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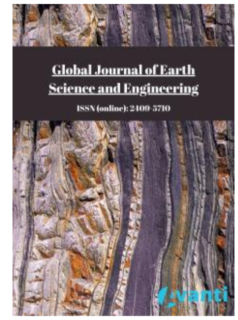

Influence of Primary Porosity on Epikarst Evolution and Surface Karst Features in Limestone, Dolomite, and Evaporites

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ABSTRACT

The characteristics and effect of the epikarst in karstifying rocks on surface feature development was studied based on literary data. Relationship of porosity, epikarst and feature development of limestone, dolomite and evaporite was established on well-soluble, less re-crystallized limestones with medium primary porosity. The degree of cavity formation is well-developed in the rock including its heterogeneous vertical percolation, which result in the development of drawdown dolines in the reviewed studied rocks. On well-soluble evaporites, the vertical percolation rate of homogeneous distribution was diagnosed and does not favour the heterogeneous cavity formation of the epikarst, the piezometric level and the development of drawdown dolines. On limestones , marble and dolomite of low porosity, the dissolution of low degree and low primary porosity hindered the development of a matured epikarst with cavities and of the piezometric surface and thus, of drawdown dolines. Surface features karren, dolines also develop on well-soluble karstic rocks with medium primary porosity. These features are well-developed with heterogeneous secondary porosity that leads to cavity formation. Low primary porosity recrystallized rocks facilitates infiltration and dissolution capacity decreases that concentrates into drainage open fractures.

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1. Introduction

In this study, the characteristics of the epikarst of various karstifying rocks were described and by this, interpreting the presence or lack of their surface karst features. However, it is also described how the heterogeneous water drainage of the epikarst controls the development of surface karst features (drawdown dolines and other karst features). During the development of the epikarst, cavity formation increases in the part of the rock that is close to the surface. Its change influences the distribution conditions of infiltrating waters and through this, geomorphic evolution. It has to be noted that surface karst features involve the features appearing on the surface of the epikarst [1]. The way and distribution of surface dissolution and the epikarst dissolution are inseparable from each other and are in interaction with each other. Thus, surface dissolution affects subsurface dissolution and the latter affects the former.

The epikarst develops during the surface and subsurface dissolution of karstifying rocks and thus, involves karren and subsurface cavities (Fig. **1**) [1, 2]. While primary porosity develops during rock development and tectonic effects, secondary porosity develops during dissolution. This constitutes the epikarst. The water is stored in the epikarst of great secondary porosity and since water motion is retarded at the interface of rock parts with different porosity (the boundary between the epikarst and the vadose zone) and because of this, it flows back into the part with greater porosity (drainage rate decreases) [3, 4]. This boundary is situated where the vertically percolating water become saturated (saturation level). The surface of the backwater which fills the cavities is the piezometric surface, which may fluctuate depending on water supply and infiltrates both vertically and horizontally [5, 6]. The developed cavities are filled for a shorter and longer time bythe laterally moving water as earlier mentioned [6]. The cavity formation of the epikarst is accelerated when the laminar water motion becomes turbulent. A precondition is the size increase of the cavities of the epikarst. According to [7], at a 1-cm passage width in the phreatic zone there is still laminar flow.

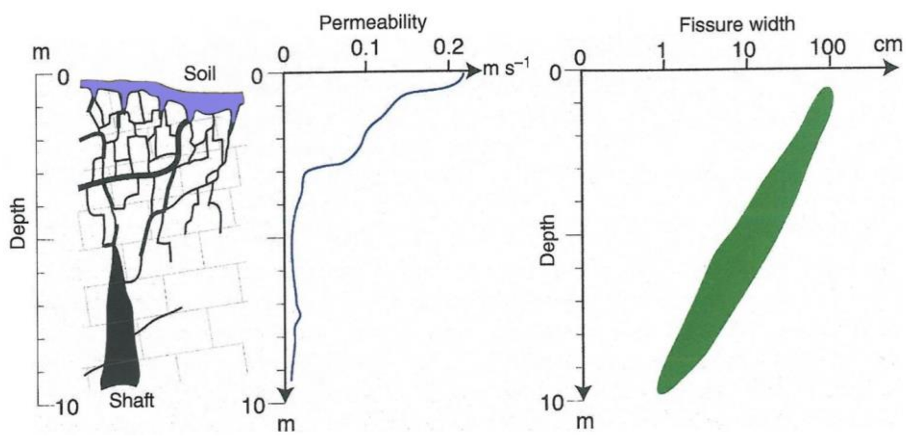


Figure 1: Main characteristics of the epikarst [2].

Primary porosity includes the gaps along the bedding planes, fractures and faults and the spaces between rock grains. Secondary porosity mainly develops during dissolution along bedding planes, fractures and faults. This may be older (paleo-epikarst) and currently developing, recent and transforming from paleo-epikarst [5]. During the cavity formation of the epikarst [8] distinguished young epikarst , mature epikarst and old epikarst. Young epikarst is described in Fig. (**2A**), mature epikarst in Fig. (**2B**) and old epikarst in Fig. (**2C**). In the case of young epikarst, primary porosity is dominant. At mature epikarst, secondary porosity is dominant and in the case of old epikarst, the rock is separated into parts. The sites and position of the cavities of secondary porosity refer to the sites and directions of water motion in the rock. At sites where primary porosity is high, no epikarst develops [5], due to vertical drainage of high rate. Although drainage of high-rate favours dissolution, dissolution of short duration decreases the quantity of dissolved material and concentrates the process to the path of vertical water motion. For doline development, there must be heterogenous cavity formation in the epikarst. This is ensured by horizontal percolation. In the case of heterogeneous cavity formation, the value of secondary porosity changes in the epikarst. This can be the result of different cavity size (passage size) or cavity density.

Figure 2: Epikarst on limestone: A. Pádis Plateau (Romania, Bihor Mountains) *1* grike wedging out downwards, *2* fracture broadened by solution, *3* grike with parallel walls, *4* bedding plane grike B. at the artificial exposure of Road Nr. 16 Bosnia, the Dinarides, 1. wide solution grike, 2 narrow solution grike, 3. fracture, 4. separated rock block C. at the artificial exposure of Road Nr. 9 Bosnia, the Dinarides, 1. wide grike, 2. narrow grike, 3. debris part of epikarst, 4. separated rock block, 5. Cavity.

The diverse texture of the limestone such as the less crystallized limestone, the well-crystallized limestone, recrystallized, clinker limestone, oolitic limestone, micritic limestone, and the limestone rich in fossils [9] as well as its stratification, the degree to which it contains fractures favour diverse primary porosity and the development of epikarst with diverse and different development. The diversity of porosity is increased by the different bedding of the rock and the different degree to which they contain fractures.

Primary porosity is extremely diverse in limestones. Packstone, grainstone, and boundstone (Reef) limestones are distinguished [10]. Primary porosity is high on packstone (built up of skeletal remains and grains) and on grainstone (built up of skeletal remains only) limestones. The porosity value of these limestones changes with age as it has already been mentioned. At Paleozoic grainstone limestones, primary porosity is 25-40%, at packstone limestones, it is 10-20 %, at Reef limestones, it is 20-40 %, but at their recrystallized varieties, this value is 5-10 % [11]. At Mesozoic limestones, primary porosity is 25-40% at grainstone limestones, it is 30-50% at Reef limestones and it is 5-10 % at recrystallized limestones [12, 13]. Primary porosity is extremely low at chemogenic limestones (calcareous sinters are exceptions) and at stromatolites, especially if they undergo diagenesis. The value of primary porosity is 1-5 % at chemogenic limestones [13], and below 1% in stromatolites [14]. The low value of primary porosity may result in the fact that the rock surfaces act as aquiclude and thus, no infiltration takes place. This does not favour the formation and development of epikarst.

Here we mention that other authors give different porosity values thus, Williams [5] claims that this value is 20-40 % on Cretaceous limestone and coral limestone. However, there are different values for secondary porosity too. Thus, in the epikarst, this value is 10-20% while in the vadose zone, it is 2% [5, 8].

