CAVERNOUS WEATHERING IN SIGRI AREA, LESVOS ISLAND, GREECE

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ABSTRACT

This study aims to explain the deriving forces of the cavernous weathering process in Sigri area on Lesvos Island. Cavernous weathering features are widespread on the Miocene volcanic formations in western Lesvos, that is known due to the presence of the Petrified Forest, a protected natural monument of great beauty.

The research area is situated Sigri, located on the western coast of Lesvos Island. Although the whole coastline seems to have such weathering features, the research was limited to the area beginning with the Plaka peninsula to the south of Sigri village and continuing all the coastline until the Sarakina peninsula.

We examine some well-developed tafoni to understand the tafoni development process. Statistical analysis showed that tafoni development is faster along the surface direction than in the depth direction. For all tafoni, group depth is either the smallest value or rarely the median. With some exceptions, width is the biggest and height is the median value. When the tafone dimensions lessen: the values approach.

Much evidence shows that tafone development is more a phase process than an infinite corrosion. Roughly, tafone development consists of three stages: initiation, development and destruction. During these phases, adjacent single pits merge to create big caverns. Finally, rock surface is destroyed by several stages of tafoni development and becomes ready for a new cycle.

Keywords: cavernous weathering, tafoni, case hardening core softening process, wind shaped cave, Petrified Forest, Lesvos Island

Introduction

Cavernous features have attracted human curiosity for thousands of years. A pictorial representation of tafoni from the 2nd millennium BC has been excavated in the prehistoric settlements of Akrotiri (Hejl, 2004). Cavernous weathering landforms have been noted and scientifically studied for over a century (Viles, 2005). Cavernous weathering features are erosional concave hollows, diverse in size and shape but mostly oval or spherical. Cavernous weathering features develop in a variety of rock types but are found mainly in crystalline, medium and coarse-grained lithologies including granite, sandstone, limestone or tuff. Their distribution on earth is highly variable. Although they are characteristic to the Mediterranean region they are found in many parts of the world, particularly in dry semi-arid environments but also hyper arid and cold arid desert environments as well as in the mild coastal zones.

Tafoni[1] (singular: tafone) is a Corsican word that means window. Tafoni are characteristic cavernous weathering features in various sizes and have arch shaped entrances, concave inner walls, overhanging margins and fairly smooth gently sloping, debris-covered floors.

The research was carried out in the area of Sigri village, at the western coast of Lesvos island, situated in North Eastern Aegean sea, which is well-known for its marvelous Petrified Forest. We examined some well-developed tafoni located in our research field which begins from the Plaka Park peninsula and continues for several kilometers along the coastline towards the Sarakina peninsula. Over 200 tafoni were measured in dimensions and locations and gained data was extracted to the tables and diagrams. For further research and exhibition, some tafoni were taken to the Petrified Forest Museum of Sigri.

The basement of the Lesvos Island consists of the broken pieces of Gondwanaland called the Cimmerian continent which moved towards Eurasia, compressed the space occupied by old Tethys and created a new ocean, the New Tethys, behind it. The geological structure of the island is characterised by a basement of alpine and pre-alpine rocks which were covered later by post-alpine formations, mainly early Miocene volcanic rocks, which dominate the central and western part of the island, as well as Neogene marine and lacustrine deposits. Lesvos is part of a belt of late Oligocene - middle Miocene calc-alcaline to shoshonitic volcanism of the northern and central Aegean Sea and western Anatolia (Fytikas et. al. 1984, PePiper and Piper 2002). During early Miocene (18.5-17 my) volcanic activity in Lesvos, a series of stratovolcanoes were present in the central part of the island. The volcanic centres: Lepetymnos, Vatousa, Anemotia and Agra were in a SW-NE direction because of the prominent crustal extensions and thinning.

[1] Plural form of tafone (Mellor *et al*., 1997)

Several volcanic rock units have been distinguished in Lesvos (Pe-Piper & Piper 1993). The Eressos formation is the oldest igneous formation, composed of porphyritic andesites interbedded with agglomerate and volcaniclastic rocks, and dated at 21.5 Ma. These lavas are 3 to 4 m.y. older than the main volcanic sequence of Lesvos consisting of andesite lavas, dacite lavas and basalts, ingnimbrites and a thick pyroclastic sequence. The Sigri pyroclastics, densest in the west of the island, are connected with the development of the Lesvos Petrified Forest and are overlain by several sheets of the Polichnitos ignimbrite, dated around 17.0 m.y. The Mytilene formation was defined by Pe-Piper (1978, 1980) as local basalt flows dated at 16.8 m.y. (Borsi, et al. 1972.). The Mesotopos dykes, dated by Pe-Piper (1978) at 16.2 m.y., are widespread throughout western Lesvos.

