0.72	4.18
K <sub>2</sub> O	0.14-0.81	0.15/0.02	0.45
Na <sub>2</sub> O	1.97-3.58	0.29 / 0.27	0.33
P <sub>2</sub> O <sub>5</sub>	0.08-0.41	0.235 /0.139	0.13
REE (ppm)			
Ni	74-138	252 /15	86
Cr	–	390 /4063	96
Sc	–	47 /45	26
V	–	724 /458	231
Ba	58-148	728 /27	79
Rb	3-37	8/0	14
Sr	158-242	23/6	60
Zr	87-235	247/101	191
Y	27-48	59/12	41
Nb	4-21	25/9	14
Ga	–	49/30	–
Cu	91-254	446/290	339
Zn	17-111	215/92	81

Source: Najafi et al. (1981), K.V Subbarao (Personal communication), Wilkins et al. (1994), Widdowson and Gunnell (1999), Kale and Joshi (2002).

#### **Stop 4: Arthur's Seat on the Western Ghat Escarpment (12 km from Mahabaleshwar)**

At Arthur's Seat, the western edge of the Mahabaleshwar Plateau is delineated by the Great Escarpment of the Western Ghats. At places the scarp has a sheer drop of several hundred meters to about a km, and is embayed. The sinuous nature of the scarp, the deeply entrenched valley heads, the elongated offshoots towards the west and the occurrence of the beheaded valley of the Krishna River suggest that the escarpment has receded eastward from an earlier westward position (Kale, 2000). In other words, the present escarpment is an erosional feature. Most of the short and deep west-flowing streams have worked backward and have cut deeply into the Ghat escarpment, forming embayment. This has occasionally given rise to the phenomenon of river capture. One such capture has been identified to the south of Mahabaleshwar, involving a lower order tributary of the Koyna River (Anantapadmanabhan, 1972).

The eastward draining Krishna River has its source on the Western Ghat's margin, just on the northern side of the Arthur's Seat. The valley is much too wide for the existing catchment area and the back wall is missing. The river presumably did not start at the place where the present source appears to lie, but originated much further west. The present river seems to have lost its headwater, and thus is beheaded. The beheading is due to the recession of the Ghat scarp (Radhakrishna, 1965). Estimates using present valley width and length indicate that the beheaded section is about 15 km (Kale, 2000). Such anomalous occurrences of wide, box-shaped valleys, 'hanging' in the escarpment of the Western Ghats have also been observed in several other Trap rivers (Newbold, 1844).

#### **Origin of the Ghat Escarpment**

The origin of the Western Ghat scarp has been a matter of considerable debate for a very long time. Although Oldham (1893) thought that the present scarp was a dead-sea cliff, many other researchers believed that the Western Ghat scarp was initiated as a fault-scarp during the Paleocene (Pascoe, 1950; Power, 1993). Numerous recent studies, on the other hand, have not been able to find any evidence of large-scale faulting in the vicinity of the present coastline and /or scarp line (Ollier and Power, 1985; Widdowson, 1997). The most popular view now is that the present escarpment might have originated due to the retreat of a continental edge that was earlier formed by rifting during the late Cretaceous period (Subrahmayya, 1887; Radhakrishna, 1991; Widdowson and Gunnell, 1999).

Since many passive continental margins reveal similar geographic situations, several workers have recognized the importance of the existence of divide asymmetry in the initial stages to account for the subsequent geomorphic evolution and recession of

the great escarpments (Kale, 2000). Several models have been suggested to explain the evolution of continental margins with great escarpments, two of which appear to be better suited to the case of Western Ghat escarpment (Kale, 2000). These are as follows.

In the first model, the initial west-facing steep slope was created by rifting or faulting along the western margin of the Indian peninsular. Aggressive headward erosion by the westward-draining rivers caused the valley heads to cut deeply into the structural escarpment. Subsequently, the valleys coalesced by back-wasting of the valley sides and the elongated spurs were destroyed, leading to the net retreat of the escarpment.