2. Methods

2.1. The Study of the Proportion of Runoff and Infiltration

The proportion of runoff and infiltrating meteoric water was calculated for limestones of bare surfaces taking into consideration different primary porosities and slope inclinations with the use of the following formulae:

Effective infiltration factor

$$f_{inf} = \min\left(1, \frac{n}{100} \cdot k_s \cdot k_r\right)$$

Infiltration in percentage

$$I(\%) = 100 \cdot f_{inf}$$

Surface runoff in percentage

$$R(\%) = 100 - I(\%)$$

Slope effect (k_s)

$$k_s = cos\ (\alpha)$$

In bare limestone, porosity is not completely active thus,

$$k_r = 0.7$$

where

- f_{inf}– effective infiltration factor (–), infiltration proportion of annual precipitation
- n– primary porosity (%)
- k_s– slope corrective factor (–), to the effect of runoff acceleration due to the slope
- k_r– effective (active from the point of view of hydraulics) porosity factor (–)
- I– proportion of infiltration (%)
- R– proportion of surface runoff (%)

At calculations, we disregarded evaporation and the hindering role of surface waters. The above correlations were made based on the following works [15-17]

2.2. The Study of the Relation between Infiltration and Secondary Porosity

The effect of the relation between infiltration and primary porosity on secondary (complete) porosity was studied. For infiltration values of 1,5,10,20,30,40%, while for primary porosity values of 10,20,30% were given. For the calculations the following works were used [16, 18-21]. The following correlations were used for the calculation:

Dissolved rock thickness

$$\boxed{\Delta h = v_{diss} \cdot t}$$

Δh	dissolved thickness	m
v_{diss}	dissolution rate	m/year
t	time	year

Secondary porosity

$$\boxed{\varphi_{sec} = \frac{\Delta h}{H} \cdot f_{inf}}$$

φ_{sec}	secondary porosity
H	studied rock thickness
f_{inf}	proportion of infiltration (0–1)

Complete porosity

$$\boxed{\varphi_{tot} = \varphi_{prim} + \varphi_{sec}}$$

φ_{prim} primary porosity

φ_{tot} complete porosity

3. Results

The calculated values which are in annual proportion are in Table **1**.

Table 1: The proportion of surface runoff and infiltration in percentages on limestones of bare surfaces and of different primary porosity at different slope inclinations.

Porosity (%)	Slope Inclination							
	0°		10°		20°		30°	
	Runoff (%)	Infiltration (%)	Runoff (%)	Infiltration (%)	Runoff (%)	Infiltration (%)	Runoff (%)	Infiltration (%)
1	99.3	0.7	99.31	0.69	99.34	0.86	93.39	0.61
5	96.5	3.5	96.57	3.43	96.71	3.29	96.96	3.04
10	93.0	7.0	93.14	6.86	93.42	6.58	93.91	6.09
20	36.0	14.0	86.28	13.72	86.84	13.16	87.82	12.18
30	79.0	21.0	79.42	20.58	80.26	19.74	81.73	18.27
40	72.0	28.0	72.56	27.44	73.68	26.32	75.64	24.36
50	65.0	35.0	65.70	34.30	67.10	32.80	69.35	30.45
60	58.0	42.0	58.84	41.16	60.52	39.48	63.46	36.54

In the case of porosity increase, surface runoff gradually decreases and infiltration increases. While at a porosity of 1%, 99.3% of meteoric water flows down, this value is only 58% at a porosity of 60% in the case of horizontal surface.

There is linear function relation among the percentage values of primary porosity, runoff and infiltration (Fig. **3**). There is direct variation between porosity and infiltration, while there is inverse proportion between porosity and runoff. Increasing infiltration and runoff differences belong to increasing porosity values and different inclinations since in the case of a higher inclination, infiltration increases to a lower degree than in the case of lower inclination. However, at runoff, in the case of lower inclination, the decrease of runoff is faster than in the case of higher inclination.

In the case of low inclination (0-10°), runoff and infiltration change at a lower degree than in the case of higher inclination (20-30°). In the case of an inclination of 30°, runoff increases to 63.46% at a primary porosity of 60% (at an inclination of 0°, its value is 58%). In accordance with this, infiltration is 36.54% at an inclination of 30° and a porosity of 60%, while at an inclination of 0°, infiltration is 42%. All this can be explained by the fact that at lower inclination, the water has a longer time to infiltrate, while at higher inclination, even at higher porosity, there is a higher chance of runoff and a lower chance to infiltrate. All this is supported if we regard infiltration belonging to porosities of 20% and 60% at different inclinations. This is the following: at an inclination of 0°, the difference of infiltration is 28% for the above two inclinations, at an inclination of 10°, infiltration is 27.44%, at an inclination of 20°, it is 26.32%, while at an inclination of 30°, it is 24.36%. Infiltration differences only to a low degree, but decrease with the increase of slope inclination.

Since infiltration increases with the increase of primary porosity, secondary porosity also has to increase if it is not modified by lithological characteristics. However, the slope angle, as it has already been mentioned, decreases this tendency. However, the increase of primary porosity, since it has a backward effect on water motion, hinders the increase of secondary porosity beyond a certain limit (see below at evaporites or at limestones of high porosity).

With the increase of primary porosity (in the domain of 10-30%), complete porosity increases, which is the sum of primary porosity and secondary porosity (Table **2**). We gave pH (5.5-6.0) and precipitation values (300-600 mm), temperature values (10-15°C) values of time scale (10^3-10^4 year), and values of denuded rock thickness.

It can be seen that complete porosity increases at every primary porosity value with the increase of infiltration. However, complete porosity values increase similarly at every primary porosity value by 4% with the increase of infiltration. This refers to the fact, at least in the studied domain, the increase of infiltration values causes the increase of complete porosity. At different primary porosity values, complete porosity is higher because their values have a share in complete porosity. Thus, the increase of complete porosity is the result of infiltration and dissolution intensity. The role of primary porosity manifests in the fact that it controls the degree of infiltration.

Table 2: The relation of infiltration and complete porosity.

Infiltration (%)	Complete Porosity (%)		
	10° pr (%)	20° pr (%)	30° pr (%)
1	10.1	20.1	30.1
5	10.5	20.5	30.5
10	11.0	21.0	31.0
20	12.0	22.0	32.0
30	13.0	23.0	33.0
40	14.0	24.0	34.0

pr: primary porosity.
We get secondary porosity if we subtract primary porosity values from complete porosity values.

4. Discussion

The value of primary porosity determines the proportion of the flow and infiltration of precipitation that falls on the karstifying rocks especially if the rock is of bare surface. Theoretically, the following cases occur:

- The primary porosity of the rock is very high mainly because of high pore volume and the rock is unstratified. The precipitation falling on its surface infiltrates and also moves fast and vertically. Therefore, secondary porosity (dissolution cavities) is related to vertical flow orbits. There is no epikarst, or it is weakly developed [5].
- The primary porosity of the rock is high enough. Gaps, fractures and bedding planes occur in it. A lot of water infiltrates at this time. Secondary porosity increases, but horizontal water motion also increases on bedding planes with clayey veneer (the latter increases secondary porosity). Well-developed epikarst is formed.
- Primary porosity is low due to low pore volume, but there are open fractures. The flow of meteoric water is limited on the surface, and the flowing water infiltrates open factures. The development of surface features and the epikarst depends on the position of the karstwater table, and on the density of open fractures, but does not depend on closed fractures (such fractures may develop at compressional stress or if fractures are filled up with precipitation material).
- Primary porosity is very low, there is no epikarst, or the epikarst is of weak development, and meteoric water flows down the surface.

The degree of infiltration is also influenced by the structure of primary porosity. Thus, the density and maturity of the open fissures of lower primary porosity may exceed the density of the open fissures of higher porosity. In this case, infiltration may also be higher at the same inclination at fissures of lower porosity than at fissures of higher porosity. The structure of porosity may also change in time. At low inclination and open fissures grikes develop. In this case, secondary porosity increases and thus, infiltration and the chance of the formation of drawdown dolines also increase. At higher inclination, karren of flow origin (mainly rinnenkarren) are formed. In this case, secondary porosity also increases, but infiltration and thus, the chance of drawdown doline development do not increase.

