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Inland notches: Implications for subaerial formation of karstic landforms —An example from the carbonate slopes of Mt. Carmel, Israel

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ABSTRACT

Inland notches are defined herein as horizontal "C"-shaped indentations, developed on the carbonate slopes or cliffs in the Mediterranean to semi-arid zones. The notches are shaped like half tubes that extend over tens or hundreds of meters along the stream valley slopes. In Mt. Carmel, a series of 127 notches have been mapped. On average, their height and width are 2–2.5 m but they can reach 6 m in height and 9.5 m in width. The geomorphic processes that create a notch combine chemical, mechanical, and biogenic weathering, which act together to generate initial dissolution and later flake weathering (exfoliation) of the bed, forming the notch cavity. We propose an epikarstic-subaerial mechanism for the formation and evolution of the notches. The notches are unique landforms originating from the dissolution and disintegration of the rock under subaerial conditions, by differential weathering of beds with different petrographic properties. The notches follow specific beds that enable their formation and are destroyed by the collapse of the upper bed. The formation and destruction alternate in cyclical episodes and therefore, the notches are local phenomena that vary over time and space.

1. Introduction

The term "notch" is used in the literature to describe horizontal C-shaped indentations that have been carved out on slopes or cliffs, regardless of their location or mechanism of formation (Reece, 2004) (Fig. 1). In Australia, such morphological features in granite are termed "flared slopes" (Twidale and Bourne, 1998), in the US as "rock shelters" and in France as "abris" (Laville et al., 1980).

Most previous studies attributed the origin of the notches to coastal processes, in which rocky shore faces are horizontally back-carved by organisms or by the sea waves. Coastal notches typically develop between mean low tide and mean high tide as a feature of "bioerosion" (Pirazzoli, 2005; De Waele and Furlani, 2013), but may also be found both above and below the tidal range and are accordingly considered to be "wave-cut" notches (Butrimovitch, 1972; Higgins, 1978). Their strong association with coastal processes has allowed these groove-like features to be used as indicators of past sea levels (Blanchon et al., 2002; Furlani et al., 2011; Pirazzoli and Evelpidou, 2013) or of tectonic uplifting (De Guidi et al., 2003; Benac et al., 2004). Coastal notches in carbonate rocks are dominated by weathering and dissolution, aided by microbial activity, commonly at the base of the cliffs.

Another category is "inland notches", comprising notches found in association with stream banks, tafoni, or karst landforms, as described below.

Notches associated with stream banks are formed by bedrock erosion, which involves mechanical breakage caused by the impact of transported particles (corrasion), by chemical reactions at the rock surface (corrosion), by hydraulic lifting and dragging (quarrying), or by the development of bubble cavities filled with high-velocity water (cavitation) (Morisawa, 1985). When these processes occur in bedrock banks, lateral lineation and grooves may form and enlarge into macroforms such as notches on stream banks. Most natural sandstone caves in stream banks began as surface river-cut notches at the foot of rock cliffs, although they may be found partway up the cliff as a result of subsequent downcutting (Lowe and Waltham, 1995).

Another notch-forming process is similar to the one creating cavernous hollows termed tafoni (Owen, 2013). Tafoni are large and small pits normally described not only in granular rocks, such as sandstone or granite, but also in limestone. The origin of tafoni has been attributed to various processes, such as salt weathering, temperature and humidity variations, drilling mollusks, or wind erosion (Robinson and Williams, 1994; Grab et al., 2011).

Corrosion notching can be formed at the surface of a standing pool and in foot caves of karst towers adjacent to alluvial floodplains (Bögli, 1980). When the water is nearly static, the slightest fluid density gradient may establish sharply delimited zones of accelerated corrosion (Ford and Williams, 2007). Notches can also form where humic soil

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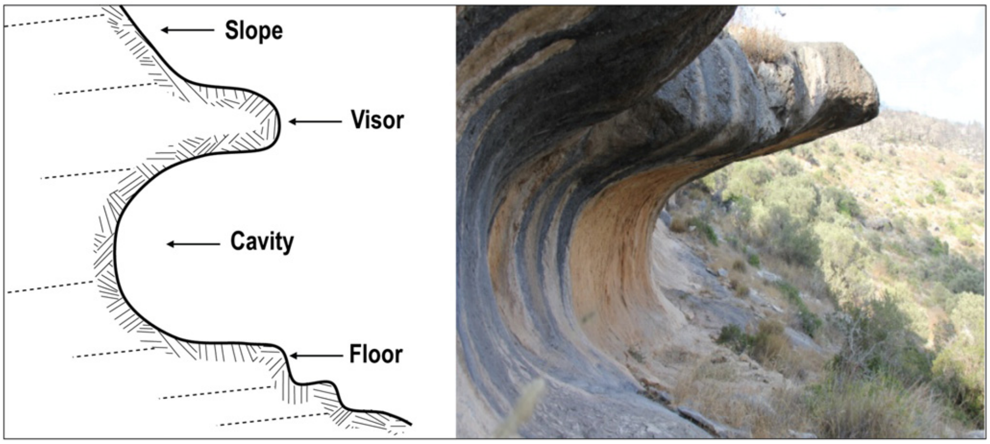

Fig. 1. Schematic section across a typical notch and its main components: visor, cavity and floor.

borders a steep or vertical limestone surface (Lundberg, 2013), as the rock is undercut by water rich in biogenic CO_2. Jennings (1985) described such a process in which water is held close against a limestone surface by an insoluble cover of sediment, which allows for dissolutional removal of bedrock irregularities and the notching of adjacent hillsides or banks: the notches are exposed as the sediment is stripped off.

Notches of karst origin are sometimes associated with the development of cave systems. Where caves are formed below the water table, notching can occur subsequent to a decline of the water table (Dublyansky, 2013). In some cases, notches are attributed to "protocave tubes" or "cave passages" formed by carbonate dissolution, under phreatic, vadose (free-flow), or alternating (floodwater) conditions (Taboroši et al., 2003; Frumkin and Fischhendler, 2005; Ford and Williams, 2007). Some nice examples are reported from sulfuric acid caves (Plan et al., 2012). Osborne (2004) used the term "pseudonotches" to describe features in dome-shaped solution cavities associated with cave passages with a circular cross-section.

A combined coastal and inland process can also be responsible for the formation of notches. Caves develop rapidly on coasts where the water table in diagenetically young limestone meets the sea. In these circumstances, the mixing of freshwater and saltwater couples with oxidation/reduction processes creates "flank margin caves". The mixed dissolution front carves out the rock at irregular intervals, leaving wide, low-roofed caves and notches between pillars of resistant rock (Mylroie and Carew, 1990; Mylroie and Mylroie, 2009).

Calcium carbonate stalactites and associated depositional features are common within notches, implying that they formed either in former caves breached by erosion, or by deposition of tufa under subaerial conditions. Tufa stalactites and stalagmites mimic speleothems and commonly grow actively in humid epigean settings (Taboroši et al., 2006). These deposits observed within notches were found to be complex structures, mediated by the development of subaerial biofilms (Jones, 2010).

Notches are a familiar phenomenon in Israel, where many have been shaped in the carbonate cliffs of the Mediterranean climate zone: notches are found in the Carmel and Galilee Mountains, as well as in the Judean Hills. Despite their wide distribution, little is known about their origin and the processes that shaped them. Few previous studies have mentioned their appearance: Michelson (1970) observed several notches on the carbonate cliffs of the western escarpment of the Carmel and attributed them to Plio-Pleistocene coastal erosion. The notches were found at elevations of 30 m a.s.l., at a maximum distance of 3 km from the present shoreline, pointing to a shore-related mechanism. Nir (1970) attributed notches of the Carmel to coastal erosion during Late Tertiary transgressions, or to karst dissolution. Butrimovitch (1972) mapped several notches at four main levels (50–70 m, 180–200 m, 280–320 m, 380–420 m) and stated that their appearance should be attributed to Lower Miocene up to Pleistocene sea levels. Based on these questionable observations, he concluded that two main phases of tectonic uplift occurred in the Carmel in the Late Miocene and the Pleistocene periods.

New field observations call these previous conclusions into doubt, as we will demonstrate herein. The aims of the present study are to investigate the distribution of the notches, the morphometric characteristics, and the mineralogical and geomorphological properties of the host rocks and to propose a hypothesis for the processes that lead to their formation.

2. Study area

Mt. Carmel covers an area of 230 km^2, extending northwest from the Samarian Hills towards the Mediterranean Sea (Fig. 2). Rising to an altitude of 546 m a.s.l., it is bounded by sharp escarpments: to the west, coastal abrasion created steep cliffs; to the northeast, the Carmel–Yagur fault line forms a steep escarpment; and to the southeast, the tilted beds descend gradually into a river valley. In general the slopes are steep; even in the stream valleys gradients exceed 50% at some places.

