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ACKNOWLEDGEMENTS. S.Y. thanks the Organization for the Prohibition of Chemical Weapons, The Hague, The Netherlands and K.P.J. thanks University Grants Commission, New Delhi for financial support.

Received 23 September 2014; revised accepted 6 April 2015

Tafoni along the east coast, Chennai to Mamallapuram, Tamil Nadu

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A study on weathering pits called tafoni was carried out on rock surfaces that age from a few hundreds to millions of years along the east coast between Chennai and Mamallapuram. Tafoni of varying sizes and shapes such as simple circular dots to oblate to prolate, hemispherical to spherical are formed on the granite, granite gneiss, charnockites (acid and mafic) and sandstone both on exposed and inner wall surfaces. In this study, their formation is related to not only tropical weathering processes, but also to sea salt water splays causing salt mineral etching, weathering processes, besides microbial activity, algal and lichen growth accentuating their formation.

Keywords: Bedrock surface, mafic minerals, tafoni, weathering processes.

WEATHERING starts generally on the rock surfaces or from their inner walls by the formation of pits[1–3]. Tafoni are pits, ellipsoidal, flat pan-like to bowl-shaped, occurring as natural rock cavities[3–9]. These cavernous weathering features include tiny pits, chemically dissolved pits, softball-sized cavities, caves and cellular honeycomb forms often lined by thin layers of dark black algae or microbial mat. Typically tafoni develop on inclined or vertical surfaces and occur in groups or clusters, and in all types of bedrocks. These cavernous weathering landforms are present on the surfaces of many different kinds of rocks located in a multitude of geographic regions around the world[1,9]. However, tafoni development and evolution are puzzling and continue to arouse curiosity[5,8–11]. Very little work has been carried out on tafoni and weathering along the east coast of Tamil Nadu from Chennai to Mamallapuram[6]. In the present communication, we describe tafoni as an important weathering type along the east coast extending from Chennai to Mamallapuram. The purpose of the study was to examine the various types and sizes of tafoni weathering features on rock surfaces of different ages, on similar/different rock types, from coastal and inland sites. Tafoni were observed over rock surfaces of different ages from a few hundred to several million years old, including on colonial grave tombstones, temple walls, sculptures (of historical periods), menhirs (ancient monumental standing stones), exposed rock outcrops, etc. Hence this study is aimed to understand the plausible causes for tafoni formation along the east coast between Chennai and Mamallapuram.

