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Excavation Features on Rock Coasts: A Study of Honeycombs, Taffoni and Caves from North Konkan

Ajay Kamble and S.R. Jog, Pune - Maharashtra

Abstract

Excavation of Geo-materials on a rocky coast, causes formation of geomorphic features like Honeycombs, Taffoni and Caves. These features mainly account for the consumption of cliff and platform surfaces. These differ not only in their size, but also as per their processes of formation.

The North Konkan region has several patches of rocky coasts where these landforms are observed at many locations. These locations were surveyed to obtain morphometric variables such as size, length, width, depth, height etc. Apart from visual interpretation, the rocks and material characteristics were analyzed using microscopic observation of thin sections.

Field survey, morphometric analysis and material analysis show that honeycombs are primarily a result of erosion by salt spray on a relatively resistant, fresh rock surface. Taffonis, which are similar features, are formed by excavation of severely weathered material. Notches and caves are larger in size, and are associated with differential weathering and erosion of different Basalt flows.

Keywords : *Rocky Coasts, Honeycombs, Taffoni, Notches, Basalt, Konkan*

Introduction

On rocky coasts, the disintegration of rocks by mechanical or chemical processes would ultimately alter a rock-mass to become physically weak and chemically unstable. The weathered and loosened material is removed by various agents of erosion. Removal of rock-mass, if it is site-specific, shall leave behind its imprints in form of small and large excavation features. Though being varied in their size and morphology, these features owe their origin to a common process, i.e. removal of rock-mass, and hence, can be grouped together. Honeycombs, taffonis, notches and caves are such excavation features, observed on most of the rocky shores. Honeycombs and taffonis are micro-features, while notches and caves are of much larger size, in increasing order. Among these, honeycombs and taffonis, taffonis and caves and notches and caves have a close association, and at times, may share a cause-consequence relationship; i.e. honeycombs may give rise to taffonis and notches may be enlarged to form caves.

The present paper attempts to describe the characteristics of these features and discuss the various processes involved in their formation, along North Konkan Coast of Maharashtra.

Study Area

The area under consideration for the study is a 40 km stretch in Raigad district of North Konkan. Extending from Dighi in the north to Velas in the south, the area lies between 17°55' to 18°19' latitude and confined between 72°55' and 73°E long (fig.1 See page 197).

The area for the present study is a part of North Konkan coast, in Raigad District of Maharashtra. It is a strip of about 35-40km, extending from Murud in the north, to Velas in the south.

The coastal area is underlain by Deccan trap formation made up of Basaltic flows. These rocks were formed due to outpouring of lava during the Cretaceous and Eocene period (Krishnan 1982).

Rocky shores are observed at several locations in the study area. Some of these were selected for a detailed study. Bharadkhol Headland near Shekhadi, Headland at Shrivardhan point, Harihareshwar and Velas have occurrence of honeycombs. taffoni, caves and notches.

Honeycombs

Also called as "Stone lattice" or "Stone lace", honeycombs are small, closely-spaced depressions, up to a few centimeters in diameter and depth (Trenhaile 1987). This definition is rather convenient to accept, since many workers define them in a genetic context, resulting due to a certain process. Honeycombs have been observed in all climatic regions; from equatorial to mid-latitudes (Palmer and Powers 1935, McGreevy 1985), and even in Antarctica (Nichols 1960). However, honeycombing contributes significantly to the consumption of rocks and may be considered as one of the primary mechanisms of rock-disintegration in coastal areas. The occurrence and characteristics of honeycomb structures in the study area can be described as follows:

1. Not all parts in the study area show a developed honeycomb pattern. Honeycombs are more commonly found in the southern part of the study area, at Hareshwar platforms, Shriwardhan point headland, and Velas platform. Towards north, Bharadkhol platform does not exhibit a developed honeycomb pattern. The platform rock rather has small pittings of 1-2mm, occupied by mollusks. Small sized, poorly developed honeycombs may be observed at Adgaon platform, though they are larger and pronounced on the Adgaon stack surface. The sheltered sites of Dighi are more or less devoid of honeycombs. However, between Sarva and Nanvel headland to the north of Velas Agar, they show an excellent development on platform surface. The following table provides a summary of location and general characteristics of the honeycombs in the study area.

Table 1 : Description and characteristics of honeycombs

Location	Description of honeycomb characteristics	Size and depth
Velas	Found over platforms and cliff face. Regular spacing, dark gray colour, sometimes reddish-brown with luster. Hard sidewalls. Found up to 4.5m above the platform on the cliff face.	2-2.5 cm in diameter. Up to 2cm deep.
Hareshwar	Found mainly on cliff face, along with taffonis. Larger range of size. Dark colour, hard sidewalls, luster. Not much on platform surface.	2-4 cm in diameter, up to 4 cm deep
Shrivardhan Point Headland	Mainly of cliff faces, very intricate, regular, deep. Max. depth observed at this site. Larger and irregular near joints. No luster. Dark brown colour.	3-5 cm in diameter, up to 6 cm deep.
Bharadkhol Headland	Formed in reddish brown altered basalt, poorly developed, not uniform lattice, in form of small pitting.	Up to 2mm in diameter and depth.
Adgaon	Small, irregular honeycombs on platform surface. Larger and deep on stack surface (3cm)	1.5-2cm on platform, 1cm deep.
Between Sarva and Nanvel Headland	Very well developed lattice, spread over entire platform surface, and insitu boulders. Absent between inter-boulder spaces. Hard sidewalls, collapse of sidewalls and fusing of honeycombs, sharp pinnacles seen. Luster on sidewalls.	Up to 3 cm in diameter, 2-2.5 cm deep.
Dighi	Almost absent, small and irregular, only on platform surface, formed in reddish altered basalt.	Up to 1cm diameter