Mt. Carmel is composed mainly of marine carbonate rocks, deposited on the Tethys platform during the Mesozoic era. These sediments generally consist of limestone, dolomite, chalk, and chert. Facies changes are common and relate to the proximity of the area to the platform edge during the Albian to Turonian stages; however, the intense faulting makes it difficult to track these changes (Picard and Kashai, 1958).

The lower part of the sequence is formed by well-stratified dolomites of the Yagur Formation from the Albian stage, which accumulated under shallow platform conditions bordered by a narrow belt of barrier reefs on its western side. The "Main Chalk Complex" (Isfiya and Arqan Formations) overlies the Yagur dolomite (Picard and Kashai, 1958; Segev and Sass, 2009). The successive Bina Formation from the Turonian stage consists of limestones and is rather uniform in its southern part. To the north and northeast it can be divided into the Muhraqa and Sumaq members. The Muhraqa member consists of a limestone facies (which contains isolated rudist reefs and bioclastic beds) and a dolomitic facies. The Sumaq member is characterized by the alternation of limestone and marl beds and also contains some rudist patch reefs. Locally developed volcanic rock units, mostly pyroclastic, are common as lenticular intercalations in the chalk (Segev and Sass, 2009).

The Carmel–Yagur fault, a major branch of the Dead Sea Transform, offsets the Upper Cretaceous sedimentary rocks vertically by about 1000 m; Tertiary structures offset them sinistrally by about 1500 m. The steep slopes of Mt. Carmel along the trace of the fault, the displaced alluvial fans and stream channels, and the formation of shutter ridges and morphological scarps along the fault trace, all indicate significant

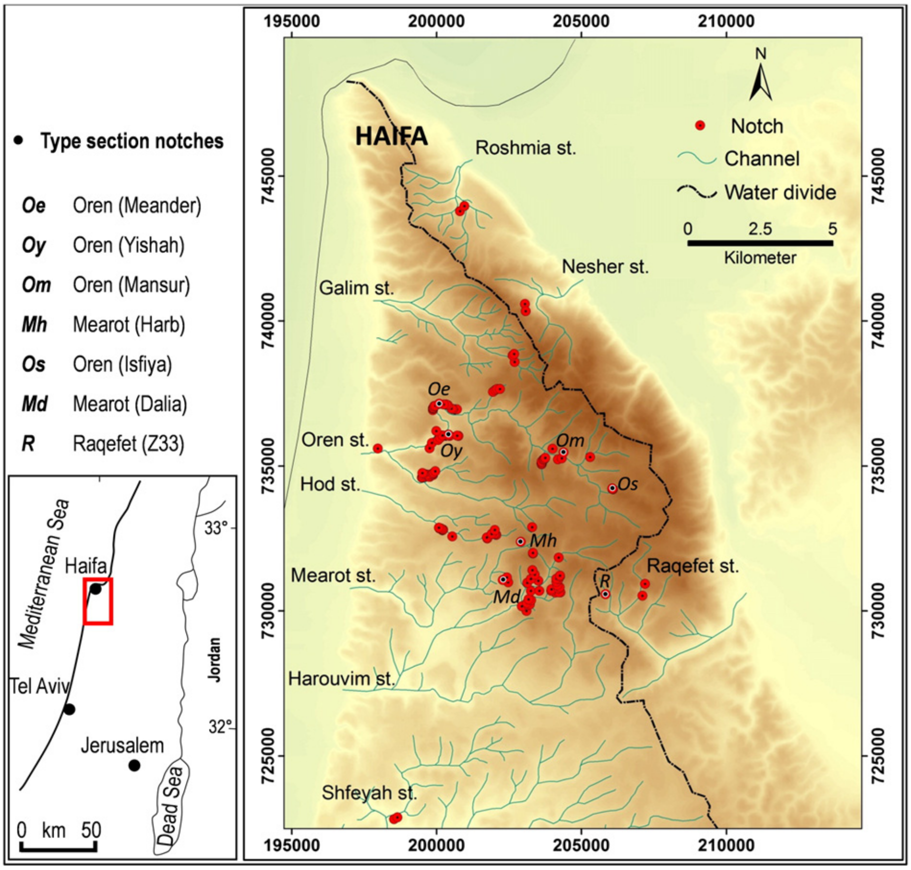

Fig. 2. Location of the study area and distribution of notches on Mt. Carmel.

vertical and horizontal movements during the Quaternary (Zilberman et al., 2007). Achmon (1986) calculated the Quaternary tectonic uplift to about 200 m, at an average rate of 100 m/Ma.

Under the present Mediterranean climate, the hard dolomites and limestones of the Carmel are subjected to intense chemical dissolution processes and exhibit typical morphologies of epikarst, caves, cavities, and speleothems. The rocks are covered by shallow soils of the terra-rossa type, combining a fine-grained texture with high stone content and rarely showing any profile development (Inbar et al., 1998).

The climate is Mediterranean, with cool rainy winters and hot dry summers. Mean annual precipitation ranges from 550 mm along the coastal plain to about 700 mm at the upper elevations. Mean annual humidity is 70%. The mean temperature is 11.2 °C in January and 24.7 °C in August. Mean annual potential evaporation exceeds 1500 mm/yr (Nevo et al., 1998).

On carbonate rocks, the activity of lithobiontic microorganisms is significant (Viles, 1995). Euendolithic microorganisms, which are very common in the eastern Mediterranean, were defined by Golubic et al. (1981) as organisms that penetrate into the interior of rocks, forming tunnels that conform to the shapes of their bodies. Endolithic green algae and chroococcoid cyanobacteria have been detected in the Negev Desert (Friedmann and Galun, 1974; Danin and Garty, 1983; Danin, 1986) as well as in the present study. Studies of the postfire recovery of lithobiontic microorganisms in Israel provide an example of the colonization of fissures and cracks in a very short time (Garty, 1990; Garty and Binyamini, 1990).

3. Methods

The methods used in this study are based on direct observations in the field, detailed mapping and measurements covering the study area, and detailed examination of the host rock characteristics in seven type-section notches, chosen on the base of lithology, accessibility, and found in all existent formations in the Carmel (Table 1). These include Schmidt Hammer (type N) tests to measure the elastic properties and rock strength (Katz et al., 2000; Goudie, 2006), a study of the structure and texture of the rocks using petrographic thin sections, and XRD analyses for mineral components. Phase analysis of the samples was performed by the X-ray powder diffraction (XRPD) method. The data were collected on a PANalytical Empyrean powder diffractometer (K_α radiation, $\lambda = 1.541$Å) equipped with an X'Celerator linear detector and operated at v = 40 kV, I = 30 mA.

In addition, measurements of the moisture and the temperature were carried out by drilling 19 mm holes to a horizontal depth of 150 mm in each visor (the upper protruding bed) and cavity in five out of seven of the type-section notches. The measurements were assessed once a month during the summer months (June to September) of 2013, using a 'Hanna Instruments' Hygrometer, with an HI 9565 sensor.

To test the potential solubility of the rock in the various parts of the notch, samples of equal volumes were taken from 5 notches of the type-section and dissolved in 5% HCl. We collected samples from the visor,

Table 1
The 'type-section' studied notches.

Notch	Drainage basin	Name	Location (ITM grid)	Geological formation
Oe	Oren	Meander	199938/737088	Yagur (dolomite)
Oy	Oren	Yishah	200456/736040	Yagur (dolomite)
Om	Oren	Mansur	204379/735471	Bina Muhraqa (limestone)
Mh	Mearot	Harb	202280/731064	Bina Muhraqa (limestone)
Os	Oren	Isfiya	206066/734208	Bina Sumaq (limestone)
Md	Mearot	Dalia	203145/732380	Bina Sumaq (limestone)
R	Raqefet	Z33	205829/730580	Arqan (limestone)

the cavity, and the floor of each of the selected notches. All samples had similar dimensions. The samples were added to a 300 ml HCl solution. At intervals of 30 min, the samples were taken out, rinsed in distilled water, dried, and weighed, and then returned to the beakers for further dissolution, up to 150 min.

4. Results

4.1. Distribution

A total of 127 notches were mapped and measured within the study area. Only 7 were observed east of the Mt. Carmel water-divide; the rest are located west of the water-divide, clustered in basins that drain into the Mediterranean Sea through the Carmel coastal plain (Fig. 2). Most of the notches are situated in three drainage basins (Oren, Haruvim, and Hod), which include 66, 30, and 16 notches, respectively. The notches follow specific beds. The cavity can be cut in two or more beds, one atop the other, but it never cuts through adjacent beds (Fig. 1).

4.2. Rock properties

4.2.1. Lithology

72 notches are developed in hard white crystalline limestone, especially the Muhraqa member of the Bina Formation. Microkarren are widespread in the Bina Formation, in the form of dissolution niches, little rills, spikes, pits and incised microchannels; 33 notches are carved into the hard, well stratified dolomite of the Yagur Formation; 20 notches are cut in the limestone horizons of the Sumaq member of the Bina Formation. Only two large and well-developed notches were observed in the Arqan Formation in Rakefet stream valley in the southern Carmel. All notches follow roughly the strike but are tilted between 1° and 5° opposite to the slope gradient. In very few cases the dip of the beds composing the notch are perfectly horizontal; in no case do the rock beds incline towards the valley.

