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KARREN OF PROVENCE (FRANCE), GRÉOLIÈRES, CAUSSOLS, TOURRETTES-SUR-LOUP AND LUBERON

ŠKRAPLJE PROVANSE (FRANCIJA), GRÉOLIÈRES, CAUSSOLS IN TOURRETTES-SUR-LOUP TER LUBERON

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Abstract UDC 551.435.81:552.513(449.1/.43)
Martin Knez, Tadej Slabe & Philippe Audra: Karren of Provence (France), Gréolières, Caussols, Tourrettes-sur-Loup and Luberon
The rock relief of karst forms, either of surface forms or of caves which are forming on different carbonate rocks and under different conditions, is one of the most telling traces of their formation, along with the characteristic factors and development. Therefore, we meticulously studied and examined the geological features and rock formations, as well as how they fit into the rocky relief. The diverse shaping of the karst surface is revealed by the rock relief of selected karren on different carbonate rocks, fine-grained homogeneous and compact limestones, as well as porous fine-grained sandstones. We have also newly explained the formation of parallel channels on the inclined surfaces of denuded rock (Gréolières); the gradual reshaping of the rock surface from a subsoil one to one directly exposed to rain and water creeping along the gently sloping rock (Caussols). Furthermore, the unique shaping of carbonate sandstones, specifically such with large channels (Tourrettes-sur-Loup) is presented for the first time. The speed of karstification of younger carbonate rocks is revealed by channels on the walls of the palace in Avignon.
Keywords: carbonate rock, rock relief, complexometry, Provence, France.

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Martin Knez, Tadej Slabe & Philippe Audra:* Škraplje *Provanse (Francija), Gréolières, Caussols in Tourrettes-sur-Loup ter Luberon
Skalni relief kraških oblik, površinskih in jam, ki nastajajo na različnih karbonatnih kamninah in razmerah, je ena najbolj povednih sledi načina njihovega oblikovanja z značilnimi dejavniki in razvoja. Zato smo natančno preučili in spoznali geološke značilnosti in skalne oblike ter njihovo povezanost v skalni relief. Pestrost oblikovanja kraškega površja razkrivajo škraplje na različnih karbonatnih kamninah, drobnozrnatih homogenih in kompaktnih apnencih ter poroznih drobnozrnatih peščenjakih. Na novo razloženo je tudi oblikovanje vzporednih žlebov na nagnjenjih površinah razgaljene skale (Gréolières), razkriva se postopno preoblikovanje skalnega površja iz podtalnega v neposredno izpostavljenega dežju in polzeči vodi po malo nagnjeni skali (Caussols) ter prav tako na novo je predstavljena svojevrstnost oblikovanja karbonatnih peščenjakov zlasti z velikimi žlebovi (Tourrettes-sur-Loup). Hitrost zakrasevanja mlajših karbonatnih kamnin razkrivajo žlebovi na zidovih palače v Avignonu.
Ključne besede: karbonatna kamnina, skalni relief, kompleksometrija, Provansa, Francija.

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1. INTRODUCTION

Karren are important landforms on the karst surface of Provence. Their diversity leaves a special mark on the landscape, revealing the diverse shaping of surface karst forms. Three examples of karren are presented – through denudation they are changing from subsoil karren to karren directly exposed to rain. Origin and development of karren is precisely presented in a book Karst rock features–Karren sculpturing (Ginés et al., 2009).

Provence is located in southeastern France (Figure 1a) along the Mediterranean coast, and consists in large part of carbonates, mainly Mesozoic ones. The earliest karstifications appeared locally on structural highs at the end of the Cretaceous period, attested by the bauxites of the Durancian bulge. Transgressions invaded the lower topographic zones until the Miocene, with the deposition of molasses, which are occasionally carbonate. The structure is mainly composed of E–W folds that formed during the Pyrenean-Provençal phase. To the west, Alpine tectonics are responsible for N–S structures superimposed on the Provençal folds. The relief consists of medium-altitude ridges and plateaus to the west, gradually rising towards the Alps, reaching elevations of 1500–1900 meters in the Préalpes de Grasse on the right bank of the Var River.

The climate is Mediterranean, characterized by heavy rainfall in autumn and spring, and a dry season in summer. Moving towards the Alps in the west, the climate retains its Mediterranean characteristics but becomes more humid, especially on the initial reliefs exposed to marine influences. As a result of deforestation and forest fires over thousands of years, the vegetation has degraded into garrigue, which has been slowly reclaimed by the forest, particularly at higher altitudes and on the wetter northern slopes, due to the rural exodus over the past half-century.

The four areas studied are spread over a carbonate plateau to the west, in the case of Buoux at the foot of the Luberon mountain range, while the other three are tiered in the Préalpes de Grasse to the east.

Gréolières

The Gréolières site is the highest (43.801902°N, 6.907847°E, alt. 1100–1150 m) of the areas studied. It lies in the Gréolières water gap on the steep rocky slopes of the Cheiron massif. The area is composed of Tithonian massive limestone (J9-n1) (Bodelle et al., 1980). The climate is mountain-Mediterranean, with annual temperatures and rainfall at the lower station of Gréolières (alt. 79 m) of 11.4 °C and 1168 mm, respectively (1971–2000). In winter, snow cover on the north-facing slopes can last for several months, with frequent sub-zero temperatures, particularly at night. As the first orographic barrier behind the coast, precipitation remains regular throughout the year, even in summer.

Caussols

The Caussols site is located along the Ravin du Logis Neuf (43.750056°N, 6.872296°E, alt. 1050–1100 m), represented by the structural outcrops corresponding to the top of the Mesozoic carbonate formation, the Berriasian limestones (N1) (Bodelle et al., 1980). The climate is similar to that of Gréolières, with a mean temperature of 9.7 °C and an annual precipitation of 1272 mm over the period 1991–2020.

Tourettes-sur-Loup

The Tourettes-sur-Loup site is located on the foothills of the Préalpes de Grasse, facing the Mediterranean (43.711942°N, 7.061447°E, alt. 300–330 m). The rock is carbonate molasse from the Lower Burdigalian of the Tourettes-sur-Loup Fm. (m1M) (Dardeau et al., 2010).

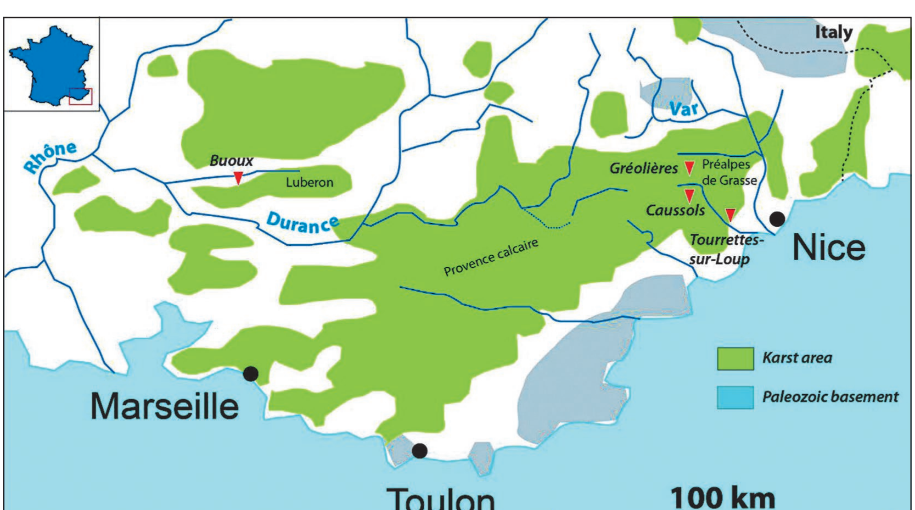


Figure 1a: Location of the studied areas in Provence, France.

The climate is Mediterranean with hot and dry summers, averaging 14.6 °C and 1031 mm (1991–2020).

Buoux

The Buoux site is a plateau dissected by dry gorges on the northern foothills of the Luberon chain (43.818522°N, 5.378624°E, alt. 450–500 m). The rock is carbonate Burdigalian molasse (m1) (Germain et al., 1966). The climate is Mediterranean, characterized by hot, dry summers, with an average temperature of 12.1 °C and an annual precipitation of 816 mm.

Findings will be of great use in differentiating the development of the karst of Provence and its formation on different rocks and under different regional conditions. They will also be important for differentiating development models of karren on different rocks and in different environments, and for differentiating the formation of characteristic rock forms and their developmental transitions (Knez et al., 2003, 2010, 2011; Debevec, 2012; Knez et al., 2012; Al Faraj Al Ketbi et al., 2014; Gutiérrez Domech et al., 2015; Knez et al., 2015, 2017, 2019; Slabe et al., 2016, 2021; Knez et al., 2020, 2022, 2023).

2. RESEARCH METHODOLOGY

We studied the rock relief and the rock features that comprise it. First, we identified the rock features in the field, then we discerned their shape and thoroughly mapped them. We linked their formation and shape with geological characteristics. The numerous photographs aided us in further researching the rock features. We then combined the studied karst features into a rock relief.

We defined the prevalent factors and the interaction of factors behind the formation of individual rock features. By combining these features into a rock relief, we attempted to determine the evolution of karst features.

We took a suitable number of rock samples from select geological profiles. We determined the appropriate distances between two samples or performed the sampling where a change in the rock was visible macroscopically.

We determined the colour of the rock using the established colour chart (Munsell Rock-Color Chart, 2009).

In the laboratory we prepared microscope slides, i.e., thin sections, from the rock samples.

All microscopic thin sections were prepared and examined by transmitted light at different magnifications. Prior to the microscopic examination, a part of each thin section was dyed with alizarin red dye (1,2-dihydroxyanthraquinone, known also as Mordant Red 11); the calcite crystals were stained red, while the dolomite and non-carbonate crystals remained unstained (Evamy & Sherman, 1962).

We devoted special attention to the porous rock samples from Tourrettes-sur-Loup. In order to present the type, shape and interconnection of void spaces as clearly and analytically as possible, we injected blue epoxy resin into a rock slice that had been prepared for attachment to the glass of a microscope slide (Gardner, 1980).

We performed complexometric analyses on all samples for the purpose of determining the proportion of calcite, dolomite, and insoluble residue in the rock. All samples were ground and dried at 105 °C for 24 hours followed by cooling in a desiccator for 30 minutes prior to weighing. We used two reference methods – determination of calcium oxide by EGTA and determination of magnesium oxide by DCTA (CEN, 2013). Both methods use photometric determination. Visual observation was performed. The indicator methylthymol blue changes colour from pale green to pink in the case of calcium oxide, and from blue to grey in the case of magnesium oxide.

Combining the macroscopic observations in the field and the microscopic analyses using a transmitted light microscope at different magnifications in the laboratory, and by applying the results of the complexometric titration analysis, we are able to determine the properties of the rock.

3. SLOPE KARREN ABOVE GRÉOLIÈRES

SHAPE OF KARREN

The slope (Figures 1b, 2) develops on thick-bedded rock layers, which dip in the direction of the slope at a small angle. The slope is crossed by the faces of rock strata of various thicknesses that create steps. In some parts the steps are taller, reaching ten meters in height.

The walls, some overhanging and spanning several rock strata, appear to be the trace of collapsed caves. The

Figure 1b: Karren of Gréolières.

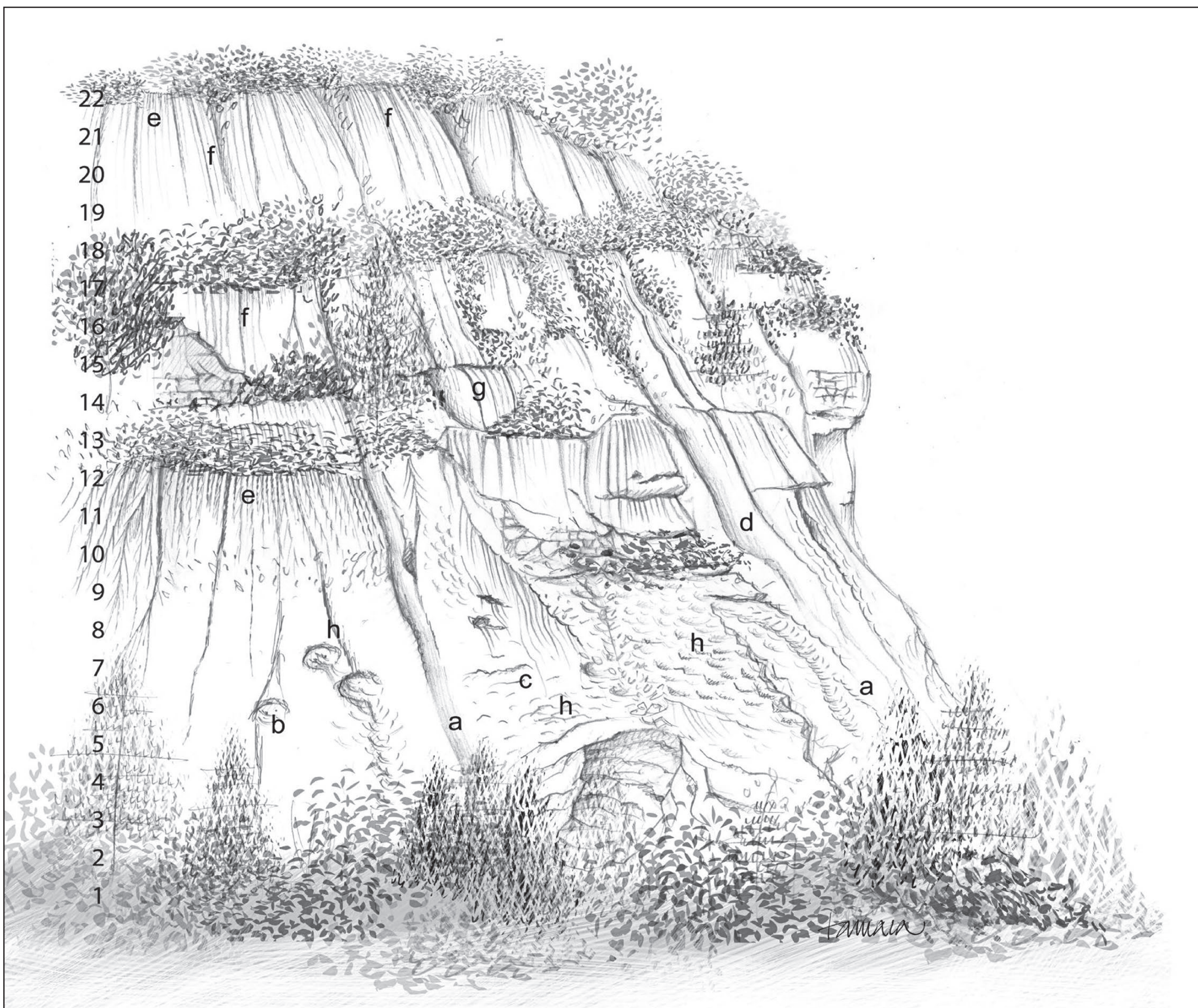


Figure 2: Karren of Gréolières: a. denuding subsoil channel, b. subsoil cup, c. subsoil transverse notch, d. channels, e. rain flutes with channels, f. channels formed mostly by water flowed from subsoil features, g. channels formed by water from bedding plane holes, h. steps. Locations of taken rock samples, numbers 1 to 22.

surface of the karren is composed of often large, inclined, but predominantly flat or only slightly mounded rock plates and steep faces of the strata and the wall. Notches also developed along the lengthwise fissures that crisscross the rock strata. The initial roundedness of the mounds, which are highest in the middle and slope gently toward the edges, the cracks that appear along the fissures and the faces, and the smoothness of the rock are the consequence of subsoil formation. These features are particularly evident in the lower section of the karren. The karren developed in three dimensions. Along the more distinctive fissures where cracks occurred and in individual places where smaller vertical hollows occurred, the water flows downward to lower-lying bedding planes and then along them. Individual strata also appear to undergo karstification. They are crisscrossed by numerous small hollows, mostly parallel to the bedding planes. The upper part of the karren is mostly denuded and the shrubbery, relatively dense in places, only grows from cracks and smaller hollows filled with soil while the lower part is largely covered with a thin layer of soil. On some larger rock surfaces there are smaller and thinner rocks, the remains of the former upper layer of the rock. The karren are dissected by characteristic rock relief forms that reveal their current formation and partly their development.

GEOLOGY

Macroscopic description

The selected profile of the rock above the village of Gréolières was examined in a thickness of around 50 m. Throughout the geological profile, the limestone is extremely hard, homogeneous, and compact. The layers are of varying thickness, mostly between 10 and 100 cm. Due to atmospheric impacts and vegetation, the surface of the rock is crushed in many places. In the lower part of the profile, which is quite overgrown and the rock is crushed on the surface, it is difficult to determine the real dip angle of the layers. In the middle part of the profile, the dip angles of the layers are between 220/35 and 230/15, and at the top of the profile 340/4. In the field we took 22 samples of a homogeneous, hard, and nonporous rock at relatively even intervals. The macroscopically examined layers did not show any major differences, so we took samples of the rock evenly throughout the profile, i.e., at about every 2 m. The rock colour changes from a dark grey (brownish grey 5YR 4/1) in the lower part of the profile, to light brownish grey (5YR 6/1) in the middle, and to almost white in the upper part of the profile (very light grey, N8).

Microscopic description

We turned each rock sample into a microscope slide. After examining all of them, we have determined that the examined geological profile is in fact made up of geologically very similar layers of rock. However, if we take a closer look, we can distinguish two groups of layers. In the lower part, the slope is made up of layers of pelbiointrasparite to microsparite (mostly grainstone, only exceptionally packstone). In the upper part of the profile, the rock mostly contains intraclasts, which is why the predominant rock is intrapelsparite (mostly grainstone), which exceptionally transitions into intrapelbiomicrite (packstone) in the vertical direction over shorter segments. Throughout the geological profile, the highly pure limestone with various intraclasts within the layer is of a very similar composition, homogeneous, compact, and nonporous.

The layers of pelbiointrasparitic to microsparitic limestone are very similar. They differ in grain compaction or cement content, in the frequency of calcite veins and, exceptionally in some layers, in the appearance of several cm large complete fossils and their fragments (samples from G1 to G12). The predominant grains in the rock are peloid grains, taking up around 80% of the volume. The majority of peloids are typical fecal pellets, which take up around 70% of the volume. The pellets are tiny; their cross-sections, which are visible in the microscope slide, have diameters from 45 μm to 0.3 mm, while the large majority of them, i.e., 90%, measure 40 and 90 μm in diameter, respectively. Intraclasts make up around 30%. They are fully micritized, with no internal structure, and mostly measure between 90 μm and 0.3 mm in diameter; they can be larger laterally, with diameters up to 1 mm. Also visible in the rock are individual bioclasts; let us mention tiny foraminifera, miliolids, echinoderms, and individual fragments of unidentifiable fossils, most likely bivalves. Most grains touch each other. No grain sorting, a form of rock texture, is visible. There is very little sparry cement due to good grain compaction. Where the grains do not touch, cement fills the rock with crystals, usually measuring around 40 μm in diameter. The rock also contains individual fenestrae filled with sparry calcite, which can measure up to 2.2 mm in diameter. No primary porosity is visible in the rock. The calcite veins of several generations are mostly thin, between 20 and 130 μm thick. The layers where grains do not touch and only make up about half of the volume have similar characteristics (Figures 3a, c; sample G8). The other half is made up of cement, all of which is equant drusy mosaic spar. Most of the cement grains are anhedral to subhedral; where spaces between the pelloids are larger, we also see euhedral crystals. The majority of sparry grains have a diameter between 0.1 and 0.3 mm, exceptionally up to 0.7 mm. In some layers, especially within thicker calcite veins, we noticed individual dolomite crystals.