In the second model (after Ollier, 1982) tectonic uplift (in response to isostatic adjustment) warped the pre-existing surface (lateritized). The up-warping of the lava flows created an asymmetrical divide with gentle slope to the east and steeper slope to the west. Following the law of unequal slopes, the west-facing steeper slope was eroded and dissected more vigorously by the streams than the gentler eastward slope. The rapid erosion created deep valleys and gorges. The elongated spurs and interflues between the valleys and gorges were eventually eroded and the valleys coalesced to create the Western Ghat escarpment and the coastal plain.

Since the Ghat has been carved out of the trap flows, it is most likely that the Ghat scarp is younger than the Traps, and might have been in the process of evolution since the early Tertiary. This observation is also supported by the occurrence of early Eocene deposits offshore. However, the exact age and position of the initial scarp is unknown. Whatever the age and position, the palaeo-magnetic age of the Konkan laterites suggests that by late Tertiary the Ghat scarp had receded by several tens of km inland.

#### **Stop 5: Pratapgarh Fort (25 km from Mahabaleshwar)**

Pratapgarh Fort is situated at an elevation of 1080 m above msl, on the western divide of the Koyana River. Chhatrapati Shivaji, the great Maratha chieftain, built it in 1656. At this fort, he killed the Bijapur General Afzal Khan by embracing him with tiger claws. The fort has a large gate, double walls and steps from the main gate for entry to the Bhavani Temple.

The top of the fort provides an impressive view of the Western Ghat Escarpment, the coastal lowland (Konkan) and the Mahabaleshwar Plateau. A statue of Shivaji has been erected here.

**Day 4: 02/11/2017**

**Mahabaleshwar to Morgaon and then to Aurangabad**

**Stay at Aurangabad.**

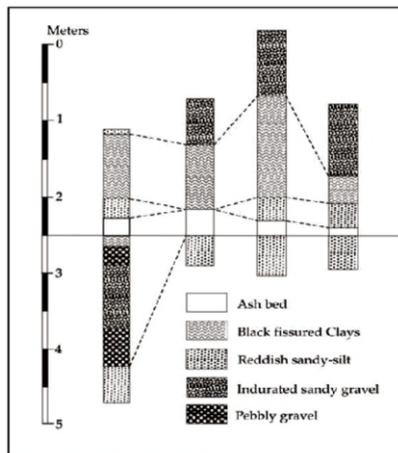
### **Stop 6: Morgaon Alluvial Deposits (80 Km)**

This site is located on a major denudational surface of about 750 m above msl in the interfluvies of the Mula-Mutha-Bhima Rivers in the north and the Nira River in the south. The site provides typical characteristics of the late Quaternary alluvium in this upland region (*Fig. 5*). The deposits belong to the “Upper Bhima Formation” (Kale and Rajaguru, 1987; Rajaguru et al., 1993).

The site is on the bank of the Karha River. The river originates in the rain-shadow zone of the Ghat and for most part of its course the river flows through a semi-arid terrain (rainfall less than 550 mm). The river is the northern tributary of the Nira River, which is the southern-most tributary of the Bhima River.

The most interesting feature of this site is the Toba Volcanic Ash (Kale et al., 1993), which occurs in the Quaternary alluvial deposits and forms a marker horizon. The best exposures of the alluvium and the ash bed are seen downstream of the Morgaon-Supa Bridge, along the channel of the Karha River. Presently, the channel is incised into its own deposits. The deposits have also been extensively dissected by bank gullies.