The climate of Lesvos Island is characterized by strong seasonal and spatial variations in rainfall and a high oscillation between minimum and maximum daily temperature changes. The rainfall data indicate that the island can be divided in two major climatic zones: the semi arid western part and the dry, sub-humid eastern part. The average annual rainfall in the western part of the island where Sigri is also situated is 414 mm. The reduced rainfall in the western part is mainly attributed to the high speed winds blowing in this area, having an average velocity of about twice as those in the central and eastern parts of the island (Kosmas *et a*l., 2000). The decrease in rainfall combined with the high evaporation demands (1533 mm per year) in the semi arid zone results in long periods lacking soil water. Erosion increases with the decrease of rainfall. Geomorphology also promotes the erosion, and the highest rates of soil degradation have been measured in areas with soils formed on pyroclastic formations (Kosmas *et al*., 2000).

In the coastal area of Plaka, the Sigri pyroclastic formation consists principally of pumice flows, mud flows, debris flows and stream conglomerates intercalated with air fall pyroclastic deposits. According to their sediment facies, a sequence of pyroclastic layers appears repeatedly in the coastal area. Within this sequence the following distinct layers can be determined:

a. An uppermost layer consists of coarse stream conglomerates, containing lava boulders, rounded to subangular cobbles of volcanic rocks and fragments of petrified tree trunks, in a fine-grained matrix of pyroclastics, strongly cemented by the circulation of silica rich solutions. This layer extends from 6-8m.
b. An underlying mud flow layer. The debris carried in the flow contains pyroclastics, primary lava flow debris, pumice pieces and epiclastic material. The matrix consists mainly of fine-grained ash.
c. The lower layer consists of fine-grained pyroclastic material and it is rich in coarse pumice debris. These are air fall pyroclastic deposits and their total thickness is less than 60-80 cm.

Cavernous Weathering

Cavernous weathering comprises of the entire concave erosional features in various sizes, shapes and destinations. The difficulties of limiting characteristic spatial scales of weathering forms were also mentioned by Turkington *et al* (2005). There is not any common classification for these features. Existing classifications mostly depend on the authors themselves and the criteria are set up arbitrarily. However many scientists agreed on two distinct features: honeycombs and tafoni.

Honeycomb-weathering features, closely spaced pits of centimetre to decimetre size surrounded by raised lips or walls, have a wide distribution on exposed surfaces of sandstone and some other rocks along coastal areas and in deserts. These distinctive weathering features also known as alveolar weathering, stone lattice, stone lace, fretting and, locally in Italy, as "sassoscritto" (stone writing) – are generally distinguished from tafoni, whose larger cavities have been eroded from granite and other rocks and characteristic overhanging lips or hoods have developed (Mcbride *at al.,* 2004). According to Uzun (1995) the diameters of alveoles usually range from 2 to 50 cm; the cavities exceeding 1m in diameter are then called tafoni. Honeycombs are the dominant cavernous weathering features in the research area in Sigri. They exist usually on the andesite outcrops but also on the pyroclastic sequences (Photo 1, 2). Tafone distribution is highly variable. They develop on the ground rocks, at the lateral surfaces of bedrocks or overhanging over the cliffs (Photo 3).

Tafoni features are classified according to their size, shape and location. The nomenclature for pitted and cavernous weathering was not harmonized throughout most of the twentieth century, but the word 'tafoni' has now become standard for all such pits, large and small (Norwick *et al.*, 2002). In this study 'tafoni' refers to all cavernous weathering features.

Tafoni formation

Wind is prerequisite for tafoni formation. It has two major effects on tafoni development. Firstly, weathering can continue occurring wherever the removal of waste keeps pace with rock weathering. There is a critical balance in budget that neither the floor is fully filled by debris nor is it completely removed.