The layers of intrapelsparite (mostly grainstone),

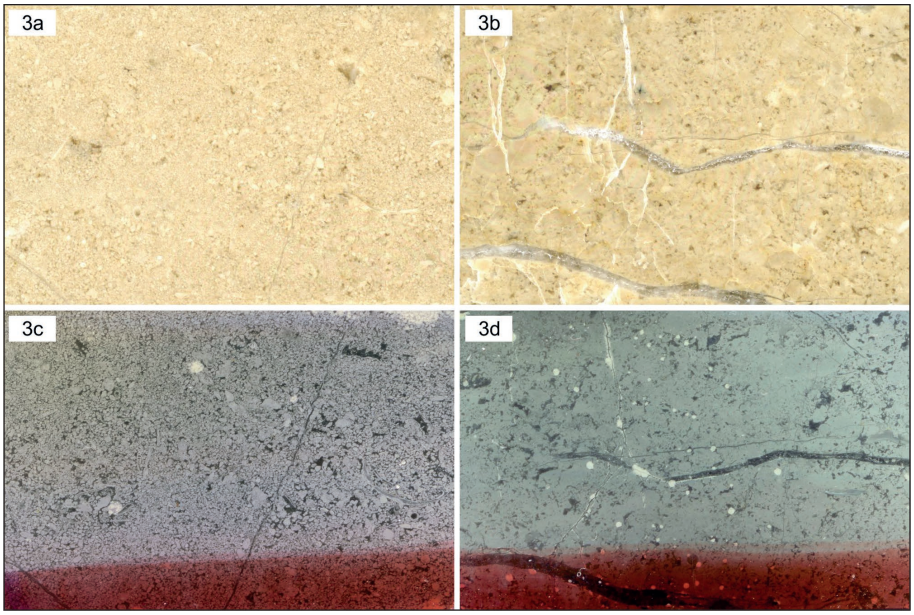


Figure 3: (a) Rock slice prepared for a thin section, sample G8. Width of view is 4 cm, (b) Rock slice prepared for a thin section, sample G17. Width of view is 4 cm, (c) Thin section of sample G8. Lower half of sample was dyed in alizarin red dye. Width of view is 4 cm, (d) Thin section of sample G17. Lower half of sample was dyed in alizarin red dye. Width of view is 4 cm.

which exceptionally transitions into intrapelbiomicrite in the vertical direction over shorter segments, are also very similar to each other. The predominant grains in the rock are intraclast grains, taking up around 70% of the volume. Pellets only make up a percent or two, and there are only a few specimens of tiny bioclasts, such as foraminifera and miliolids (Figures 3b, d; sample G17). The intraclast and pellet grains are fully micritized and with no internal structure. Most intraclasts have diameters between 0.2 and 0.5 mm, and the pellets between 45 and 90 µm. All the cement between the grains is equant drusy mosaic spar. Most of the cement grains are anhedral to subhedral, exceptionally euhedral crystals. The majority of sparry grains have a diameter between 90 and 180 µm, exceptionally up to 0.7 mm. There are at least two generations of calcite veins in the rock. Most of them are thin, from 25 to 45 µm thick; only a few are thicker. No primary porosity is visible in the rock.

Complexometric analyses

Using the dissolution method (CEN, 2013), we performed 13 complexometric analyses on 13 selected rock samples (Table 1). It has been determined that all profile samples exceed 99% of total carbonate content. The average value

Table 1: Complexometric analyses of rock samples from Gréolières.

Laboratory designation of the sample	Rock sample	CaO (%)	MgO (%)	Calcite (%)	Dolomite (%)	CaO/MgO	Total carbonate (%)	Insoluble residue (%)
V- 110/24	G1	55,36	0,46	98,81	0,96	120,35	99,77	0,23
V- 111/24	G3	54,96	0,76	98,09	1,59	72,32	99,68	0,32
V- 112,24	G4	55,61	0,36	99,25	0,75	154,47	100,00	0,00
V- 113/24	G6	55,12	0,58	98,38	1,21	95,03	99,59	0,41
V- 114/24	G8	55,39	0,31	98,86	0,65	178,68	99,51	0,49
V- 115/24	G9	53,95	1,62	96,29	3,39	33,30	99,68	0,32
V- 116/24	G12	55,63	0,34	99,29	0,71	163,61	100,00	0,00
V- 117/24	G13	55,64	0,33	99,31	0,69	168,61	100,00	0,00
V- 118/24	G15	55,51	0,36	99,07	0,75	154,19	99,82	0,18
V- 119/24	G17	55,56	0,37	99,16	0,77	150,16	99,93	0,07
V- 120/24	G18	55,65	0,32	99,32	0,67	173,91	99,99	0,01
V- 121/24	G20	55,61	0,36	99,25	0,75	154,47	100,00	0,00
V- 122/24	G23	55,62	0,35	99,27	0,73	158,91	100,00	0,00

of all samples amounts to 99.8%. All samples show a high calcite percentage. Five samples have a calcite content of less than 99%; the average value of all samples is 98.8%. All samples also contain a small proportion of dolomite. Only one sample has a dolomite content of over 3%. The average value of all samples amounts to just over 1.05%. The samples also contain a small proportion of insoluble residue. Five samples contain no insoluble residue. The average value of all samples is 0.16%.

Impact on karstification

The entire profile of the rock, i.e., all the layers, react similarly to karstification. The limestone is fine-grained; only in some places does it contain fossil remains, several cm large. It is homogeneous and compact. Its calcium carbonate content is almost 100%. The examined rock has excellent properties; on it, subsoil and rain rock features can develop efficiently, smoothly, and successfully.

ROCK RELIEF

Subsoil rock forms

The most characteristic rock forms are subsoil channels and subsoil cups (Slabe & Liu, 2009). The cross-sections of both reach several decimetres in size. The subsoil cups reach one meter in diameter only on the gentlest sloping surfaces. Subsoil channels (Figures 2a, 4a) are found on the upper inclined and gently sloping surfaces as well as on the faces of strata where they are vertical. The bottoms of the channels that formed along fissures are hollowed by vertical tubes (Figure 4b). The subsoil cups (Figure 4c) are shallow on the more gently sloping upper surfaces while at the edges of the strata they are deeper and open on the outer side. The latter are in the developmental transition into subsoil funnel-like notches (Figures 2b, 4d). Along a long-term soil level on the lower strata steps a few decimetres in size can occur on the face of the upper strata. They are also found at the bottoms of denuded funnel-like notches. A large proportion of the subsoil cups are filled with sediment and overgrown (Figure 4b). Their edges are raised above the rest of the rock surface. Funnel-like subsoil notches (Figure 4d) developed on steep edges where water converged from the larger surfaces of sloping tops. The largest reach one meter in diameter.

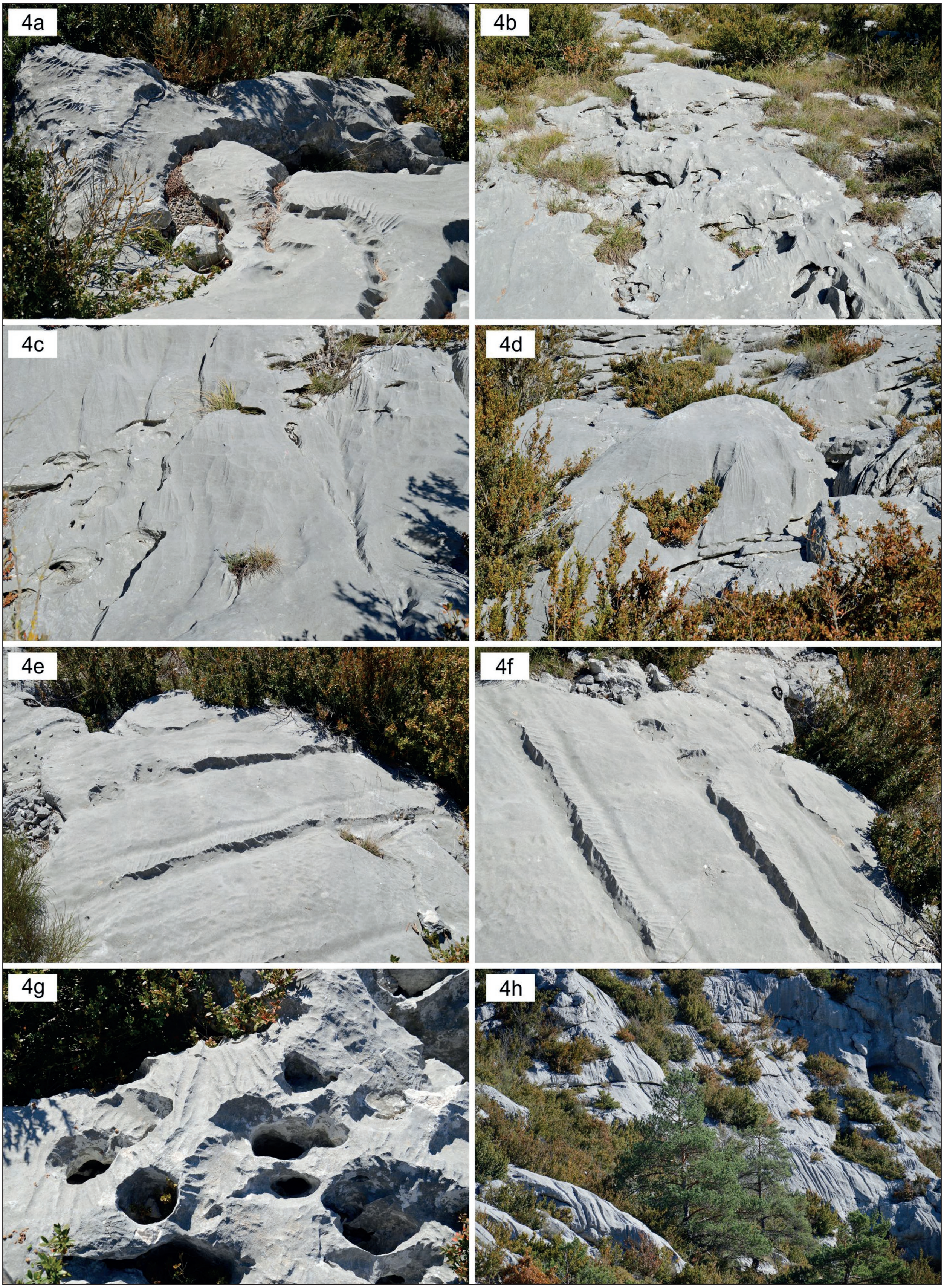
The more gently inclined surfaces are dissected by transverse notches (Figures 2c, 4e). They are several meters long and only a few centimetres deep and wide. They have flat and smooth bottoms. Often they have been transformed into channel-like solution pans. Some have widened in a circular fashion and are open on the runoff side (Figure 4f). This indicates a long-term level of soil cover where water flowing to it from the higher bare rock surface was dammed by the soil. At some levels only individual horseshoe-shaped open cups developed. These forms are often found one above the other along the fall line of the slope, which indicates gradual denudation. Descriptions of such rock forms are not found in the scientific literature.

Subsoil-shaped fissures are found along more distinct cracks. On their walls are vertical subsoil channels while subsoil tubes with circular cross sections are found along smaller cracks. They can be connected by subsoil fissures, channels, and cups. The relatively dense perforation on bedding planes and vertical fissures as well inside the strata has a subsoil origin (Figures 4a, 4b, 4g).

Traces of rainwater and creeping and trickling water

Well preserved subsoil rock forms and the rounded and often smooth rock surface testify to the relatively recent denudation of the karren. Denuded subsoil forms are transformed by rainwater and trickling water, and from the overall rock relief it is possible to discern the progress of the gradual denudation of the karren. It occurred on individual surfaces from the top down or vice versa as the faces were denuded first and then the surfaces above them. The lower part of strata faces often developed longer under the soil.

Channels (Figures 1b, 2, 4h) are the rock form that gives the primary stamp to the formation of karren. They are found on both steep and gently sloping surfaces. They occur individually but most frequently lying parallel to each another. They can be several meters long and their diameters range from a few centimetres to decimetres in size. Depending on their origin they can be classified into several types. The first type of channel (Figures 2d, 4i) collects water, mostly rainwater, which flows across relatively large areas on more or less flat and gently inclined tops of karren. On the evenly gently sloping surfaces the upper parts of channels are up to five centimetres wide and shallow and increase steadily in size toward the bottom (Figures 4j, 4k). They are relatively wide from the start. Upwards they gradually transform into a smooth or stepped surfaces from which water flows into them. In places they lie side by side. The laboratory experiment on the formation of rain flutes in plaster of Paris showed a similar formation process on the soluble surface of plaster exposed to rain (Slabe 2005, 113). In dense networks, there are only ridges between channels. Shallow channels are stepped. The steps are only one centimetre high. On previously dissected parts of surfaces, which are relatively few in number, branched networks developed. Protrusions with rain flutes and smaller funnel-like notches are found among them. Some developed from denuded subsoil channels while others could have originated as the lower parts of bedding plane anastomotic tubes.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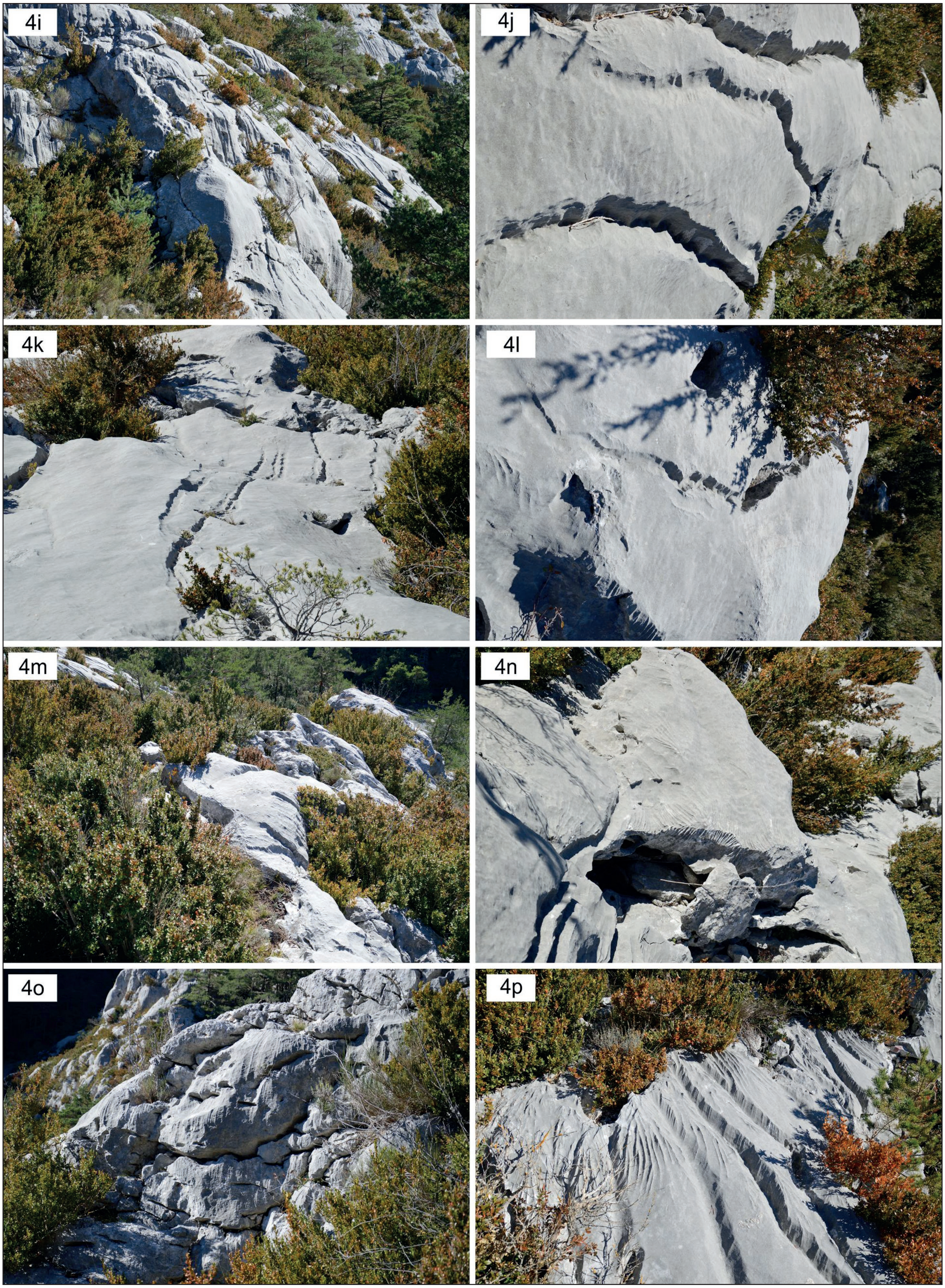
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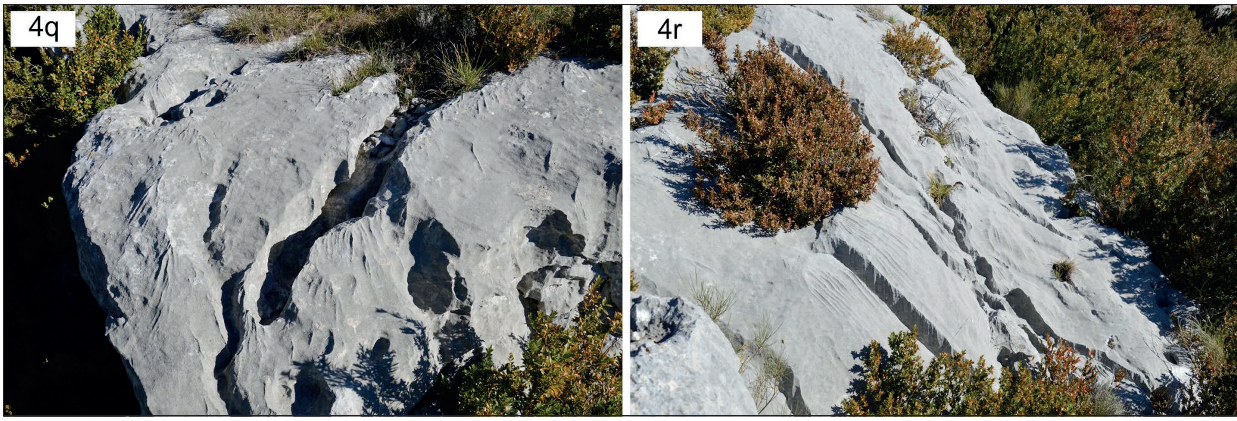


Figure 4: (a) Subsoil channel and meandering channel in the middle right, (b) Subsoil hollows, (c) Subsoil cup. Width of view is 2 m, (d) Subsoil cup in the bottom of funnel like notch, (e) Transverse notch. Width of view is 6 m, (f) Transverse notches with cups. Width of view is 4 m, (g) Hollows. Width of view is 2 m, (h) Channels, (i) Channels, (j) Channels on evenly gently sloping surface. Width of view is 10 m, (k) Channels on evenly gently sloping surface. Width of view is 5 m, (l) Channels on evenly gently sloping surface. Width of view is 2 m, (m) Channels on steep slope, (n) Channels below rain flutes. Width of view is 4 m, (o) Channels below rain flutes, (p) Channels below rain flutes, (q) Channels below subsoil features. Width of view is 3 m, (r) Channels below subsoil features.

At the bend below a gently sloping surface where it becomes steeper, channels form where the water consolidates in a stream after creeping evenly across the large surface above. They are dissected by steps. This applies to channels on steep surfaces that have grown upward. Laboratory testing on plaster of Paris also revealed this type of formation (Slabe 2005, 116). The channels have semi-circular mouths and some resemble solution pans that over time develop into funnel-like notches (Figure 4l). On steeper surfaces such channels can be stepped (Figure 4m). Their circumference is dissected by a number of funnel-like notches arranged one above another. A channel of a different origin, described below, can also lead into an initial funnel-like notch. This could therefore be a composite rock form. On the steeper slopes channel (Figures 2e, 4h, 4n, 4o, 4p) develop under the edge with rain flutes. They begin with funnel like notches. They develop from rain channels.

Channels also form due to water trickling from the soil that fills cracks and subsoil cups (Figures 2f, 4h, 4q, 4r, 5a, 5b, 5c). These too form mostly in parallel where rainwater and water trickling down inclined surfaces both contribute to their development. They are frequently larger and especially deeper on the inflow side and have funnel-like mouths. This characteristic helps us distinguish them from channels formed primarily by rainwater or to understand the development of composite channels. The beginning section can meander due to the locally smaller incline of the rock surface. This kind of channels prevail and they are the most expressive rock features. The deepest channels have winding bottoms.

A special type of channel (Figure 5d) forms due to the discharge of water from tubes that develop along bedding planes, that is, from under upper-lying rock strata. They often begin with funnel-like notches that are wide if the water flows from a larger surface (Figure 5e). Narrow forms whose cross sections resemble an inverted omega sign occur when the water flows continuously from a tube.