As mentioned above, all the notches are developed in extremely hard carbonate rocks. These were measured using a Schmidt Hammer for their elastic rebound and the results were converted into compressive strength units (Table 2). All of the measured notches yielded very high compressive strength values, both on their visors and floors, as well as in the cavity walls, although the cavity walls rock is always slightly weaker than the rocks that form the visor and floor. Most values exceed 600 kg/cm^2; that is, they are close to those for cast concrete or hard and dense magmatic rocks. The Yagur dolomite values exceeded the measuring range of the instrument. Fig. 3 shows that, for all the measured notches, the beds that form the cavity walls of the notch are weaker than the neighboring beds of the visor and floor. These differences in the rock's elastic reaction are relatively small, ~15%–20%.

4.2.2. Mineralogy

Within the dolomites, the minor phase is calcite (a few percent); within the limestones the major phase is calcite and the minor phase is quartz (less than 1%). No significant differences were found between the composition of the visor-rock and that of the cavity-rock (Table 3).

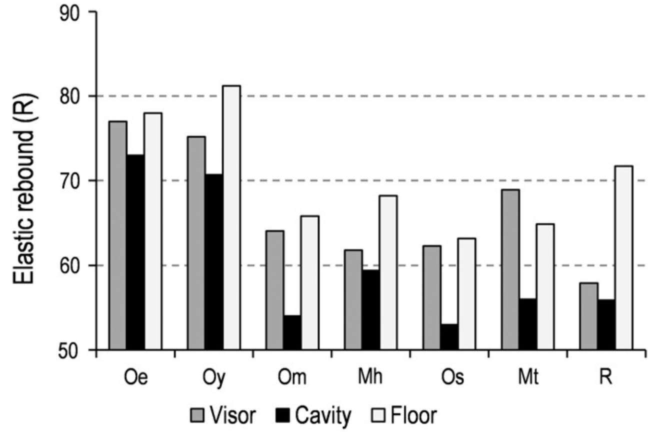

Fig. 3. The elastic rebound (R) measured by a Schmidt Hammer, obtained for the visor, the cavity and the floor of selected notches.

4.2.3. Potential solubility in HCl solution

The potential solubility results, shown in Fig. 4, indicate the percentage of the insoluble residue remaining after 150 min in the solvent. In general, the limestones reacted more rapidly and to a greater extent, with up to 85%–90% dissolution. In all cases, the rock sampled from the cavity of the notch is more soluble than that from the floor or visor, for both limestone and dolomite. In dolomite ("Oren Yishah" and "Oren Meander" notches), the difference between the visor and cavity may exceed 20%, indicating a change in the composition or petrographic properties of the two parts of the notch. The smallest differences between the cavity and the visor and floor beds, were found in notch Mt (from Mearot drainage basin), which is carved in Muhraqa limestone.

4.2.4. Temperature and humidity of the host rock

The temperature and humidity were measured at the visor and cavity of the notch, at a horizontal depth of 15 cm inside the drilled holes, and in the air (Fig. 5). It was found that the rock humidity remains high (above 85%) and relatively stable throughout the summer months, with no significant differences between visor and cavity. In addition, the humidity of the air in the cavity is typical of Mt. Carmel in the summer (30%–50%).

By contrast, the temperature of the rock in the visor and cavity shows major variations, as a function of the air temperature. The visor absorbs direct solar radiation and heats up faster than the cavity, which remains cooler. The temperature differences between the visor and cavity are on average 4.5 °C, but may reach 12 °C. The temperature at a horizontal depth of 15 cm within the visor averaged 3 °C lower than that of the ambient air, but the difference can reach as much as 10.8 °C. In the cavity, at a depth of 15 cm, the temperatures are cooler still and average 7.6 °C less than the ambient air, with a maximum difference of 16 °C.

Table 2
Elastic rebound (R) measured by a Schmidt Hammer, converted to pressure units (kg/cm^2). The two columns on the right show the percentage of difference relative to the cavity, calculated for R values.

Notch	Drainage basin (and name)	Geological formation	R, (kg/cm^2) * visor	R, (kg/cm^2) * cavity	R, (kg/cm^2) * floor	Ratio between visor and cavity [%]	Ratio between floor and cavity [%]
Oe	Oren (Meander)	Yagur (dolomite)	R = 77 (>75)	R = 73.7 (970)	R = 78.6 (>75)	>4.5	>6.6
Oy	Oren (Yishah)	Yagur (dolomite)	R = 75.2 (>75)	R = 70.7 (840)	R = 81.2 (>75)	>6.4	>14.9
Om	Oren (Mansur)	Bina Muhraqa (limestone)	R = 64.1 (615)	R = 54 (375)	R = 65.8 (665)	18.7	21.9
Mh	Mearot (Harb)	Bina Muhraqa (limestone)	R = 61.8 (550)	R = 59.4 (490)	R = 68.2 (730)	4	14.8
Os	Oren (Isfiya)	Bina Sumaq (limestone)	R = 62.3 (560)	R = 53 (360)	R = 63.2 (585)	17.5	19.2
Md	Mearot (Dalia)	Bina Sumaq (limestone)	R = 68.9 (770)	R = 56 (514)	R = 64.9 (635)	23.0	15.9
R	Raqefet (Z33)	Arqan (limestone)	R = 57.9 (785)	R = 55.9 (690)	R = 71.7 (920)	3.6	28.3

Table 3
Phase composition of the "type-section" notches. (V) = visor, (C) = cavity.

Notch	Major phase	Minor phase
Oe (V)	Dolomite ($CaMg(CO_3)_2$)	Calcite ($CaCO_3$) (8 wt.%)
Oe (C)	Dolomite ($CaMg(CO_3)_2$)	Calcite ($CaCO_3$) (5 wt.%)
Oy (V)	Dolomite ($CaMg(CO_3)_2$)	Calcite ($CaCO_3$) (7 wt.%)
Oy (C)	Dolomite ($CaMg(CO_3)_2$)	Calcite ($CaCO_3$) (1 wt.%)
Om (V)	Calcite ($CaCO_3$)	Quartz (0.2 wt.%)
Om (C)	Calcite ($CaCO_3$)	Quartz (0.45 wt.%)
Os (V)	Calcite ($CaCO_3$)	Quartz (0.2 wt.%)
Os (C)	Calcite ($CaCO_3$)	Quartz (0.2 wt.%)
Md (V)	Calcite ($CaCO_3$)	Quartz (traces)
Md (C)	Calcite ($CaCO_3$)	Quartz (0.3 wt.%)
R (V)	Calcite ($CaCO_3$)	Quartz (0.2 wt.%)
R (C)	Calcite ($CaCO_3$)	Quartz (0.35 wt.%)

4.2.5. Flake weathering

Field observations and petrographic thin sections indicate that the cavities of all the notches, those etched in dolomite as well as those in limestone, have a common denominator: the typical weathering of the back wall of the notch is flake weathering or exfoliation. This kind of weathering was not observed on the visor or floor beds and in general it is not characteristic of the carbonate outcrops of Mt. Carmel. However it is evident that flake weathering is typical of shallow walls and notch cavities. The size of the flakes varies from a few millimeters to several centimeters (Fig. 6).

4.3. Morphometric characteristics

4.3.1. Dimensions

The dimensions of the notches are very variable (Table 4). The maximum height ranges from 1 to 6 m, with an average of 2.5 m. The lowest elongated cavity defined as a notch is only 0.5 m high. No smaller notches were found or surveyed. It is possible that they exist but are covered by vegetation or soil; or they may simply not exist. The tallest notch has a height of 6 m. The width of the notches is similar to the heights, with an average of 2.1 m. The widest notch reaches 9.5 m. The length of the notches, too, varies from site to site, with an average of 25 m. The standard deviation is high, because the longest notch measured extends over 198 m (Fig. 7), while the shortest section defined as a notch is only 2 m long.

The ratio between height and width of the cavity is significant for the definition of what a notch is: this ratio must be at least 0.2. In the widest notches, the cavity may be 3 times as wide as it is high. No structures with a greater ratio were found.

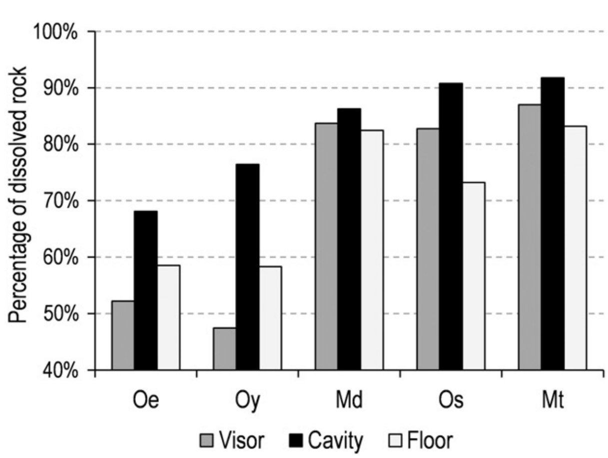

Fig. 4. Percentage of dissolved rock from selected notches after 150 min in HCl (5%) solution.