Secondly, wind erodes the tafoni surface by deflation, the removal of loose, fine-grained particles by the turbulent eddy action of the wind, and by abrasion, the wearing down of surfaces by the grinding action and sand blasting of windborne particles. Wind effect on tafoni development is determined by wind speed, blowing frequency, tafoni position to the dominant wind sector and lithology. Wind speed and continuance are important factors because the amount of the floor sediments replaced by the wind is proportional to its speed and blowing duration.

Lithology is another important factor. Tuff and ignimbrites present well-developed samples due to their low resistance against wind erosion.

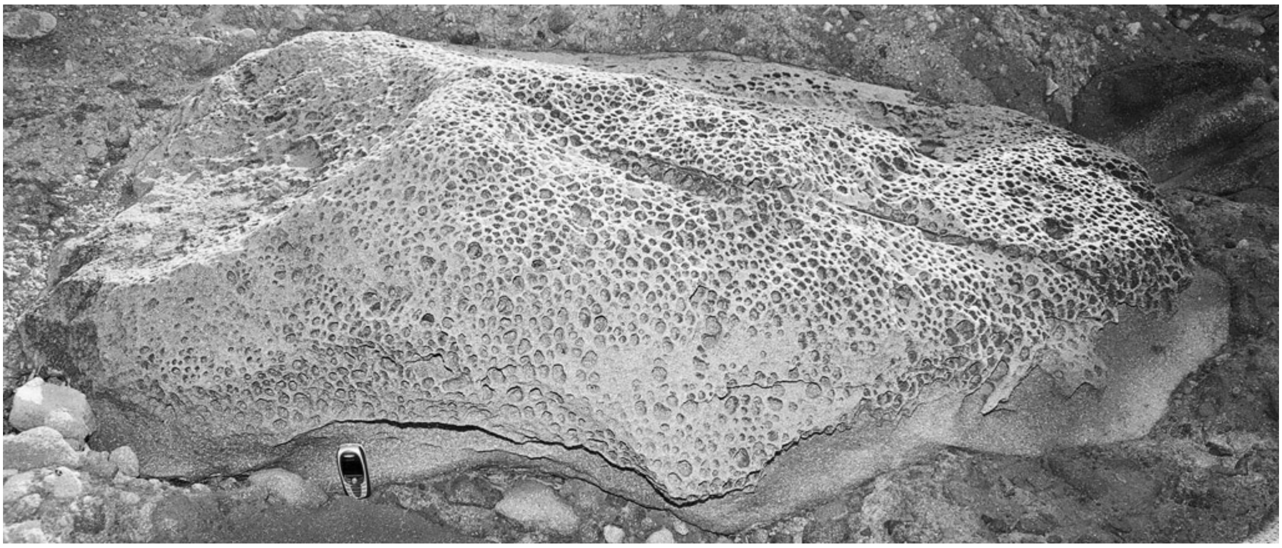


Photo 1: Honeycomb tafoni on an andesite rock near Plaka Park.

Photo 2: Honeycomb tafoni on pyroclastic layer in Sigri

Since tafoni are more widespread on the coastline or near the coast where there are huge amounts of salt, they are understood to be the result of salt weathering. Kircher (1996) emphasized the importance of the salt source vicinity. In Sigri area it was found that tafoni development is related to the distance from the sea. However, there are some samples out of the intense sea effect range but they are not widespread. The case hardening and core softening process is very significant on the tafoni of Sigri, which are not more than 10m from the sea. The lack of a huge homogeneous rock structure restricted the tafoni development. As a result, tafoni spread unequally along the coastal zone.

Salt weathering affects the rock both chemically and physically. A chemical process occurs when salt is a dissolution. In this case, hydration and dehydration are the most important chemical reactions. During the wet-dry cycle this process refreshes itself many times, resulting in a cumulative effect of disintegration.

Tafone geometry and distribution

More than 200 tafoni were measured in situ. Their dimensions and orientation were recorded. For a comprehensive approach tafoni were selected from different locations, size and rock formations.

Most of the tafoni were less than one meter in scale. Dimensional measurements comprise two different rock types. One of them is on the andesite boulders, the other one is on the pyroclastics. Responding to the increase of tafoni size we increased the sample area too. On the other hand, for small cavern groups sample amounts were determined arbitrarily. For sampling, minimum sample areas were used to reflect the tafoni development condition of the individual rock. Group sampling included 31 tafoni from 10 cm^2, 108 tafoni from 20 cm^2 and 57 tafoni from 100 cm^2 areas. The results of each group were sorted according to the increase in their height, width and depth.