Taking into consideration primary porosities and solution capacities, we analyse the degree of runoff and infiltration, water motion in the rock, secondary porosity (epikarst) and feature development at different karstifying rock. The role of interlayer fissures in surface runoff has been studied [22]. It was established that their presence decreases surface runoff.

Primary porosity and thus, the proportion of infiltration and drainage may change depending on time. During recrystallization or depending on the character of tectonic stress, if there are only closed fractures (at compression, paraclase and lithoclase), as a result of the decrease of primary porosity, infiltration decreases and surface runoff increases. Surface runoff increases surface dissolution, while infiltration increases subsurface dissolution. Even at high porosity, if the rock is well-stratified, horizontal water motion will be significant, while vertical infiltration will be more developed in the case of relatively low porosity and in the lack of stratification.

4.1. The Porosity, Epikarst and Geomorphic Evolution of Limestone

Mostly, the epikarst of limestone is known (Fig. **2**) [5]. In addition to karren, the most widespread features of its surface are drawdown dolines, which develop to the effect of the epikarst [5, 23-27]. At sites in the epikarst where the degree of cavity formation is higher (where water with higher dissolution capacity arrives at fractures), vertical water motion is accelerated, and therefore, more water arrives at the karst from the surface too. As a result, the surface is dissolved to a higher degree and indentations develop (Fig. **4**). More water and dissolved material may reach the main drainage from the indentation through its deepest point. Here, the degree of cavity formation and the rate of drainage continue to increase and as a result of the latter, the piezometric surface is warping. The surface indentation becomes deeper and deeper in its centre because a greater amount of material is transported away from this place due to the greater quantity of water [5, 23-25]. In the epikarst, both the horizontal cavity formation and vertical drainage will become heterogeneous because due to different water quantity, the degree of dissolution will be different horizontally and thus, cavity formation will also be different. However, as a result of different cavity formation, the efficiency of vertical drainage will also be different.

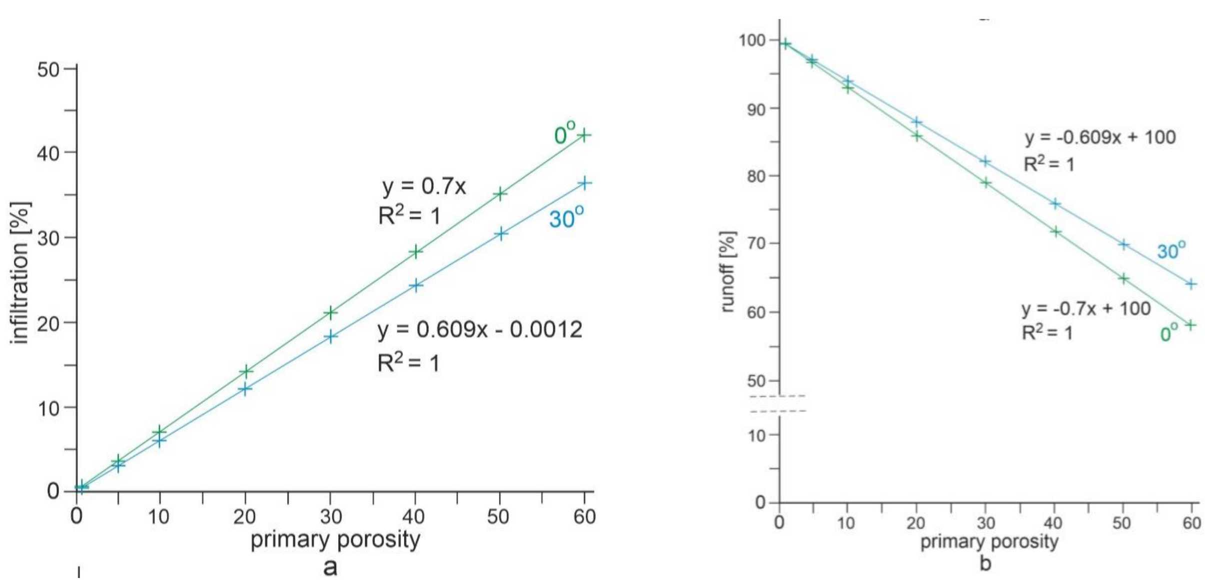


Figure 3: The relationship of primary porosity, infiltration (**a**) and runoff (**b**) (The data used for the calculation of the function are in Table **1**).

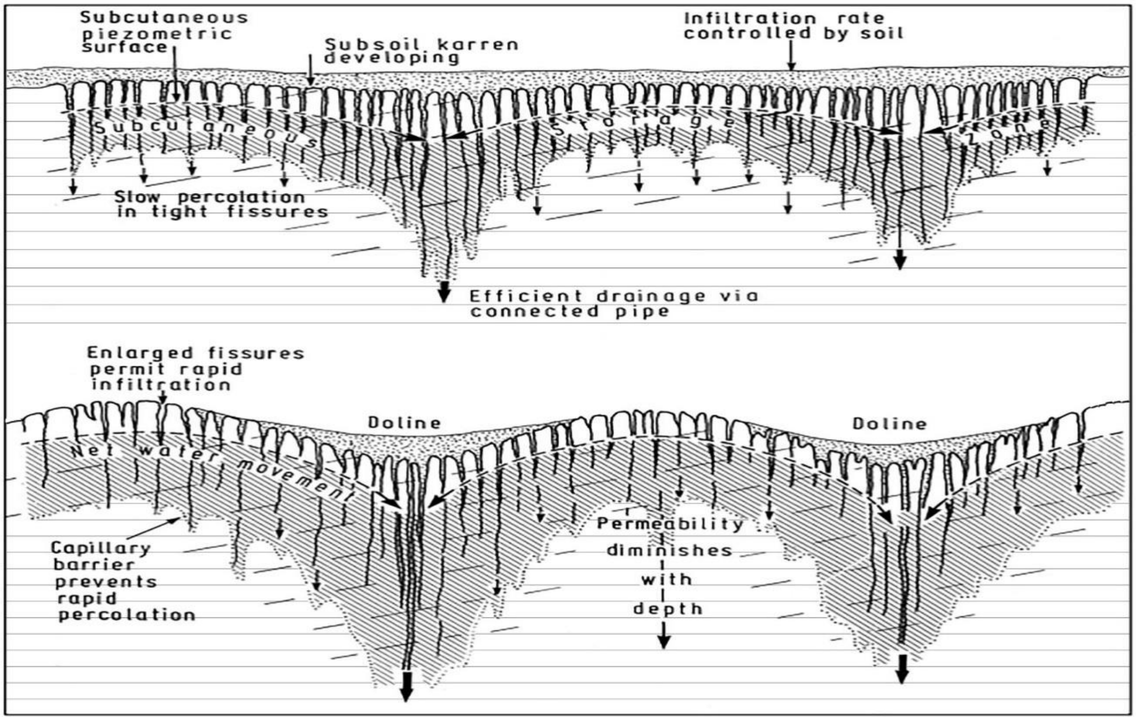


Figure 4: Development of doline and epikarst [5].

It is not favourable for epikarst development if CO_2 content is low or there is no CO_2 content (only carbonate dissolution takes place) or the rock surface is impermeable (or nearly impermeable) because of the low porosity of the rock because there is no infiltration in this case. However, drawdown dolines may also develop at low or very low primary porosity if the density of open fractures is high in the rock and the rock is well-stratified. Therefore, drawdown dolines develop at sites where cavity formation is horizontally heterogeneous in the epikarst since this is a precondition of heterogeneous vertical drainage rate, which is marked by the caved-in piezometric surface and by this, it is a precondition of drawdown doline development at the surface. There are limestones with very high, low and very low primary porosity. However, among those of low porosity (low pore volume) there may also be limestones at which the density of open fractures is high or low. In the former case, the karst water table may be close to the surface or lower than it.