The distance between the notch and the nearest water divide above the notch is indicative to the dimensions of the drainage area of the notch. These distances, too, are variable; some notches are very close to the water divide (30–40 m), but most are located hundreds of meters downslope.

The notches' elevation above the channel was measured to determine whether there is any correlation between the notches dimensions and the channels below, given that the vast majority of the notches develop along the valley slopes. The average elevation above the channel is 56 m, with a maximum of 270 m.

In attempt to find a possible correlation between the notches and past sea levels, we studied the distribution of the channels by elevation (Fig. 8A and B) and searched for preferential levels, with a greater abundance of notches. It seems that the notches are scattered at all elevations, ranging from 56 to 420 m a.s.l. without any specific level. Moreover, approx. 50% of the notches are found at elevations exceeding 300 m a.s.l., far from the present sea level or any known Plio-Pleistocene sea level.

Nevertheless, many notches developed facing roughly westward, towards the Mediterranean Sea, which is the main source of humidity and winter storms in Israel. Fig. 9 shows that 65% of the channels face westward (azimuth of 181° to 359°). There were no significant differences between the northern and southern aspects (91°–180° and 271°–90° respectively): 51% of the notches face southward and 49% face northward.

The cross-section of the notches (expressed as the ratio of height to width) was plotted against geographical variables such as altitude, elevation above the channel, distance from the water divide, aspect, and slope. Fig. 10 shows the large dispersion of points in each graph, implying that the notch dimensions are not related to any of the environmental parameters listed. Hence, we infer that their origin is more likely related to the rock properties of particular beds and the notches occur as local phenomena on the slopes. Both small and large notches can appear at any altitude and any elevation above the channel, as well as at any aspect or slope gradient. Nor does the drainage basin area of a notch, expressed by the distance between the notch and the nearest water divide, affect its size.

4.3.2. Classification

The notches were classified into six types, based on their geometry and the morphology of the cavity (Fig. 11). "Shallow notch" (Fig. 11A) type include approximately 31% of the notches of the Carmel. They are characterized by a width–height ratio of 0.2–0.5 and frequently occur alongside wider ones. Commonly, "shallow notches" are segments of a notch whose visor collapsed and the scar can be identified by the lighter color of the visor, or by the fallen boulders found at the base of the notch. Fig. 11B shows "Developed notches", which include 58% of the notches in the Carmel. The width-to-height ratio ranges from 0.5 to 1.5. Another category is "Over-developed notches", one of which is shown in Fig. 11C. Only 11% of the notches in the Carmel fall into this group. The floor is extensive, usually horizontal or sub-horizontal and in some cases remnants of the activity of prehistoric humans are visible, similar to those found in the cave-sites of the Oren stream valley (Nadel et al., 2012). An over-developed notch combined with a thin visor-bed, favor the collapse of the visor and the destruction of the notch morphology (Fig. 11A). Fig. 11D and E shows tufa filling the cavity of a notch. In Fig. 11D the tufa is deposited along the line of water flow on the back wall of the notch, forming flowstone and draperies. The tufa accumulates in the rainy season, when water flows along the bare rock. The color of the active tufa is blackish, due to the presence of bacteria, algae, and other lithobionts. Tufa flowstones that are not currently active are lighter in color — grayish or yellowish. Occasionally, tufa stalactites and stalagmites grow within the cavity of the notch (Fig. 11E). In extremely rare cases they merge into columns, detached from the back wall. The tufa fill, both along the back wall of the notch and in detached stalagmites, is more typical of notches located on north-aspect

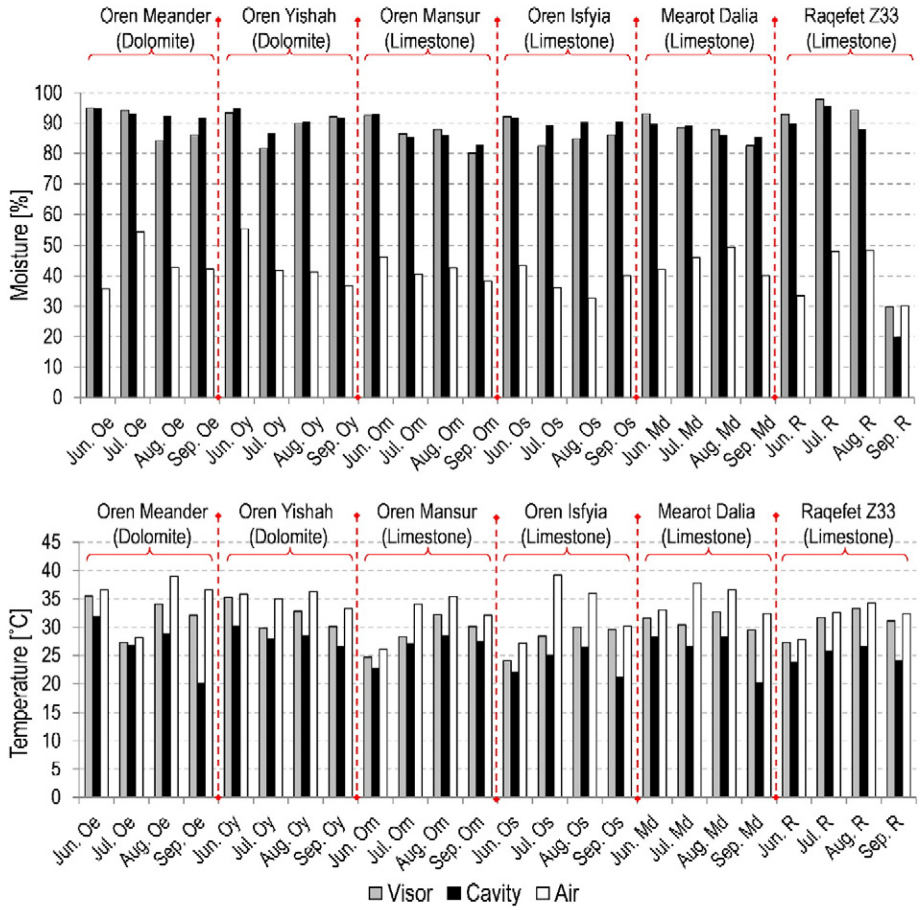

Fig. 5. Moisture and temperature measurements of the visor-bed, cavity-bed and air, performed during the summer of 2013. Rocks were measured at a horizontal depth of 15 cm.

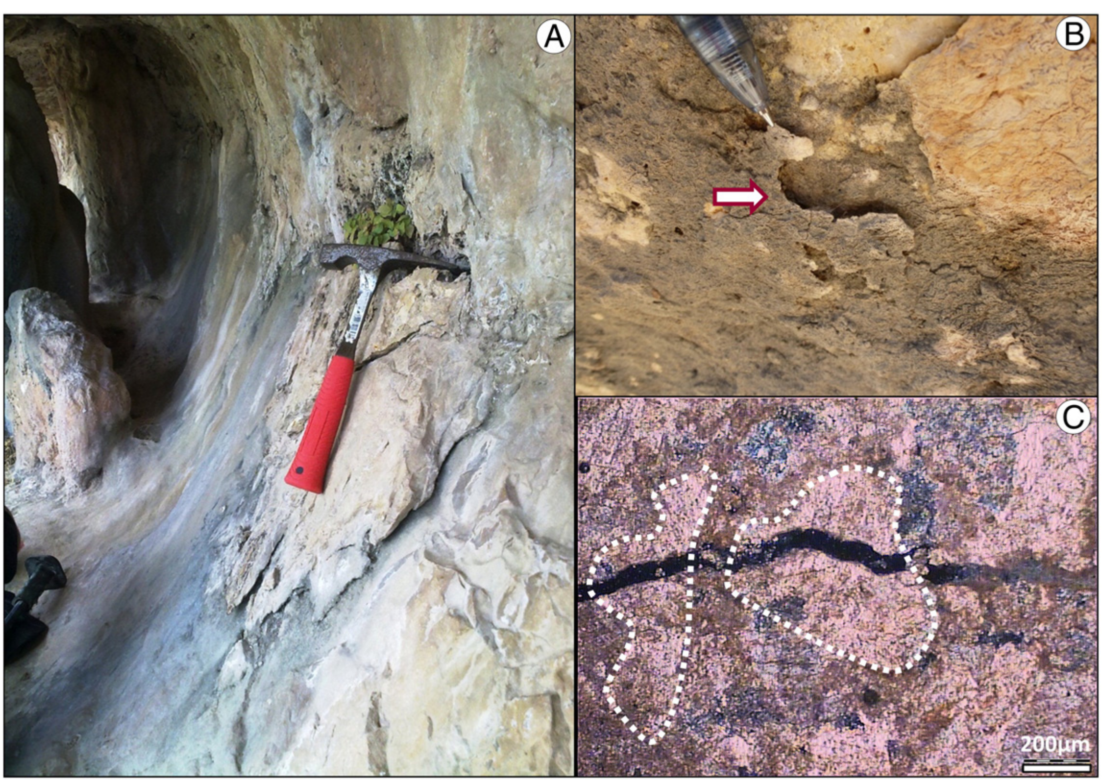

Fig. 6. Flake weathering (exfoliation) along the cavity wall: (A) A 15 cm thick flake detaches from the wall; (B) characteristic flakes of several mm thicknesses; and (C) a thin 5 mm deep fissure within the cavity skin. Note that the fissure cuts through the limestone grains, marked by dashed white lines.