For all tafone groups depth is either the smallest value or rarely equal to the width value. The 100 cm^2 sample area is on the vertical surface of a thick ignimbrite layer on the coast. Tafoni on this surface are relatively big compared to the other samples, occurring on andesite rocks. The depth values of these tafoni are always lesser than width and height values. With some exceptions, width values are always bigger than depth and height.

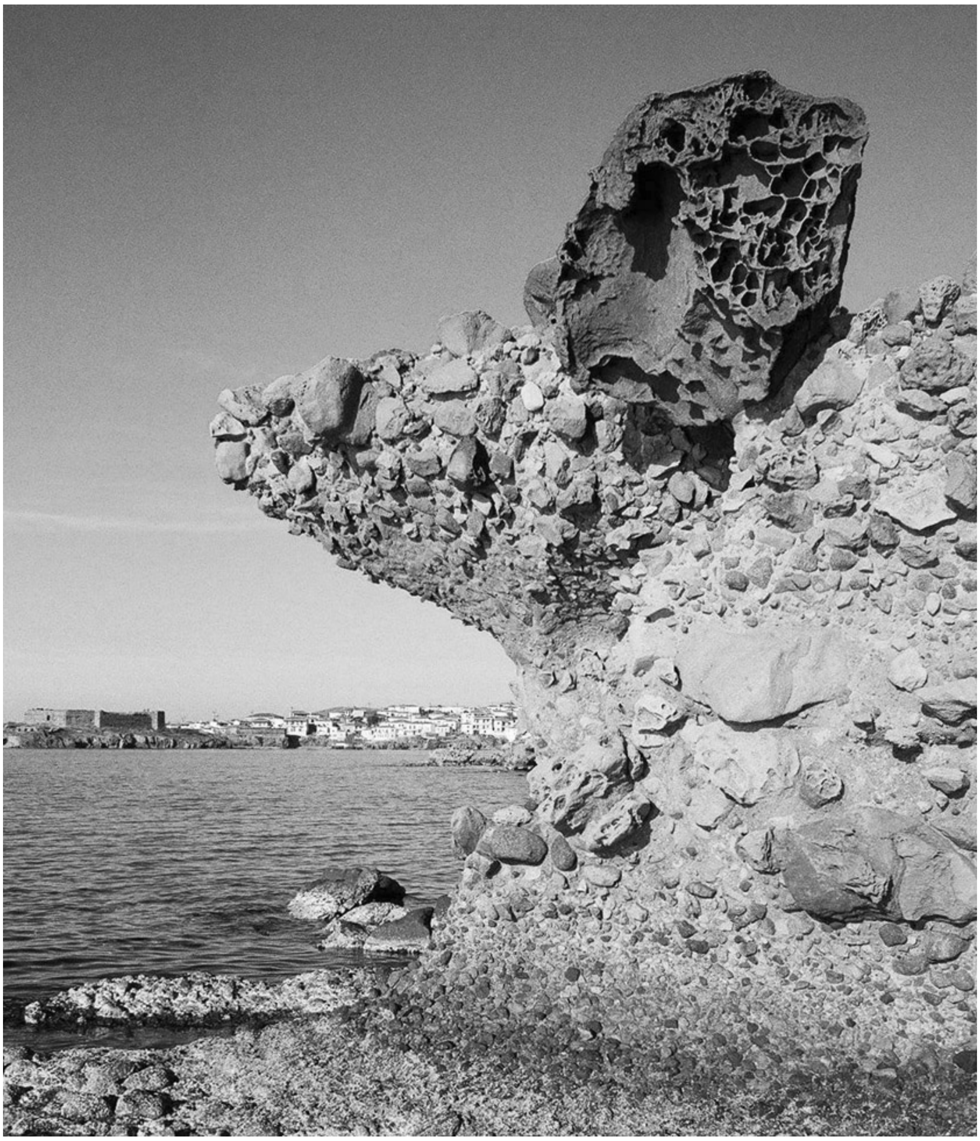
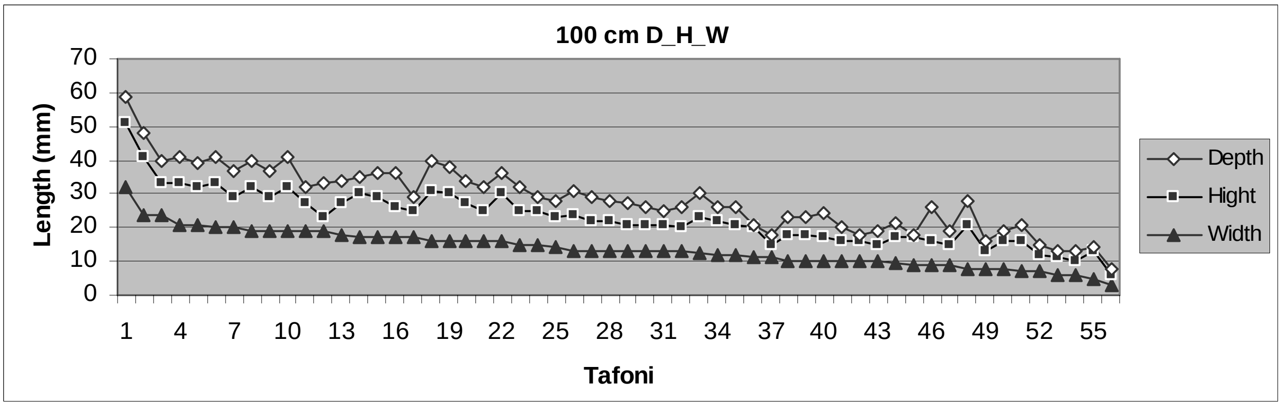