2. It may be observed that development of honeycombs falls more or less in line with the exposure to the sea. Velas, Hareshwar and Shrivardhan point headlands have larger, regular and deeper honeycombs, than Adgaon or Dighi, which are sheltered sites. Bharadkhol platform may be cited as an exception to this pattern, where honeycombs show a poor development despite occupying a headland location.

3. Honeycombs do not show any affiliation to slope. Vertical, sloping, as well as horizontal surfaces have developed honeycomb lattice, hence it is difficult to associate their presence with surfaces having a certain degree of slope.

   A strong relationship, however, may be identified between honeycomb development and the type of rock. The best developed honeycombs were

observed at Velas, Hareshwar and Shrivardhan Point headland, sites which have a massive, compact basalt (Plate 1a See page 198). This material is cohesive, fine grained, and has little amygdales, vesicles and secondary minerals. The thin section of these rocks show that the basalt has not been altered much (Plate1b See page 198). On the other hand, coarser and altered basalt in the northern parts, i.e. Bharadkhol and Dighi, do not exhibit appreciable honeycomb development. Bharadkhol headland does have harder, compact, vertically jointed basalt forming cliff and stack-top, but no honeycombs are observed on these rocks.

4. Neither the host rock, nor honeycombs exhibit presence of any weaker material. The honeycomb surface is smooth, sidewalls are hard and have a metallic luster of reddish-brown colour. No rock-debris is found in the honeycomb depressions, except precipitation of salt.
5. Within a given cliff-platform complex, honeycombs have certain preferred locations. They are rarely observed near the low-tide cliff or at platform margin. It is rather the central and landward portions of platforms which have a concentration of honeycombs. The cliff face also has honeycombs up to a height of 3-4m. The existence of honeycombs does not seem to be guided by joints. They are present on surfaces with, or without joints, with almost equal frequency. However, honeycombs tend to be larger and irregular in shape, near the joints. The ones, occupying homogenous, joint-free areas, are more circular in shape and smaller.
6. The maximum depth of an individual honeycomb structure observed is about 6cm. Beyond these depths, the honeycomb walls either collapse, leaving behind sharp pinnacles. Fusing of honeycombs forms larger, irregular shapes, but does not cause any increase in depth.
7. A close observation of an individual honeycomb reveals that the depression has vertical walls, and the mouth of honeycomb does not show any overhang or lip (Fig.2).

Taffonis

Taffonis and honeycombs may often be confused with one another, due to similarity in form. Since there is no precise criterion for differentiation between the two, taffonis may be taken as large honeycombs. Some authors have also considered honeycombing as taffonis developed under unfavourable conditions, so that their full size could not be attained (Martini 1978). It seems to be an accepted fact that the taffonis are hollows carved in the rocks, which are larger than honeycombs. Occurrence of taffonis is not restricted to coastal environments alone. They have been reported even from deserts (Mabutt

1977) and over a variety of rock-types, ranging from Granites (Bradley Et al 1978, 1979), Sandstones (Mustoe 1983), Limestones (Kelletat 1980) and Ash flow tuffs. (Mc Bride et al., 2000)

Taffonis observed in the study area have a restricted occurrence, but their peculiar characteristics differentiate them from honeycombs, and also offer a clue in understanding their origin. These observations are as follows:

1. Fully developed taffonis are observed only at one site in the study area, i.e. at Hareshwar platform. Restricted occurrence and relatively immature taffonis are also found on velas platform. Overall, it may be said that taffonis are confined to the southern portion of the study area. Velas area has simple Aa basalt flows, while Hareshwar has simple and some compound basalt flows exposed in the shore zone (Parthasarathy et al, 1984). The highly altered coarse basalt does not support much taffoni development.
2. Though taffonis have been formed over bare cliff faces, their best development can be seen on the cave walls and ceilings (Plate 2 See page 199) It may be noted that almost all these are the "sidewall taffonis". No taffonis are observed on the platform surfaces. Intricate pattern of taffonis exist on the cave ceiling. The interior of the caves receive sunlight only in the late afternoon, and for rest of the day, the cave interiors are shady.
3. The sidewall taffonis and the ones occupying the cave ceilings, are markedly different in their shapes. The sidewall taffonis are comparatively smaller in size (<20cm diameter) and generally, are circular. On the other hand, the cave ceiling taffonis are larger but elongated, elliptical or irregular in shape (Plate 2).
4. The material in which the taffonis are carved, is severely weathered. Taffoni walls are weak, and can be broken by hand. The thin section of this material shows a highly altered basalt (Plate 4b See page 199) which is comparatively coarser and appears like a sedimentary formation in hand specimen (Plate 4a See page 199).
5. Orientation and shape of taffonis is influenced by plains of separation, like joints. Joints seem to be the favoured locations for developing taffonis. In case of longitudinal taffonis, ledges of dark coloured resistant material can be observed within the taffonis (Plate 3 See page 199).
6. Cross-section of a singular taffoni (fig.2) shows the difference between the taffoni and honeycomb shape. While honeycombs have wider opening and vertical walls, taffonis preserve a pot-like shape, having enlarged, hollow interior and comparatively smaller opening. The taffoni mouth generally has a lip or an overhang. Interior of taffonis can be as deep as 1m and are cool and shady.