Channels also lead from some larger solution pans. Channels of various origins are thus interwoven on larger rock surfaces and can assume the role of a direct collector of rainwater and water that trickles down the rock. Channels that occurred due to the water discharging from the soil can be left hanging and transformed by rainwater (Figure 4p). Due to the three-dimensional development of the karren, the level of the soil in a vertical subsoil tube can lower faster than the deepening of the channels that originally led from it.

Solution pans (Figure 2h, 4f) are found in places at the bottom of the more gently sloping channels (Figure 5f) and notches, and weathered debris from fallen vegetation periodically builds up in other channels. They are partly subsoil deepened and widened at the bottom.

The walls of larger channels are dissected by vertical channels a few centimetres in size where water flows in from the surrounding surface (Figures 4j, 4p, 5g). On laterally inclined surfaces on the upper rims of channels there are small channels, and rain flutes (Figures 4a, 4p) are found on the lower edge. The distribution of these rock forms on dissected surfaces varies. The bottoms, however, are smooth as a rule, and often more distinctly winding than the rest of the channel.

On the bends where inclinations of the rock surface change distinctly, all the larger channels are distinctly deeper. Relative to their formation, the latter types of

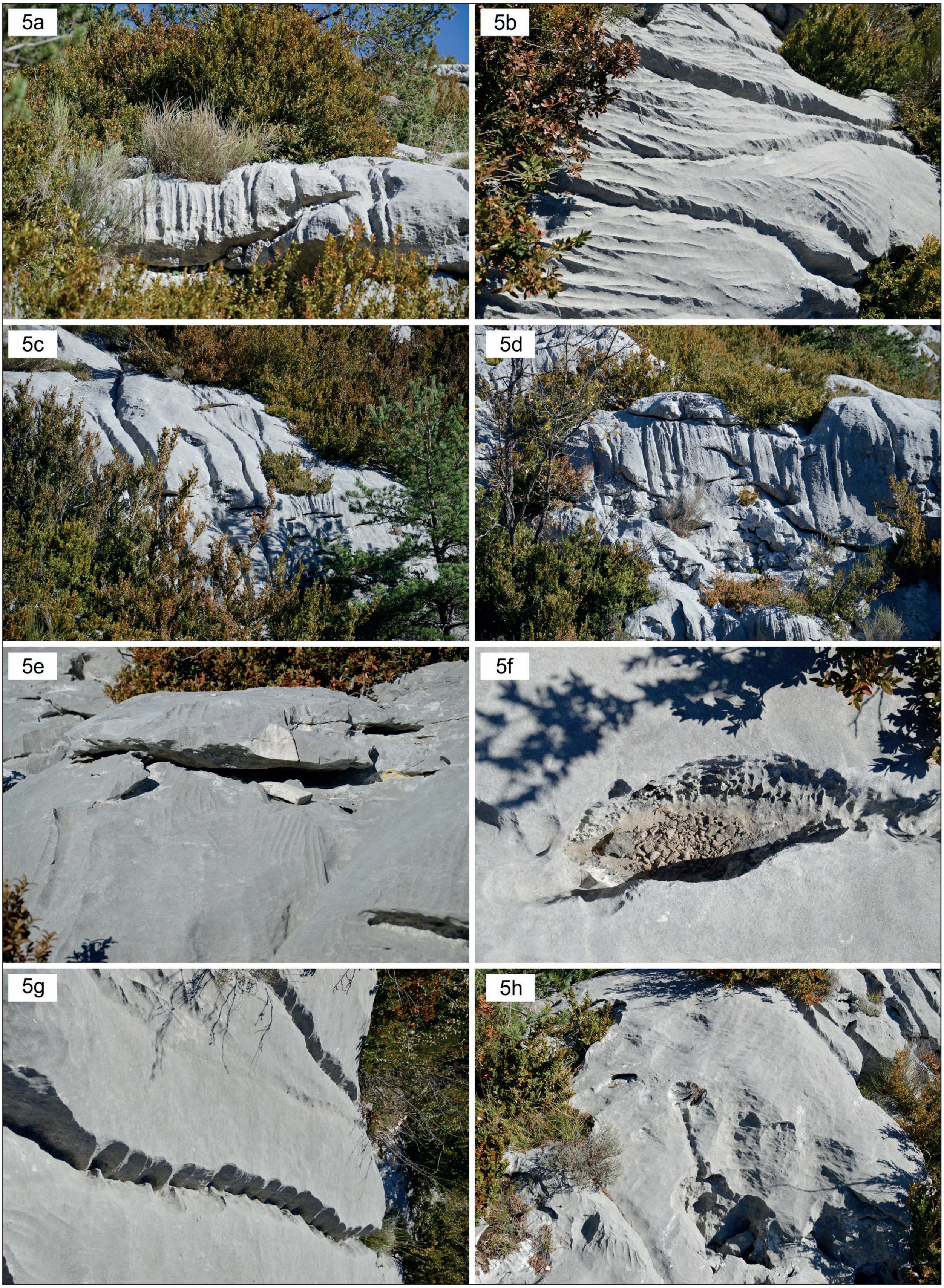

5a
5b
5c
5d
5e
5f
5g
5h

Figure 5: (a) Channels below subsoil features, (b) Channels below subsoil features. Width of view is 4 m, (c) Channels below subsoil features, (d) Channels below bedding planes, (e) Channels below bedding planes. Width of view is 2 m, (f) Solution pan. Width of view is 0.5 m, (g) Channels in the wall of large channel. Width of view is 5 m, (h) Large steps. Width of view is 2 m, (i) Longitudinal steps. Width of view is 5 m.

channels also rank among the composite rock forms. They are sculpted jointly by rainwater and trickling water.

The development of parallel channels in the direction of the surface dip is characteristic of these karren. Branched connections are rare. This seems to be the characteristic of the recent formation of larger surfaces of relatively gently sloping flat and smooth rock where the main factor of its formation is the rainwater flowing to channels from the side. Between the protrusions with rain flutes that dissect the surface in some places are the outlines of branched networks of channels. Longer ridges occur between larger channels of subsoil origin and channels lying side by side and the surface between them is the ridge itself. It appears that like this is a more mature form of karren dissection.

Smaller rock forms carved by rainwater and water trickling down the rock reveal an even more detailed development of the recently denuded rock.

Rain flutes (Figure 4n) as a rule dissect the upper edges of the larger inclined flat surfaces of the tops (Figures 4p, 4r, 5b, 5d, 5e).

On the surface below them a layer of water that originates from the water trickling downwards is too thick and prevents rainwater to reach the rock directly, so, no rain flutes are found here. These only occur on rare smaller protrusions dissecting the relatively flat tops (Figure 4a). Larger and smaller steps (Figures 4j, 4k, 4l), the trace of the relatively even creeping of water across larger rock surfaces, form on the flat surfaces below the rain flutes. There are flutes on the faces of strata and their lateral edges only if they are not covered by larger amounts of water from the upper part of the strata, if the surfaces above them are short, or if the edge is higher. This type of formation also appeared in laboratory tests with plaster of Paris (Slabe, 2005, 2009). Only if these strata are shorter are flutes found across the entire surface. Rain flutes also dissect protrusions, which in most cases are the ridges that eventually dissect the surfaces of originally flat tops. Funnel-like notches (Figures 4p, 5b, 5d) form at the beginning of surfaces, relatively small at first, with flutes at the circumference.

The relatively large, flat, and inclined surfaces of the tops are dissected by larger and smaller steps (Figures 4j, 4k, 4l). On the lower part of the surface, the water from them flows over the edge of the face in channels whose upper parts are co-formed by rainwater (Slabe, 2005, 2009). The thick layer of water creeping across the steps from the upper part of the surface to the edge of the rock strata where channels with funnel-like mouths are often found does not allow drops of rain to contact the rock directly and consequently the formation of rain flutes is not possible except at the beginning edge of the surface. Traces of an even sheet of creeping water therefore dominate on the rock. This requires fulfilling certain conditions relative to the amount of water on the rock and the size of the surface and its inclination. In this case, the conditions are very favourable for the development of this type of rock relief. This is a young stage in the development following denudation from under soil.

In most cases the rock forms are composite. Large steps (Figures 2h, 4f, 5h) have circular or horseshoe shapes and those which lie crosswise to the slope are often several meters long and a few decimetres in width (Figures 4e, 4f). They are open on the runoff side and have steep upper edges. Some steps are partly closed on the runoff side by smaller protrusions. Protrusions are steep on the inflow side of the steps, and rain flutes dissect the outer side. Together, the connected circular steps and channel-like steps often create the appearance of undulation in the rock surface.

Larger surfaces of non-dissected rock and the forms described above have small steps (Figures 2h, 4j, 4k, 4l, 6a) a few centimetres in diameter, while medium sized steps are up to one decimetre in diameter and relatively shallow. They are open on the outflow side. The small steps lie side by side, connected in a network whose shape is dictated primarily by the composition of the rock and its inclination. They are also found in channels especially in the initial periods of development of channels on gently sloping surfaces; on steep slopes, however, they are characteristic of channels even later (Figure 4n). In smaller and medium-sized channels the small steps are elongated

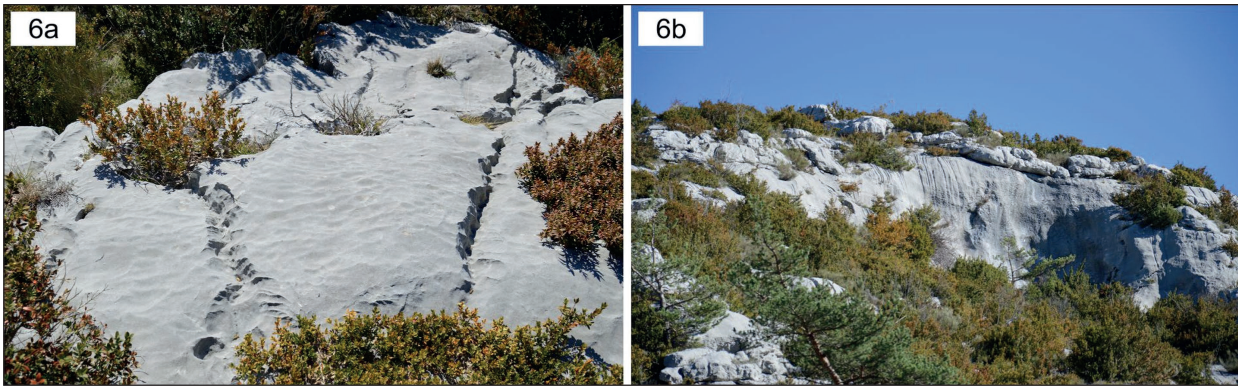


Figure 6: (a) Small steps. Width of view is 5 m, (b) Scallops od trickling water on overhangs.

as a rule, as long as they are wide, and larger channels are dissected by a network of small steps.

The network of various steps and small steps that reveal the sheet pattern of flow over the rock is more distinctly developed on surfaces denuded for a longer time. These forms are naturally not found on rock that has been covered by soil until recently; such surfaces are smooth or have a network of mostly individual cups in the initial phase of development.

Solution pans often develop from subsoil solution pits at the bottom of gently sloping, longitudinal, and channel-like notches of subsoil origin. They are shallow and open on the runoff side. On denuded rock some notches transform into channel-like solution pans. Pans are also found at the bottom of larger gently sloping channels (Figure 5f).

There are scallops on overhanging surfaces (Figure 6b) that reveal the way water trickles: the faster the flow, the smaller they are.

DEVELOPMENT MODEL

At the top of the karren on the upper surfaces of an inclined rock strata along which a slope formed a unique rock relief developed that reveals the manner of karren formation and its development. Relatively large surfaces of unfissured, mostly evenly composed, and largely subsoil rounded and smooth and later denuded rock mostly exposed to rain resulted in special hydraulic circumstances that fostered the formation of rock forms and the development of the rock relief. On the parts of rock directly exposed to rain there are rain flutes, and where the layer of water trickling down the inclined surface is thicker, there is a system of large and small steps that dissect the surface in an undulating fashion. The trickling water collects in channels that in parallel dissect the surface and together with the channels that conduct the water from subsoil rock forms gradually assume the role of the main conductors and increasingly distinctly dissect the tops of the karren. Relatively flat surfaces with dominant traces of sheet flow of large amounts of water therefore represent one of the initial stages in the development of the denudation of this type of rock base. New factors gradually transform the subsoil rock relief that is revealed when the rock is denuded. Only in individual places does the composition of the rock dictate the development of protrusions on flat surfaces. The long-term parallel position of channels also appears to be dictated by the hydraulic conditions of this type of formation of larger inclined surfaces, which has been confirmed by laboratory tests with plaster of Paris. On the latter, the most conductive channels gradually assume the leading role. A number of forms have been newly identified and described in detail for the first time with the development of this type of the relief.

4. THE KARREN OF CAUSSOLS

SHAPE OF KARREN

The central part of the karren is characterized by a relatively flat, gently sloping and mostly denuded rocky top surface, which rises towards the west in the form of large steps. The western part is more steeply stepped and overgrown with trees (Figures 7, 8).

It seems that the karren were entirely overgrown with a thin forest of pines and oaks, and that the entire

Figure 7: Karren of Caussols.

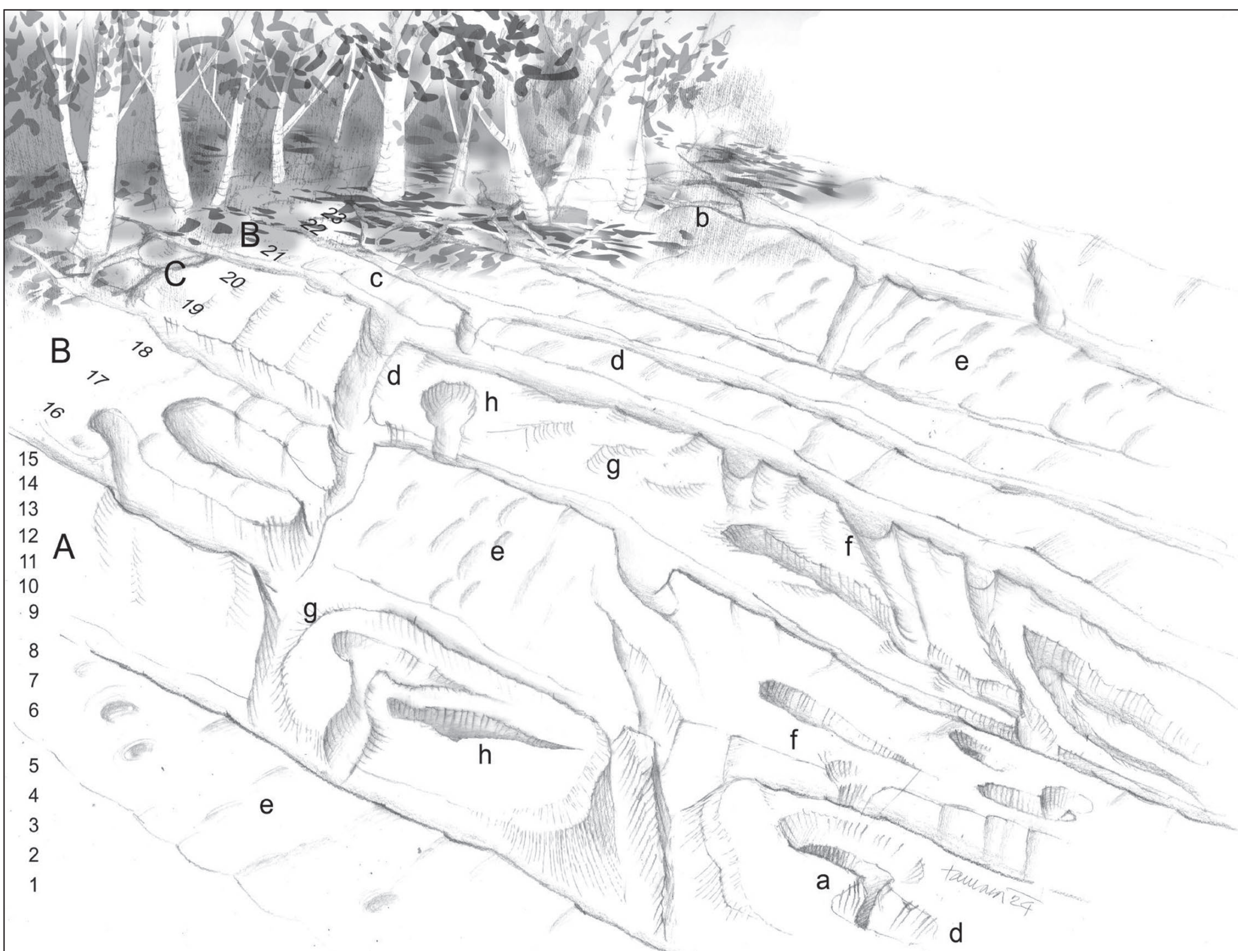


Figure 8: Rock relief of karren. a. subsoil shaft, b. uncovered subsoil funnel-like notch, c. subsoil channel, d. uncovered subsoil channels, e. steps, f. funnel-like notch, g. rain flutes, h. transformed subsoil cups. Locations of taken rock samples, numbers 1 to 23.

Figure 9: Part of the karren overgrown by vegetation.

rock was covered with soil and moss. Their top section and their lowest section are like that now. In the top, overgrown section the surface of the karren is dissected by rocks and stone teeth (Figure 9). Water is intensely dissolving the rock beneath the vegetation and soil. The denuded rock in the central part is being reshaped by rainwater. That is why the top beds of the rock are disintegrating and sliding downwards along the bottom beds. A section of the karren might have been artificially uncovered, most of it a long time ago, as indicated by the rock relief. The latter is completely flat and free of rocks, i.e., of the remains of rock beds. A part of the top section of the karren is covered with rocks that were thrown there during road construction.

All the stages of denudation caused by the disintegration of the top rock beds and uncovering of soil are being revealed, as are the stages of the reshaping of the relatively flat, vast and gently sloping surfaces of the tops of karren. The karren rock relief is made up of subsoil rock forms; of rock forms being created beneath the moss; of rock forms that develop due to their reshaping by rain; and of rock forms hollowed out by rainwater and the water trickling down the rock.

The distinct rock relief enables us to clearly define the development model, which is widely applicable to similar rock surface formation.

GEOLOGY

Macroscopic description

We thoroughly examined a 9 m tall geological profile of limestone, where a few layers outcrop roughly in the middle over a larger surface, containing well-developed karren. In the lower part of the profile the layers, up to a few dm thick, are quite crushed, while those in the middle and upper part are hard and compact. The dip angle of layers from the foot to the top varies slightly; the predominant angle is to the north and between 16 and 26^0. The direction of the layers' dip angle is between 5 and 26^0. In the field we took 23 samples of a homogeneous, hard, compact, and nonporous rock at relatively even intervals. No major differences were detected in the samples macroscopically. The rock was of a light grey to brown colour, with the colours pinkish grey (5YR 8/1) and light brownish grey (5YR 6/1) being predominant.

We mostly focused on the subvertical cracks in the rock layers exposed to the atmosphere and on their average directions, on the width of the karstified cracks and on the depth of karstification, as the dip angle and direction of the layers change slightly in the lateral direction from the east to the west side. At a dip angle of 25/16 the cracks have the prevailing direction of 170–350, and width of 5–10 and 30–40 cm. At a dip angle of 22/19 the cracks have the prevailing direction of 35–215 and 10–190, and width of 10–20 cm. At a dip angle of 25/16 the cracks have the prevailing direction of 165–345 and 0–180, and the prevailing width of 10 cm. At a dip angle of 20/25 the cracks have the prevailing direction of 0–180 and 170–350, and width of 100–200 cm, exceptionally 20–30 cm. At a dip angle of 10/22 the cracks have the prevailing direction of 175–355 and 0–180, and width of 50–100 cm. Most cracks are karstified up to the depth of 10 cm and between 30 and 40 cm; in some areas they are even karstified up to the depth of 100–150 cm. The karstified cracks are either interconnected or unconnected, and have in some places widened into isolated holes.

Microscopic description

Based on 23 microscope slides, one from each rock sample, we divided the rock in the examined profile into three lithological types that alternate in an irregular sequence in the vertical direction, in groups of several layers about half a meter thick. In roughly half of the thickness of the geological profile we can trace layers of pelsparite to pelintrabiosparite of grainstone type. The other half of the profile's thickness is largely taken up by layers of intrabiosparitic to intrabiomicritic limestone with numerous calcite veins and grainstone- to packstone-type fenestrae, and by several layers of micritic limestone of mudstone type with stylolites. These properties of the layers were not visible during the sampling and macroscopic determination. The group of layers on or in which the examined rock features have developed the most, are almost entirely fine-grained with a sparry cement, or fine-grained and micritic. These layers contain no larger fossils or their fragments, nor any larger intraclasts.