Photo 3: A side tafone (up right), Sigri village and Sigri Castle at the background

Table 1: Tafoni dimension for 100 cm² sample area by depth constant



As the tafoni become bigger, the difference between width, depth and height values increases. In 85% of these tafoni, width is at least twice as big as the height or depth values. Nevertheless, the motion of the depth values is more regular than width values (Table 1).

On the other hand 10 cm² and 20 cm² sample areas exist on the coastal zone on the andesite rocks, several meters from the sea. The tafoni on these rocks are in a horizontal position so they do not have height and width values. Instead each tafone has a long axis and a short axis.

The samples from both the 10 cm² and 20 cm² areas are sorted descending according to the depth value. (Table 2 – 3 - 4). These charts showed that unlike the 100 cm² surface, depth is not always the lowest value for these groups. Depth is almost the lowest value for the first smallest 55 pits which represent the initial stage of tafone develoment. But when the depth value reaches 1 cm then it is no longer the smallest value. In contrast, depth is the dominant value for the last 55 pits.

Table 2: Dimensional relationship of the tafoni of Sigri

	100 cm² sample area	**20 cm² sample area**	**10 cm² sample area**
Tafone amount	57 pieces	108 pieces	31 pieces
Depth percent	% 19.7	% 31.8	% 35.8
Height percent	% 32.1	(Long axis) % 37.2	(Long axis) % 37.1
Width percent	% 48.2	(Short axis) % 31	(Short axis) % 27.1
Depth (max/min)	10	20	20
Height (max/min)	6.3	(L. Max/S. Min) 16	(L. Max/S. Min) 16
Width (max/min)	10.6		