According to their development, corrosion plains can be put into two types. During the development of one of them, drawdown dolines are formed, which are not deepening if their floor reaches the karst water table, when they also coalesce [28]. The surface of the plain is constituted by the floors of former dolines. In the other cases, there is no doline development, but below the superficial deposit, expanded dissolution and horizontal dissolution take place for example on a polje floor [29]. Dissolution below the cover takes place on bedrock of any porosity. In the case of bedrock of high porosity, if the cover is denuded, doline development takes place and then a corrosion plain is formed. There is no doline development, if the karst water table is at the surface of the bedrock or the superficial deposit is denuded from the limestone of very low primary porosity or there was no superficial deposit on it either. In the latter cases, the formation and development of corrosion plains continues even in the lack of doline development. Corrosion plains occur on tropical karsts even if these features develop from dolines such as on cockpit karst [24]. Planation takes place below the superficial deposit both on cockpit karst and on fenglin [24, 30]. Planation cannot be preceded by doline development because the karstwater table is at the bedrock surface on fenglin karst 302].

On limestones of very low porosity, corrosion plains can also develop on uncovered surfaces, even if their development was not preceded by doline formation. There is a low chance for this at carbonate dissolution thus, at recent atmospheric CO_2 level. In the Precambrian (or at the beginning of the Palaeozoic, when rocks of very low porosity were not denuded yet) hydro-carbonate dissolution may have taken place at high atmospheric level of that time and thus, there will be a chance of the development of these features on chemogenic limestones and on stromatolites. At the micritic variety of chemogenic limestones, primary porosity is 1-5% [13], the development of which on the Earth began 3.8 billion years ago [31]. On diagenetic stromatolites, primary porosity is below 1% [14]. The development of stromatolites has been going on for 3.5 billion years [32]. However, these features were denudated because the thickness of bearing rocks was probably low and their development age was old.

On the bare surfaces of high-mountains and glaciokarsts, rinnenkarren and grikes occur in high density and expansion [33]. Rinnenkarren develop by water flow, while grikes are formed by percolation [16, 33, 34]. Rinnenkarren and grikes developed on rocks of low or very low porosity. On the Dachstein limestones of Dachstein plateau, primary porosity is below 1 % [35]. A similar porosity value can be expected at the Triassic limestones of Totes Gebirge. The presence of karren features of two types refers to the fact that the circumstances of their development are different and the type of fractures changes on low porosity rocks, here. Rinnenkarren are formed on inclined surfaces and not along fractures. However, grikes develop on nearly plain surface sections, along fractures [33]. If fractures occur in the environment of rinnenkarren, the density of which is high (it may exceed two fractures/dm), they are filled with concretions [33]. Thus, at rinnenkarren, fractures are closed, in the environment of grikes, they are open. Therefore, in the case of low porosity, the type of the fracture may also affect the development of a karren feature. Below rinnenkarren and below grikes which occur in small expansion, the cavernous part ofepikarstdoes not develop and if it does, it is predominantly made up of karren. In addition to low porosity, predominantly carbonate dissolution does not favour the development of the cavernous part of the karst either.

A similar, less-developed epikarst can be expected on marble thus, on the island of Diego de Almagro (Fig. **5A**), but surface karren, and the phreatic zone [36] are well-developed. Also in this case, the weak maturity of the epikarst can be explained by great degree of recrystallization and by the resulting low primary porosity. Precipitation mostly flows from the surface of the marble at the surface which is proved by the large diameter of giant kamenitzas, whose diameter may exceed 50 m. Another evidence for this is that kamenitzas have decantation rinnenkarren or meanderkarren [37]. At some kamenitzas, lakes with permanent water also occurs which marks that infiltration is very low or there is no infiltration. Dissolution exclusively takes place along fractures. This does not favour different vertical drainage rate and heterogeneous cavity formation either, thus drawdown doline development.

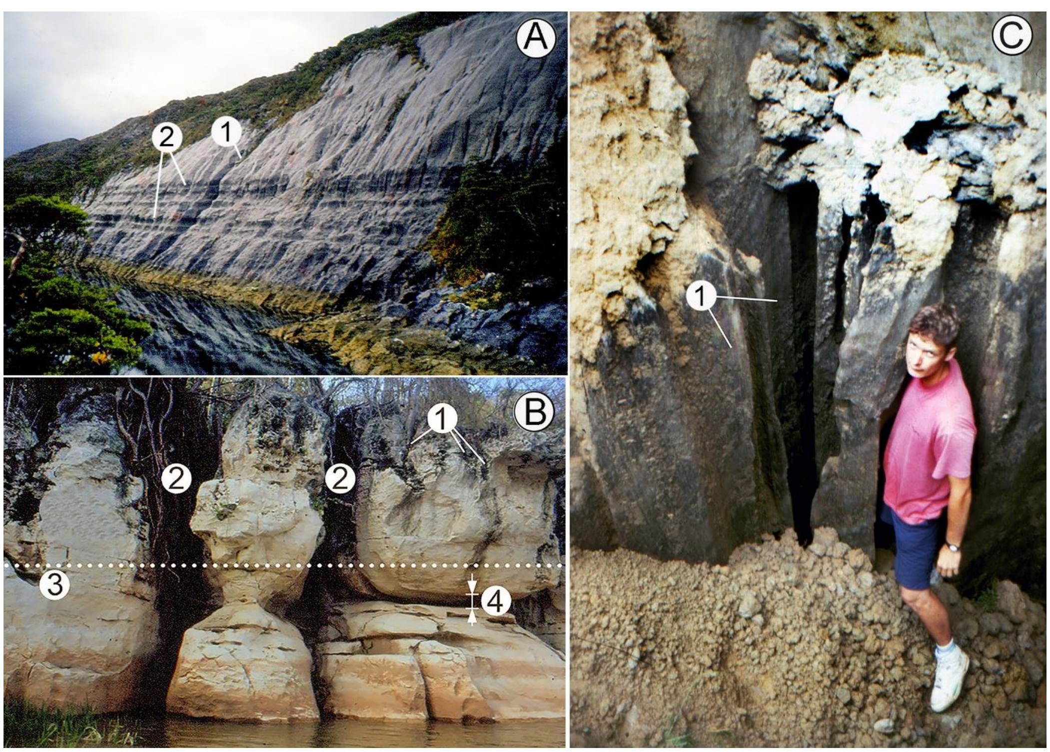


Figure 5: Exposures with or without epikarst on different rock.

A. the epikarst of marble (Diego de Almagro Island, Chile) in the coastal zone, 1. rinnenkarren, 2. notch B. limestone features of low porosity which were exposed by River Manambolo (Bemaraha Little Tsingy Madagascar), 1. smaller grikes developing above cavities, 2. developed grikes that coalesced with cavities, 3. presumed former karstwater table 4. cavity that developed below the karstwater table, C: Coalesced pits of Parajd (Romania) salt karst that was exposed by collapse, 1. complex pits

The bearing rocks of tropical karren are also of low porosity. Thus, Salomon [38] claims that primary porosity is 1-2 % at the bearing rock of the Bemahara tsingy. However, in addition to low porosity, the density of open fractures is significant which is proved by the distribution of large grikes. Grikes are clustered along to directions being perpendicular to each other (NNE-SSW – WNW-ESE). This results in the concentrated flow of surface stream into the fractures. Grikes of intensive development coalesced with phreatic cavities (Fig. **5B**) because the karstwater table was and is also close to the surface [39]. Evidence for the existence of former cavities are the features of grike walls (e.g. notch), concretions in grikes and cave relicts disrupting the grikes [39], and also the fact that there are active caves with water, phreatic caves or caves close to grike floors [40]. The orientation of the phreatic passage system below the grikes of the tsingy and the grike character of passages are evidence for tectonic preformation (Fig. **6**).