Layers of pelsparitic and pelintrabiosparitic limestone (grainstone) can be found throughout the middle part of the profile (samples C3 to C6, C11 to C17). Peloid grains are almost entirely predominant in the rock, taking up between 80 and 90% of the volume. Most of the peloids are pellets (90 to 95% of the volume), while intraclasts take up between 5 and 10%. The intraclasts are micritized, with no internal structure, and mostly measure between 0.3 and 1.1 mm in diameter. Also visible in the rock are individual bioclasts, mainly miliolids and uniserial and biserial foraminifera, mostly measuring 0.2 mm in diameter and not exceeding 0.9 mm. Only exceptionally do we see bivalves in the rock with a shell diameter of up to 4.5 mm with no shelter porosity in the shells. Bioclast grains, which also make up the rock, only amount to a few percent. As regards textures, we observe a distinct roundness of the grains in the microscope slide, whereas various cavity structures are not visible. All the cement between the grains is equant drusy mosaic spar. Most of the cement grains are anhedral to subhedral; where spaces between the pelloids are larger, we also see euhedral crystals. The majority of sparry grains have a diameter of 45 μm, exceptionally up to 0.4 mm. Thus, the xenotopic to hipidiotopic spar texture and fabric are predominant among the micritized pelloids (Figures 10a, c; typical example sample C3). The grains of typical fecal pellets and intraclasts are highly micritized; the spaces within the bioclasts are filled with mosaic drusy sparry calcite with no internal structure. There are no signs of compaction in the rock, nor any stylolites. Exceptionally we observe secondary porosity in the rock; the cracks of a single generation, with diameters up to a few μm, are entirely filled with mosaic drusy sparry calcite and individual spar crystals in them are dolomitized. There is no visible primary porosity.

Layers of intrabiosparitic to intrabiomicritic limestone with numerous calcite veins and fenestrae (grainstone to packstone) can be seen partly in the lower and partly in the upper part of the profile (samples C1, C2, C7, C8, C18 to C23). A typical example of this group of layers is sample C19 (Figures 10b, d). The rock is almost entirely made up of fully micritized intraclasts with no internal structure, of varying shapes and sizes. Most intraclasts measure between 0.2 and 0.5 mm in diameter, followed by those with diameters between 45 μm and 0.2 mm; only individual intraclasts have diameters larger than 0.5 mm.

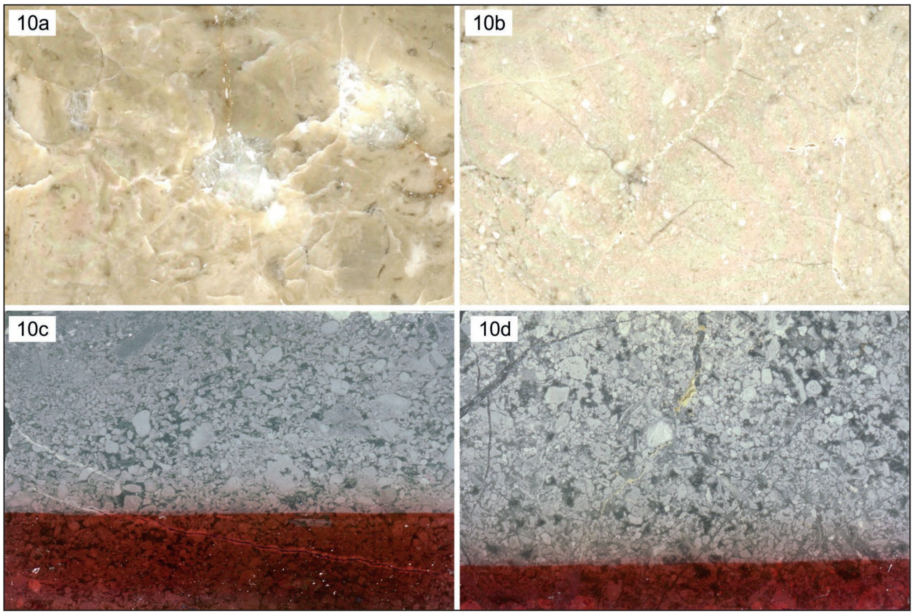


Figure 10: (a) Rock slice prepared for a thin section, sample C3. Width of view is 4 cm, (b) Rock slice prepared for a thin section, sample C19. Width of view is 4 cm, (c) Thin section of sample C3. Lower half of sample was dyed in alizarin red dye. Width of view is 4 cm, (d) Thin section of sample C19. Lower half of sample was dyed in alizarin red dye. Width of view is 4 cm.

In most cases the intraclasts, which take up around 80% of the rock, touch each other, forming areas without a sparry cement in between, measuring between 0.4 and 2.2 mm in diameter. Other clasts that make up the rock, in addition to those mentioned above, are bioclasts of several types. The prevailing types are miliolids and uniserial and biserial foraminifera, mostly measuring up to 0.2 mm in diameter; only individual ones reach 0.9 mm. The microscope slide also contains individual specimens of poorly preserved algae and echinoderms, of gastropods filled with sparry calcite, usually measuring around 0.5 mm in diameter, and of individual fragments of bivalves transferred to a secondary location. No texture characteristics, such as sorting, are visible in the rock. Judging from the good compaction of micritized intraclasts, we can describe the mostly unconnected areas in between, which are estimated at around 15%, as fenestrae filled with drusy sparry calcite. Most of them have diameters between 90 μm and 0.9 mm, but those with diameters around 0.5 mm are predominant; they are evenly distributed throughout the rock. Most of the sparry cement grains are anhedral to subhedral; in some places we also see euhedral crystals. The majority of sparry grains have diameters from 45 to 90 μm, exceptionally also up to 1 mm. Thus, sparry cement is predominant as xenotopic to hipidiotopic texture and fabric. There is no visible primary porosity. In the rock, many calcite veins of several generations are distributed in various directions and with a thickness between 20 μm and 0.4 mm. The predominant ones are between 90 μm and 0.4 mm thick; only individual ones are thicker, measuring up to 1.1 mm. All of them, with the exception of the thickest ones, are entirely filled with mosaic drusy sparry calcite. In the vertical direction the described layers gradually transition into layers of pelsparitic and pelintrabiosparitic limestone, and into layers of micritic limestone.

Layers of micritic limestone of mudstone type with stylolites are located in the middle part of the profile (samples C9, C10). The fully micritic rock contains only individual bioclasts, well-preserved miliolids, ostracods and, due to intense micritization, unidentifiable tiny fossil fragments. Together, they make up less than 1% of the space. The rare fenestrae are also entirely filled with drusy sparry calcite, measuring from a few μm to 0.9 mm in diameter. There is no primary porosity. There are many stylolites in the rock, which are characteristic of this rock type; they are distributed in various directions and with amplitudes between 0.4 and 1.3 mm.

Complexometric analyses

Using the dissolution method (CEN, 2013), we performed 15 complexometric analyses on 15 selected rock samples (Table 2). It has been determined that all profile samples exceed 98.7% of total carbonate content. The average value of all samples amounts to 99.6%. All samples show a high calcite percentage. Only one sample has a calcite content of less than 98%; the average value of all samples is almost 98.8%. All samples also contain a small proportion of dolomite. Only one sample has a dolomite content of over 1%. The average value of all samples amounts to just over 0.85%. The samples also contain a small proportion of insoluble residue. Three samples contain no insoluble residue, while in two samples the value of insoluble residue exceeds 1%. The average value of all samples amounts to 0.37%.

Table 2: Complexometric analyses of rock samples from Caussols.

Laboratory designation of the sample	Rock sample	CaO (%)	MgO (%)	Calcite (%)	Dolomite (%)	CaO/MgO	Total carbonate (%)	Insoluble residue (%)
V- 95/24	C1	55,38	0,47	98,84	0,98	117,83	99,82	0,18
V- 96/24	C2	55,37	0,46	98,82	0,96	120,37	99,78	0,22
V- 97/24	C3	55,65	0,32	99,33	0,67	173,91	100,00	0,00
V- 98/24	C6	55,60	0,36	99,23	0,75	154,44	99,98	0,02
V- 99/24	C7	55,60	0,37	99,23	0,76	150,23	100,00	0,01
V- 100/24	C8	55,57	0,38	99,18	0,79	146,24	99,97	0,03
V- 101/24	C10	55,03	0,43	98,22	0,90	127,98	99,12	0,88
V- 102/24	C11	55,61	0,36	99,25	0,75	154,47	100,00	0,00
V- 103/24	C14	55,41	0,35	98,90	0,73	158,31	99,63	0,37
V- 104/24	C15	54,98	0,49	98,13	1,03	112,20	99,16	0,84
V- 105/24	C16	55,58	0,38	99,20	0,79	146,26	99,99	0,01
V- 106/24	C17	55,26	0,42	98,63	0,88	131,57	99,51	0,49
V- 107/24	C19	55,56	0,40	99,16	0,84	138,90	100,00	0,00
V- 108/24	C20	54,74	0,46	97,70	0,96	119,00	98,66	1,34
V- 109/24	C23	54,79	0,48	97,79	1,00	114,15	98,79	1,21

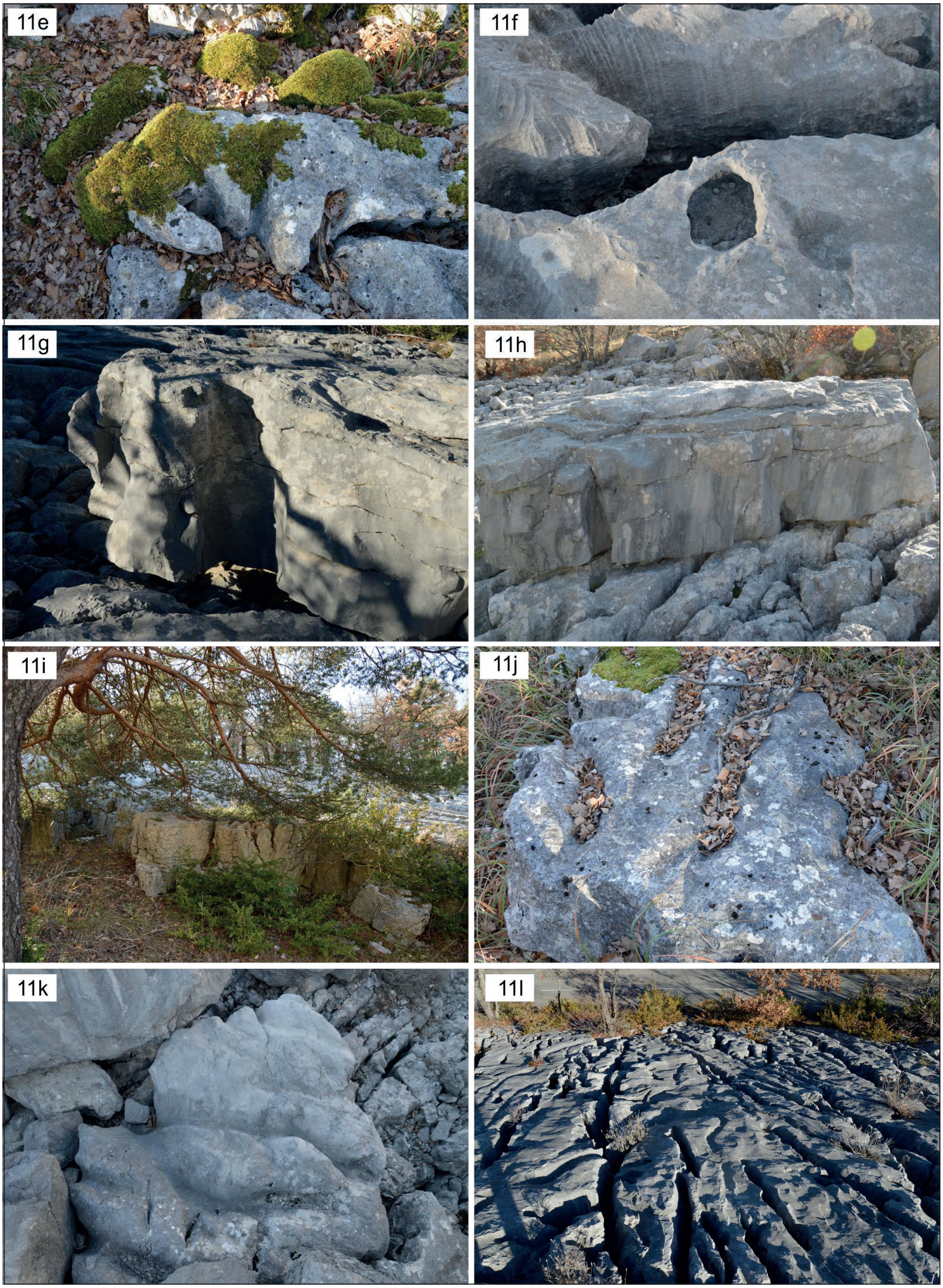
Impact on karstification

The entire geological profile, i.e., all the layers that make up the geological profile, react similarly to karstification. Fine-grained, homogeneous and compact limestone with a high calcium carbonate content is a rock with excellent properties, on which subsoil and rain rock features can develop efficiently, smoothly, and successfully. The development of karren is mostly influenced by the cracking of the rock.

ROCK FORMS AND ROCK RELIEF

Subsoil rock forms

Subsoil holes formed along bedding planes and vertical cracks. Their diameter reaches 10 cm and some of them have been paragenetically raised (Figure 11a) and deepened with a floor channel (Figure 11b) after the denudation of karren. There are subsoil shafts (with cross-sections in the cm to m ranges), which are dissected in some places (Figure 8a, 11c), and fissure caves along the cracks. In the overgrown section of the karren, trees and bushes are growing out of them (Figure 11d). The funnel-like notches on their top edges (Figure 8b, 11e) indicate a downward percolation of water through the vertical fissures. The funnel-like notch is a typical rock formation created by water runoff from karst surfaces into the rock's interior by gradually eroding the rock. On larger peaks, the mouth of a wall channel typically forms along the peak's edge (Knez et al. 2015), while in fractured rock areas, they tend to appear between the tips of rocks into which the surface has been dissected (Knez et al. 2012). As water continues to dissect larger rock surfaces on peaks, it can create new rock tips through prolonged erosion (Slabe et al. 2021). Thus, funnel-like notches represent erosion paths formed by water runoff from expansive surfaces or dispersed sources (such as rainwater or water seeping through soil), which eventually gathers into streams, further eroding the rock. Smaller holes have also formed from the subsoil cups at the edges of fissures (Figure 11f). The walls also contain subsoil channels (Figure 11g); smaller subsoil half-bells (Figure 11h); subsoil longitudinal notches, which show that soil surrounded the rock for a longer period of time; and subsoil scallops (Figure 11i) on the overhangs, which are a trace of the sheet trickling of water at the contact with soil. Notched into the surface of the top of the karren are subsoil channels (Figure 8c, 11j), which sometimes continue down the wall (Figure 11k), and subsoil cups. In some places, the subsoil cups continue in the form of channels. On the vaster and sloping surfaces, parallel and meandering subsoil channels have formed (Figures 8d, 11l, 11m). At the edge they flow into a wall channel via a funnel-like notch (Figure 11n). The channel dissects the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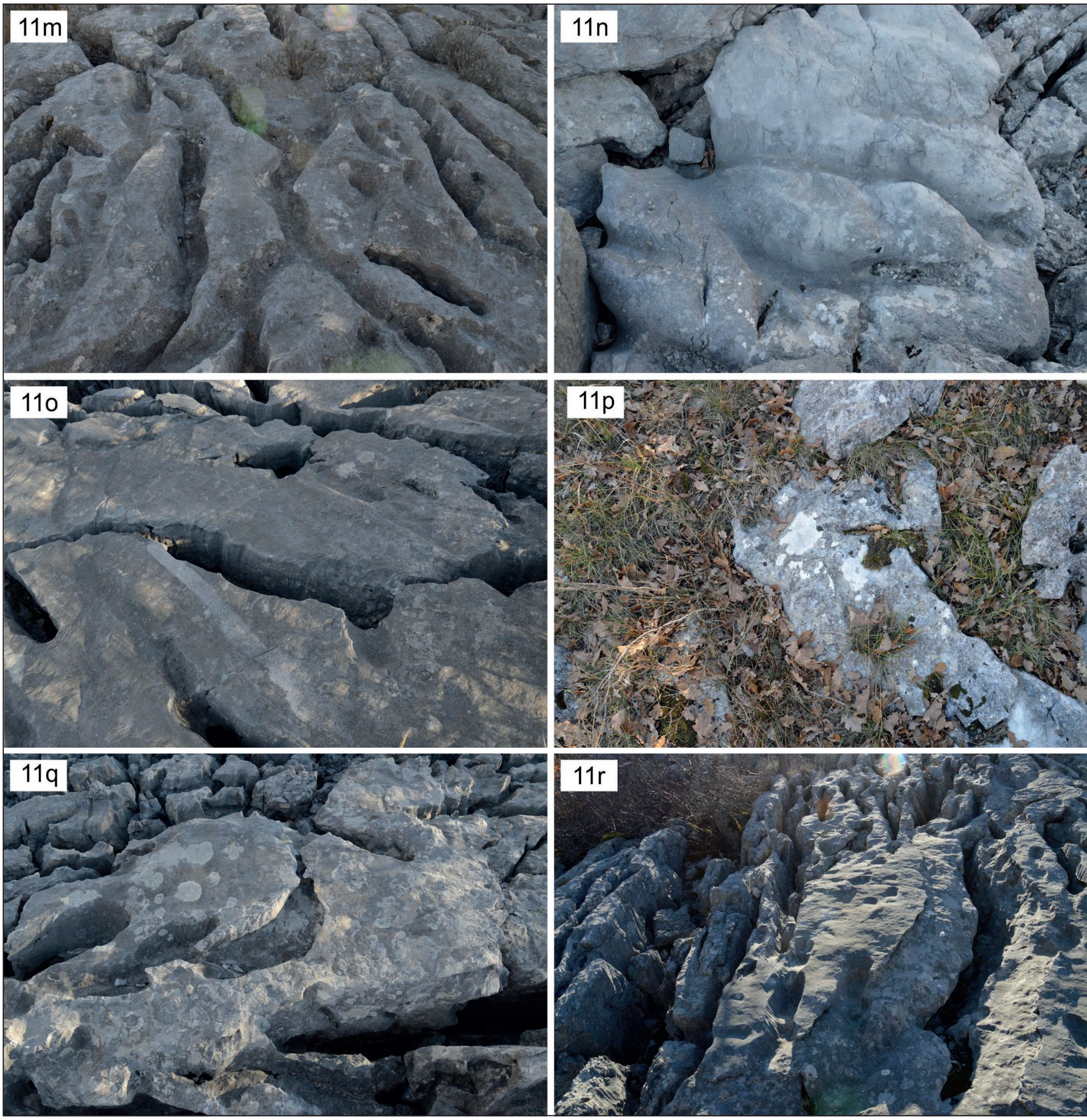
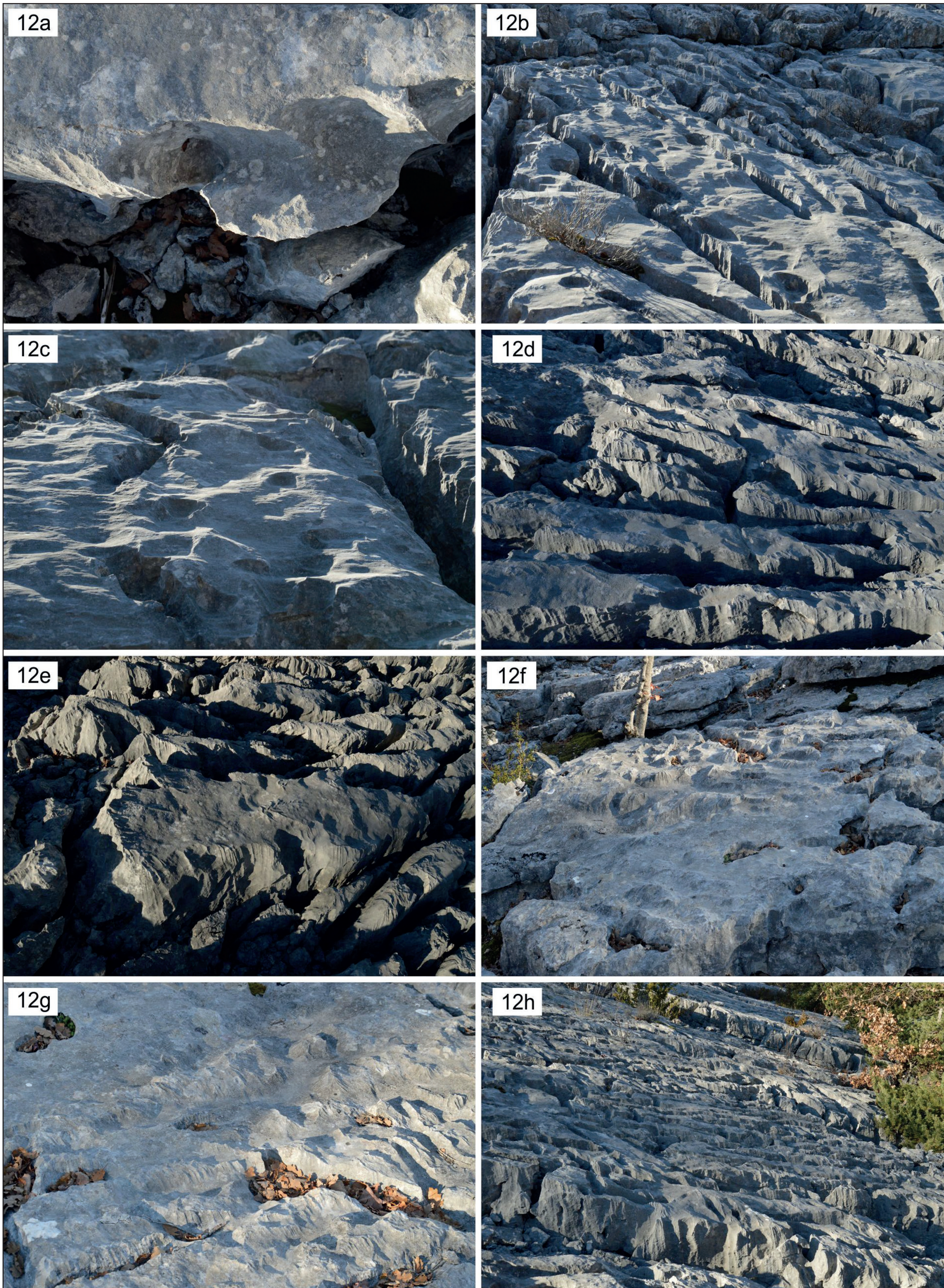