Table 4
Morphometric properties of Mt. Carmel notches.

[Meters]	Average	St. dev	Max	Min
Height	2.5	1.3	6	0.5
Width	2.11	1.56	9.5	0.3
Length	24.7	26.4	198	2
Distance to water-divide	186.7	109	623	27
Elevation above channel	56.1	45.6	270	5
Slope	21.3	8.6	36	0.7
Width/height ratio	0.9	0.6	3	0.2

slopes, which are characterized by a more hydric environment — that is colder, more humid and with a more stable microclimate, allowing to a higher amount of water to percolate in the ground (Nevo et al., 1998). The largest notch-stalagmite in Mt. Carmel is 1.8 m high and 2 m in diameter at its base (Fig. 12). "Double notches" (Fig. 11F) occur where two notches have been carved out one above the other, with only a thin layer of rock (0.5–1 m) separating them. The height of the entire structure may reach 10 m. Double notches are comparatively rare in the Carmel; we have observed them only in the Kelah stream valley, the Haruvim stream valley, and the upper reach of the Oren stream valley. There are very impressive double notches in Burqa stream valley in Samaria, developed in the dolomite rocks of Weradim Formation (Fig. 13), and near the village of Salt, in Jordan (Fig. 14).

5. Discussion

5.1. Mapping, profiling and geomorphometry

Most notches in the Carmel are developed in three carbonate rock units: in the dolomitic Yagur Formation of the Albian stage and in the limestone beds of Muhraqa and Sumaq members of the Turonian stage. The notches are always carved in hard and dense rocks, resistant to directed compression, similar to those of hard magmatic rocks or rigid concrete. They are associated with one specific bed on the slope, even where this bed is folded or faulted. They disappear and reappear on a different slope when this bed is exposed again.

The morphology of the notch landform varies as a function of the thickness of the visor-bed. Where the visor-bed is thick (exceeding 1 m) the notches are commonly wide; the underside of the visor-bed and the floor are flat and the rounded concavity that is so typical of notches is evident only on the back wall of the cavity. In notches of this type, the beds tend to be horizontal or dipping slightly (0°–2°) against the slope (Fig. 15A). Such notches belong to the "Over-developed notch" type (Fig. 11C) and are found in the Carmel mainly in the

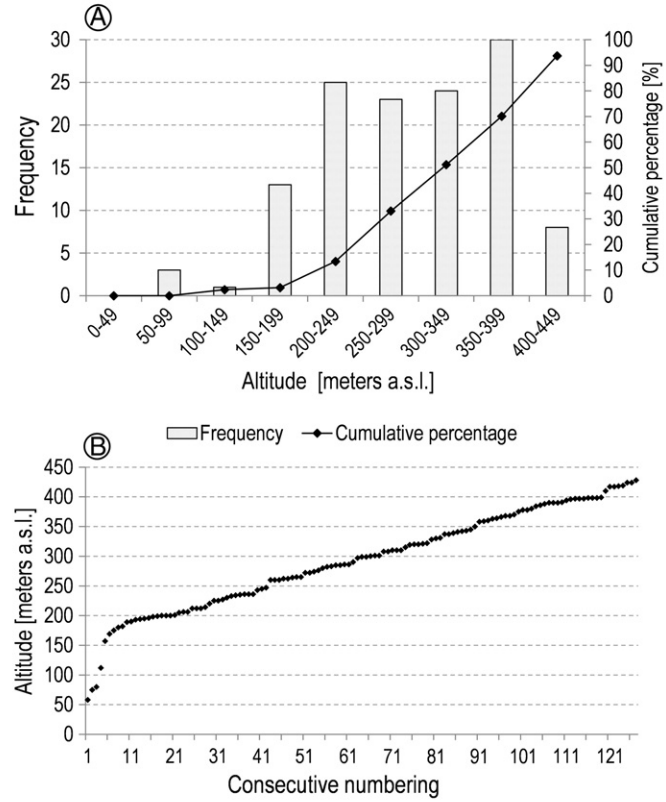

Fig. 8. Distribution of Mt. Carmel notches by altitude. Note that 80% of the notches are found between 200 and 400 m a.s.l.; 50% of the notches are found above 300 m a.s.l.; no preferential levels were observed. (A) Frequency histogram and cumulative frequency by altitude; (B) all notches, ordered by consecutive numbers and altitude.

Fig. 7. The longest notch of Mt. Carmel, cut into dolomite, is associated with one specific bed on the slope, folded and faulted. Extending almost 200 m, it is 3 m high, 2 m wide, and 45 m above the stream channel.

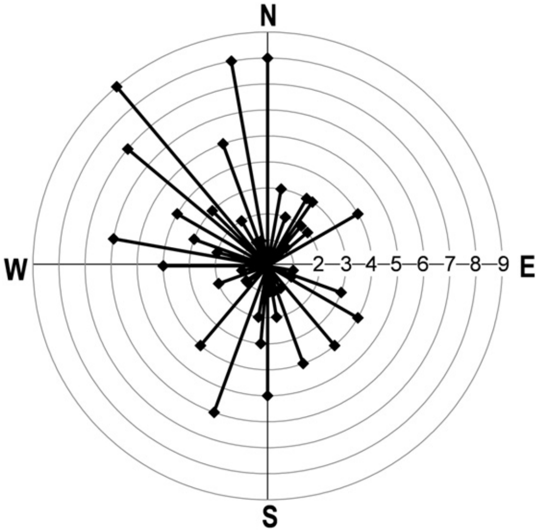

Fig. 9. Notches distribution by aspect.

Bustan stream valley (a tributary of the Oren stream valley) and near the Yishah cave.

Where the visor-bed is thinner than about 1 m, the cross-sectional profile of the notch is curved from the underside of the visor-bed all the way to the floor, in the shape of the letter C. The beds are commonly inclined at an angle of 1°–5° away from the slope (Fig. 15B) and the notches tend to be shallower. This type of notch is more common than the type with thick visor-beds and can be found throughout the Carmel.

5.2. Possible origins of the notches and their connection to the research findings

As mentioned, the worldwide literature refers to notches of coastal, ‘flank margin’, stream bank, or karst origin. Can one of these formerly studied mechanisms explain the formation of the notches in the Carmel?

Field observations of the Carmel notches and their surroundings discard the possibility that they are of coastal or stream bank origin. First, the morphology and dimensions of the Carmel notches are not similar to the above-mentioned types. Coastal notches are smaller and shallower; they are not subcircular and certainly are never found hundreds of meters above sea level as in the Carmel, or at 700 m a.s.l. as in Burqa stream valley (Fig. 13), or at 900 m a.s.l. in Jordan (Fig. 14). Nor does the distance of the Carmel notches from the coast fit with the hypothesis that they are associated with the shore of the Mediterranean Sea, given that similar ones are located on the slopes of Samaria Hills, or even in Jordan, at a distance of more than 100 km from the sea. Moreover, the morphology and profile of the Carmel notches are similar at all elevations, and their shape and size are not statistically related to certain altitudes.

Nor can the notches have a coastal origin, because the rate of tectonic uplift of Mt. Carmel is slower than the rate of erosion of the slopes. It is difficult to say when the present summit of the ridge formed the coastline, but a calculation based on the known uplift rates indicates that Mt. Carmel had already been uplifted during the Pliocene and perhaps even earlier (Achmon, 1986; Begin and Zilberman, 1997), meaning that outcrops found currently at elevations of 300–400 m were already uplifted by that time.