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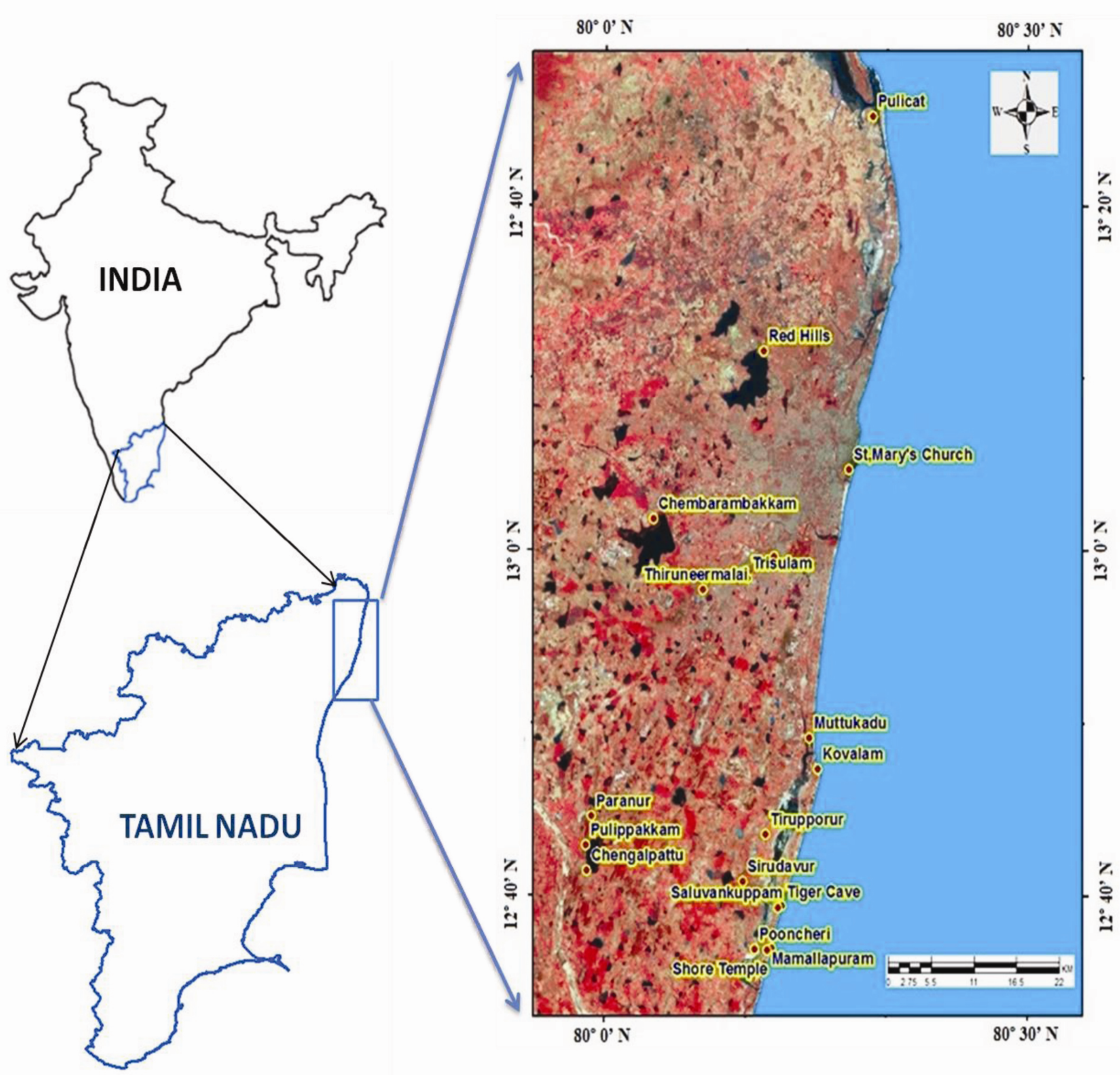

Figure 1. Location map of the sites studied along the east coast from Chennai to Mamallapuram and few inland sites.

The study area covering nearly 150 sq. km consists of low, slightly undulating terrain with a general slope of less than 1° towards the east and southeast. The coastal strip is largely sandy with isolated exposures of charnockites, granites, granite gneiss, sandstone, laterites and vertisols representing remnants of an ancient eroded landscape (Figure 1). The bedrock lithology is mostly crystalline, including granite, banded granitic gneiss, 'acid charnockite' (hypersthene granite with very minor biotite, and no muscovite), 'mafic or basic charnockite' (a similar rock but with more dark minerals and less quartz) and norite (hypersthene gabbro) of Precambrian age. These bedrocks are overlain by sandstone and shale of Gondwana age (Upper Permian to Lower Cretaceous), which in turn are overlain by the Mio-Pliocene sandstone and shale that are lateritized[6]. All these bedrocks are draped by a thin veneer of Quaternary sediments.