Figure 11: (a) Parageneticaly increased hollow. Width of view is 3 m, (b) Flor channel in hollow. Width of view is 2 m, (c) Subsoil shaft. Width of view is 1 m, (d) Trees grown from karren, (e) Funnel-like notches. Width of view is 1.5 m, (f) Hollow, developed from subsoil cup, (g) Subsoil wall channel. Width of view is 2.5 m, (h) Subsoil half-bells. Width of view is 3 m, (i) Subsoil scallops, (j) Subsoil channels. Width of view is 1 m, (k) Subsoil wall channels. Width of view is 1.5 m, (l) Subsoil channels. Width of view is 5 m, (m) Subsoil channels. Width of view is 2.5 m, (n) Subsoil wall channels. Width of view is 1 m, (o) Subsoil channels. Width of view is 2 m, (p) Covered subsoil channels. Width of view is 1 m, (q) Deep subsoil channel. Width of view is 2 m, (r) Subsoil longitudinal notch. Width of view is 5 m.

wall of the fissure hole or shaft (Figure 11c). The channels often merge into a larger channel in the form of branches. On the densely cracked and fissured rock, the smaller tops are more densely crisscrossed with smaller, longitudinal and transversal subsoil channels and subsoil cups. Some of them continue on the rock beyond the fissures, which indicates that they were relatively tightly filled (Figure 11o). They can continue to develop even after they are fully or partially filled with soil and the rest of the rock is bare (Figure 11p). Some develop cross-sections resembling an upside-down omega (Figure 11q). There are individual subsoil cups on the bottoms of larger and denuded subsoil channels. In some places, there are subsoil notches around the mouths of fissures and small shafts (Figure 11r), which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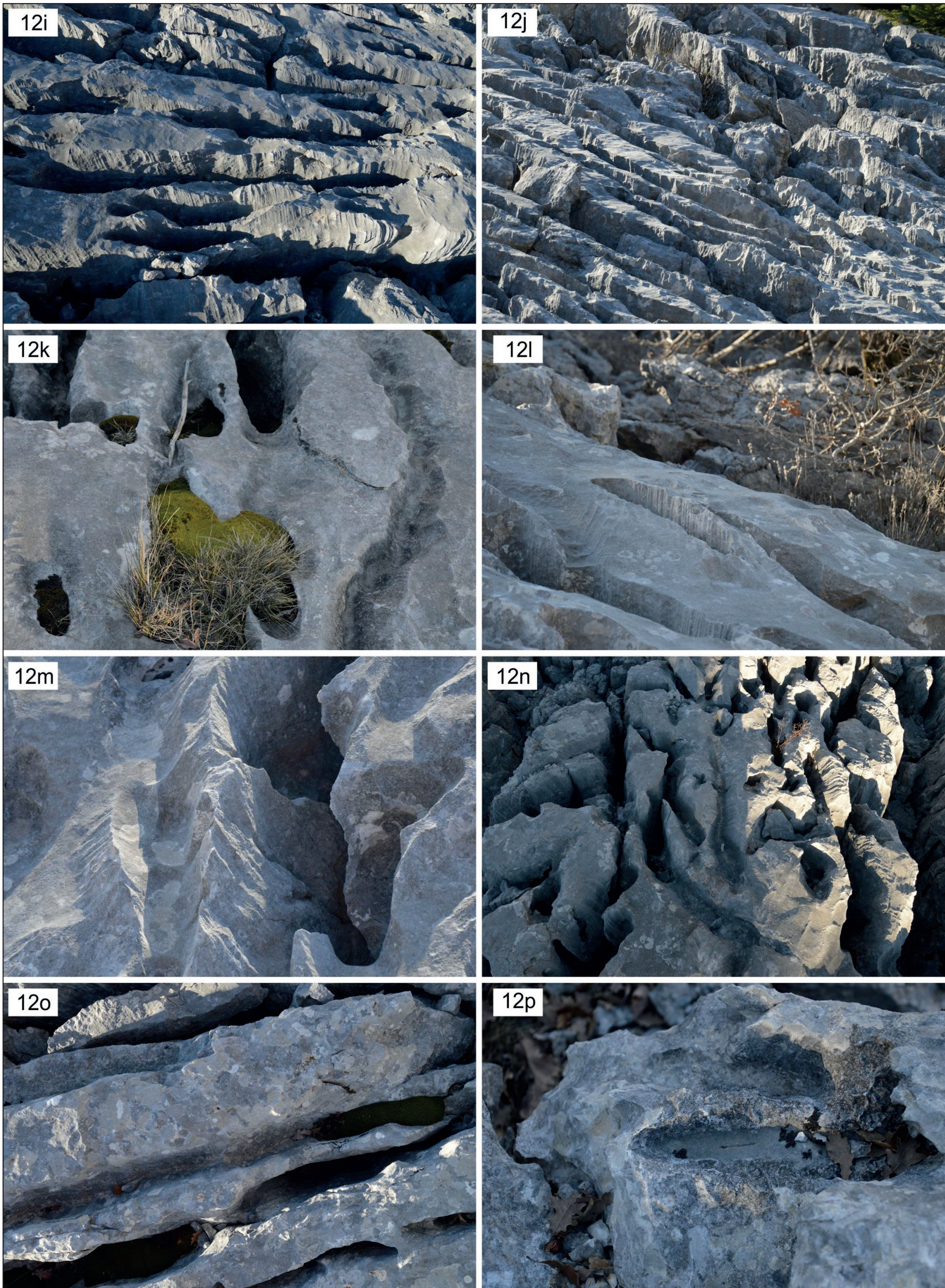
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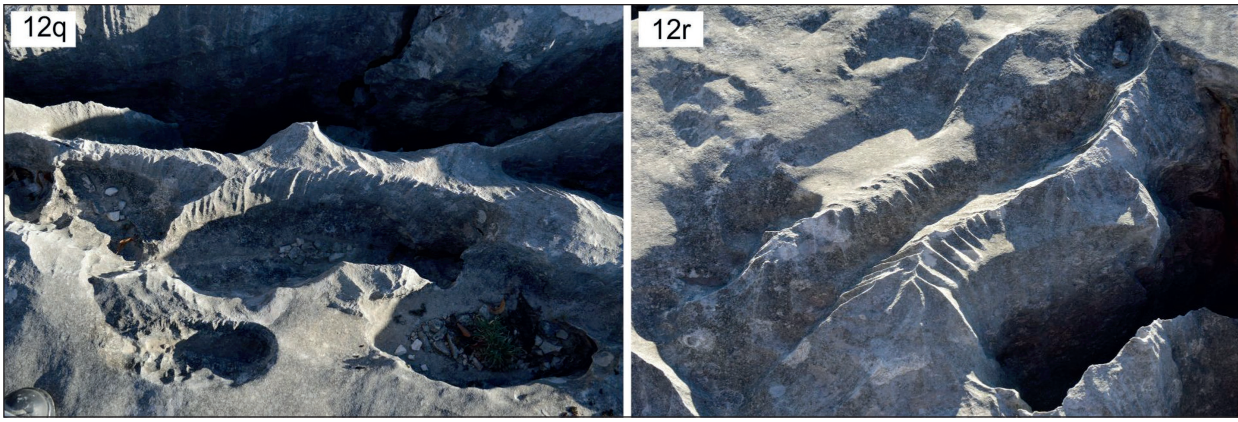
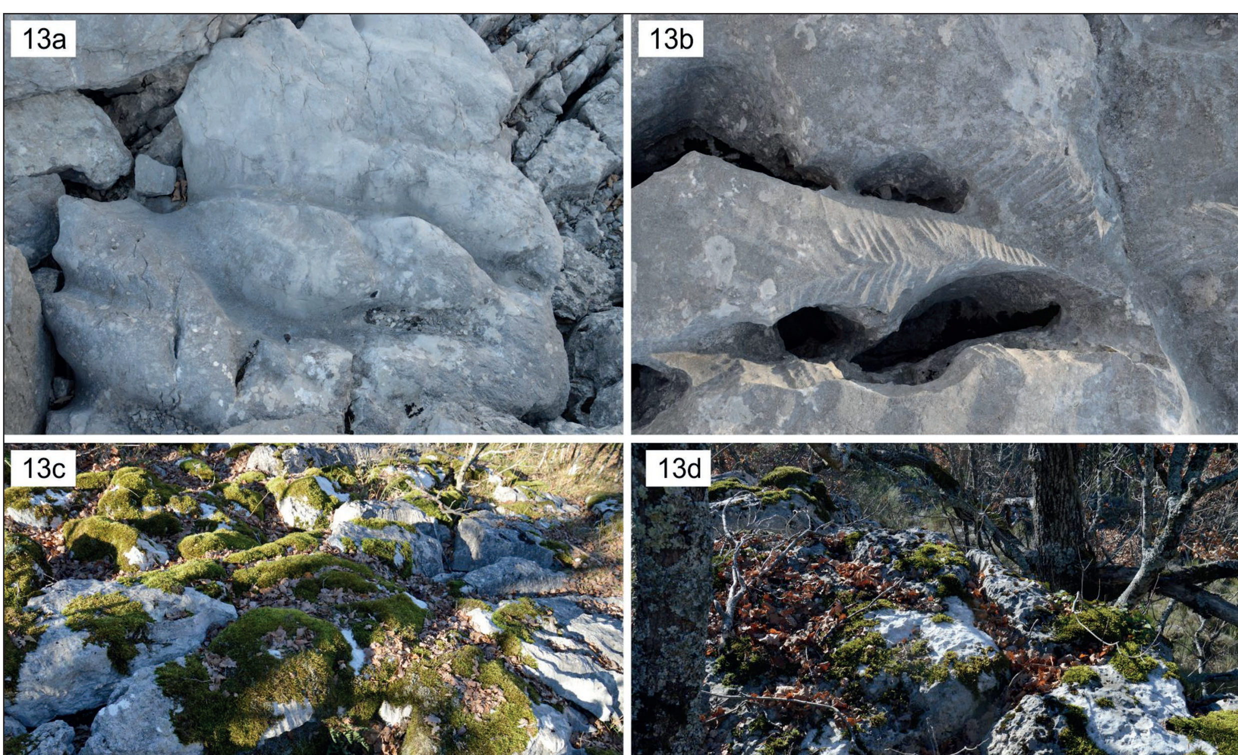


Figure 12: (a) Subsoil channel with notch. Width of view is 0.75 m, (b) Steps. Width of view is 5 m, (c) Steps. Width of view is 3 m, (d) Rain flutes. Width of view is 4 m, (e) Rain flute and steps bellow. Width of view is 3 m, (f) Rain flutes on the wall of steps. Width of view is 4 m, (g) Channels. Width of view is 1.5 m, (h) Funnel-like notches with rain flutes. Width of view is 6 m, (i) Rain flutes. Width of view is 2 m, (j) Different tops. Width of view is 5.5 m, (k) Small channel in the bottom of larger. Width of view is 1 m, (l) Cascade bottom of the channel, (m) Rain flutes on the wall of the channel, (n) Deepen denuded subsoil channel. Width of view is 1.5 m, (o) Moss overgrown bottom of the channel. Width of view is 1 m, (p) Solution pan. Width of view is 1 m, (q) Solution pan with rain flutes on walls, (r) Solution pan, transformed in to the channel.

were formed when the holes were still full and the surrounding surfaces above them were covered or when subsoil channels led into them (Figure 12a). They are dissected into funnel-like notches. The surfaces between them have already been exposed.

Rock forms hollowed out by rainwater and water trickling down the rock, and the reshaping of subsoil rock forms

The vaster and relatively flat and smooth surfaces of the tops of karren, which are formed on the less densely



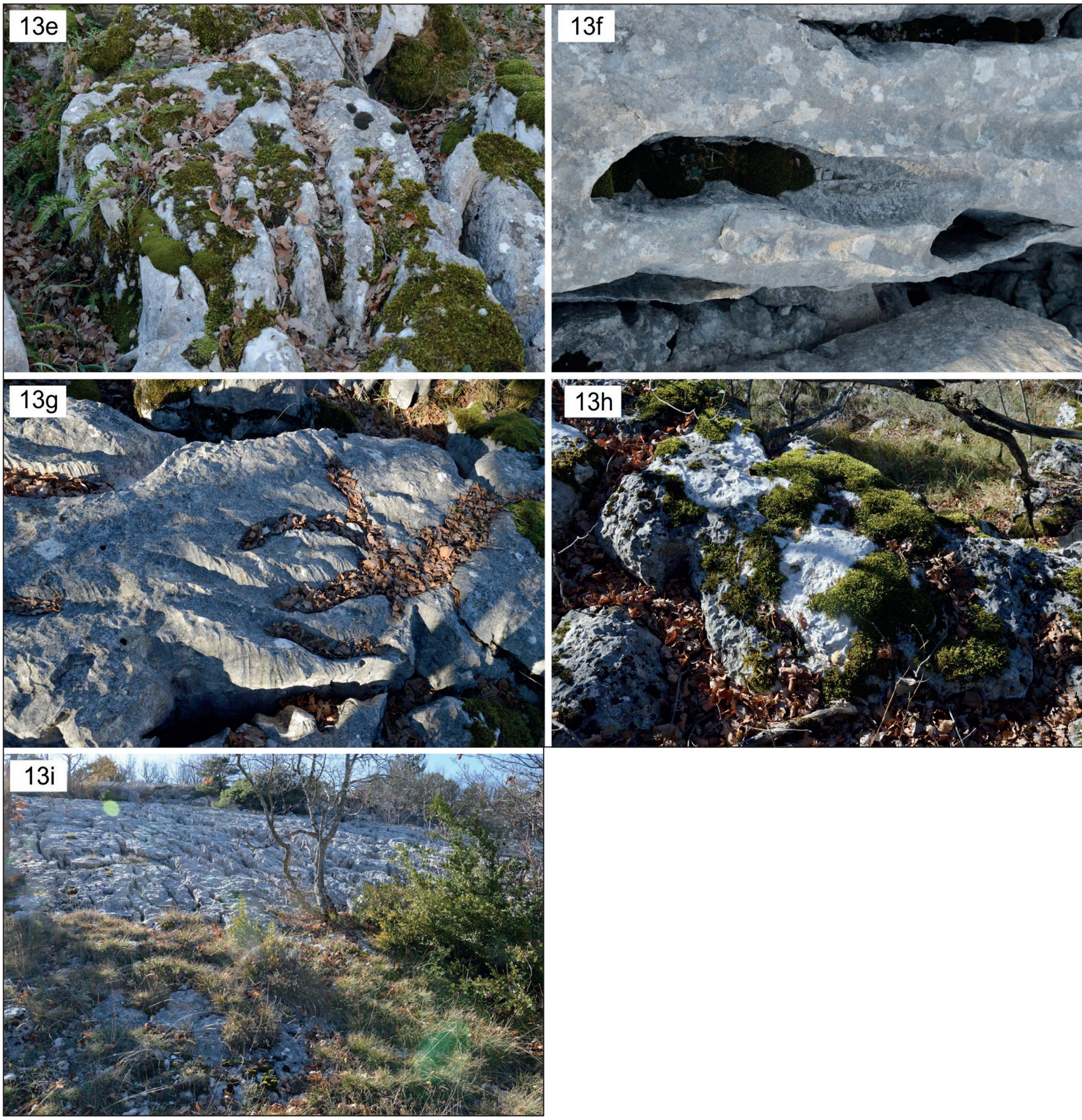


Figure 13: (a) Solution pans on the bottom of denuded subsoil channels. Width of view is 1.5 m, (b) Rain flutes on the walls of funnel-like notch and mouth of the shaft, (c) Rock overgrown with moss. Width of view is 3 m, (d) Cups, developed bellow moss. Width of view is 3 m, (e) Overgrowing of denuded rock by moss. Width of view is 2 m, (f) Moss in the solution pans. Width of view is 0.75 m, (g) Rock top, covered by leaves. Width of view is 2 m, (h) Pits, formed bellow moss. Width of view is 4 m, (i) Several time denuded and overgrown top of the karren.

cracked rock, are mostly reshaped by a thicker layer of water flowing downwards. Such surfaces are initially subsoil or form along bedding planes as the top bed of the rock is disintegrating. Steps in the centimetre and decimetre size ranges are forming (Figures 8e, 11r, 12b, 12c) (Knez et al., 2015). Funnel-like notches and channels below them (Figures 8f, 12b) are forming on the side edges of larger steps. Rain flutes (8g) are forming on the higher top edge and in some places on the side edge (Figure 12d) where raindrops reach the rock directly. The rock is being dissected three-dimensionally and rain flutes are also forming on the higher parts of faces (Figure 12e), over time also dissecting the walls of rocky steps (Figure 12f). Channels are forming between the smaller tops dissected with rain flutes; water flows away from the tops along these channels (Figure 12g). We can trace the first stages of the development which is described in the development model of the shaping of a flat rock surface into rock spikes (Slabe et al., 2021). Funnel-like notches are forming on the mouths of shafts and fissures with rain flutes in the higher part of the rim (Figure 12h).

On the densely cracked rock on the denuded ridges (Figure11a), which are being sharpened, rain flutes form instantly between the fissures (Figure 12i). Different surfaces are crisscrossed (Figure 12j).

The subsoil rock forms are gradually transformed. Some of the fissures are still filled, while the higher surfaces between them have been exposed (Figure 11r). The larger and denuded subsoil channels that are crisscrossing the tops and whose cross-sections shaped as an upside-down omega are opening up, are deepened with a smaller channel (Figure 12k), or with a cascaded bottom in the steep sections (Figure 12l), into which flows the water from the rain flutes that eventually dissect the walls of channels (Figure 12m). The channels between the ridges with rain flutes, which collect water, are likewise often transformed from subsoil ones; the wider ones are cascaded or are deepened with a smaller channel (Figure 12n). The bottoms of deeper and shady channels are overgrown with moss in some places (Figure 12o). The denuded subsoil cups (8h) transform into solution pans (Figure 12p) and when they open up, their walls are dissected by rain flutes (Figure 12q) and they can eventually transform into channels (Figure 12r). Solution pans also form on the bottoms of denuded subsoil channels (Figure 13a). Rain flutes are also dissecting the walls of subsoil funnel-like notches and shafts (Figure 13b).