The alluvial sequence at Morgaon consists predominantly of calcareous black fissured clays, with a number of gravel lenses (indurated or non-indurated), often overlying the ash bed. The ash is underlain by calcrete-rich reddish sandy-silts or old gravel. The deposits reflect different styles of sedimentation and indicate noteworthy changes in the hydrodynamic conditions in the past. Bedrock is exposed at a number of places along the channel. Coarse to fine grained sandstone and conglomerates predominantly occur on the left bank. Within these sediments, large-scale tabular cross-bedding, horizontal parallel bedding and ripple, as well as parallel and convolute laminations are noticed, which indicate their deposition by a meandering river. A generalized section across the alluvial deposits is given in *Fig 4* and the characteristics of the major sedimentary units are described in *Table 2*.



*Fig. 5.*

*A generalized section across the alluvial deposits at Morgaon.*

**Table 2: Major Quaternary lithounits exposed on the bank of the Karha River at Morgaon**

Litho-unit	Thickness (m)	Dominant texture	Characteristics
Holocene flood deposits	0.5-1.0	Sandy-silt	Dark-brown in color, devoid of calcrete; recent over-bank deposits
Younger sandy gravels	0.25-1.50	Sand and gravel	Unsorted gravels, containing reworked calcrete nodules, microliths, mollusk and ostrich eggshell (dated to 26-22 ka) occur above the black fissured clays or in some cases are inter-bedded with the clays. The deposits imply a semi-arid to arid climate
Indurated gravelly sandstone/ conglomerate	2-4	Sand and gravel	Occurs particularly on left bank; sedimentary structures suggest meandering; U/Th date on cement is 40 ka; (OIS3)
Black fissured clays	2-4	Silt and clay	Rich in calcretes; dominated by montmorillonite clay; deposits of semi-arid wetland, drained by sinuous streams; gravel lenses are present
Ash bed	0.2-0.5	Silt size	Light buff to creamy white; highly friable; contacts with units above and below are well defined; similar to Bori Tephra (c. 74 ka); often below fissured clays and above reddish sandy-salt/gravel
Reddish sandy- silt	1-2	Sand and silt	Rich in calcretes and fossil fragments; dominated by montmorillonite clays
Pre-ash gravel	1-2	Pebbly-cobbly	Sometimes overlain by ash bed; calcrete pebbles absent
Bouldery - Cobbly conglomerate	5-6	Cobbly-bouldery	Rounded boulder, cobble, gravel; about 400 m away from modern channel; thick weathering rind indicates antiquity of deposits; couplets of sand and silt at the top

Source: Atkinson et al. (1990), Sheilla Mishra (personal communication), Kale and Joshi, (2002).

### Age of the Volcanic Ash

The Morgaon Ash is similar to the Bori Tephra, occurring on the bank of the Kukadi River which is to the northeast of Pune. Ar-Ar, K-Ar, Fission Track and TL ages of the ash from Bori range from 23 ka to more than 1 Ma (Korisettar et al., 1983; Horn et al., 1993; Mishra et al., 1995). Presently, the ash is believed to be about 74 ka old because the trace element chemistry of the Bori Tephra exactly matches with the youngest Toba Tephra (Acharyya and Basu, 1993; Westgate et al., 1998). Further, considering the thickness of the overlying sediments, the thickness of the ash unit, the C14 ages of the youngest gravels (22-25 ka) covering the top of the alluvial deposits, and the slight degree of weathering of the ash bed and weathering rinds of gravels overlying and underlying the ash bed, it appears that the tephra at Morgaon/Bori ash is not very old. The 74 ka Toba event has been identified as one of the mega-volcanic events in the geological record. Toba ash is an isochronous stratigraphic horizon, also directly correlated with the Arabian Sea and the Greenland Records. This suggests that the latest Toba event (74 ka) was most widespread and is clearly identifiable in the marine and terrestrial records. This, along with the simple sedimentological fact that most recent alluvial records and ash deposits are likely to be ubiquitous and best preserved, suggests that Morgaon/Bori Ash is Younger Toba Tuff, deposited at about 74 ka. The ash bed is well preserved in the Quaternary deposits. Such preservation is possible only if younger sediments cover the ash deposits without any delay or break. Therefore, it appears that the ash fall was immediately followed by large influx of black clays that buried and covered the ash unit. The deposition appears to have occurred under very low energy conditions.