The Precambrian charnockites occur as monadnocks with pediments all around displaying differential weathering pattern, whereas the Quaternary deposits occur either as regolith over the pediment or as valley fills[12]. The coastal plain slopes from about 200 m in the foothills to sea level, ranging from 2° to 3° in the foothills to 1° to nearly horizontal along the coast. Along the coast a tectonic event is represented by a north-south trending fault. Relative uplift has been mainly reactivated along a NNE–SSW and NNW–SSE trending lineament from the Proterozoic through to the late Cenozoic[12] defining a series of tilted fault blocks. Uplifted parts of these blocks are dominated by charnockites, whereas sandstone and shale draped by a thin veneer of vertisols, lie mainly along the

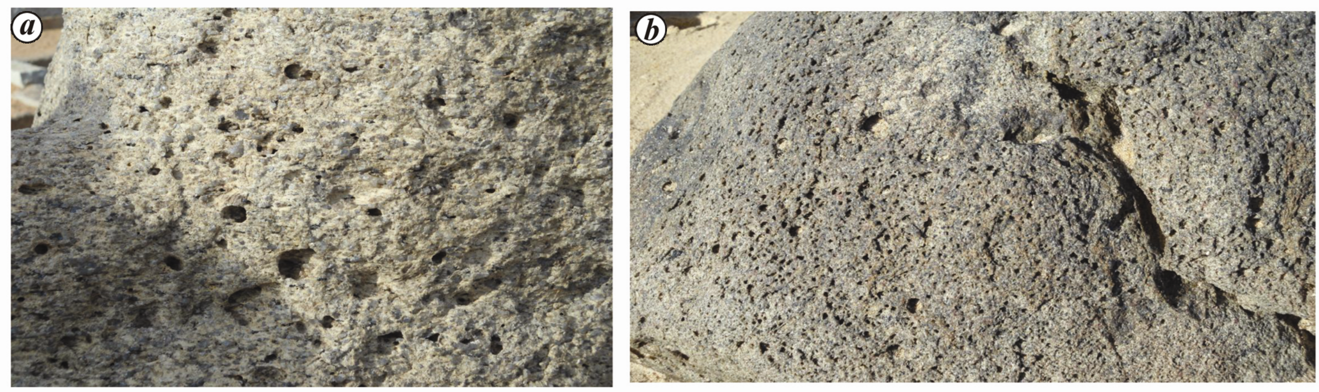

Figure 2. ***a***, A granite gneiss boulder surface with oriented and smoothened rim, coalesced tafoni and exfoliation on the surface. ***b***, Different sized pits on the mafic charnockite rock surface as seen at Kovalam.

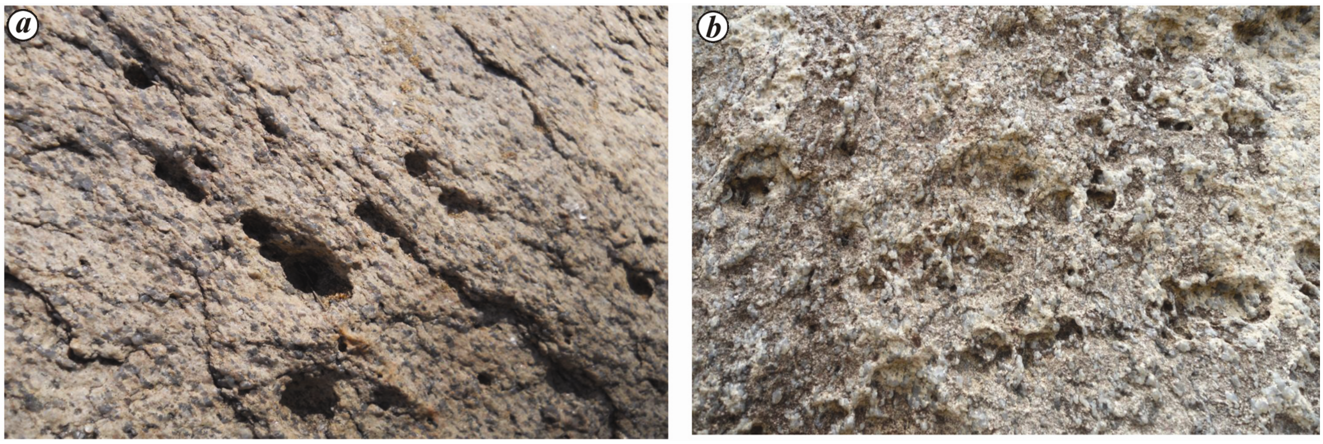

Figure 3. ***a***, Increased pore volume with higher pore size (large and small) aligned in a direction as observed in Tiger Cave. ***b***, Salt crystals around the pore on the granite gneiss rock surface as observed at Mamallapuram.

present coastal valleys. Bedrock exposure gradually decreases towards the east with the down-tilted edge of the blocks beneath a cover of highly weathered bedrock, fluvial, alluvial, lacustrine and aeolian beach sediments and duricrust.