Table 3: Sorting of tafoni dimensions for 10 cm² are by depth constant

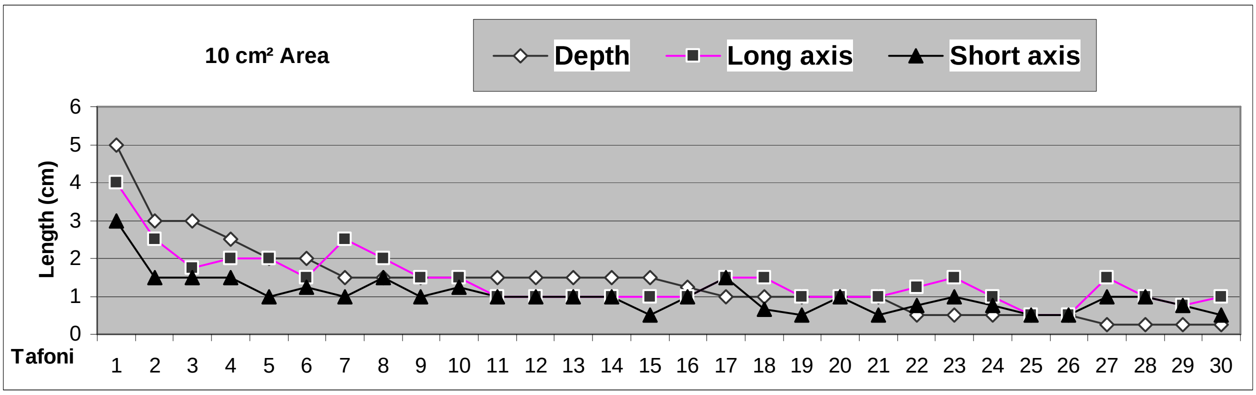


Table 4: Sorting of tafoni dimensions for 20 cm² are by depth constant

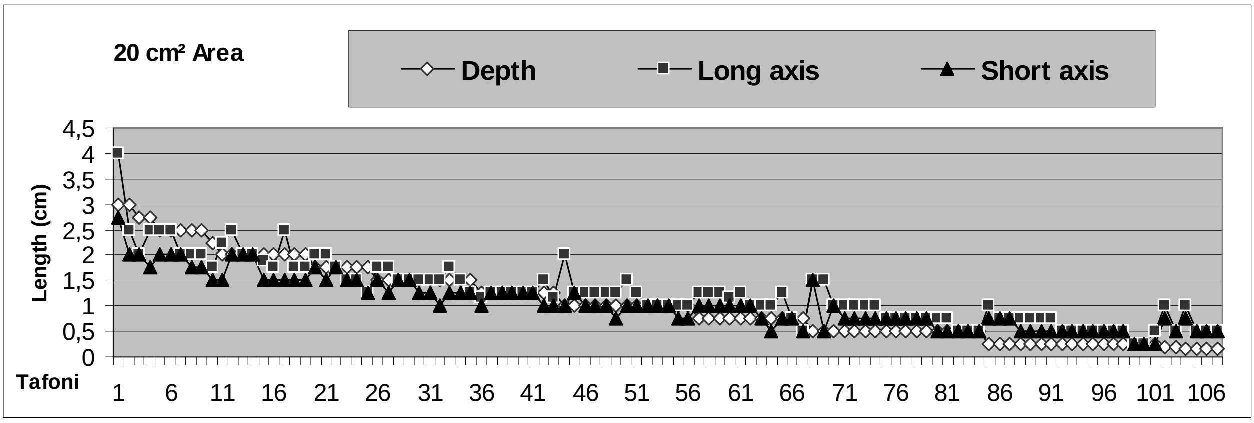


Table 5: Directional tandem of tafoni development and relationship between lichen cover and sea

Sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Tafoni	30° SE	E	15° SW	20° SW	10° E	30° SE	30° SE
Lichen	N-NW	N	10° NW	20° NE	30° NE	N	30° NW
Sea	W	W	W	W	W	W	W
Sample	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Tafoni	30° SW	S	S	10° SW	10° SW	40° SE	S
Lichen	30° NE	N	N	N	20° NE	50° NW	N
Sea	W	W	W	W	W	W	W
Sample	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Tafoni	10° SW	10° SE	S	S	S	S	S
Lichen	N	N	N	N	N	N	N
Sea	W	W	W	W	W	W	W

It was found that most of the tafoni faced to the south, which is the dominant wind direction in the area (Table 5). It must be pointed out that such regular tandem could not be found on the tafoni which are close to the sea and sea effect. Evaporation and insulation conditions seem to be responsible for directional tendency. Consequently, we can assume that tafoni structures in Sigri are mainly products of aeolian and chemical erosion.

Much evidence shows that on some rocks, tafoni development is more a phase process than an infinite corrosion. There are two factors restricting constant development. One of them is the limitation of the case hardening and core softening process, and the other one is tafoni merge. These two agents work together and they are interdependent. Tafoni merge is only effective in the development stage; however case hardening is effective both in the initiation and the development stage.

Tafoni merge shows itself by unusual values in long and short axis in the table. These extremes resulted from adjacent tafoni merge. Tafoni usually merge in horizontal or vertical directions and thus develop faster on the surface direction than in the depth direction (Photo 4). As mentioned before, depth is usually the lowest value. This may be the result of case hardening and core softening process.