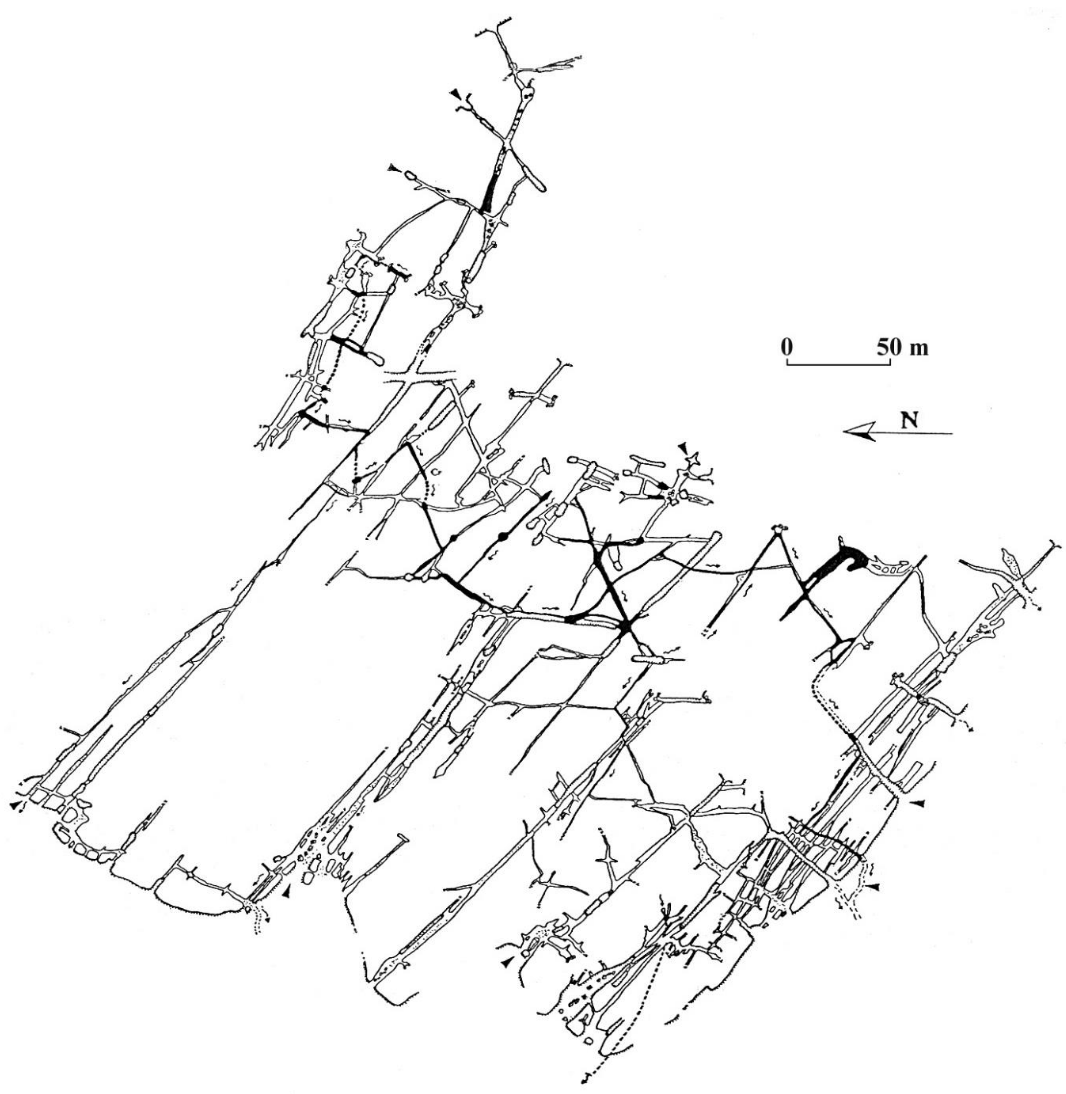


Figure 6: The Tsiliko cave (Bemaraha tsingy) [40].

Here, low pore volume can be traced back to microcrystal texture, cementation and the sedimentation of fine calcareous mud [41]. Similar features occur on tropical karren on which grikes coalesce with cavities or there are features in their sides which developed below the karstwater table (Fig. **6B**) [42-45]. Thus, on the ceiling of the

Bullita cave (Judbarra Karst, Australia) which is of low porosity and close to the karstwater table [43-45], and on the Tanga Karst of Tanzania [42]. This refers to the above-described grike development here, but it is also characteristic of other karsts such as in Chillagoe Karst and Mitchell-Palmer Karst [46] (Fig. **6**).

In the area of stone forests, the karstwater table is at a great depth, the epikarst is well-developed [47] and porosity is low, its value is below 6% [48]. Stone forests developed at places where the rock beds are well-bedded, the thickness of beds is 1-5 m, and the beds are of horizontal position and contain open fractures [49-50], but the karstwater table is deep relative to the surface. The great density of bedding planes and open fractures results in relatively high primary porosity. The horizontal position of the beds favoured homogeneous cavity formation, while open fractures favoured homogeneous vertical drainage of great degree. Therefore, the upper part of the epikarst became separated into parts along the developing pits, shafts and grikes. Probably, the development of the epikarst has many centres, which did not favour the warping of the piezometric surface and thus, the development of drawdown dolines.

With the primary porosity increase of the limestone and as the degree to which the rock contains fractures is higher, vertical water motion becomes more and more dominant. Horizontal water motion and dissolution are less and less specific. If the rock is non-bedded and primary porosity is high, pits reaching great depths are formed as in the case of well-soluble evaporates (see below). Pits develop during vertical dissolution. On the coastal rocks of the San Diego Bay (Madagascar), which are probably limestones with coral beds and conch beds, the estimated value of primary porosity may reach 60%. Therefore, pits and pit groups occur. These go transversely through some hanging large rock blocks above the sea level (Figs. **7**-**8**). The lower end of the pits is hanging above the ocean level since an abrasion indentation developed below the rock block. On their side walls, there are no cavity remnants which would refer to horizontal dissolution and thus, to horizontal water motion.