7. Taffoni interiors have an accumulation of rock-debris obtained from the sidewalls and roofs. This material is essentially in form of thin flakes of less than 1mm thickness (Plate 4a) The flakes are fragile and have small holes on their surface. These holes in fact, mark the positions of secondary mineral particles, which did not fall off along with the flake. The taffoni walls and roofs show presence of secondary minerals, but they are hardly found among the deposited flakes at the taffoni-base. No salt was found in the taffoni deposits.

Notches and caves

Notches and caves, otherwise, are prominent features of limestone coasts, where the process of solution of the rocks forms these features. A typical notch would be in form of a narrow, deep undercut at the cliff base. Notches are commonly found in warm, tropical limestone coasts. Caves are larger and deeper, caused by solution and excavation of the cliff.

These definitions, however, cannot be applied to the study area. Features referred to as 'caves' in the study area, are much smaller in dimension. They occupy the cliff base in form of wide semicircular or parabolic openings, cut due to wave action. Since solution notches have a little scope of formation in basaltic areas, notches in the study area basically reflect the imprints of tidal fluctuations. The surveys and observations confirm the following characteristics of notches and caves.

1. Caves and notches in the study area can be differentiated on the basis of their shape and sizes. Caves are generally elongated, wide openings, more than 3m in height and depth. Notches are comparatively smaller, not exceeding 1.5m in height and depth. The shapes of caves are semicircular or irregular, while the notches are generally parabolic. Despite these differences, caves and notches are much associated with each other, with respect to their location.
2. Developed cave structures are found only along Hareshwar platforms, though some smaller caves are seen a Velas. Caves are not observed on Bharadkhol, Adgaon and Dighi platform.
3. There is a little variation in the occurrence pattern of notches and caves. Notches are generally found along with caves, but caves may not be essentially associated with notches. On Bharadkhol platforms, notches have developed, but caves are not found. Neither caves, nor notches are found at Adgaon and Dighi.
4. Notches located at the cliff-base, are formed in homogenous, cohesive material. Velas, Hareshwar and some parts of Bharadkhol platforms have such basal notches. Their shape is generally parabolic.
5. Caves are of variable heights. On Hareshwar platforms, cave heights between 3-11m were observed (Plate 6 See page 200). The shapes of caves are semicircular,

or irregular, with overhangs at the cave mouth.

6. The interiors of the caves invariably have taffoni development. Not a single cave could be located at Hareshwar, without taffonis on its sidewalls. Notches, however, are free of taffonis, and are carved in fresh or honeycombed rocks.
7. In case of larger caves, rocks above the cave top are visibly different than the ones, which host the cave. Cave formation generally coincides with the margins of two different basalt flows.
8. Formation of caves at the low-tide level could not be confirmed. However, some tunneling action can be inferred, as one can observe air bubbles escaping through platform joints, as a wave approaches the platform margin.

Discussion

As mentioned at the outset, honeycombs, taffonis, notches and caves are different geomorphic features with respect to their origin, form and size. However, since all of these are residuals of rock-mass excavation process, a combined discussion of their genesis may lead to a better understanding. If the characteristics of honeycombs and taffonis are analyzed, it suggests that honeycombing is a result of salt spray on un-weathered rocks, while taffonis originate due to mechanical excavation of a severely weathered rock.

Association of honeycombs with wave-splash, is reflected in the observation that vigorous wave environments on headlands and exposed coasts have the best development of honeycombs. Bruthans (2018) also concluded that the hydraulic process, and alternate wetting and drying was an important process in honeycomb formation.

Honeycomb development is least affected by slope of the surface on which it develops, suggesting that it must essentially be a physical process, proceeding from exterior of the rock towards the interior. If honeycombs were a result of chemical weathering, their occurrence would have shown some affiliation to surfaces having a particular slope value, where degree of moisture accumulation was higher. Contrary to this, the material in which honeycombs are formed, are more or less unaltered, fresh rock faces. The thin sections as well as rebound values confirm that the honeycomb-hosting material has not undergone much chemical alteration. Since chemical weathering does not seem to be the controlling factor for honeycombing, one may attempt to explain their origin due to mechanical wave erosion or salt spray. Of the two, the mechanical wave erosion cannot be assumed to operate so uniformly so as to produce a regular, equispaced honeycomb lattice. Moreover, the areas which are close to the platform termination at the seaward side, and which receive maximum wave impact, are surprisingly devoid of honeycombs.