The climate is dominated by the seasonal migration of the inter-tropical discontinuity that causes the northeast monsoon in October and November, which is the period of heaviest rainfall. The coastal strip experiences an average maximum temperature of around 36°C during July and the average minimum temperature in January is 15.8°C. This means that the temperature varies widely between summer and winter with a range of about 20.9°C. Such varied temperatures in different monsoons have a considerable impact in accelerating the weathering process. The area is characterized by sub-tropical climate with an average annual rainfall of 1200 mm.

Tafoni on different natural outcrops such as granite (Figure 2 *a*), acid and mafic charnockites (Figure 2 *b*), granite gneiss (Figure 3 *a* and *b*) and sandstone exposed along the coast and few sites inland (~40–45 km inland towards southwest and west of Chennai), recent statues and recent stone buildings, colonial buildings and European colonial gravestones were studied besides ancient Hindu temples, Jain rock-cut temples, bas reliefs, and prehistoric Iron and Bronze age megaliths. Tafoni types and patterns were studied and recorded using a geographical positioning system (GPS) at different sites (Table 1). During the field work, the dimensions, orientation and position of the cavity, and the opening and the depth of the cavities (around 500 in number) were measured using digital Vernier caliper. Thin sections of the rock from the tafoni pits were prepared to study under the microscope to understand patterns of mineral alteration (Figure 4 *a*–*f*).

Pits, large and small, are generally found on the coasts and in deserts[5]. The pits on the granite gneiss rock surface at Tiger Cave, north of Mamallapuram, and an ancient Hindu rockcut temple of the Pallava period of 9th–10th century AD (Thiruvadanthai) on the coast, north of Mamallapuram, exhibit smaller pits than those exposed at the Shore Temple, Mamallapuram (Figure 1 and Table 1). Pits grow more rapidly on sandstone as observed in the sandstone exposed around the Chembarambakkam Lake