Moreover, if the Carmel notches marked out the Pliocene or Miocene shoreline as Butrimovitch (1972) stated, their morphology would not have survived to the present, as the erosion would have removed them entirely or at least modified their appearance. The rate of denudation of the Mediterranean region in Israel has been estimated in 10–20 m/Ma (Gerson, 1976; Ryb et al., 2014), while the rate of slope

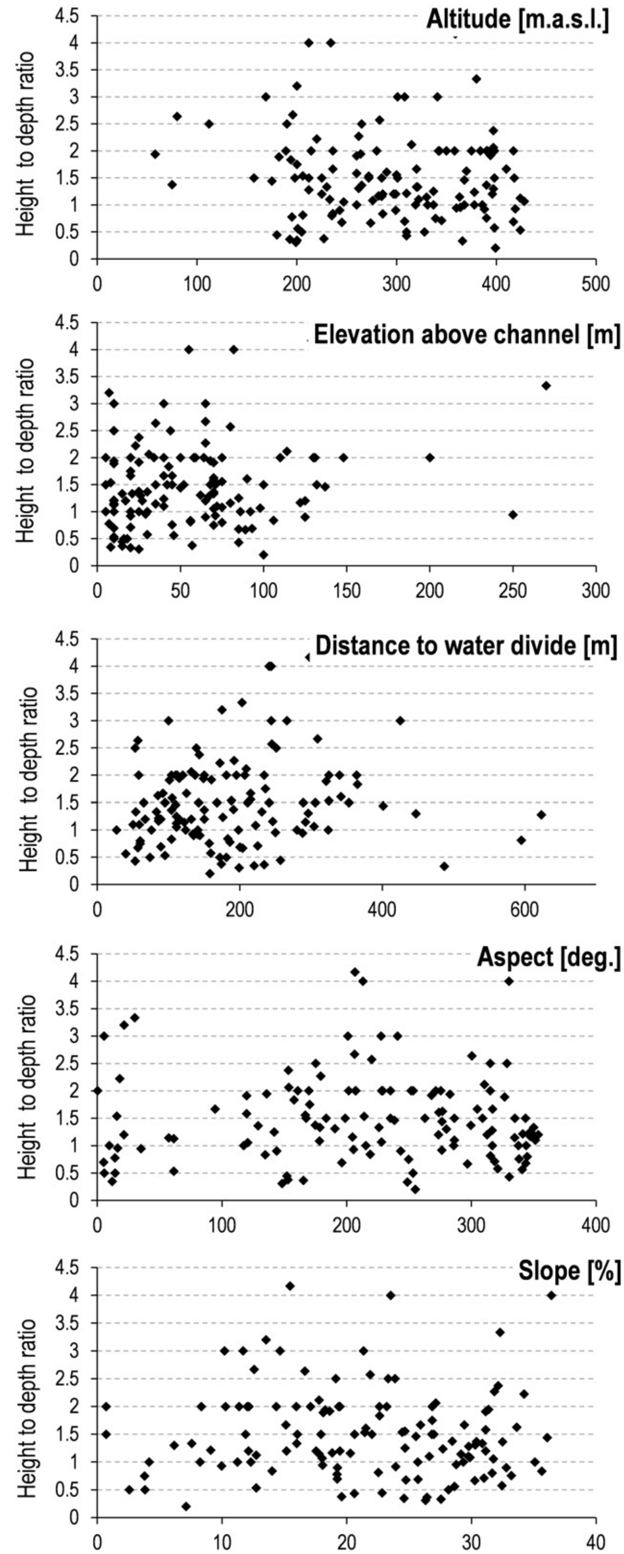

Fig. 10. Height to width ratio of the cavity plotted against environmental variables. No significant correlations were found.

retreat was calculated as max. 200–1000 m/Ma (Begin and Zilberman, 1997). At these rates, no Pliocene or Miocene morphological features would survive.

Similar arguments can be brought against a possible stream bank mechanism. Although most of the notches in the Carmel follow the valley slopes, some do not. There are notches that also cut along the escarpment of the Carmel–Yagur fault, facing northeast. Moreover,

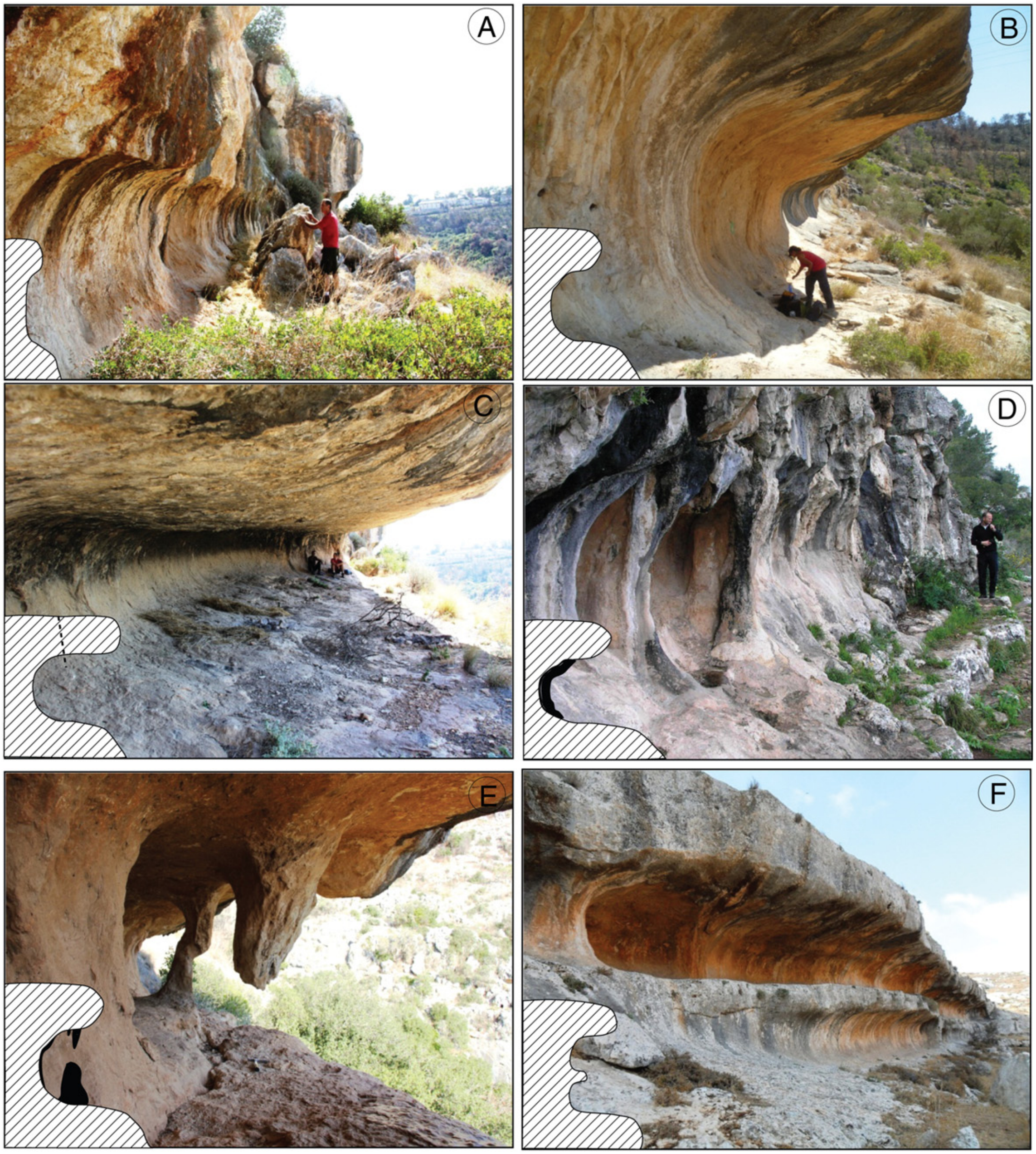

Fig. 11. Six types of notches represented by their morphology and internal deposits. (A) Shallow notch; (B) developed notch; (C) over-developed notch; (D) tufa infill within the cavity; (E) large tufa stalagmites developed within the notch; (F) double notch structure.

stream-bank notches commonly do not stretch for tens and even hundreds of meters; they are short, adjacent to the stream bed, and certainly do not appear tens or hundreds of meters above the active channel, as in the Carmel valleys.

Another consideration is that the notches follow the same beds and do not cut through adjacent beds. Had they been formed by the past shorelines or streams, we would expect to see them cutting through several beds, whatever their type or tilt. In the Carmel we find quite a few cases where the notch is inclined to one direction (following the bedding), while the channel flows in the opposite direction. For example, in the upper Oren stream valley, the notches follow the limestone beds that incline to the northeast, whereas the channel flows southwest (Fig. 16).

Nor can the notches derive from underground conduits, although phreatic conduits tend to follow the strike of the beds. Were they underground conduits uncovered by erosion and cut by the stream valleys, we would see a network of caves and passages connecting with them at any angle; but notches are usually superficial landforms, with no connection to caves, large conduits, or other passages. Although small phreatic conduits (of several cm in diameter) are in places draining into the notches cavities, not even one large connected passage was found in the Carmel. The morphological uniformity, the fact that the notches appear only parallel to the slopes, and their development only within specific beds, strengthens the hypothesis that the notches were created by slope erosion processes.