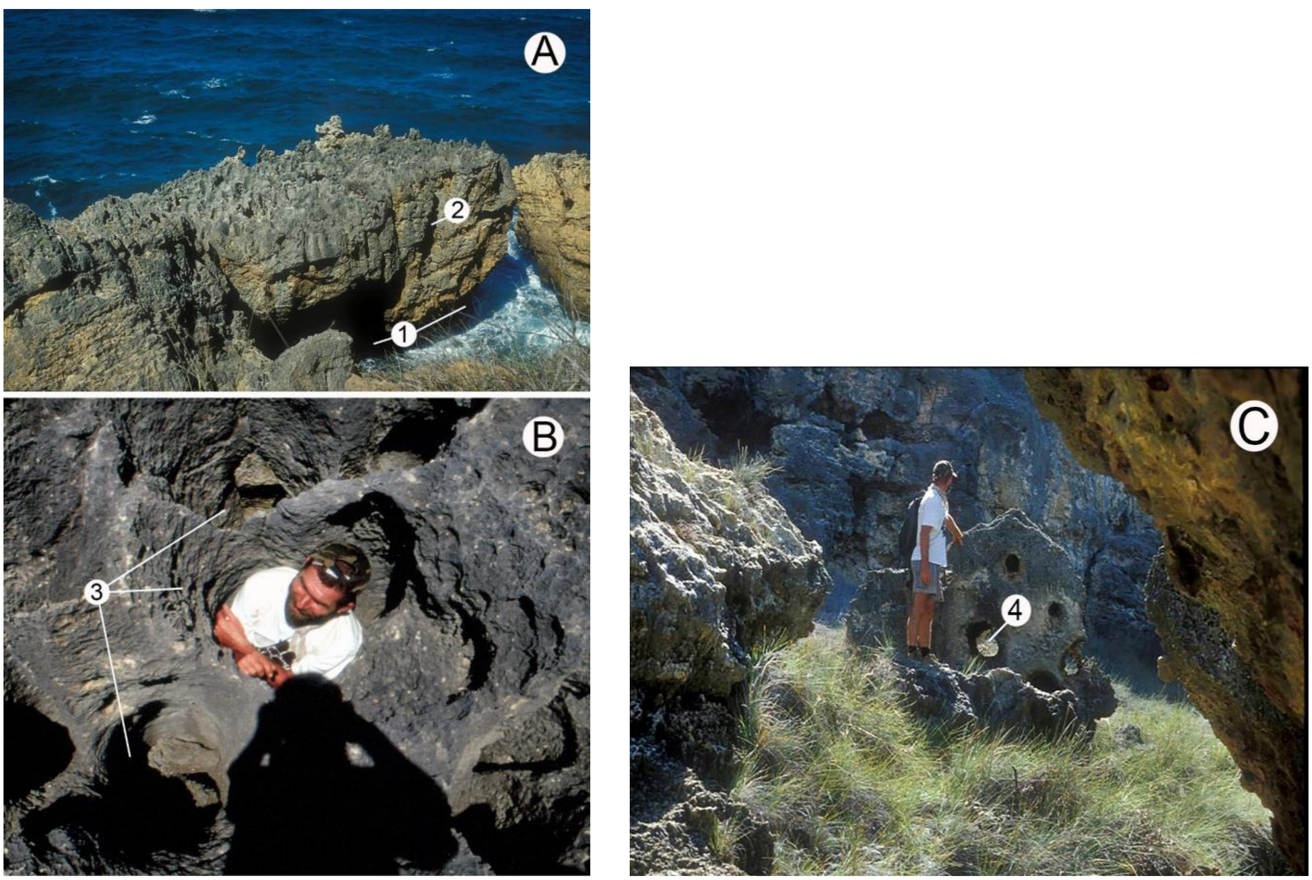
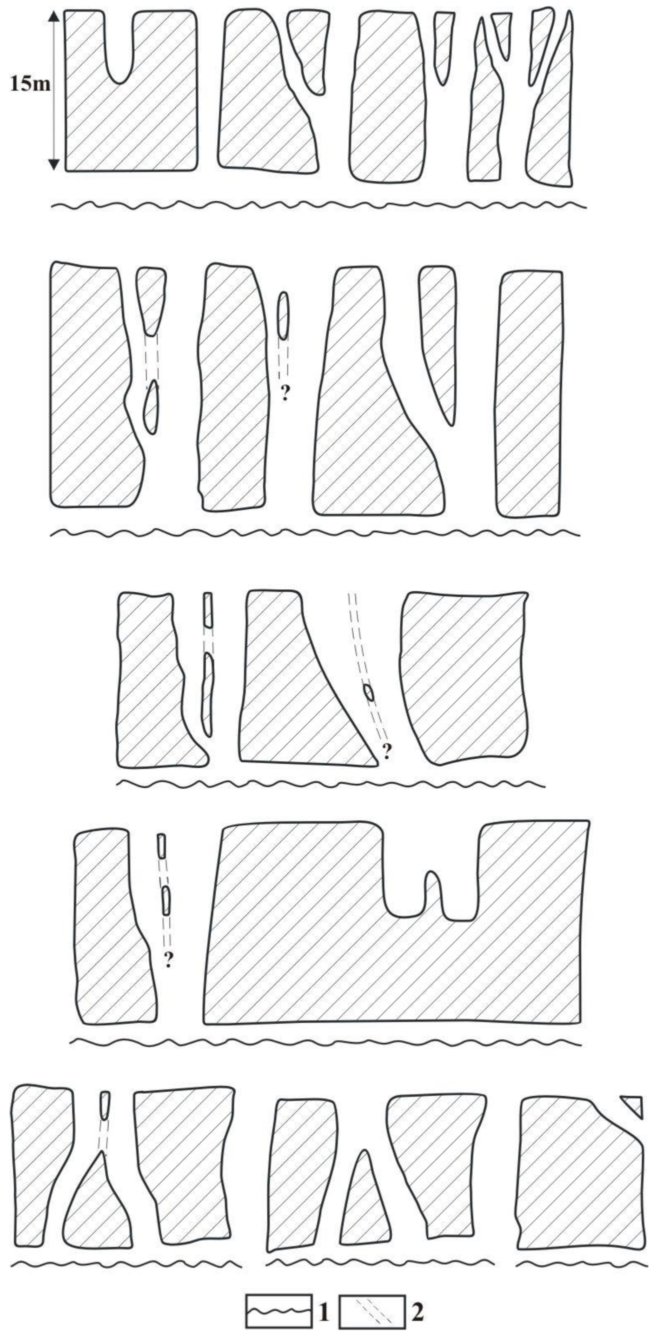


Figure 7: Pipes on rock of high primary porosity (Madagascar San Diego Bay) **A**. the bearing rock block that is destroyed by abrasion, the upper part of which is dissected by a number of pits, **B**. Group of solution pipes on the Madagascar coast, **C**. remnant of destroyed rock block through which pipe remnants go transversely, 1. abrasion notch, 2. exposed pipe, 3. active pipe, 4. pipe remnants of adismembered block.



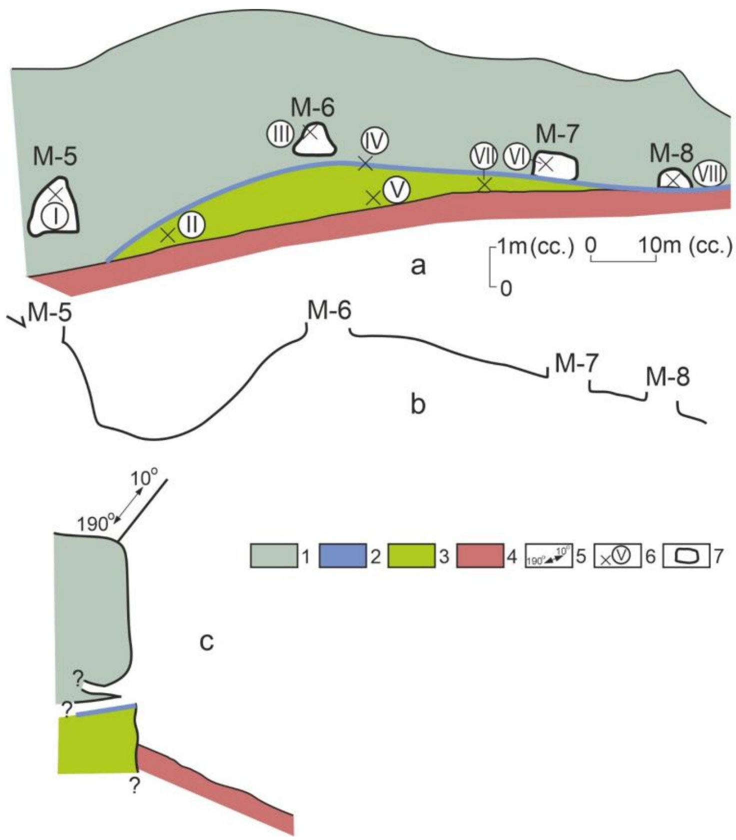
Legend: 1. sea, 2. former diving wall

Figure 8: Main patterns of solution pipes of the rock block that is in Fig. (**3A**) [51].

4.2. Porosity and Landscape of Dolomite

On dolomite, karren [52] and mostly depressions of small depth [53, 54] may occur. According to [55], these features develop on non-recrystallized dolomite, but they do not develop on the recrystallized version of the rock.