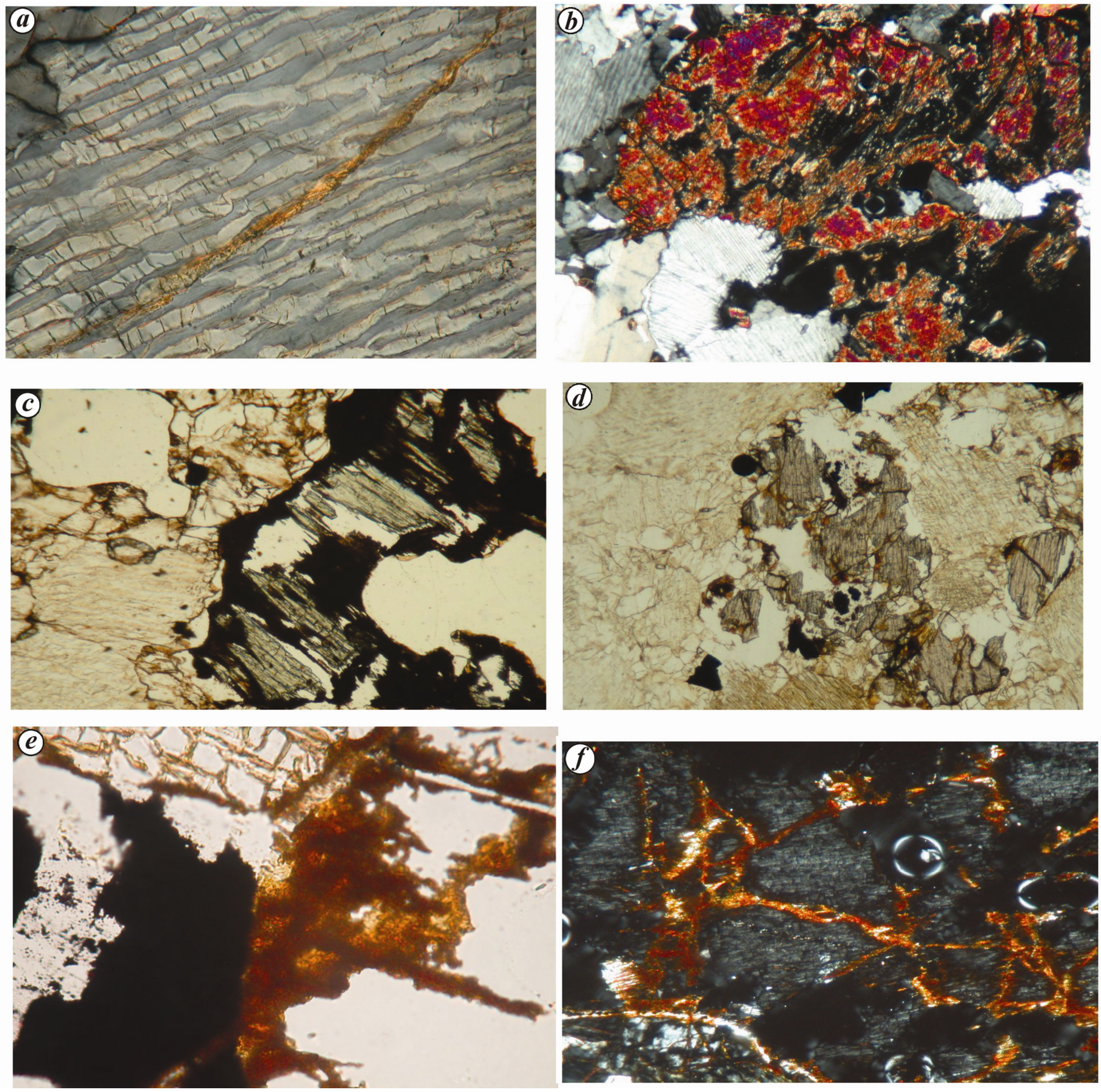

Figure 4. ***a***, Alteration of the plagioclase grain and impregnation of iron oxide along the fracture. BXN: Cross Nicols (magnification ×80). ***b***, Modification of pyroxene grains in the mafic charnockites. BXN: Cross Nicols (magnification ×80). ***c***, Mafic charnockite showing amphibole grain altering and impregnation of dark iron oxide. Plane polarized light (PPL) (magnification ×80). ***d***, Fragmented hornblende with discrete iron oxide precipitates along the grain margins with dispersed magnetite grains. Cavity with no infillings leaving a void. PPL (magnification ×100). ***e***, Different forms of iron oxide phases occurring along the grain margins PPL (magnification ×100). ***f***, Iron oxide along the altered feldspar grain margin. BXN: Cross Nicols (magnification ×100).

than on crystalline rocks (Tables 1 and 2). It is also observed that pitting is much more rapid and more intense along the coast than inland; the frequency distribution of the size of pits is log normal and heteroskedastic[5]. Many of our findings along the east coast from Chennai to Mamallapuram are consistent with studies from other regions[3–6].