5.3. The mechanism proposed for the formation of the Carmel notches

The process of formation of a notch requires beds of hard carbonate rock, limestone or dolomite, exposed on the slope and lying horizontally or dipping slightly (1°–5°) against the slope. The upper bed (the visor) is harder and less soluble. The bed below it (the cavity) is weaker and less pure, but more susceptible to dissolution. Although the differences in

Fig. 12. The largest tufa stalagmite known in the Carmel. The underside of the visor-bed is dark due to abundant microorganism colonies. Tens of small stalactites are seasonally dripping (Arbel et al., 2008).

the hardness and purity of the two beds are small, they are essential for the formation of a notch.

Runoff penetrates along the contact between the two conformable beds: the visor and the cavity. It is quite likely that this initial process takes place when the slope is covered with soil, as soil water enriched with CO_2 increases the aggressiveness, enhancing dissolution. In this first stage, a narrow curvature is formed at the base of the outcrop, within the more soluble bed, forming a proto-notch. This initial cavity favors a special microclimate: being more shaded, temperature decreases within the cavity, improving the conditions for condensation and also the humidity regime on the cavity-rock surface.

Within the cavity bed, fissures and cracks are formed parallel to the surface. These are well known from direct observations, as well as from the results of the Schmidt Hammer tests; the cavity rock was always weaker, enhancing the formation of a flaked structure that continues inward, at an unknown horizontal depth. These fissures favor the introduction of water, dust, clay particles, and living organisms—bacteria, algae, and fungi—as well as growth of plant roots which enhance bioerosion processes (Fig. 17). Endoliths and other living organisms are common also on the visor and floor units, but are always found underneath flakes, within the cavity. Fungi and thin roots are commonly found even at depths of several centimeters under the flakes (Fig. 17B), while endolithic communities are frequently observed several μm to several mm within the rock (Fig. 17D). We propose that all of these living organisms together with dust and clay particles work to expand the fissure until it creates a flake, whose thickness can vary from a few

Fig. 13. Double-notch in the Burka stream valley (Samaria) cut in the dolomitic Weradim Formation. The notch is faulted by a small reverse fault. Note the truncated slope above.

Fig. 14. Notches near the village of Salt, Jordan (32°2′N, 35°44′E), 900 m a.s.l. and 100 km away from the Mediterranean Sea. The resistant visor-bed protrudes through the soft marly carbonate slopes.

millimeters to several centimeters. At the end of the process of expansion and separation, the flake breaks off the back wall of the notch. This style of weathering, known as flake weathering or exfoliation, is presently the main active mechanism within the cavity of the notches.

We propose that the semi-circular profile takes shape at an early stage in the formation of the notch as a result of water flowing along and within the back wall and flaking (Fig. 18A). The form that develops as the cavity enlarges further is a function of the interaction between

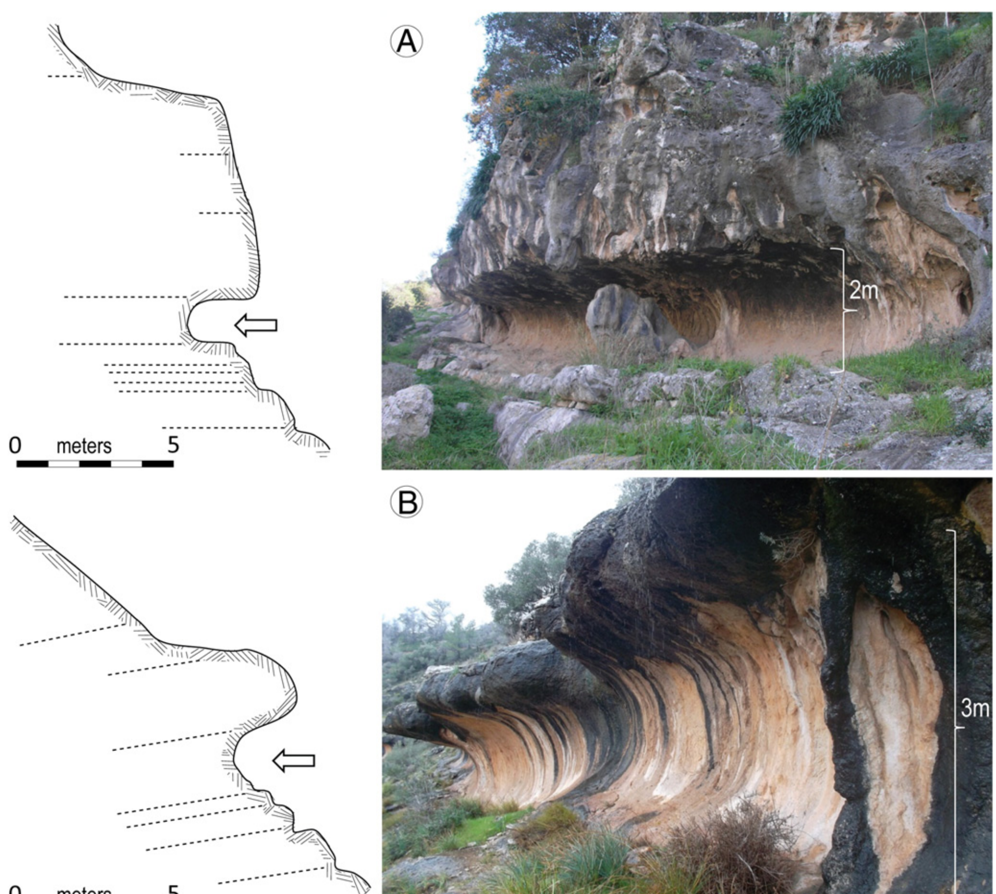

Fig. 15. Typical morphologies of notches are formed in accordance with the thickness of the visor bed. (A) A thick horizontal visor favors the development of wide, horizontal cavities underneath: (B) Where the visor beds are thin (<1 m), the cavity cross section is more rounded, and usually shallower, as the visor is more susceptible to breakdown.

Fig. 16. A double notch structure in Sumaq limestone. The beds and the notches dip northeastward (marked by white arrows), while the channel flows southwestwards (black arrows).

passive variables and active mass-transfer variables (such as lithological/structural variables), as well as fluid velocity and dissolutional potential. As a result, the minimum-friction cross-section (a circular shape) is maintained even when the cavity extends for several meters (Fig. 18B).

Under shaded conditions, especially on north-facing slopes, where water regime is most favorable, stalactites and stalagmites made of porous tufa can be deposited. They cover the back wall of the notch or grow inside the cavity and their thickness may reach tens of centimeters (Fig. 18C). Large stalactites and stalagmites, too, can grow in the cavity

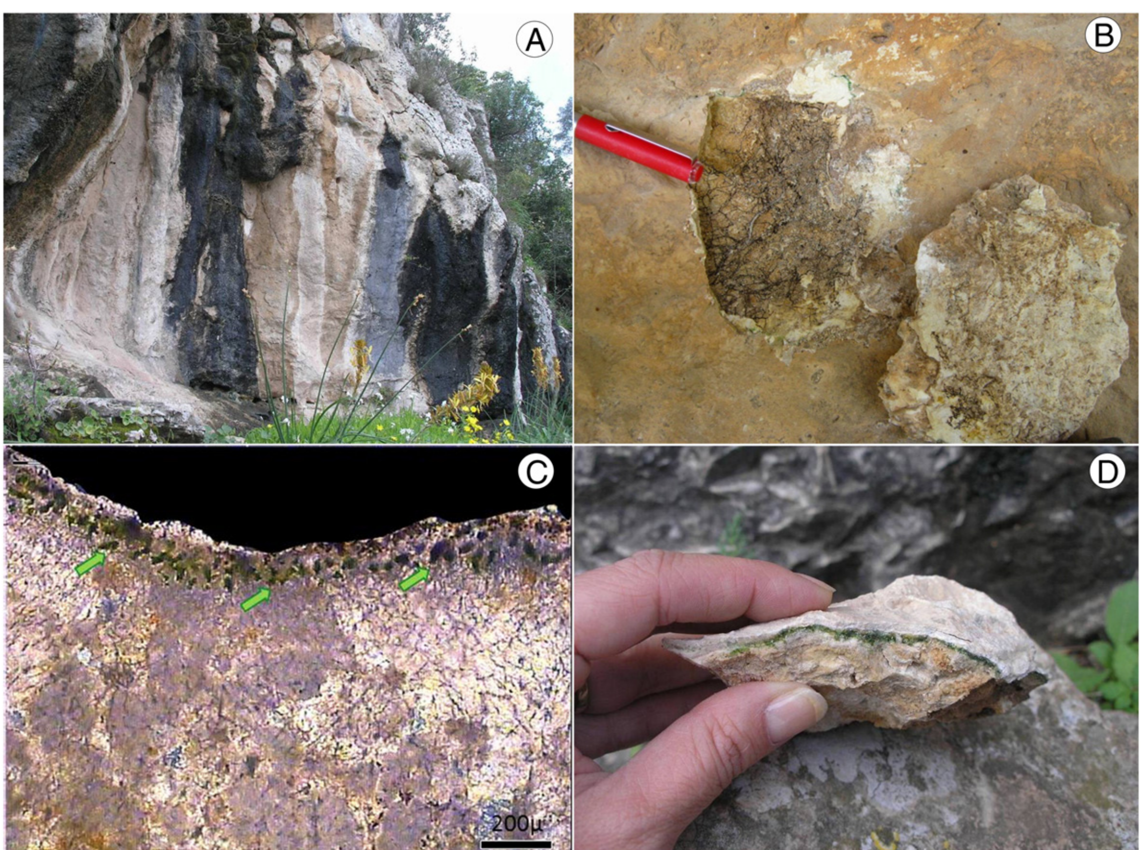

Fig. 17. Bioerosion: Chasmoendolithic microorganisms develop within the cavity. (A) The black and white streaks indicate cyanobacteria activity. The dark black stains change to light brown during the dry season; (B) roots are common underneath partially exfoliated flakes; endolithic communities are frequently found several μm (C) to several mm (D) within the rock.