Impact of vegetation and overgrowing moss

The roots and trunks of trees influence the formation of intrastratal holes, shafts, fissures and channels (Figure 11d).

Under the thick vegetation the rock, which has already been shaped by rain in some places (rain flutes), is the most overgrown with moss (Figure 13c). In the overgrown parts of the rock the moss covers the entire surfaces of the larger tops; rounded cups can be seen below them (Figure 13d). Moss is also growing over the denuded subsoil forms (Figure 13e) beneath the vegetation and the shady parts of denuded subsoil cups on the bare rock, some of which have already been transformed into solution pans (Figure 13f), and of channels (Figure 12o). Channels are forming on the walls below the tops overgrown with moss; they are caused by water secreting from the moss (Figure 13c). In the overgrown section of the karren the rock relief is also being reshaped underneath the decaying leaves (Figures 12g, 13g); the rock is overgrown with different lichens (Figures 12g, 12k, 12l, 12o, 12p, 3b, 13f).

Pits are forming beneath the moss that covers the rock in some places (Figure 13h). The rock surface is smooth under the thicker layer of moss with soil underneath, while the surface is finely dissected under the thinner layer of moss.

DEVELOPMENT MODEL

We can discern several most typical stages of karren development. We can classify them into the development model that shows the transformation of gently sloping and vast rocky tops from flat surfaces to rock spikes (Slabe et al., 2001). The three-dimensional, initially subsoil formation of karren, when intrastratal subsoil holes, shafts and fissures were also created, was followed by the development of tops from subsoil ones to ones exposed to rain and trickling water. When they form on densely cracked rock, the tops are narrow, spiked or longitudinal ridges, which are at first dissected subsoil with funnel-like notches and wall channels, and later denuded and reshaped by rain flutes and the water trickling down the walls (Figure 8A). Because the top rock beds are disintegrating or because they are denuded of soil, the vaster, gently sloping and denuded tops are being shaped by the sheet trickling of water that is hollowing out small steps (Figure 8B). Rain flutes are forming on the top edges and on some of the higher side edges. Subsoil rock forms are being transformed: solution pans are created from subsoil cups; the funnel-like notches on the edge and the channels crisscrossing the tops are deepening, with cascades created in the steep ones.

Afterwards, the tops become increasingly three-dimensionally dissected (Figures 8C, 12f). The subsoil rock forms are undergoing a great transformation: solution pans are opening up, with rock spikes and sloping surfaces forming between them; the walls of large steps, solution pans, channels and the initially subsoil funnel-like notches are being dissected by funnel-like rain notches and rain flutes.

In the overgrown section, the rocky tops are covered with moss; in the denuded section of the karren, the moss is found only in the shade, i.e., in the fissures, deep channels and cups. The rock is being dissected also under the decaying vegetation. The rain flutes in the overgrown and in the predominantly moss-overgrown sections of karren indicate that the tops of karren were alternately overgrown and denuded on multiple occasions (Figure 13i). The predominantly round shape of some of the denuded sections of karren testifies to the fact that the reshaping caused by rain and trickling water was relatively short-term.

The karren were initially formed as subsoil karren. The vaster tops were dissected by subsoil cups and channels, and with funnel-like notches on the edges. Three-dimensional dissection was predominant on the densely cracked rock. The fissures spreading along vertical cracks and the subsoil shafts were crisscrossed with subsoil holes formed along bedding planes.

Small steps have formed on the vaster, flat and gently sloping tops, which were denuded of soil or as the top rock beds disintegrated; the steps are traces of the sheet flow, while rain flutes have formed on the top edges. Eventually the tops become three-dimensionally dissected and rain flutes form in all the higher sections and on the edges of steps. The stages of the development model of the dissection of such surfaces into rock spikes are being revealed (Slabe et al., 2021).

The exposed subsoil rock forms are being transformed. Rain flutes are dissecting the walls of channels and funnel-like notches; solution pans are forming from subsoil cups, which over time open up; water is reshaping the wall channels. Smaller tops on the densely cracked rock are instantly dissected by rain flutes.

5. KARREN ON CLASTIC CARBONATES IN TOURRETTES-SUR-LOUP

SHAPE OF KARREN

Beds of Miocene carbonate sandstone and conglomerate have been deposited on the limestone folds on the slope, resembling a topping; their total thickness amounts to tens of metres. They are relatively impermeable and the water flowing downward has cut through the limestone folds below in several places, carving out smaller canyons.

The karren are domed. The top surfaces of the rounded masses of Miocene sandstone measure tens of metres or even 100 metres; along the rock beds, they dip in the same direction as the slope (Figures 14, 15, 16). At the edge, they turn into a rather steep step that reaches a height of ten metres in some places. Larger steps are usually made up of several smaller ones; some of them are overhanging. Steps can also be seen in the middle of the larger top surfaces of the karren, but they are generally lower. The karren were formed at the transition between rock beds. They were formed subsoil, underneath a thin layer of soil and vegetation, by water flowing down the slope. The denuded sections, in some cases measuring hundreds of square metres, are transformed by rainwater and by the water trickling down the surface of the rock. Only individual channels that dissect these sections are filled with soil and vegetation. Water can also flow onto them from under the soil covering the surface above them. The water flows into channels; in some places, streambeds are created (Figure 15) which pour over the edge in a waterfall, cutting deeper and deeper into the rock.

The larger areas have been affected by construction and water regulation. The water flowing along the top towards the edge of the domed step has been diverted into channels and roads have been cut into them. Houses have been built into the overhangs of larger steps.

Figure 14: Karrren Tourettes sur Loup.

Figure 15: Karren, dissected by channels and stream bed with waterfall.

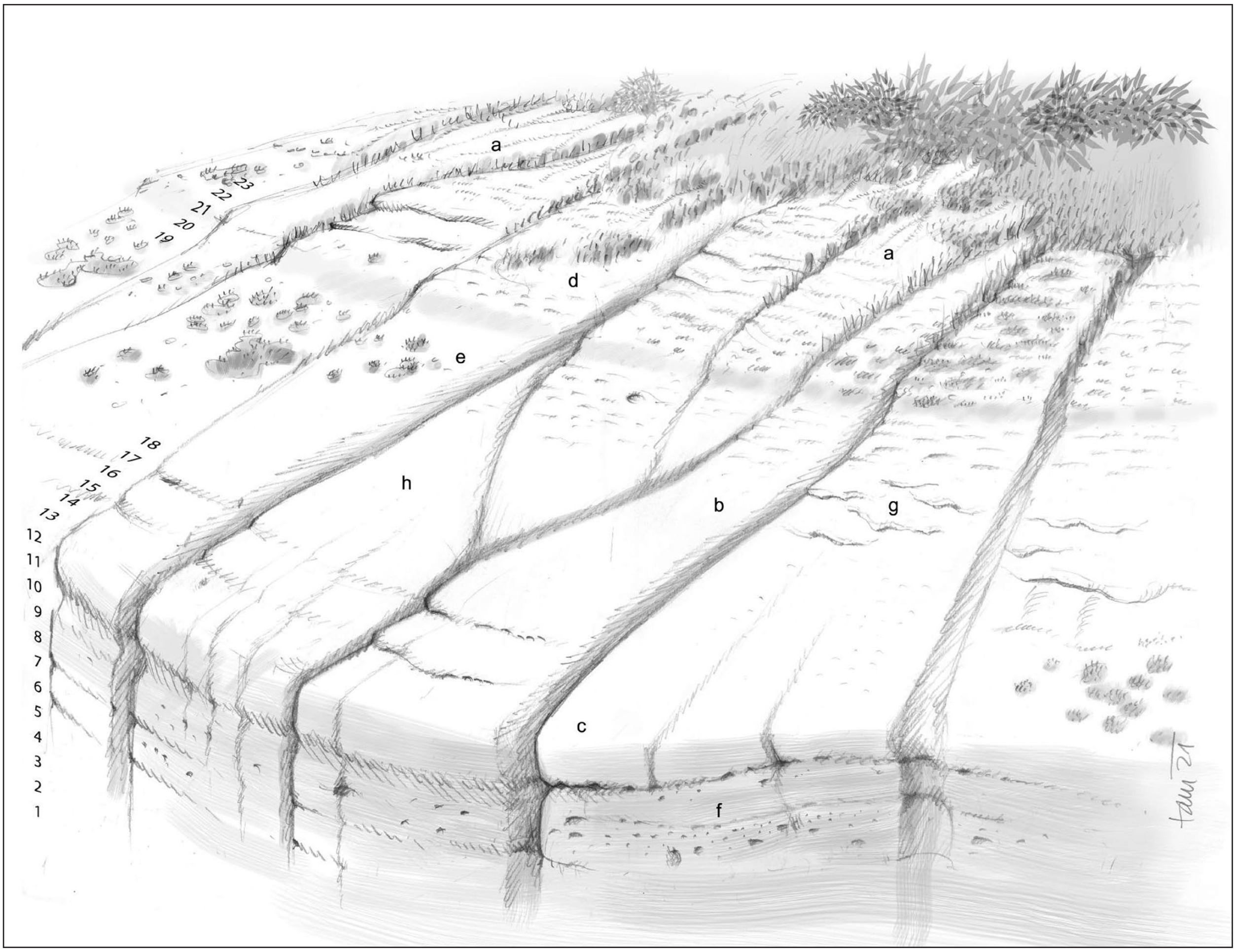


Figure 16: Rock relief of karren. a. subsoil channels, b. longitudinal notch, c. funnel-like notch, d. subsoil cup, e. cup under moss, f. pits, g. steps, h. rock rib. Locations of taken rock samples, numbers 1 to 23.

Karren have developed on fine-grained Miocene carbonate sandstones and conglomerates. The shape of karren is mostly dictated by the rock, in addition to their development process. They have developed from subsoil karren. A thorough examination of the karren rock relief and of the rock on which they were created explains how they have formed and developed.

It is the first description of the development of karren formed on this type of rock, which uniquely influences the shape and development of karren.

A settlement has developed on the domed and stepped karren; within the settlement, individual areas have been denuded, in particular the largest steps and the rock surrounding them.

GEOLOGY

Macroscopic description

In this rock outcrop we examined the clastic sedimentary rock, i.e., molasse, which consists of multiple rock sequences. In the selected 15 m tall geological profile, layers of sandstone and conglomerate alternate, laterally transitioning from one lithological type to the other. The bedding planes in the rock are not clearly discernible and it is difficult to clearly define the discontinuity surfaces. In some places, the outcrop could be described as massive or thick-bedded rock, whereas in other places we could laterally predict poorly expressed layers, around 10 cm thick. The profile contains a few heavily karstified sedimentation contacts. The rock is homogeneous, hard, compact, yet considerably porous. The dip angle of the denuded and karstified rock is generally between 320/10 and 330/12. The rock colour alternates between dark yellowish orange (10YR 6/6), pale yellowish brown (10YR 6/2) and pale brown (5YR 5/2). We took 23 rock samples in the vertical direction at relatively even intervals.

Microscopic description

We turned the 23 rock samples into 29 microscope slides, i.e., thin sections. Due to the porosity that was visible macroscopically during sampling, and to achieve better visibility during subsequent microscopy, we injected blue epoxy resin into rock slices that had been prepared for attachment to the glass of microscope slides. Some samples contained multiple cracks; the epoxy resin (Gardner, 1980) further strengthened the rock in those areas, preventing it from disintegrating when making the thin section. In the examined profile we microscopically determined three lithological types, namely sandstone in the lower (samples TSL1–TSL4) and upper part of the profile (TSL13–TSL23), and conglomerate in the middle part (samples TSL5–TSL12). Both sandstone types have the same properties.

The sandstone samples are made up of more or less evenly sized detrital rock fragments (Figure 17a, c; sample TSL22). Predominant in the rock are inorganic grains of dolomite and non-carbonate grains; calcite grains constitute only a few percent. The dolomite grains are evenly distributed throughout the rock, with no apparent pattern. They are mostly angular or slightly rounded, all with cross-sections between 0.1 and 0.4 mm. According to the complexometric analysis, they make up less than 14%. The amount of non-carbonate grains is similar. These likewise have no apparent pattern and are evenly distributed. Most of them are rounded and smaller, usually with diameters between 90 and 180 μm. Calcite almost always appears in the rock as the fine-grained cement of the above-mentioned grains, i.e., as drusy sparry calcite. The rock also contains individual bioclasts, including nummulites, operculinas, miliolids, foraminifera, fragments of algae and of unidentifiable bivalves. The bioclasts are likewise calcite and make up less than one percent of the rock. Porosity is both intergranular and intragranular. Intergranular porosity has been made even more visible in the microscope slide through impregnation with blue epoxy resin. Intragranular porosity is noticeable in the chambers of larger fossils. This lithological type does not really contain any typical cracks in the rock.

Conglomerate samples are made up of the same detrital grains or rock fragments as the sandstone, only larger (Figure 17b, d; sample TSL6). Dolomite grains are predominant, making up more than half of the rock. In terms of quantity, they are followed by carbonate fragments of various limestones, whereas non-carbonate grains or rock fragments with no identifiable internal structure make up just over 10%. The dolomite fragments are made up of xenotopic dolomite with mostly anhedral crystals, which often laterally transition into hypidiotopic and idiotopic dolomite with subhedral and euhedral crystals. The dolomite fragments of baroque type and mostly unimodal crystal size have diameters between 1 and 5e, while the dolomite grains in the conglomerate have diameters between 2.2 and 4.5 mm on average. Among the limestone calcite grains in the rock are micrite grains, pelsparite grains, and grains containing different fossil fragments. The rock also contains fragments of larger bivalves as individual grains in the conglomerate. Dedolomite crystals are clearly visible in one of the limestone grains. The diameters of limestone fragments are, on average, somewhat smaller than the dolomite ones – between 1.1 and 2.3 mm. Non-carbonate grains make up around 10%. Primary porosity is mainly intergranular. The fine-grained cement of rock fragments in the conglomerate is drusy sparry calcite, just as in the sandstones. This lithological type does not really contain any typical cracks in the rock either.

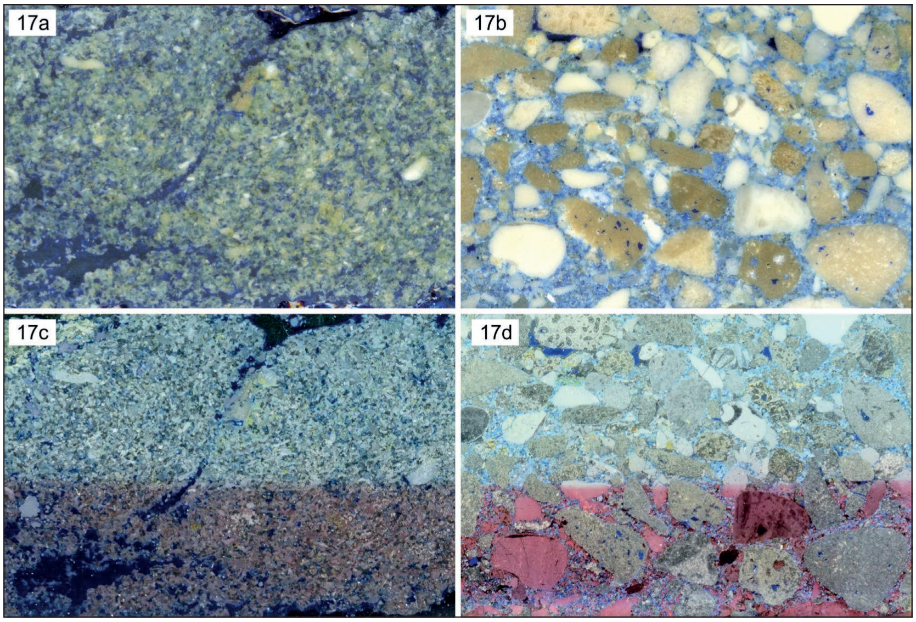


Figure 17: (a) Rock slice prepared for a thin section, sample TSL22. Blue epoxy resin injected. Width of view is 4 cm, (b) Rock slice prepared for a thin section, sample TSL6. Blue epoxy resin injected. Width of view is 4 cm, (c) Thin section of sample TSL22. Blue epoxy resin injected. Lower half of sample was dyed in alizarin red dye. Width of view is 4 cm, (d) Thin section of sample TSL6. Blue epoxy resin injected. Lower half of sample was dyed in alizarin red dye. Width of view is 4 cm.

Complexometric analyses

A complexometric analysis was performed on each rock sample (Table 3). The sandstone samples in the lower part of the profile have an average calcite content of 46.6%, dolomite content of 49%, insoluble residue content of 4.2%, and total carbonate content of 95.8%. The sandstone samples in the upper part of the profile have an average calcite content of 68.9%, dolomite content of 16.7%, insoluble residue content of 14.3%, and total carbonate content of 85.7%. The conglomerate samples have

Table 3: Complexometric analyses of rock samples from Tourettes sur Loup.

Rock sample	CaO (%)	MgO (%)	Calcite (%)	Dolomite (%)	Total carbonate (%)	CaO/MgO	Insoluble residue (%)
TSL 1	39.93	12.34	40.65	56.43	97.08	3.24	2.92
TSL 2	38.08	13.71	33.94	62.70	96.64	2.78	3.36
TSL 3	43.41	7.78	58.16	35.59	93.75	5.58	6.25
TSL 4	42.85	9.15	53.76	41.86	95.62	4.68	4.38
TSL 5	39.09	3.83	60.26	17.52	77.78	10.21	22.22
TSL 6	35.78	11.93	34.22	54.59	88.81	3.00	11.19
TSL 7	34.83	4.92	49.95	22.50	72.45	7.08	27.55
TSL 8	40.38	10.16	46.85	46.47	93.32	3.97	6.68
TSL 9	42.73	8.18	55.93	37.44	93.37	5.22	6.63
TSL 10	43.29	8.47	56.25	38.73	94.98	5.11	5.02
TSL 11	45.65	7.80	62.10	35.69	97.79	5.85	2.21
TSL 12	44.98	6.05	65.27	27.66	92.93	7.43	7.07
TSL 13	46.52	5.62	69.05	25.73	94.78	8.28	5.22
TSL 14	45.99	6.01	67.17	27.48	94.65	7.65	5.35
TSL 15	45.87	6.77	65.05	30.98	96.03	6.78	3.97
TSL 16	45.48	4.76	69.37	21.76	91.13	9.55	8.87
TSL 17	44.64	2.82	72.66	12.91	85.57	15.83	14.43
TSL 18	43.74	2.62	71.56	11.99	83.55	16.69	16.45
TSL 19	39.37	1.01	67.77	4.61	72.38	38.98	27.62
TSL 20	39.26	1.17	67.17	5.35	72.52	33.56	27.48
TSL 21	43.69	1.41	74.48	6.45	80.93	30.99	19.07
TSL 22	38.53	1.69	64.55	7.75	72.30	22.80	27.70
TSL 23	44.36	3.02	71.66	13.83	85.49	14.69	14.51

an average calcite content of 52.2%, dolomite content of 36.1%, insoluble residue content of 11.6%, and total carbonate content of 86.4%. The samples of the entire profile have an average calcite content of 62.2%, dolomite content of 26.5%, insoluble residue content of 11.3%, and total carbonate content of 88.7%.

Impact on karstification

The entire profile of the rock, i.e., all the layers, react similarly to karstification. The sandstone is fine-grained, while the conglomerate contains slightly larger grains; despite their porosity, both are homogeneous, compact, and hard. Their carbonate content is almost 89%. Both examined rocks have excellent properties; on them, subsoil and rain rock features can develop efficiently, smoothly, and successfully, except for the smallest features, i.e., rain flutes, due to the composition and disintegration of the rock. The porosity of the rock and the fine-grained calcite cement further accelerate karstification.

ROCK RELIEF

The surface karren have developed from subsoil karren. Most of them are covered by a thin layer of soil and vegetation. Subsoil channels (Figures 14, 15, 16a) have formed beneath the soil, dissecting the karren into rounded rock ribs, elongated in the dip direction. The channels are either separate or, especially in the upper section, merged into branches. The largest ones are several metres wide and relatively shallow. In some places, large, elongated notches have formed with channels at the bottom. Some of these notches beneath the edge of the soil and vegetation cover and on the widened, more gently sloping sections (Figure 18a) are still filled, while the rock ribs in between are already bare. The fragments splitting from the bare rock are transported by water and deposited on the more gently sloping sections, where soil also accumulates. Therefore, the subsoil cups are also formed in other ways, not just by corrosion underneath the remains of the original soil cover.