Tafoni comprising relatively deep, rounded to elongated rock pits are bored primarily by algae and lichen generating and developing the pits. As reported in an earlier study[7], several pits to a considerable depth are observed; depth is the best tafoni parameter to measure. The size of the pit increases significantly with increasing inclination of the rock surface; it is best developed in terms of size distribution 30°–35° slope (Figure 3 *a*). The size of the pit also decreases further inland as observed around Chengalpattu, 40–45 km southwest of Chennai. Although weathering and alteration occur on the rock

Table 1. Location and characteristics of the tafoni measured

Location	Rock type	Sharpness of the rim of tafoni	Thickness of the outer rim of tafoni (mm)	Slope and major direction of inclination of tafoni
St Mary's Church	Mafic charnockite, acid charnockite, laterite	Very sharp to sharp, rim very thin; in laterite rim is thick and blunt	0.2–1.0	180°, flat, N–S
Kovalam	Sandstone, mafic charnockite	In sandstone blunt and thick; in mafic charnockites very sharp to mildy sharp	0.2–1.0	3°–5°, N–S
Saluvankuppam	Granite gneiss	Mildly sharp to blunt and thick	0.2–1.0	30°–35°, NNE–SSW and 3–5°, E–W
Tiger Cave	Granite, granite gneiss	Sharp, thin to blunt and thick	0.3–1.5	3°–5°, N–S and E–W
Mamallapuram	Granite, granite gneiss	Sharp, thin to blunt and thick	0.5–2.0	2°–3°, N–S and E–W
Chembarambakkam	Sandstone	Blunt rim, thick and shallow depth	1.0–2.0	Flat, NNW–SSE

Table 2. Correlation coefficient matrix of the tafoni parameters measured in different rock types

	Tafoni parameters		
Rock type	Length (mm)	Breadth (mm)	Depth (mm)
Mafic charnockite			
Length	1.00		
Breadth	0.79	1.00	
Depth	0.68	0.68	1.00
Acid charnockite			
Length	1.00		
Breadth	0.67	1.00	
Depth	0.26	0.58	1.00
Granite			
Length	1.00		
Breadth	0.43	1.00	
Depth	0.57	0.49	1.00
Granite gneiss			
Length	1.00		
Breadth	0.57	1.00	
Depth	0.43	–0.28	1.00
Sandstone			
Length	1.00		
Breadth	0.64	1.00	
Depth	–0.27	–0.32	1.00

surfaces, they occur at significant depths; for example, due to percolation of groundwater through fractures in the bedrock and growth of fungi, algae or lichens[13,14]. This usually results in changing the colour, texture, composition or hardness of the affected rocks. The different rock types and the persisting climatic conditions largely promote the weathering process[14,15]. As weathering proceeds, the individual grains become etched over highly weathered formations[14]. Algae and lichen occupy these pore spaces and flourish altering and etching the mineral for their metabolic activity and thus widening or deepening the pores[13–15].

Field observations revealed the inner surface of the tafoni as more weathered with greater flaking, granular disaggregation and exfoliation, and confirmed the possible key role of thermal stress on the formation. Exfoliation processes diminish the exposure and tafoni formation. The high wind speed on the outer surfaces enhances the drying rate.

The thermal regime within the tafoni is probably one of the key factors in their development. The rock surface temperature within the tafoni is clearly driven by the incoming solar radiation. The degree of weathering at some places like Tiger Cave (Figure 3 *a*), showed increased pore volume with higher pore size distribution, whereas stations such as Thiruvadanthai and Chengalpattu showed lower pore size distribution. These weathering patterns are indicators of variation in the degree of mineral alteration with depth along the east coast (Figure 4 *a–f*; Tables 1 and 2). However, the correlation coefficient matrix of the tafoni parameters developed on different rock types shows good to moderate relationship with length, breadth and depth. Length and breadth of the pores are not well correlated (Table 2) in granite, granite gneiss, acid and mafic charnockite. The depth and breadth of the pores are positively correlated. Tafoni developed in sandstone show poor correlation with depth, length and breadth; larger the pore length and breadth, smaller is the depth (Table 1). This supports the view that tafoni are more a phase process than continuous or endless corrosion.