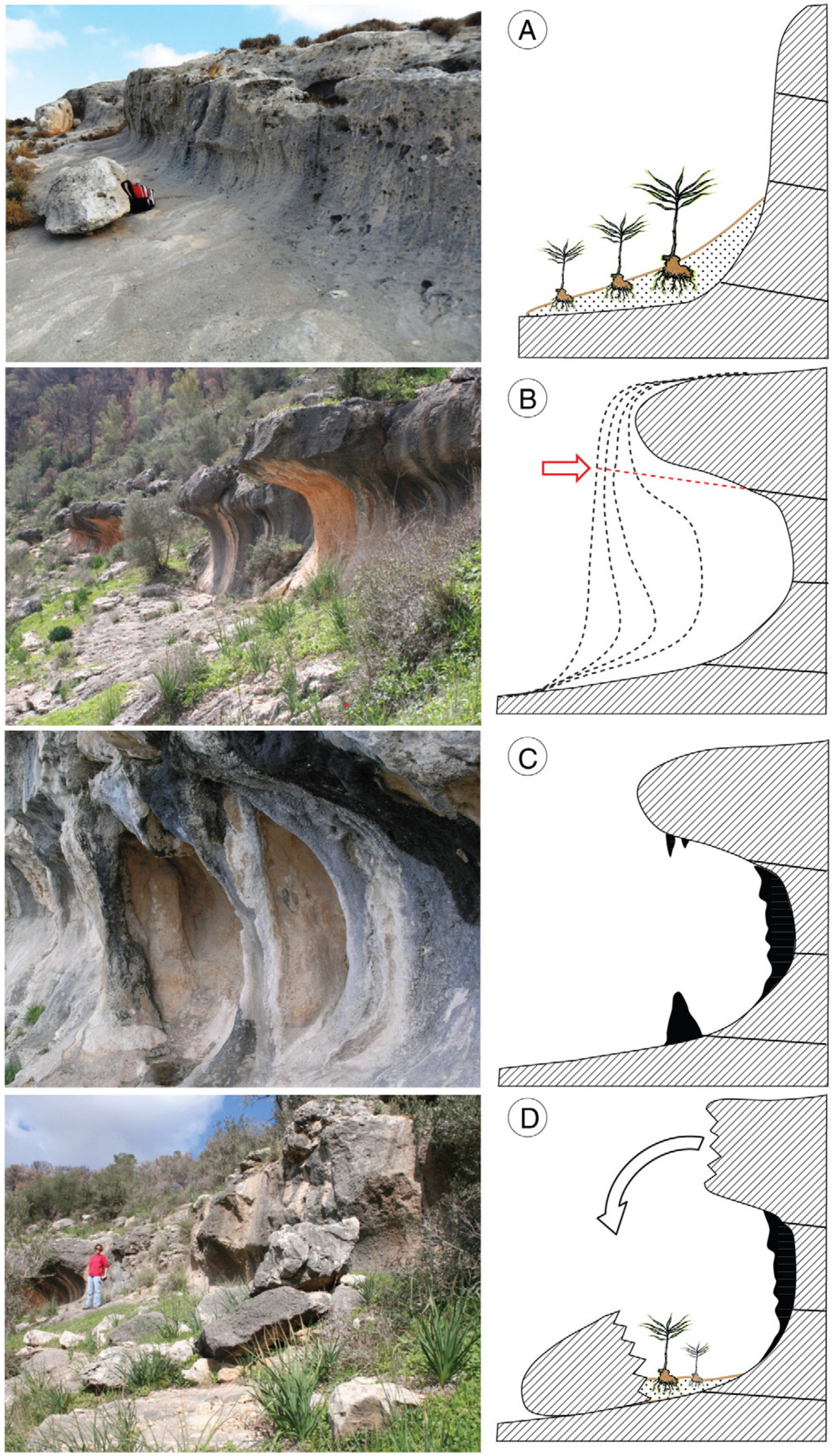

Fig. 18. Stages in the construction and destruction of a notch: (A) A proto-notch is formed at the base of a more resistant bed. It is possible that at this stage, soil was abundant on the slopes, increasing water aggressivity; (B) water penetrates through the space between the more resistant bed (visor) and the more weathering susceptible bed underneath. The red arrow marks the contact between the two beds. The notch is widening due to back erosion caused by exfoliation and flake weathering; (C) in places, tufa is deposited within the notch, either along the cavity walls or as detached stalagmites, stalactites and columns. It is characteristic mainly to the northern aspects, although tufa deposits can be seen in both aspects. Stage C is not mandatory to the development of the notches; (D) the visor-bed collapses as the cavity enlarges. Colluvial sediments are deposited behind and between the fallen boulders. The widening process (B) is now repeated.

of the notch, as the result of water dripping along a fissure and causing the accumulation of tufa. Flake weathering causes the cavity-bed to grow wider and retreat into the cliff, until the visor-bed collapses (Siman-Tov, 2009) and the notch morphology is erased (Fig. 18D). Henceforth, the process by which the notch widens begins all over again, as the differential weathering encourages differential rates of slope-retreat.

It seems that the studied notches are landforms associated with slope phenomena, in which local weathering processes, especially exfoliation, cause a back retreat of the slopes at different rates of erosion. The back wall of the cavity recedes faster than the more durable visor bed. By contrast, the main weathering mechanism that affects the visor is breakdown and rockfall.

It is evident that at present the notches are geomorphically active, whether through bioerosion and flake weathering of the back wall of the cavity, or through accumulation of tufa. Bioerosional processes, carried out by cyanobacteria or other organisms, continue to act upon the carbonate substrate, contributing to the further development of the notches.

The impact of the climate on notches is not sufficiently clear, although in the Carmel it is evident that most of the notches face roughly westward, towards the Mediterranean Sea and the main precipitation systems. Notches similar to those of the Carmel are common throughout the Mediterranean zone of Israel as well as in other carbonate areas surrounding the Mediterranean Sea. They appear in the Judean Hills and Samaria as well as in Jordan, in regions with annual precipitation of 300 mm. The notches known from desert areas, with less than 200 mm/y precipitation, have a different morphology and are possibly produced by a different evolutionary mechanism (Haviv et al., 2010). On the other hand, at the upper end of the scale we observe notches in the Upper Galilee, under annual precipitation of 700–800 mm/y. However, in Mt. Hermon, where precipitation reaches 1200 mm/y, although the rocks are composed of well stratified limestone beds and epikarst morphologies are abundant, no notches were observed.

6. Conclusions

1. A number of preliminary conditions are required for notch development:
   a. Soluble, hard carbonate slopes, composed of limestone or dolomite.
   b. Mediterranean to semi-arid climate (300–700 mm of rain per year).
   c. A succession of beds with different solubilities: beds which are more resistant to weathering for the visor and floor, and a less resistant bed between them.
   d. Horizontal beds or slightly inclined against the slope.
2. The geomorphic processes that shape a notch combine chemical, mechanical, and biogenic weathering. The first stage is marked by chemical weathering, as water percolates through the contact between two beds of different solubilities, creating an initial indentation (a proto-notch) in the soluble rock. In the second stage, mechanical weathering contributes to the process: shallow parallel micro- and macro-fissures develop in the back wall of the proto-notch. They expand by dissolution, as well as by trapped clay particles, and by organisms (bacteria, algae, fungi, roots, and larger life forms) — that penetrate and widen them. The water regime in the cavity of the emerging notch is improved and the fissuring process results in flake weathering and exfoliation of the back wall. The flakes range in thickness from several millimeters to more than 10 cm. In this way, the notch cavity is widened into the slope. By contrast, the main geomorphic process that erodes the visor is breakdown and rockfall.
3. We propose an epikarstic mechanism for the formation and evolution of the Carmel notches. The notches are geomorphic phenomena originating from the dissolution and disintegration of the rock at the surface or right below it, by differential weathering of beds with different morphological properties. The notches follow specific beds having specific characteristics, and are destroyed by the collapse of the visor. The formation and destruction alternate on the slope in a cyclical manner, and therefore the notches are local phenomena that vary over time and space.

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