Deccan College (Deemed University), Pune, excavated the black fissured clays that overlie the tephra horizon at Morgaon and discovered some Acheulian artifacts. Their study indicates that the artifacts were not transported by geological agents and do not occur within the layers but on the contacts between them. The artifacts are highly weathered. The assemblage includes boulder-sized anvil stones, but even the smallest artifacts are misfit within the clays and the fine gravels they occur on. The deposition of the clays, therefore, is contemporary with the artifacts, and later than the tephra, which lead to disagreement of these workers with the 75 ka date for the tephra. Artifacts of the types recovered from Morgaon and Bori (where they also overlie the tephra) are "Early Acheulian". These types of artifacts, wherever dated, belong to the Lower Pleistocene. Recently, an ESR date of more than 1.2 Ma has been obtained from Isampur in the Krishna-Bhima Doab (Paddayya et al., 2002) for an assemblage very similar to that at Morgaon.

**Day 5: 03/11/2017**

**Field visit between Aurangabad and Lonar Crater**

**Stay at Aurangabad.**

**Stop 7: Lonar Crater (the best preserved impact crater in the basaltic terrain (385 km)**

Lonar Crater is located in a small town named Lonar in Buldhana district of Maharashtra, in the central part of Deccan Traps region (Fig. 6). The origin of the Lonar Crater has been debated since the 19th Century. There are several hypotheses regarding its origin, be it as the only available evidence of a volcanic outburst, or great

gaseous extraction, or even a crypto-volcanic origin with deep-seated carbonatite. But now there is enough evidence to suggest that the crater has been formed by an impact event.

The impact was caused by a hyper-velocity bolide or a meteor. The relatively unaltered morphology of the crater and the identification of subsurface breccias beneath the sediments in the crater provide evidence to this argument (Bodas and Sen, 2014). This is one of the very few hyper-velocity impact craters in the world, carved out from the basaltic



*Fig. 6.*

*A Google Earth image of the Lonar Crater.*

target rocks, and is the only crater in lava flow sequence of a Continental Flood Basalt Province (Bodas and Sen, 2014). The crater is located on the drainage divide between the Purna and the Penganga rivers. The climate is semi-arid, with an average annual rainfall of 680 mm.

The crater has a diameter of 1830 m, and is remarkably circular and bowl-shaped (Fig. 6). The depth of the crater is approximately 150 m and the rim is raised nearly 20 m above the surrounding area. The crater floor is almost flat and covers about 1200 m in diameter. Gully erosion can be seen everywhere in the interior part of the crater. Presently, it is occupied by a saline lake of about 5-7 m depth. We can also see dense vegetation carpeting the inner slope of the crater. Within the crater, centripetal drainage system can be observed.

At a distance of about one km to the north of the main Lonar Crater, there is another smaller crater of about 300 m diameter. It is called the Ambar Lake (also called the 'Chotta Lonar', meaning the small Lonar). Although not yet confirmed, it is believed that this crater was also formed at the same time that the main crater was formed,

possibly as a result of the impact of a smaller fragment (Fredriksson et al., 1973). The geological succession of the crater consists of three components. These are: the basaltic lava flows (target rocks), rocks formed as a result of the impact, and the unconsolidated lake sediments (Bodas and Sen, 2014). Of these, the uppermost layer of the unconsolidated clayey to silty sediments with salt encrustations can be seen on the crater floor and basaltic lava flows.

Fall-back fragmentary breccias can be best observed along the foot tracts that join the crater floor with the rim. The ejecta blanket with fragmented breccias and suevitic breccias, formed as a result of impact, is well-exposed in the rim area of the crater and radially outside the crater for distance of more than 2 km. Lonar town is located on the ejecta blanket (Bodas and Sen, 2014).