From this study, it is evident that weathering of rock formations and tafoni development along the east coast of Chennai may be due to multiple causes: internal and external variations in temperature, moisture, wind velocity, structure and composition of the rock, and these are important parameters. Tafoni on rock boulders also indicate the prevailing wind direction, predominantly towards north-northeast, ensuring site preservation and survival of the shore temple facing north and east. Salt spray and salt weathering[16] on the rock-sculpted base as observed around the Mamallapuram area is a common feature (Figure 3 *b*). White powdery salt crystals on the granitic gneiss rock surface have altered minerals such as garnet and feldspar and have left a fine white powder as residue. Salt weathering has defaced many of the sculptures facing the ocean at Mamallapuram (Shore Temple). However, salt crystals inhibit the growth of tafoni.

Till date, there are no ages arrived on the natural surfaces of inselbergs and tors around Chennai. However, they are suggested to be several hundred thousand to a few million years old[17]. These surfaces show clear signs of granular disintegration, exfoliation and large tafoni. Mafic minerals weather much faster on modern stone structures in Tamil Nadu than felsic minerals in the same rock. Yet mafic charnockite (Figure 3 *a*) weathers more slowly than acid charnockite. Thin sections of the pits reveal alteration of the easily weatherable minerals such as feldspar, amphibole and pyroxene grains (Figure 4 *a–f*) releasing iron oxide. The altered mineral space remains as a micropore. These micropores eventually grow both in size and shape as macropores. Pits on the mafic and acid charnockites are flatter, with sharp edges (Figure 3 *a*) than those on the coarse-grained granite gneiss. This indicates that the feedback mechanism causes tafoni to deepen faster than weathering on the surface outside them. This is stronger than the resulting mineralogical difference due to weathering[6].

Rock surfaces, that are only a few hundred years old and well dated are not common around Chennai. The statues of stone buildings and stone memorial plaques that are nearly 30 years old, for example, around Chennai, revealed that the mafic minerals (mostly hypersthenes with minor oxides and pyrite) are often weathered up to 2–3 mm depth below the polished surface. On the other hand, polished stone surfaces 40 km or more inland, belonging to the last century, still appeared well polished with very few tafoni, so that they reflected identifiable images. Exfoliation has occurred rapidly close to the coast as observed near Mamallapuram (Shore Temple 9th to 10th century AD), but much more slowly inland. Thirty-year-old coastal monuments built close to the beach have minor but obvious differential weathering and extensive exfoliation damage with minor granular disintegration. Weathering pits are clearly due to differential weathering of mafic minerals such as those observed at the Muttukadu rock quarry of mafic charnockite.

The colonial graveyards at Pulicut and at St Mary's Church near Chennai range in age from the 1650s to the early 1800s. The tombstones at St Mary's Church graveyard in Chennai and Dutch graveyard in Pulicat have small but obvious pitting, oriented dominantly in the N–S direction. The English colonial graveyards found inland, also 200–300 years old, have no pits and still appear highly polished so that images may be seen reflected on their surfaces. Most of the headstones are composed of mafic charnockite. These rock surfaces are now covered with hundreds of tiny smooth spots per square metre that represent incipient tafoni. About 3–5% of the surface is pitted. The coastal and inland monuments that are a few hundred years old have very little exfoliation. There is also very little granular disintegration on the surfaces between the pits. The areas between the pits still appear polished, but not so well as to reflect a coherent image. The exterior walls of sections of the buildings that are between 1100 and 900 years old and temples we reexamined wherever possible (Table 1). It was found that these temples, like the colonial gravestones, are mostly composed of mafic charnockite and granite gneiss. The stones on the outside walls of the temples along the coast and inland have some differential weathering pits and exfoliated surfaces[2] and also tiny pits that are round in surface view and smooth in cross-section. There are generally a few hundred of these small pits per square metre[6]. Mafic minerals are always observed at the base of the large pits and usually at the base of small round pits and many a times lined with algae. Except in odd places where the roof has clearly been leaking for long periods of time, the inside walls of the temples have no weathering pits. The granitic gneiss making up the exterior walls is more exfoliated than charnockite and the flakes are both wider and thicker[6].