The rock beneath the steps, which have formed in the middle of the top of the karren at the transition from the top bed to the bed below, is often covered by soil. Longitudinal notches (Figures 16b, 18b) have formed alongside it, and funnel-like notches (Figures 16c, 18c) at the end of the channels. They can be a metre wide or wider and relatively shallow.

In some places where the soil and vegetation cover the rock, subsoil cups (Figure 16d) have formed. The diameter of the relatively shallow cups is in the centimetre to metre range. Their rims are of different shapes, depending on the cover. They are either round or dissected (Figure 18d). Most of them are located at the edge of the soil cover (Figure 18e), which is either washed away or deposited by water. In the areas containing several cups, a network of channels has formed between them, with diameters in the centimetre range (Figure 18e).

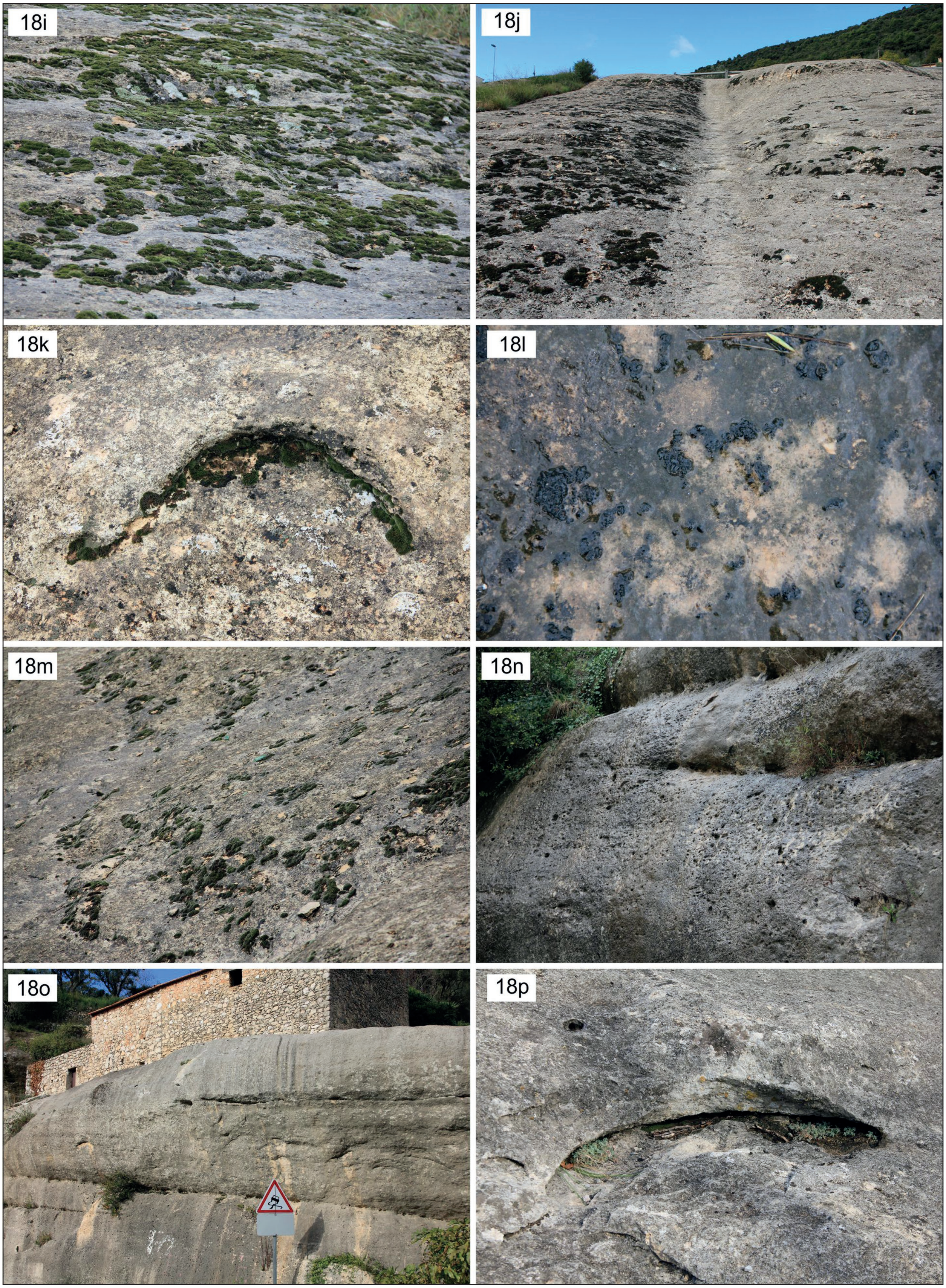
Lower down the top surface of the karren we can see individual cups, usually created where the rock is corroded and dissected at the contacts between beds (Figure 18f), and where it transitions into denuded subsoil channels, transformed by rain and trickling water (Figures 18a, 18g). They are also found at the bottom of funnel-like notches on rock steps (Figure 18h).

Relatively large areas of the rock surface are covered by moss. The diameters of moss rhizoids are in the centimetre and decimetre range. There are either individual mosses or, as is most often the case, clusters of them (Figure 18i), some of which measure several metres in diameter. Such surfaces are most often the slopes of rock ribs above larger water channels, especially those on the shady side (Figures 14, 18j). Moss clusters are often arranged in the zones of steep and mostly overhanging parts of steps, which have formed at the transitions between rock beds (Figures 14, 15, 18k). They are also located at the edges of solution pans. It appears that small cups have also formed under the moss, in the centimetre size range. Their bottoms are dissected by even smaller cups (Figures 16e, 18l). Apparently, the moss is causing or at least accelerating more pronounced splitting of the rock, as the majority of fresh fractures are located in the areas with moss clusters (Figures 18i, 18k, 18m). The scales are the same size as the moss rhizoids. Thus, the scales measure 20 cm in diameter, or most often less than that, and are up to a centimetre thick; only the largest ones are thicker. The rock is weathering and splitting under the moss. The water trickling down the surface of the rock transports the scales downward into the channels and gradually crushes them into sand.

There are gently sloping pits (Figures 16f, 18n) on the vertical and overhanging surfaces, i.e., on the walls of the karren that are transverse to the beds of porous rock. Their diameters and lengths are in the centimetre range. Parts of the rock are densely pitted in the horizontal zones of more porous beds. They appear to have formed on the surface, meaning that they are being hollowed out by the water trickling down the wall. Is the rock porous enough for water to percolate through it?

Small hollows (Figures 18n, 18o) are generally formed at the contacts between rock beds. Their diameters range from one centimetre to several decimetres. There are wall channels below some of these hollows, created by the water flowing out of them. They are usually single channels, while several smaller channels can sometimes be seen below the wider small hollows (Figure 18p). That is why the bottom parts of the small hollows are often deepened.


18a
18b
18c
18d
18e
18f
18g
18h


18i
18j
18k
18l
18m
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18o
18p

Figure 18: (a) Subsoil shaping of the channel, (b) Along-sediment notch, (c) Funnel-like notch, (d) Subsoil cups, (e) Subsoil cups. Width of view is 2 m, (f) Subsoil cups. Width of view is 3 m, (g) Subsoil cups, (h) Subsoil cups, (i) Moss on the rock. Width of view is 5 m, (j) Moss on the shadow part of the rock surface, (k) Moos on the wall horseshoe notch on the end of rock layer. Width of view is 0.75 m, (l) Splitting of the rock under moss. Width of view is 0.5 m, (m) Splitting of the rock under moss. Width of view is 3 m, (n) Wall pits. Width of view is 4 m, (o) Wall hollows and pits, (p) Hollow with channels. Width of view is 0.75 m, (q) Steps on the steep wall. Width of view is 4 m, (r) Steps in the stream bed. Width of view is 5 m.

Well-developed large and small steps (Figure 16g) can be seen on the gently sloping, flat and gently rounded surfaces, and on the steeper surfaces shaped by the sheet flow. The large steps (in the decimetre to metre size range) are formed at the transitions between rock beds (Figures 14, 15, 16). They dissect the gentle slopes and the steep slopes. The steep slopes of large steps are often dissected by smaller steps, placed one above the other in longitudinal rows (Figure 18q). The most pronounced angular edges and relatively large level tops can be seen on the small steps that have formed along thin (centimetre-wide) rock beds in the bed of the stream that is cutting away the top of the karren (Figure 18r). They are arranged one above the other in the form of scales, and their edges on the inflow side are curved inward. The unique shape of the steps is the result of a larger and stronger flow of water.

The medium-sized steps, up to a decimetre high, have been created where the rock is disintegrating due to biocorrosion underneath the moss (Figures 18i, 18j, 18l, 19a). The splitting sites, which are predominant in some places, especially on the steep, usually most overgrown sections of the rock, are being transformed by the sheet flow. There, steps are even more pronounced. Moss is also growing over the steep parts of larger steps, often creating overhanging walls. Higher steps are usually located in the steeper areas of the surface.

The smallest steps (Figure 19b), in the centimetre size range, are traces of an even trickling of the sheet flow along the coarse surface of the rock, which is not directly reached by rainwater (Knez et al., 2015). They are formed on surfaces with varying gradients – on the top surfaces with a gentle slope and on the steep edges. Most of them have round edges on the inflow side. At the bottom of the steps, especially the larger ones, we often find a shallow cup which retains water for a longer period of time. It is a composite form somewhere between a step, hollowed out by the sheet flow, and a solution pan. A distinct network of steps, usually arranged in a cascade, dissects the bottoms of channels (Figures 18g, 18h, 18j, 19c); these channels collect water from the dissected surface or water from the soil and vegetation cover. The steps are often as wide as the bottom of the channel. The larger ones have been deepened in some places to form a solution pan or a smaller pothole. Less pronounced steps can be seen in the smaller, higher areas.

Gradation is therefore dictated by stratification, biocorrosion-induced erosion, the coarseness of the rock and by the predominant factor shaping the rock, i.e., the sheet flow. The latter flows into the subsoil-formed or young channels that collect rainwater; it also flows directly and evenly onto the edge of the karren (Figure 19d). The channels intertwine in different ways. The rock is impermeable, which is why the amount of water that is shaping it evenly and then merging it into channels is relatively large.

It seems that rain flutes cannot form on such a coarse surface, which is mostly the result of the rock composition. The formation of rain flutes can also be influenced by time, e.g., if the rock has only recently been denuded, and by a predominant sheet flow.

Channels are the most typical form on the denuded rock on the top surface of the karren. These uncovered, yet subsoil-formed channels are described above.

Another type is a channel shaped by water that flows from the soil and vegetation cover if it covers the top part of the karren, while the bottom part, which often has a higher gradient, has already been denuded. The densest network of such smaller (with diameters in the centime-

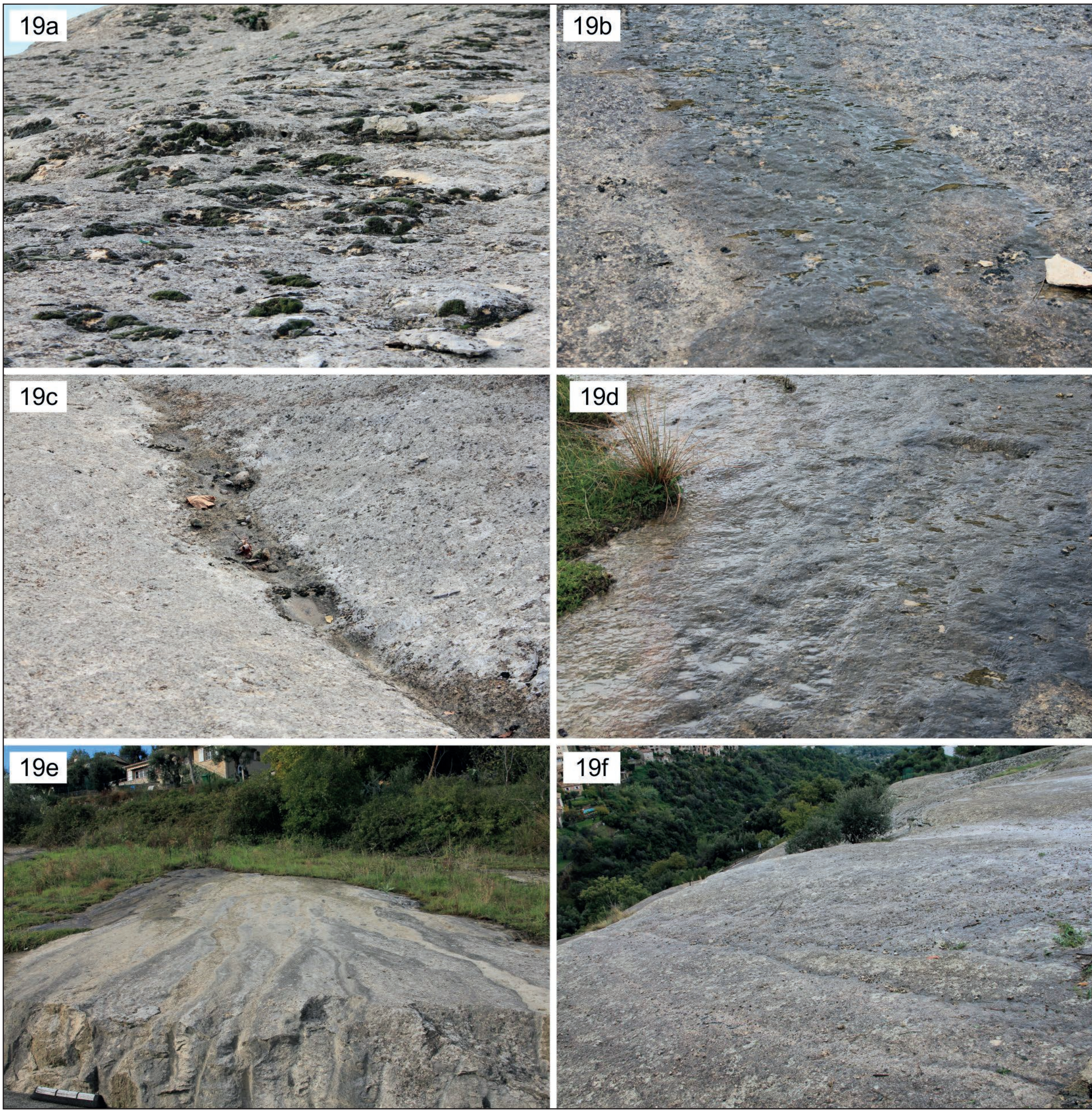

Figure 19: (a) Steps bellow moss. Width of view is 5 m, (b) Steps under layer of trickling water. Width of view is 1 m, (c) Steps in the channel. Width of view is 1.5 m, (d) Steps under layer of trickling water. Width of view is 1.5 m, (e) Net of shallow channels, (f) Channels.

tre range) and meandering channels (Figures 18e, 19e) is created on gently sloping surfaces below the edge of the cover, which is often dissected into smaller areas of soil and vegetation, with subsoil cups forming underneath. The larger channels with diameters in the decimetre range are straighter. When the surface below the cover is steep, the channels are straight and can merge lower down, especially in funnel-like notches (Figure 18h). They are also formed under surfaces partly covered by soil and vegetation in the bottom part of the karren, which is otherwise mostly denuded. They often deepen the bottoms of larger, originally subsoil-formed channels and notches. The latter continue upwards beneath the soil cover, from where water is already flowing into them (Figure 14).

A level surface can be formed subsoil or a surface dissected by large channels, with rounded rock ribs in between (Figure 16h). Water trickles down the steps in a sheet flow along the denuded, relatively level or evenly rounded rock surface. Eventually, the denuded rock is increasingly dissected and the water merges into currents

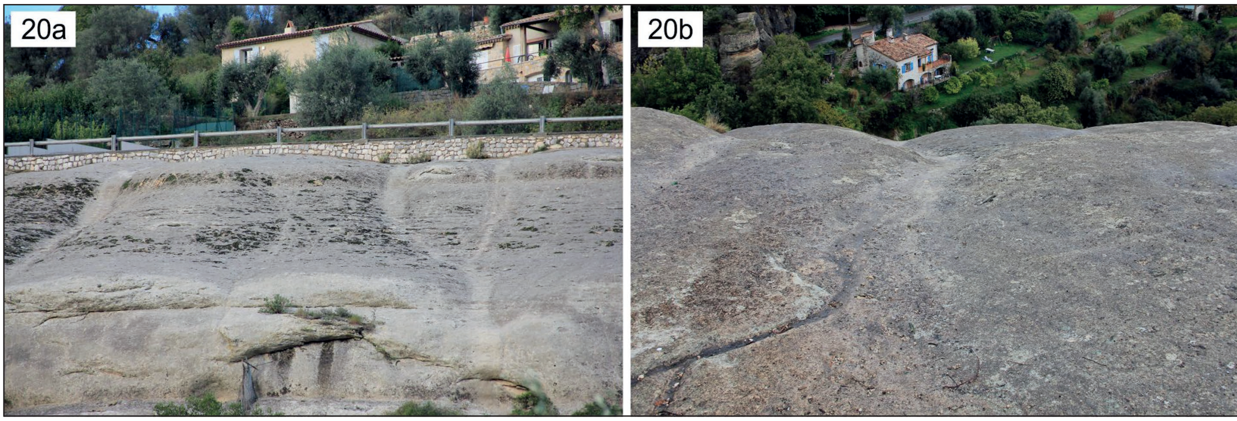

Figure 20: (a) Branching web of channels, (b) Larger channel in with contributory from smaller channels.

in the lower-lying areas. Relatively wide and shallow channels are formed, which meander on gently sloping surfaces and are dissected by steps (Figures 19c, 19f). A dense network of such channels is created (Figures 14, 15, 20a). In the steep sections, especially on the edges of large steps, the channels are straight, narrower and deeper (Figures 14, 18h, 18o). Afterwards, the main water collectors are formed, namely larger and straighter channels (Figure 20b), which have diameters in the decimetre range and can be tens of metres long; their bottoms are often relatively wide, flat and smooth (Figures 18j, 20b). On the subsoil-dissected surface this role is taken up by the former subsoil channels.

The formation of channels is therefore generally a combination of different factors – of the water flowing underneath the soil and of the rainwater either directly reaching the rock or trickling in a sheet flow or stream across the surface and, of course, of the development or denudation of the rock.

The largest funnel-like notches, whose diameters reach several metres, are subsoil-formed notches created along the main subsoil channels that dissect the tops of karren into rock ribs (Figures 14, 15). They were created when they were either fully underground or when only their bottom part was; when the bottom ledge (Figures 16c, 18c) is covered by soil and the water flows to it along the channel that dissects the bare rock, or when the rock above the ledge is covered and the water flows from the soil over the edge. Apart from the latter, such notches are relatively wide. The denuded notches have been transformed. There is usually a channel at their bottom that deepens them and, in some places, also widens their bottom part. As a rule, smaller notches are formed along younger channels that collect water from the bare rock and from the soil that covers the top part of the rock. They can be dissected by smaller channels (Figure 18h) leading to the bottom of the notch, from where one wall channel leads onward. Their diameters are in the centimetre to decimetre range. Both are co-shaped by rainwater that reaches them directly. Eventually, smaller rock steps cut through it, creating a flat-bottomed channel, with the notch becoming its high walls. The most distinct notch can be seen at the top of the waterfall, where a water-rich stream flows down (Figure 15).

This relatively common rock form has resulted in genuinely jagged rock overhangs, both those at the edge and the smaller ones on top of the karren (Figure 14).

Wall channels can be seen below the funnel-like notches; on the overhangs these channels widen into a bell shape (Figure 14).