It was thought till recently that Lonar Crater was of the same age as Meteor Crater in Arizona, USA, with an age of between 15 and 50 ka. Recent dating of the “impact melt rock” samples from the Lonar Crater by  $^{40}\text{Ar}/^{39}\text{Ar}$  technique has yielded an age of  $570 \pm 47$  ka, an age ten times older than the oldest date given by the non-isotopic methods (Jourdan et al., 2011). Dating with fission tracks and thermo-luminescence methods indicate a much younger age. According to Jourdan et al. (2011), these impact rocks have been perturbed by the post-impact processes that include alteration and wild fires that have partially erased and reset the fission tracts, or would have affected electron charge traps used in thermo-luminescence dating (Bodas and Sen, 2014).

The lake was first mentioned in the ancient scriptures such as the Skanda Purana, the Padma Purana, as well as in the Aain-i-Akbari, written during the reign of Emperor Akbar in 16th Century. The first European to visit the lake was a British officer, J.E. Alexander, in 1823. Several temples found on the periphery of the lake are known as Yadava temples and also as Hemadpanti temples (named after Hemadri Ramgaya). Numerous temples surround the lake, most of which stand in ruins today, except the temple of Daitya Sudan at the centre of the Lonar town, which was built in honour of Lord Vishnu's victory over the giant Lonasur. It is a fine example of early Hindu architecture. The other temples, found within the peripheries of the crater, are Vishnu Mandir, Wagh Mahadev, Mora Mahadev, Munglyacha Mandir and Goddess Kamalaja Devia. The area was once part of Ashoka's empire, and then of Satavahana's. The Chalukyas and Rastrakutas also ruled this area. During the period of the Mughals, Yadavas, Nizam and the British, trade prospered in this area.

Geological Survey of India (GSI) has enlisted Lonar Crater as a National Geological Monument. This is a major tourist destination in Maharashtra, not only for the crater but also for the ruins of the historical temples.

**Day 6: 04/11/2017**

**Aurangabad to Ajanta Caves and back  
Stay at Aurangabad.**

**Stop 8: Ajanta Caves, a World Heritage Site (337 Km)**

The Ajanta Caves are situated in Aurangabad district of Maharashtra. They are cut into the volcanic lava of the Deccan Trap in the forest ravines of the Sahyadri Hills and are set in a beautiful sylvan surrounding (*Fig. 7*). These magnificent caves, containing carvings that depict the life of Buddha, are considered to be the beginning of classical Indian art. The caves have been named “Ajanta” from a nearby village whose name is also Ajanta. During a hunting expedition in 1819, an army officer in the Madras Regiment of the British Army found these caves. Since then it has become one of the most important tourist destinations in the world. The caves are famous for their murals and paintings that stand as the finest surviving examples of ancient Indian art.

The caves are cut on the side of a cliff nearly 76 m high, which rises above a meander bend of the Waghora River (*Fig. 7*). The valley is situated at a calm and scenic location and Buddhist monks used to retreat in these caves during the rainy seasons and pursued intellectual discourses. Today the caves are reached by a road which runs along a terrace mid-way up the cliff. Each cave was once linked by a stairway to the edge of the water, but almost all of them are now obliterated, albeit traces of some that could be noticed at some places.

There are about 30 rock-cut Buddhist cave monuments which date from the 2nd Century BCE to about 480 or 650 CE. The excavation of the caves began in the 2nd Century B.C and continued till the 6th Century A.D. The sculptures, murals and paintings belong to different periods, resulting in the difference in styles in the execution of these paintings and sculptures. The mid-5th Century A.D to mid-6th Century A.D witnessed a flurry of activities at Ajanta. A famous Chinese traveler, Hieun Tsang, visited India during the first half of the 7th Century A.D, and left a vivid and graphic description of the flourishing Buddhist establishment here.