On non-recrystallized dolomite, calcium carbonate and magnesium carbonate occur in uniform dispersity [55]. Regarding dissolution, the rock is homogeneous thus, the different components may be dissolved. Homogeneous dissolution favours cavity formation and thus, epikarst development. Its development may be hindered by the low dissolution capacity of the rock [56] and thus, the epikarst may be absent or is of limited development. The dissolution of the dolomite is independent of recrystallization, but dependent on temperature. In water with a temperature of 40ºC, the quantity of Mg reaches and exceeds Ca quantity [55]. At this temperature the Ca:Mg proportion decreases from 2 to 0.5. The lower dissolution capacity of the dolomite is also supported by field observations. In the Bakony Region (Hungary), the Triassic main dolomite is often overlain by Eocene (Middle-Eocene) nummulitic limestone in a thickness of some metres. This can be seen in the exposure of the rock wall of Mount Magos in Dudar, which is a valley side of a stream. In Eocene, nummulitic limestone, primary porosity is quite high, 10-20% [57], while in bedrock main dolomite, it is much lower than this (see below). Therefore, in the Eocene nummulitic limestone, there is well-developed cavity formation (a row of caves, among which some have an expansion of 10-20 m), in bedrock dolomite, secondary porosity is absent (Fig. **9**). This can be observed at sites of the Bakony Region: the subsurface Eocene limestone contains cavities, while the bedrock dolomite does not [53]. Different primary porosity results in different drainage capacity and thus, in different dissolution. The different degree of cavity formation in the two rocks refer to different degree of dissolution, which is not epikarstic, but of karstwater origin. This is proved by the large size of the cavities of the Eocene limestone and the fact that spherical cavities also occur in some caves. Thus, the rock and its cavities got into an epikarstic environment during the uplift of the bearing area.



Legend: 1. Middle Eocene limestone, 2. slightly marly limestone, 3. Triassic main dolomite, 4. deluvium, 5. direction of cliff wall, 6. site and identification mark of point-like sampling, 7. cave, I, III, VI. limonitic limestone, VIII. limestone, IV. slightly marly limestone, II. dolomite with breccias, V. limonitic dolomite with breccias, VII. dolomite, a. front view, b. plan view, c. cross-section.

Figure 9: Different cavity formation between dolomite and overlying limestone (Mount Magas Bakony Region, Hungary).

On recrystallized dolomite, the homogeneity of dissolution stops, and the $CaCO_3$ with sticking ability is dissolved out of the rock [55], then first calcium ion from dolomite crystal. The dolomite undergoes rubble formation, which results in the failure of subsurface cavities (if they developed at all) thus, of the epikarst.

During rubble formation, the primary porosity of the rock decreases [58], but it increases during tectonic stress. The primary porosity of non-recrystallized dolomite may even reach 10-15% (grainstone or packstone facies), while that of recrystallized dolomite, is 0.1-4% [59].

Rubble formation of dolomite occurs at a place where fracture density is high, at sites where it is low, no rubble formation occurs. Thus, in the Bakony Region there are rubble terrains at sites where fracture density reaches

3.34 fractures/dm, while on non-rubble terrain this value is 0.92 fracture/m [53]. High fracture density favours water motion and thus, the dissolution of calcareous material thus, rubble formation. In addition to fracture density, another important factor is calcareous content and the inclination of the bearing terrain. On a terrain with higher inclination, the degree of infiltration is less and thus, dissolution is also of lower degree. Secondary porosity is low in recrystallized, dolomite with rubble. Evidence for this is the fact that in the drilled wells of the dolomite, the water becomes saturated after a long time [34]. Low secondary porosity can be seen in the mines of rubble dolomite terrains around Veszprém (Hungary) where the epikarst is of limited expansion and weak cavity formation (Fig. **10**) [53]. Here, the development of the epikarst was also hindered by the fact that the karstwater reached or approached the dolomite surface at surface sections of lower elevation [53]. As a result of rubble formation and high fracture density, on this rock (on its recrystallized, calcareous variety), vertical drainage is predominant and there is no horizontal water motion. (However, slow saturation may favour dissolution that penetrates into great depth.) Therefore, in the Transdanubian Mountains, on Middle Triassic dolomite, on core samples (at depths of 3795-3798 m), (secondary) porosity was 2.15-6.87 %, while in greater depth on Lower Triassic dolomite (8 core samples on average) it was only 0.81 % [60].

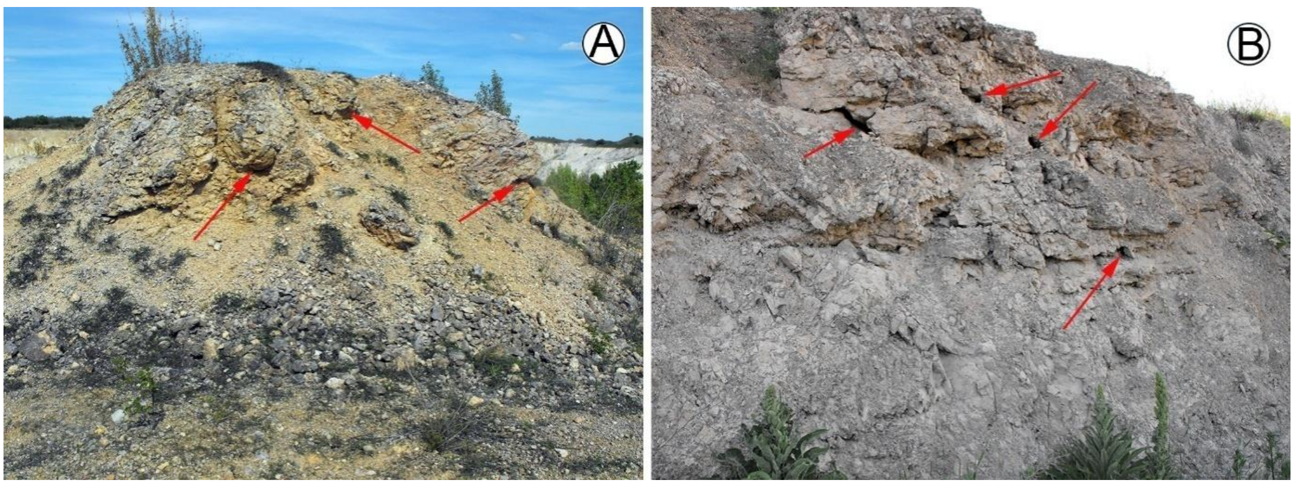


Figure 10: The epikarstic cavities of the mound abandoned in the strip pit of the dolomite A. Sóly mine (Bakony Region, Hungary), B. Kádárta mine (Bakony Region), Legend: 1. arrows refer to cavities.

In the primitive epikarst of the dolomite, a piezometric surface may develop, but the vertical infiltration rates show a slight deviation from each other and they may not be of permanent difference. As a result of the homogeneity of vertical drainage rates, cavity formation is of low degree and homogeneous on such dolomite variety and thus, no dolines develop either. On the rubble dolomite of the Bakony Region, depressions with a small depth occur, but rarely [53]. These features may probably have been primitive drawdown dolines. Their existence may refer to the fact that epikarst may develop in a limited way on dolomite affected by rubble formation as it can be observed on the unquarried rocks of the residue in the depressions of some surface mines. These were left during mining since they are dirt rocks from the point of view of rubble mining. Cavity formation below primitive (small) drawdown dolines may not show high heterogeneity and here, the epikarst is also primitive.

In addition to fractures, other factors also contributed to rubble formation. [61] analysed rock samples from the rubble mines of the Bakony Region. Deduction from collected data established that the value of Mg ion content changes and the calcareous content is lower on rubble samples. The Mg ion content can change because it is lower where the rock was affected by heat effect. This heat effect is explained by the dissolution capacity of the warming karstwater. The heating up of karstwater can be associated with basalt volcanism of the Upper Pannonian Balaton Uplands [62]. The fluctuating karstwater table reached (but reaches at some sites) the dolomite surface of low altitude. Calcareous content is higher on non-rubble dolomite because it could not be dissolved since it was not reached by karstwater of higher temperature close to the surface. The crystal shape may also have played a role in rubble formation. In rhombohedral crystals, there are cation planes constituted by calcium and magnesium ions [63]. The crystals can be broken easily. The dissolution of calcium ions along the planes can also promote physical weathering.

4.3. The Porosity and Vertical Dissolution of Evaporites

On rocks with good drainage capacity and high primary porosity, vertical pipes and passages (karren wells, solution pipes), referring to vertical water motion are widespread particularly below superficial deposit [64] thus, in calcareous dune sand [65-67], and chalk [68]. These features developed below superficial deposit in chalk too [69]. Similar circumstances also occur on evaporites. On gypsum where the water storage capacity is low [70], the epikarst is weakly developed [2]. This is explained by surface crust and the calcite that precipitated in fractures [2]. However, in artificial exposures it can be seen that vertical passages of similar size developed in the rock at nearly similar distances (Fig. **5**), [2, 24]. This can be explained by the high dissolution rate of gypsum because relative to limestone, it is dissolved 183 times faster in distilled water with a temperature of 20ºC, while the dissolution of halite is 25000 times greater [55].