Therefore, the only process which can account for their occurrence and characteristics, is the salt spray and

related mechanisms. This also explains the absence of honeycombs near platform margins. Since these parts are always kept wet by waves and splash, an alternating wetting and drying does not take place, which is essential for salt crystallization and precipitation. Platforms portions near the cliff base frequently undergo wetting and drying, and hence, honeycombs are located in these zones. As observed by McGreevy (1985), salt crystallization is capable of dislodging mineral grains like quartz, causing microscopic cavities in the rock surface.

Exploring salt spray as a probable reason for honeycomb formation, answers most of the queries. It not only accounts for the salt precipitation observed in the honeycomb depressions, but also explains why honeycombing is poorly developed in coarse-grained rocks of Bharadkhol or Dighi. Since salt crystallization causes granular disintegration, and proceeds grain by grain, the process shall work much uniformly in fine-grained, homogenous rocks. Thus, the honeycomb lattice shall be uniform in terms of size and depth. Shapes shall be circular, as the grain-dislodgement shall happen uniformly in all directions. If a patch of comparatively weaker or weathered material is encountered, the grain dislodgement shall not act uniformly, causing a change in honeycomb size and distortion in shapes. It has already been mentioned that honeycombs are larger but irregular near the joints, as joints have a weathered material in the vicinity, due to moisture accumulation.

Altered basalts with coarser grains, do not possess the required granular structure for honeycomb development. As the grains are larger and the secondary minerals form bigger crystals, salt precipitation may not be able to dislodge them. Even if some grains are removed, their effect is masked by the overall coarse texture. Moreover, accumulation and crystallization of salts does not remain uniform on rough surfaces. As a result, unequal distribution of grain dislodgement cannot produce a regular honeycomb structures. It would rather produce a rough, pitted surface, which is observed at sites like Bharadkhol and Adgaon. Bharadkhol headland does have a compact, vertically jointed rock, but it overlies the altered basalt and falls much away from the spray zone. On the Dolerite dykelets of Dighi, honeycombs fail to develop because of the dense jointing. Before honeycombs can develop, these rocks may get eroded by waves.

Once developed, a honeycomb structure can be stabilized by precipitation of iron oxides, which can harden the sidewalls. The smooth surfaces and metallic reddish-brown luster suggests that case-hardening of honeycomb structures has occurred due to precipitation of iron oxides. However, the fact that honeycombs do not penetrate much in depth, supports the assumption that they are a result of salt spray. As a honeycomb deepens, its interiors shall he protected from salt spray and precipitation. Eventually, their deepening shall cease. Honeycomb walls being harder, may resist erosion

for some time and remain as pinnacles. Finally, they shall collapse, exhuming a fresh surface for honeycomb formation. Thus, it may be said with a fair degree of confidence that honeycombing is essentially a physical process, associated with splash and salt spray on a relatively fresh, fine grained rock. It is a multi-nuclii, uniform process and hence, produces a regular pattern of excavation holes, i.e. honeycombs.

Taffonis are a much different structure, larger and deeper than honeycombs. An important characteristic of taffonis is that they are always associated with a weak and weathered material. The thin sections (plate 4b) of taffoni-host material and the taffoni wall, shows that the basalt is altered to such an extent that it resembles a sedimentary formation in hand specimen. Thus, process of chemical weathering seems to be an essential condition for taffoni development. The best development of taffonis in cave interiors, must be related to the accumulation of moisture, at these locations. The typical taffoni shape, having smaller openings and comparatively larger interiors also suggest that the deepening and widening of the taffoni-interior is related to the weathering of the rock-mass. It has been observed that the taffonis on the walls of the caves, are more or less regular in shape, while on the ceiling, they are larger but irregular (Plate 2). On the cave walls, the moisture obtained is by spray action, which has a uniform distribution. However, on the cave ceilings, the spray is aided by a water-seepage from the cave top. This seepage may follow the existing joints or root penetrations, thereby causing a concentrated weathering along the paths of seepage. Thus, longitudinal taffonis shall originate, when these weathered tunnels are excavated. The material resistant to the weathering shall remain as residual ledges within in taffoni structures (Plate 3).

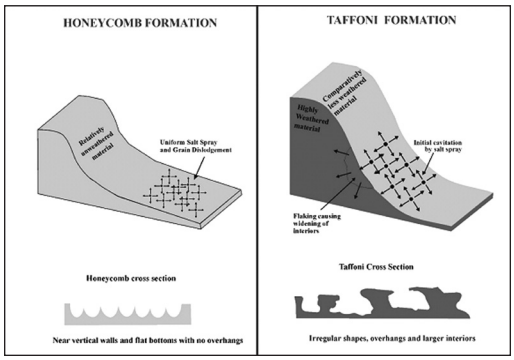

Fig. 2: Difference between Honeycomb and Taffoni formation processes

If a homogenous, but weathered rock is exposed to spray action, it would start carving small pitting on the rock-surface. Thus, in coastal areas, the initial stage of taffoni development may be similar to, or same as that of honeycombs. Paradise (2013) has also attributed an important role to salt weathering in Tafoni formation. However, the grain-dislodgement and excavation may proceed at a much faster rate, in all directions, imparting a spherical interior to the depression. As the structure enlarged, and deepens, granular disintegration may slow down or cease. Since the taffoni depressions