The minerals in the rock dissolved by the seawater or the rainwater are carried to surface by capillarity. Due to the mineral movement towards the surface, a weak zone occurs beneath the surface. However salt dissolution and water penetration in the rock is limited by the rock structure and local factors. Thus the depth corrosion is restricted by the thickness of the loosened layer.

Conclusion

The study of tafoni structures on andesitic boulders located within Miocene pyroclastic formation in Sigri area showed that they are products of aeolian and chemical erosion and their development has a strong relation to the wind direction and the distance from the sea.

Statistical analysis showed that tafoni development is faster along the surface direction than in the depth direction. For all tafoni, group depth is either the smallest value or rarely the median. With some exceptions, width is the biggest and height is the median value. When the tafone dimensions lessen: the values approach. Local variations in the same zone may alter the dominant process resulting in the diversity of the features. Tafoni initiation and development is a process where more than one factor is effective. Tafoni distribution in

Sigri corresponds to the salt source. Most of the tafoni are situated on the coastal zone, not more than 100 meters away from the sea.

Case hardening, near surface cementation and surface vanish all refer to the outer crust development and the increase in resistance by salt drawn to surface by capillarity. However it was found that case hardening is also effective on the base of the tafoni structures. This can be identified when two tafoni begin to merge into each other.

Much evidence shows that tafone development is more a phase process than an infinite corrosion. Roughly, tafone development consists of three stages: initiation, development and destruction. During these phases, adjacent single pits merge to create big caverns. Finally, rock surface is destroyed by several stages of tafoni development and becomes ready for a new cycle.

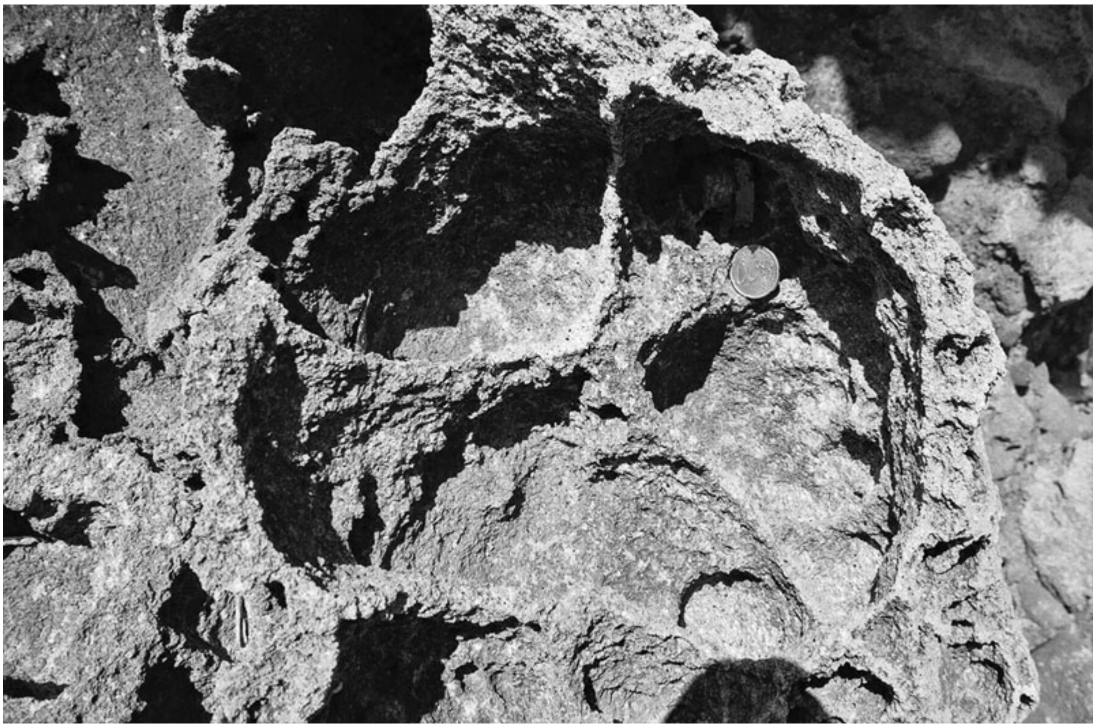


Photo 4: Tafoni enhancement by merge of adjacent neighbours.

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