Although primary porosity is low at evaporites, depending on the type of gypsum, it is 0.5-10%, higher values may also occur [71], at halite, it is below 0.1 [72]. At the same time, good dissolution capacity controls the direction of water motion. In the case of gypsum, dissolution coefficient increases depending on water flow [73] and thus, dissolution capacity also increases. Potential porosity increase will be the highest along vertical water motion and this coincides with percolation of gravitational direction. Therefore, pore growth takes place in the direction of the water percolation in gravitational direction. Due to fast dissolution, pores coalesce vertically and make pipes. Vertical water motion and dissolution are favoured by the fact if the rock contains fractures and the solution is still unsaturated and if the density difference of the water is great.

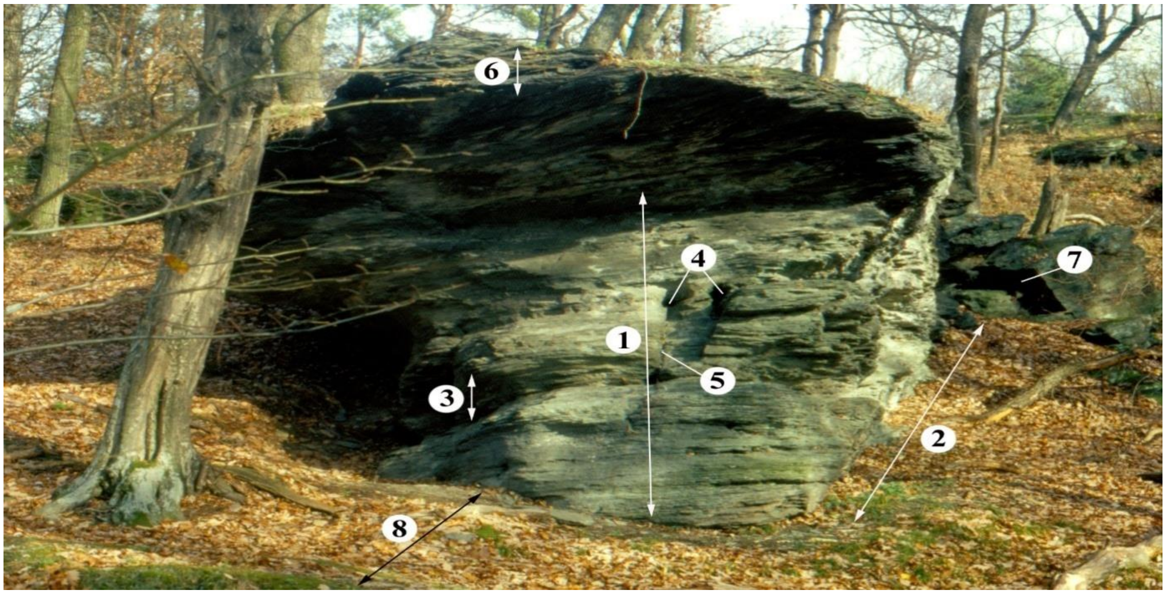
Due to good dissolution capacity, vertical percolation and dissolution takes place along the fractures and thus, deep penetrating vertical passages are formed. Therefore, there is neither horizontal water motion nor water storage or water storage is weakly developed. Due to similar or nearly similar vertical drainage, the vertical percolation rate and cavity formation are homogenous. If there is also a piezometric surface, it is of horizontal position and thus, drawdown dolines do not develop. Since the dissolution of the halite is even faster, vertical passage development is much more significant (Fig. **5C**). Thus, the horizontal cavity formation and the vertical drainage rate are homogeneous, if a piezometric surface exists, it is not warping, therefore drawdown dolines do not develop, but during the breakdown of pits and shafts, indentations may develop below the superficial deposit on halite.

4.4. Cavity Formation of Cavities with Calcareous Content

In Hungary, on the metamorphic rocks of the Kőszeg Mountains such as in greenschist and calcareous phyllite, local calcareous intercalations occur [74]. The calcareous content may reach 30 % in the rock [74]. The infiltrating waters dissolve the calcareous material along the fractures and bedding planes (Fig. **11**). Primary porosity marks out sites of secondary porosity, while calcareous content marks out the degree of secondary porosity. The primitive epikarst that develops at dissolution cavities does not have a piezometric level. Horizontal cavity formation and vertical percolation rate are determined by calcareous intercalations. Cavity formation and vertical drainage may increase locally at calcareous intercalations. As a result of local cavity formation, at the surface neither karren, nor dolines develop.

4.5. Model of Feature Development on Karstifying Rocks

Water input, primary porosity, epikarst and feature development are the most diverse on limestone. On rocks of very low porosity, if the surface is of low inclination and there are open fractures, concentrated infiltration takes place into the rock. In this case, grikes and giant grikes develop. If the grikes coalesce with cavities that are situated below the karstwater table, giant grikes are formed. If there are no open fractures, surface water flow is dominant and thus, corrosion plains develop and giant kamenitzas are formed on marble. On inclined surfaces, even when open fractures occur, karren features of flow origin (rinnenkarren) develop, predominantly when there is surface runoff. In the case of higher porosity, dolines are formed. In this case, flow is vertical and horizontal. The dolines, if they reach the karstwater table, develop into corrosion plains. If the corrosion plains coalesce, intermountain plains are formed and fenglin develops. On limestones of extremely high porosity, water motion is vertical and pits may develop.



Legend: 1. uncovered portion of a big notch, 2. filled-up notch, 3. medium-sized notch, 4. passage, 5. fissure, 6. top of the hat, 7. ruined cave, 8. present-day terrace development

Figure 11: Pseudoepikarst (Kőszeg Mountains, Hungary Kalapos-kő).

On dolomite, on non-recrystallized rock, homogeneous dissolution takes place. The increase of water temperature increases dissolution in the epikarst, dolines and even fenglin may develop. On recrystallized dolomite, heterogeneous dissolution takes place, the rock is affected by rubble formation, no epikarst develops or it becomes destroyed.

On evaporites, good solubility favours vertical water motion and dissolution. During this, pits are formed.

5. Conclusions

The relationship between the primary porosity, the epikarst and feature development of different karstifying rocks (carbonates, evaporites) was overviewed and studied. This relationship is the most diverse of limestones which have diverse porosity, stratification and good dissolution capacity. Surface features (karren, dolines) only develop on well-soluble karstic rocks with medium primary porosity, at sites where well-developed and heterogeneous secondary porosity (cavity formation) develops. On extremely dissoluble rocks, both cavity formation and percolation rate are homogeneous due to high drainage rate. No piezometric surface develops. Due to homogeneous cavity formation, if a piezometric surface does develop, it is not warping, which is a necessary precondition for drawdown doline development.

On recrystallized rocks of low primary porosity, infiltration and thus, dissolution capacity decreases and concentrates into drainage open fractures (crystalline limestone, marble), or the developed cavities are destroyed during rubble formation (dolomite). Local dissolution does not favour the development of such epikarst where the water motion is horizontal and does not favour heterogeneous vertical drainage rate either, but the development of the piezometric surface and of drawdown dolines. However, surface dissolution takes place, and thus, with the exception of the dolomite that undergoes rubble formation, karren are widespread on karstifying rock even if there is no piezometric level.

The value of primary porosity and inclination determine the proportion of surface runoff and infiltration. Primary porosity and solubility affect the direction of water motion. The proportion of denudation and infiltration, the position of the karstwater table and dissolution effect directly or through the epikarst indirectly serve as a basis for surface feature development. All this determine the type of feature development, but feature development (size, density) itself is shaped by CO_2 content, precipitation quantity and water temperature.

Conflicts of Interest

The authors declare no conflict of interest.

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