occupy cool, shady areas, they shall experience alternate warm and cool micro-climatic conditions during sunny days and nights. As compared to taffoni openings which are always warm, the taffoni interiors shall experience a larger range of temperature variations. The severely weathered rock, having a higher swelling and insolation coefficient (Parthasarathy and Shah 1984, Joshi 1980) shall readily respond to these micro-climatic variations. The alternate expansion and contractions of this material shall cause flaking of the material from taffoni-roof and sidewalls. Flaking process shall be more effective in the interior of the taffonis, as compared to its mouth. Thus, widening of the mouth does not take place as much as excavation of the interior. Formation of the typical taffoni-shape with narrow mouth, and large, hollow interior, can be explained by the above-mentioned process. The resistant secondary mineral particles do not expand and contract, and hence, remain embedded in the rock-mass. The surrounding layer of weathered material falls off as a flake, having perforations or holes, where secondary minerals were once located (plate 4a). Coarse-grained rocks, therefore, are less suitable for taffoni development. The coarse texture, with a larger grain-size, shall restrict the formation of the flakes. Thus, the coarser rock continues to weather in a non-uniform pattern, thereby producing rough surfaces and irregular depressions, rather than producing taffonis. Therefore, it can be said that unlike honeycombs, taffonis are a result of salt spray and consequent thermal flaking in severely weathered, homogenous rocks.

The caves and notches in the study area are found in proximity. Comparatively smaller size of the notches, leads to an assumption that they are formed in comparatively resistant material. This assumption is strengthened by the observation that notches are developed in bare or honeycombed rocks, which are less weathered. The erosion and removal of rock-mass, therefore, shall be restricted within the tidal range. Notches, therefore, preserve the imprints of tidal inundation zone, in a roughly parabolic shape. A compact, un-weathered material is more suitable for the formation of a typical notch. If the rock is weathered, the notch-roof may become irregular, widening the notch opening and forming a feature similar to a small cave. Caves on Velas platform, appear to be a result of deformation of existing notches. In that respect, notches formation in the study area, may represent an initial stage in cave formation, where massive, homogeneous rocks are found (Plate 5 See page 200).

Larger caves may seldom form in an un-weathered material. All large caves in the study area essentially have taffoni development. Caves and taffonis appear to share a cause-consequence relationship, with one favouring the development of the other; i.e. formation and fusing of large taffonis may form a cave, while caves provide a cool, shady place for further taffoni development. Occurrence of largest caves coinciding

the margins of basalt flows, shows that flow margins are the potential sites for cave formation. Weathering and excavation of a comparatively weaker flow between two resistant flows, can initiate cave formation. As the cave deepens, weathering penetrates into the resistant flows as well. Large boulders are loosened from the cave roof and collapse, forming overhangs at the cave mouth(Plate 6). Thus, while notches develop in a homogeneous rock exposed to tidal oscillations, caves are a result of a varying rock strata exposed to a tidal impact.

Conclusions

1. Honeycombs develop on exposed parts of rocky shores and are a result of erosion and salt spray on un-weathered rocks.
2. Taffoni develop in sheltered locations. These are formed due to mechanical erosion of highly weathered rock.
3. Notches are formed at exposed locations on relatively un-weathered rocks and are formed due to tidal oscillations.
4. Cave formation in the study area is primarily due to differential weathering on the margins of varying lava flows.

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Dr. Ajay Kamble
Associate Professor in Geography
Bhavan's College, Andheri, Mumbai
ajaybhavans70@gmail.com

Dr. S.R. Jog
Professor of Geography (Retired),
Dept. of Geography,
Savitribai Phule University of Pune.jog.
suresh2@gmail.com