The famous Shore Temple of Mamallapuram shows some of the tafoni, exfoliation and granular disintegration that have disfigured this world-famous monument. After the great Indian Ocean tsunami of 2004, numerous ancient buildings which had been covered by sand along the coast of India, were exhumed by the backwash of the waves[19]. At Mamallapuram, only a few metres from the Shore Temple, several small, unfinished temples and blocks from the debris were found to be made of the same acid granite gneiss and were scoured in the same style as the Shore Temple. The base reliefs that had been covered with sand, perhaps for a thousand years, showed no visible disintegration, exfoliation or pitting. At the lower level, perhaps in the capillary zone, iron oxidation and salt precipitation were observed. A few boulders (Figure 3 *a* and *b*) and statues were badly damaged by pitting, fractures and exfoliation. The surrounding temple walls had only small, incipient tafoni similar in size and shape to the pits on the coastal colonial gravestones. The damaged statues were clearly made of different rock types such as granite and granite gneiss than the temples made on acid and mafic charnockite.

The modern sculptors and rock masons at Mamallapuram prefer carving mafic charnockite for a large part of their work. These rocks are capable of developing smooth, highly polished surfaces on which there are almost no pits or protrusions. Nearby menhirs at Sirudavur and Thiruporur (nearly 14 km northeast of Mamallapuram) are made of similar rocks that have larger pits. The cist (a tomb consisting of a stone chest covered with stone slabs), graves and dolmens (stone tables) were covered with red soil and only later subjected to weathering, whereas the menhirs of about the same age have been exposed to the elements since they were erected several thousand years ago. The menhirs are coated with lichen crust, yellowish in colour, above about 1.2 m, and there are fewer and smaller pits under the lichen. These lichens are symbiotic organisms that combine with fungi and algae and are powerful weathering agents, secreting chemicals called chelates that work to breakdown minerals. The tafoni at the top of the menhir are greater in diameter than at the bottom, strongly suggesting that not only is pitting slower under the lichen, but granular disaggregation and exfoliation as well. Tafoni are smaller and have developed more slowly under the lichen at the top of the menhirs, than on the same stone without lichen at the bottom of the same menhirs, some species of lichen protect the surfaces, whereas others attack them.

Our observations along the east coast of Chennai suggest that the tafoni pits vary in size and shape (pits, oblate to spherical). The pits on coastal mafic charnockite, acid charnockite and sandstone, however, become more hemispherical with time. Tafoni along Chennai to Mamallapuram begin within short time as differential weathering pits, with the angular shape of the more rapidly weathering dark minerals, especially amphibole, pyroxene and the feldspar. Within a few centuries the pits enlarge and develop smooth shallow surfaces. The tafoni pits are less on the British colonial gravestones that are few hundred years old and less than 1% on the surface of the inselbergs that are several millions of years old as compared to tafoni that cover the entire surface on the menhir rocks indicating differential weathering phenomenon. This indicates that the development of tafoni and the process of exfoliation are generally antagonistic to one another. The giant tafoni as observed around the Tiger Cave seem to have deepened faster and survived removal by exfoliation. Lichen, algae and salts due to sea spray occupy the pits and enhance the size of the tafoni, but some lichen and algae protect them from further pitting. This represents an irreversible condition on different scales. Interpreting tafoni on a local scale, landscape/form, requires a holistic approach towards the behaviour of elements that host these forms, such as fractures, blocks, slopes and watersheds.

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ACKNOWLEDGEMENTS. M.A. thanks Rajiv Gandhi Fellowship, UGC, New Delhi and the Head, Department of Geology, Anna University, Chennai for providing the necessary facilities to carry out this research work. H.A. dedicates this work to late Dr Stephen Norwick, Sonoma University, California, USA, for introducing this fascinating weathering feature.

Received 20 August 2014; revised accepted 21 April 2015