*Fig. 7.*  
*A view of the Ajanta Caves*  
*(photo by V. Joshi).*

There are in all 30 caves hewn out of rock, which also include an unfinished one. The caves display sculptures which are masterpieces of Buddhist religious art, with figures of the Buddha and depictions of the Jataka tales. Execution of the paintings began with elaborate preparation of the rock surface. Chisel marks and grooves were left on the surface of the rocks so that the layer applied over it could be held firmly. On the rough surface of walls and ceilings, a blend of ferruginous earth mixed with rock-grit or sand, vegetable fibres, paddy husk, grass and other fibrous material of organic origin was applied. Over this ground surface, a second coat was applied that consisted of mud and ferruginous earth mixed with fine rock-powder or sand and fine fibrous vegetable material. The final finish was with a thin coat of lime wash. The outlines were drawn boldly over these lime-washed surfaces and then the spaces were filled with requisite colors in different shades and tones to achieve the effect of rounded and plastic volumes. Glue was the chief binding materials used for these paintings.

The object of worship is a Stupa. In date and style, the caves can be divided into two broad groups. These are (1) a Buddhist community, comprising of five sanctuaries or Chaitya-grihas (caves 9, 10, 19, 26 and 29), and (2) a monastic complex, Sangharamas or Viharas (all the other caves). The caves were excavated during the supremacy of the Vakatakas and Guptas. Under the reign of the Gupta Dynasty, Indian art reached its peak. The earliest excavations belonged to the Hinayana phase of Buddhism. The second phase saw the introduction of new patterns in the layout, both in paintings and in sculptures. The main theme of the paintings is the depiction of various Jataka stories, different incidents associated with the life of Buddha and the contemporary events and social life. Geometrical and floral designs decorate the ceilings of these caves (Fig. 8).

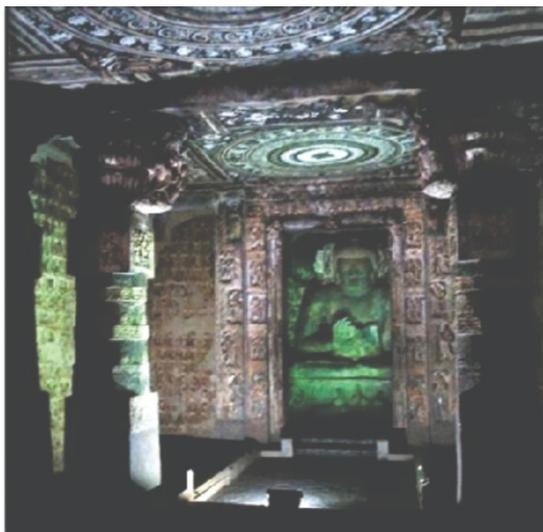


Fig. 8

*A sculpture of Budha in one of the caves at Ajanta  
(photo by V. Joshi).*

The styles presented by Ajanta Caves have exerted a great influence on the art and architecture within and beyond India, extending up to Java. The Ajanta Caves indeed bear exceptional testimony to the evolution of Indian art, as well as to the determining role of the Buddhist Community, intellectual and religious foyers of the Gupta Dynasty and their immediate successors. The refined decoration, the balance of the compositions, and the marvelous beauty of the feminine figures depicted in the paintings were among the major achievements of the Gupta and post-Gupta styles and confer on them the ranking of a masterpiece of universal pictorial art (UNESCO/CLT/WHC).

**Day 7: 05/11/2017**

**Departure from Aurangabad to New Delhi by Flight**

**Stay at New Delhi.**

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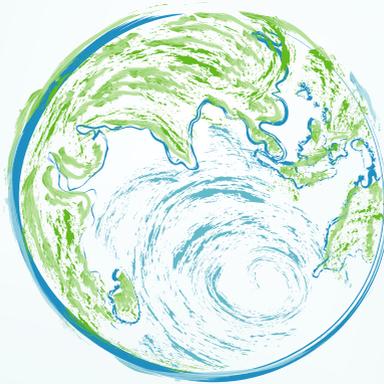
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