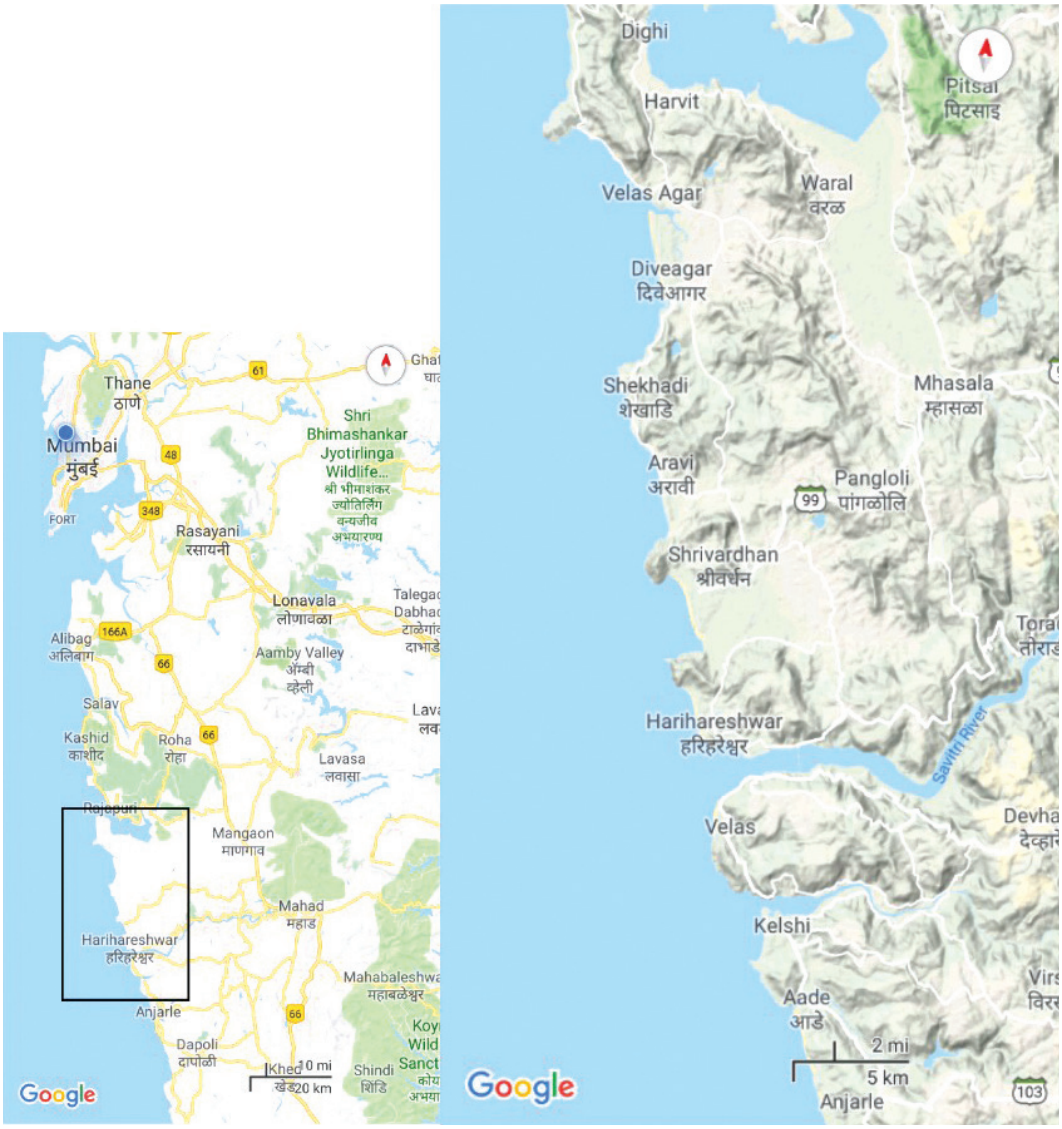

Fig. 1. The Study Area (See page 186 for the text).

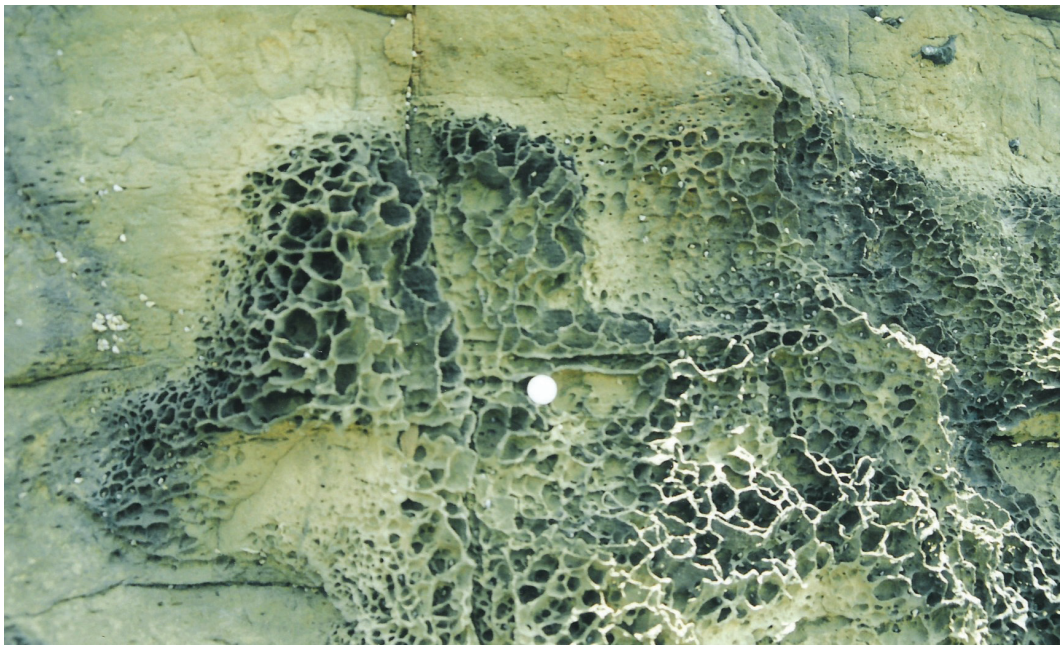

Plate 1a: Well-developed Honeycomb structure on cliff face, Velas
(see page 188 for the text)

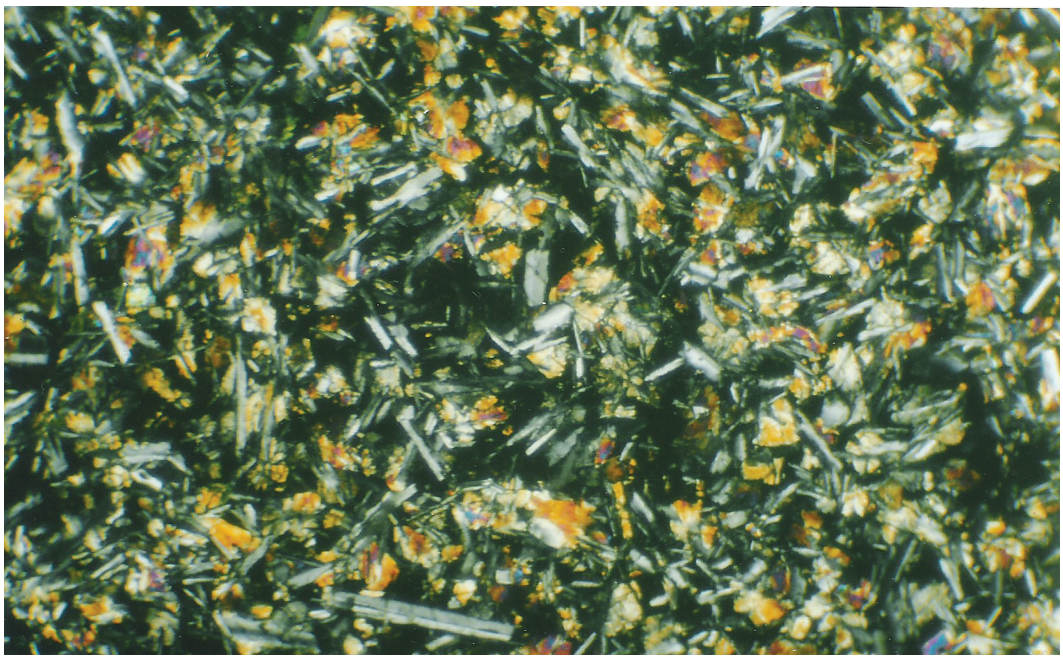

Plate 1b : Thin section of Honeycomb rock material showing almost unaltered Basalt with groundmass of pyroxine and feldspar (X40 CP) (see page 188 for the text)

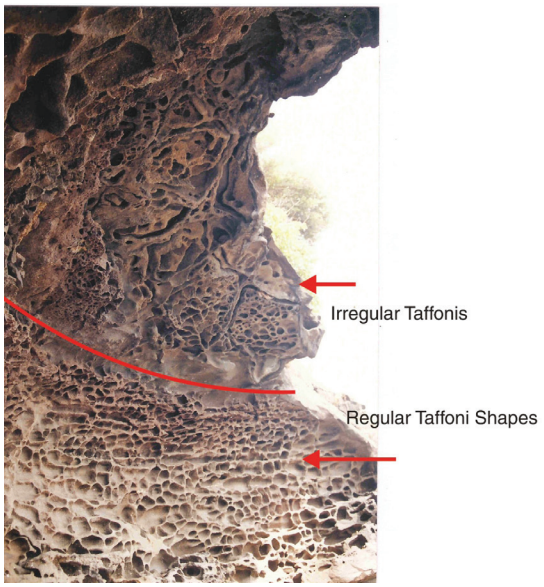

Plate 2: Variation in Taffoni Shapes on Cave wall and Cave ceiling, Hareshwar

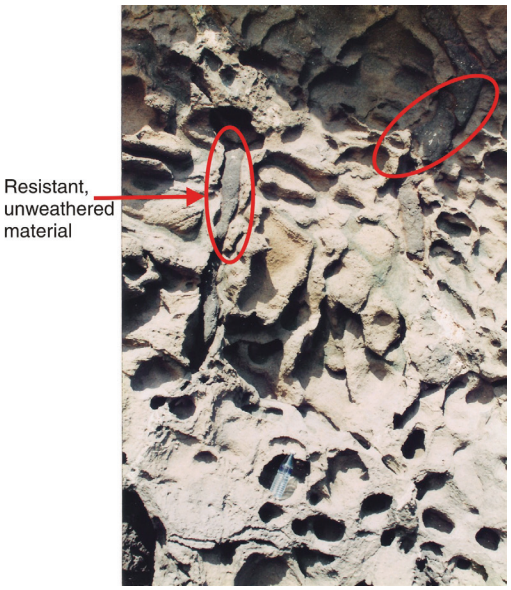

Plate 3: Irregular-shaped, medium sized (15-20 cm) Taffonis, Hareshwar

(Plate 2 & 3 - See page 190 for the text)

Plate 4a: Weathered flaky debris found in Taffoni interior

(Plate 4 a&b See page 190 for the text)

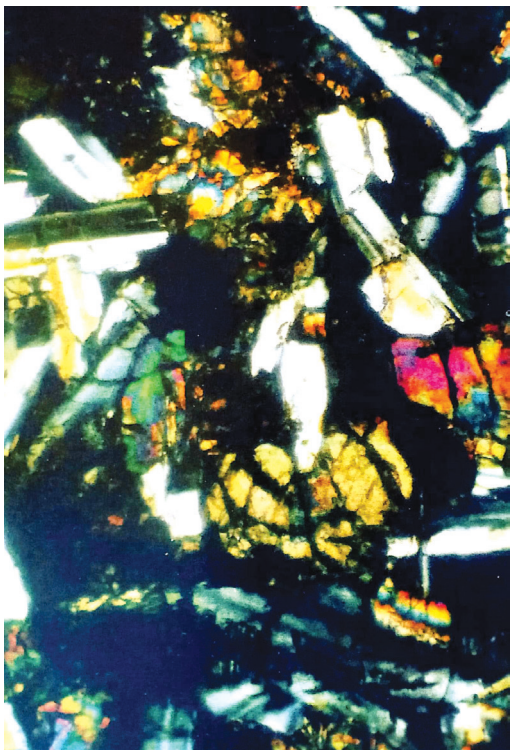

Plate 4b: Thin section of Taffoni-debris showing highly altered Basalt (X40 CP)

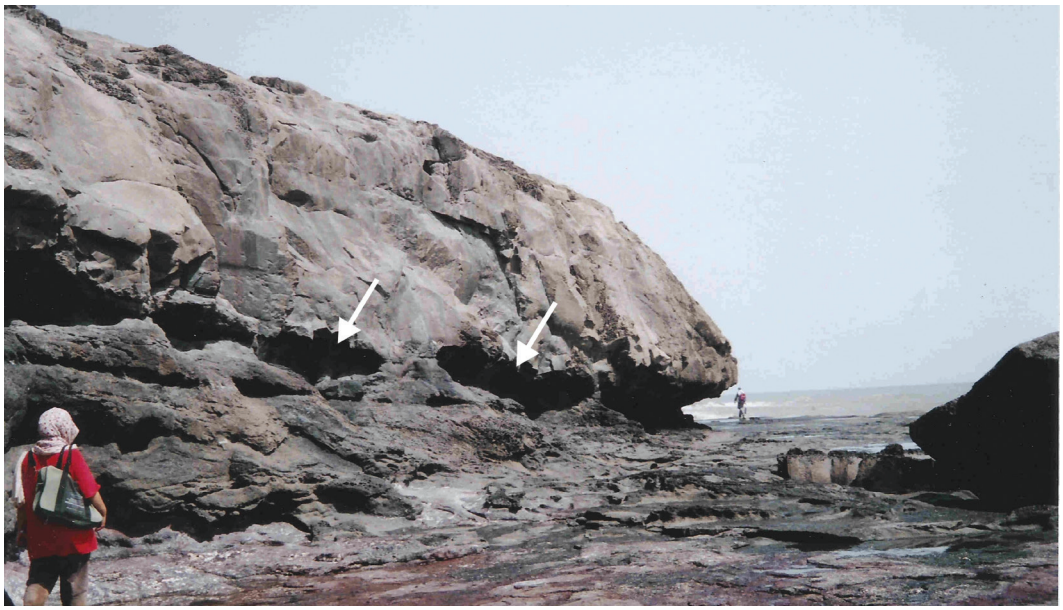

Plate 5: Notches coinciding High-Tide level in un-weathered basalt, Velas Platform
(See page 190 for the text)

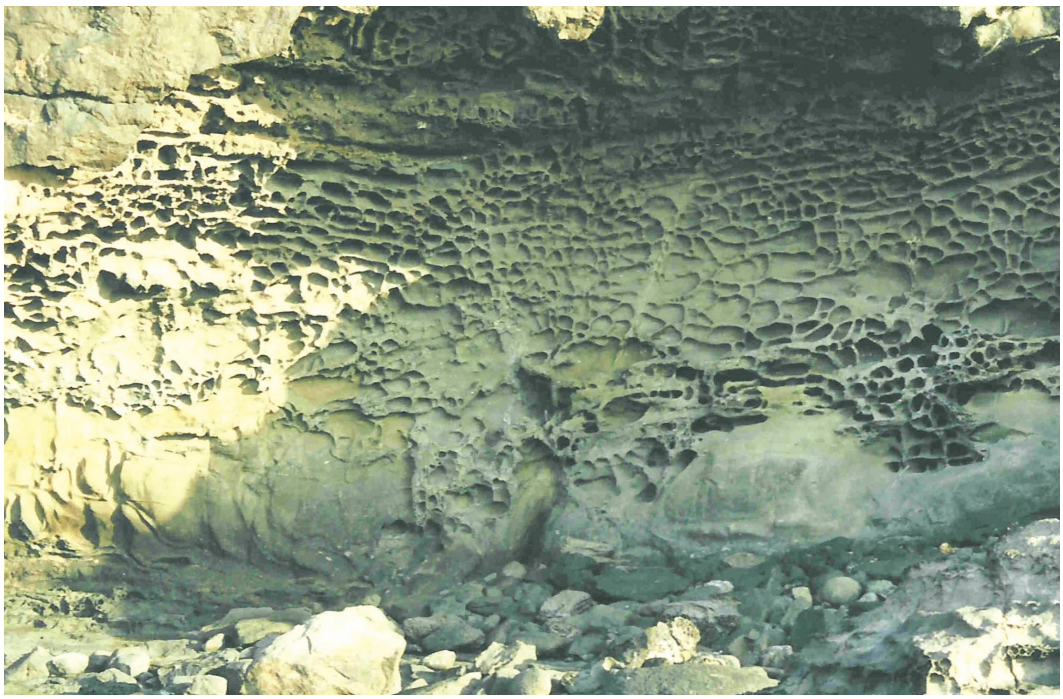

Plate 6: Cave formation in weathered Basalt, Hareshwar Platform
(See page 190 for the text)