The solution pans are of different origins and their diameters are in the centimetre to metre range. Smaller solution pans are predominant or shallow ones if they have larger diameters, which indicates their recent formation, or the recent relatively even shaping of the rock beneath the soil and vegetation cover. They develop from denuded subsoil cups (Figure 18d), from small biocorrosion cups, and due to water being retained on the coarse rock, on larger steps and in channels (Figures 18g, 19c). The latter can be singled out as a special type of solution pan. They are often a composite rock form combined with a pothole; they are largest in the larger channels. They are occasionally shaped by erosion as the water swirls, gathering the sand that has been created by rock splitting. Where larger periodic streams flow, the diameter of solution pans exceeds one metre. In the section of the rock that is dissected by larger steps, i.e., usually in shallow channels, we find solution pans that are also mostly shallow and of different shapes, arranged one above the other in a cascade. They are wider on the inflow side and narrower on the outflow side. Their diameter ranges from one centimetre to several decimetres. The solution pans that are developing from small biocorrosion cups, which were formed beneath the moss, at first consist of several smaller cups with diameters in the centimetre range (Figure 18l).

DEVELOPMENT MODEL

In terms of composition, the relatively uniform, uncracked, stratified and rather impermeable rock mass is dissected beneath the soil by subsoil channels, most of which individually dip in the same direction as the rock bed. Only in the upper part do they merge into a larger channel. Notches are created along the larger channels and if the channels are close by, then rounded rock ribs are formed in between. The larger surfaces without any distinct channels are relatively level.

Where the rock has been denuded, the top of the karren, apart from the channels, is shaped by sheet flow. Steps are formed. Eventually, a network of smaller channels develops. They often funnel into a larger channel and merge with the large channels formed beneath the soil. Funnel-like notches are growing at the edges of the karren or at the ends of the channels, followed by wall channels below them (Figure 14).

In the case of gradual denudation, the water flows from the soil at the top mostly in a condensed manner along smaller and larger channels (Figure 19e). These channels join a network of rain channels (Figure 20a).

The tops of the karren are relatively poorly dissected, so it can be assumed that they have been denuded recently.

The karren are dissected three-dimensionally only by individual small hollows formed along bedding planes.

The development model can be defined as typical of the recent formation of gently sloping surfaces of rock being denuded of soil (Knez et al., 2011, 2015). In this case, the shape is also influenced by stratification, composition, the rare cracks in the rock, the moss growing over it, and the disintegration taking place under the moss. The bumps between the channels are rounded and the rock surface is coarse. It appears that rain flutes do not form on such rock.

The characteristics of the "plastically" deposited sloping, uniquely composed and predominantly uncracked beds of Miocene carbonate sandstones, which have a major impact on the formation of karren, are intertwined with the typical rock relief development model, which reveals a transition from subsoil formation to denuded rock exposed to rain. Rock denudation is gradual and the water often flows onto the bare rock from the soil covers. The bare, sloping peaks reveal the characteristic formation of a slightly inclined and relatively smooth rock. Such surfaces are initially shaped by sheet flow; steps are a characteristic trace of that. As the surface is being dissected, the water begins to merge into streams and channels are formed. Along these channels, the rock is becoming increasingly dissected. That indicates the initial stage of the formation described above. The composition of the rock that is splitting, especially under the moss, does not enable the development of the smallest rock forms, such as rain flutes, whereas its splitting causes the development of rounded peaks.

The special features of karren formation on this unique rock within an otherwise typical development model are broadening our understanding of the formation of the rocky karst surface.

6. KARREN OF LUBERON

We have supplemented our study of the formation of karren on the Miocene carbonates of Tourrettes-sur-Loup with research of the most characteristic rock forms and rock relief of Luberon.

Most of the surface is covered by soil and vegetation. Hence, the subsoil rock relief is predominant. The newly denuded rock surface is smooth and rounded (Figure 21a). The edges of steep slopes, of the rocky walls of valleys, and of cuttings are being denuded and the subsoil rock relief is being reshaped. The majority of subsoil rock forms on steep surfaces are large subsoil channels (Figure 21b). Sediment is accumulating below the denuded steep sections, with subsoil cups (Figure 21c) and solution pans (Figure 21d) forming underneath the sediment.

There are cups (Figure 21e) on the overhanging walls that only a small amount of water reaches. The rock is flaking (Figure 21f). Crust forms on the rocky surface that is reached by greater quantities of water.

The characteristic and most distinct rock relief dissects the rocky walls and steep slopes. It is mostly made up of wall channels (Figures 22a), into which water flows from the overgrown surface. These are individual channels that are dependent on the inflow of water. They are often found along cracks and crevices (Figure 22b) or bedding planes (Figure 22c). Typical rain flutes (Figure 22d) form on the uncracked rock that is directly exposed to rain. These rain flutes are interconnected into a network.

The denuded walls are often dissected by hollows in the centimetre size range (Figure 22e) or in some places by larger ones, with diameters in the decimetre range (Figure 22f). They are traces of the point-accelerated dis-

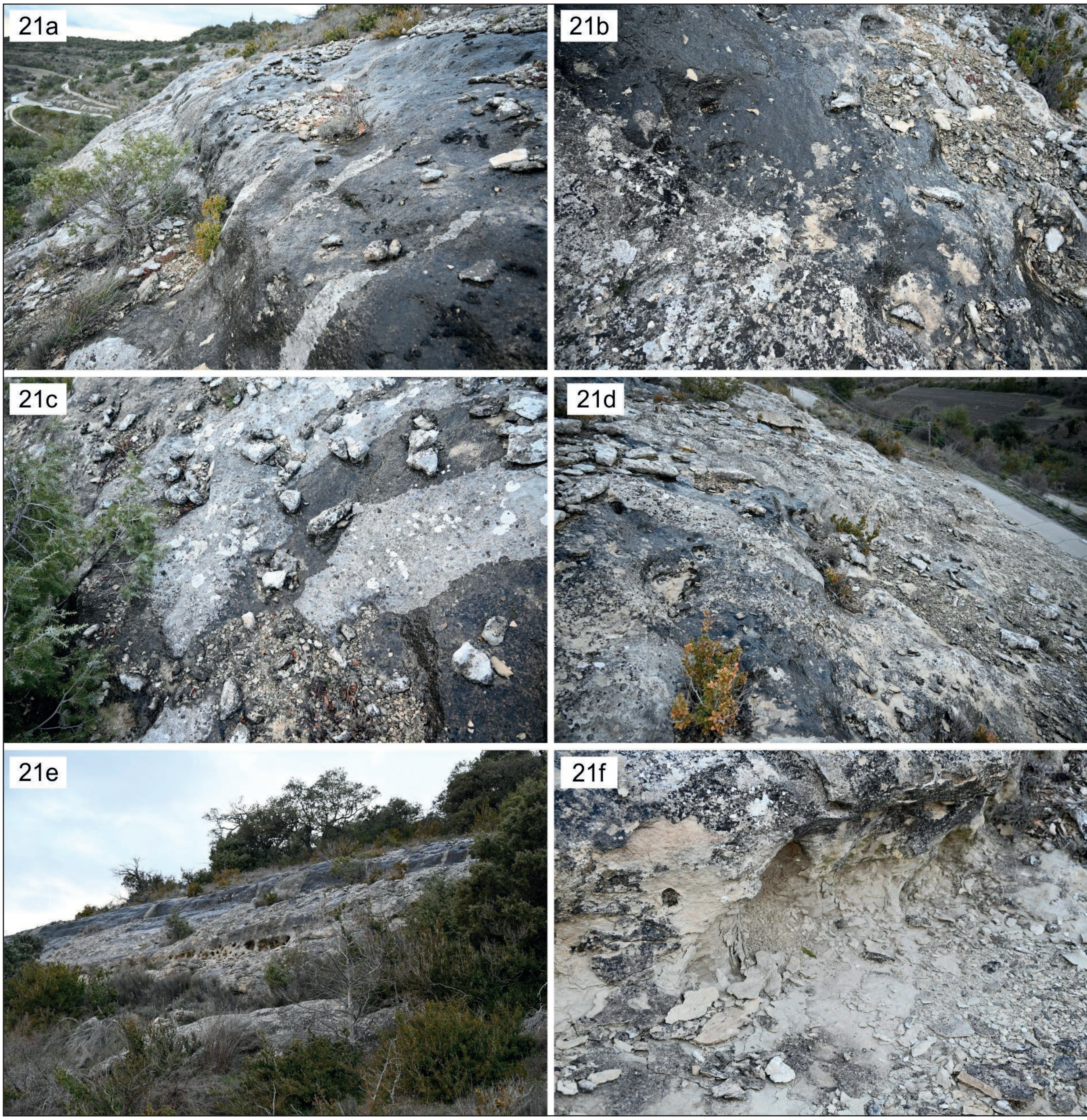

Figure 21: (a) Subsoil rounded and smooth rock surface, (b) Subsoil channels. Width of view is 4 m, (c) Subsoil cup. Width of view is 2 m, (d) Solution pan, (e) Wall cups, (f) Splitting of the rock. Width of view is 1.5 m.

solution and disintegration of the rock and of the forming of a crust on the rocky surface surrounding them.

The soft rock that was used for construction reshapes quickly, as attested by the dissected walls of the 14th-century Palace of the Popes in Avignon. Channels have formed on the walls, with water running down them from the top (Figure 23a). Beneath the moss, the rock is dissected by cups (Figure 23b). The rock is disintegrating quickly in the spots that water does not reach (Figure 24).

Subsoil cups filled with sediment and soil (Figure 25a), solution pans (Figure 25b) and channels are developing on artificially uncovered layers on the gently sloping surfaces at Fort Buoux (in the middle of Luberon), which began construction in the 11th century, with the majority of traces dating from the 13th century, while the oldest ones' date back to the Bronze Age. The channels are also found on the walls (Figure 25c). The rock is also being distinctly dissected under the moss (Fig. 1904).

Large solution pans (Figure 25d) have also formed on the denuded rocky peak above Saignon.

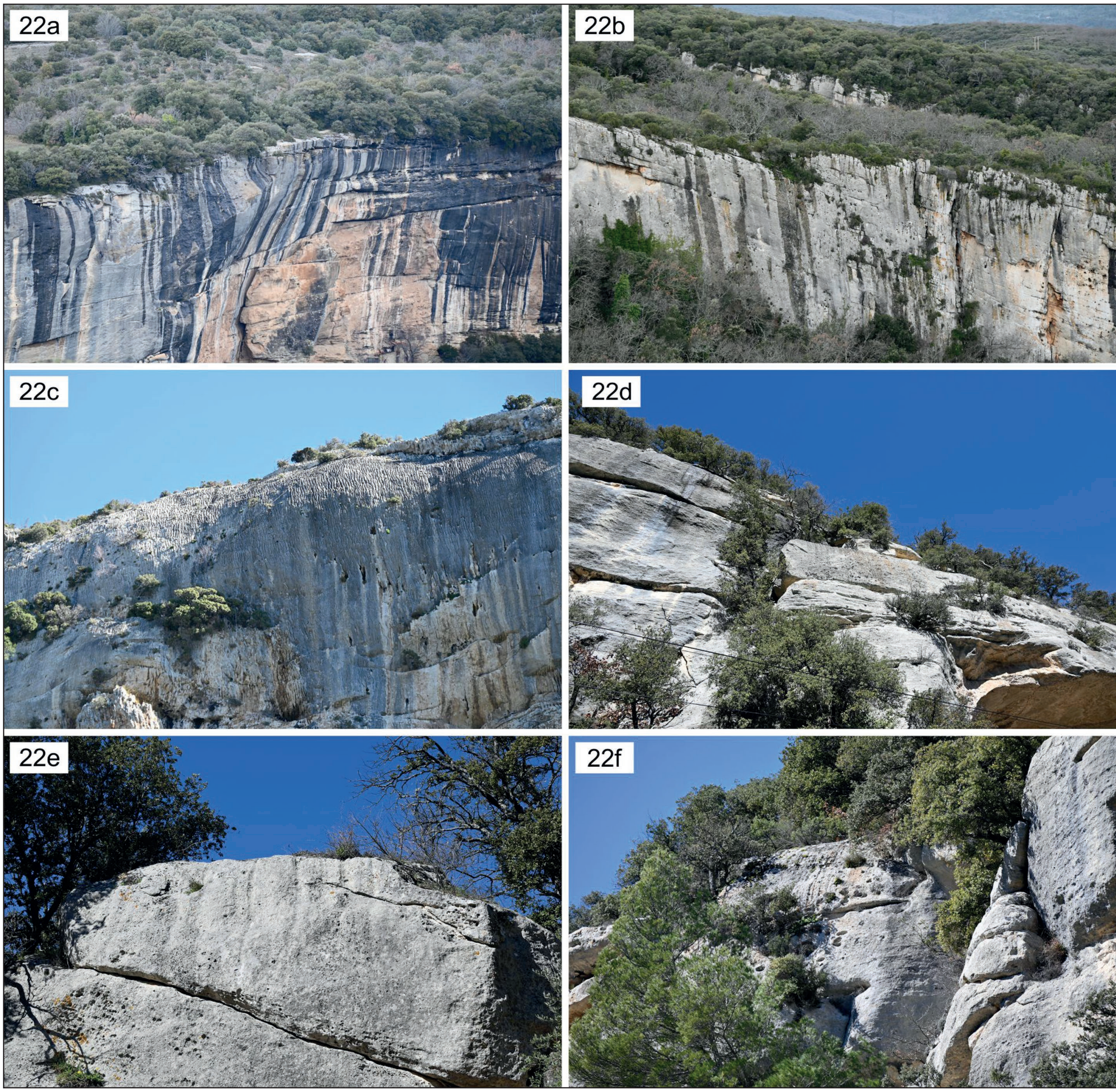

Figure 22: (a) Wall channels, (b) Wall channels along fissures, (c) Wall channels along bedding-planes, (d) Rain channels, (e) Wall pits, (f) Wall cups.

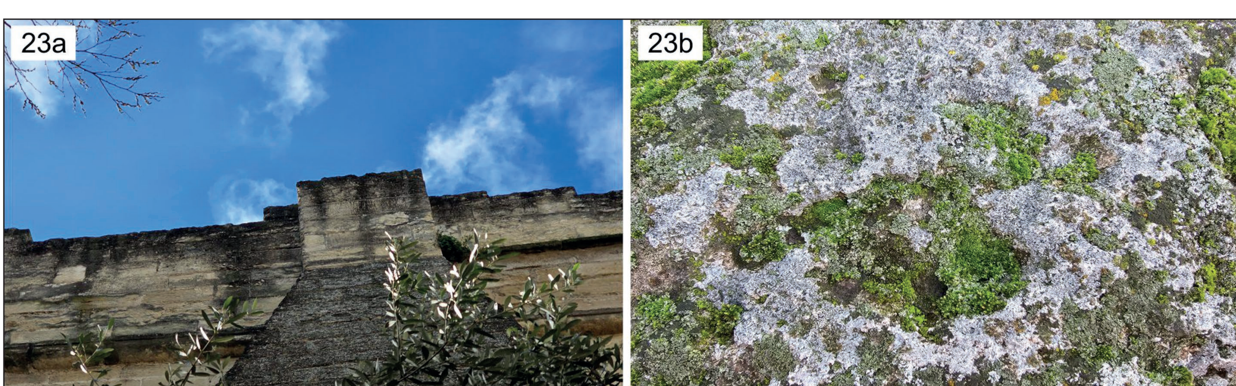

Figure 23: (a) Wall channels, (b) Cups bellow moss. Width of view is 1 m.

Figure 24: Decaying rock.

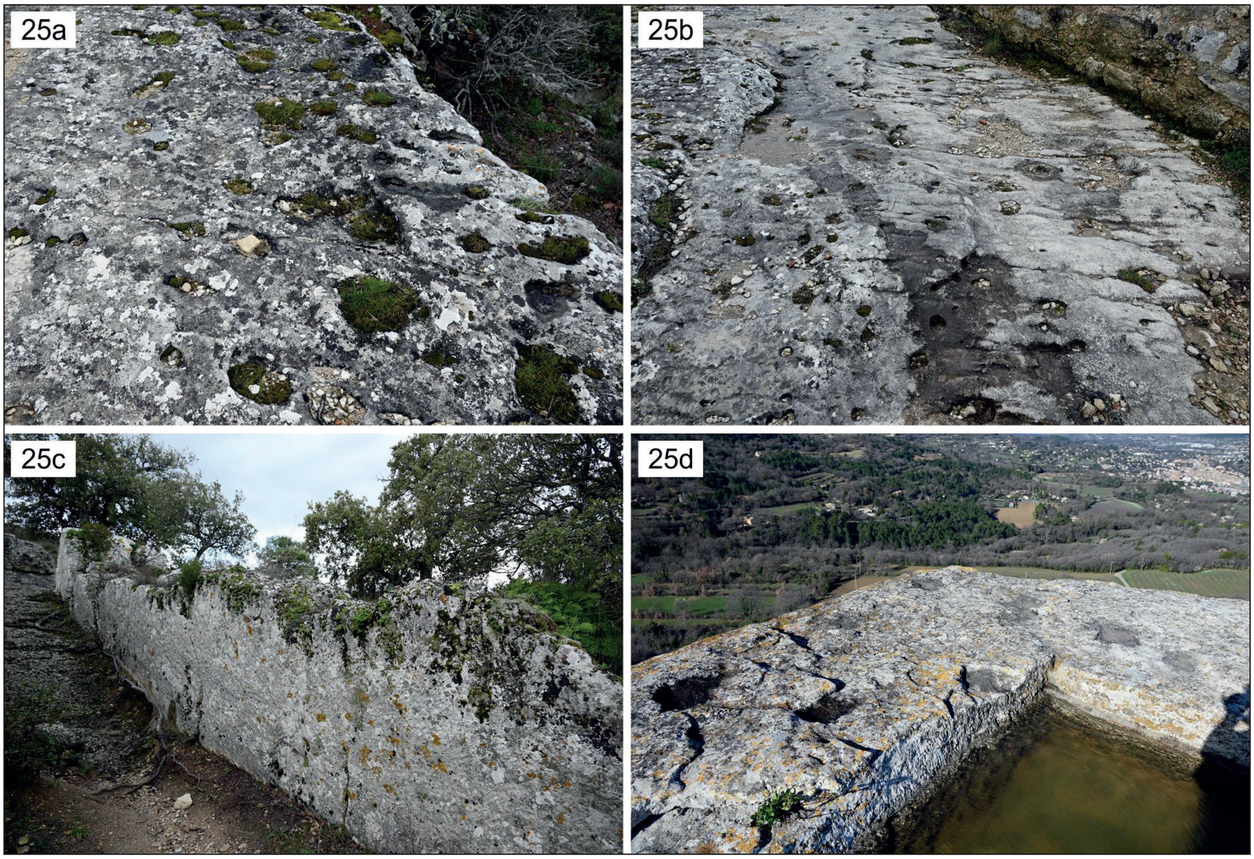

Figure 25: (a) Subsoil cups. Width of view is 3 m, (b) Solution pans. Width of view is 4 m, (c) Wall channels, (d) Solution pans.

7. CONCLUSION

The karren of Gréolières and Caussols are developing on similar rock and under similar conditions. What differs, however, is the dip and thickness of the rock strata. This also dictates the shaping and development of their rock relief. Parallel channels are predominant on the steep slopes of Gréolières on fine-grained homogeneous and compact thick-bedded limestone with almost entire calcium carbonate content. On the flat and steep surfaces, the abundant water flow splits into parallel branches. They are gradually reshaped three-dimensionally. The rain flutes, which are initially characteristic of the upper parts of surfaces that are directly reached by rain, eventually also dissect all the larger channels and the surface between them. The surfaces of the tops of the karren of Caussols on the likewise fine-grained, homogeneous and compact limestone with a high calcium carbonate content, which are more gently sloping and flat due to the denudation of soil or the disintegration of older rock layers, are initially dissected into steps by the sheet flow. The water also reshapes the denuded subsoil channels, and solution pans form from subsoil cups. Afterwards, the surface is dissected three-dimensionally. Rain flutes also form on the walls of the above-mentioned rock features and of the funnel-like notches at the edges. Three-dimensional dissection prevails on the densely cracked parts of the rock strata. Examples of such karren formation have been described in the development model (Slabe et al., 2022).

The karren of Tourrettes-sur-Loup where homogeneous, compact, hard, and partly porous fine-grained sandstone alternates with conglomerate, with the fragments bound together by fine-grained calcite cement are dissected by large channels which collect most of the water that trickles downward. They are created subsoil but are later reshaped into denuded channels. They are constantly deepening and the surfaces between them are being reshaped accordingly. The rock enables the development of such channels, as it is mostly secondarily impermeable and three-dimensional dissection is therefore less distinct. Smaller rock features, such as rain flutes, do not form on such rock. The rock is also flaking.

Thus, all karren are formed from subsoil ones through gradual denudation. The subsoil rock relief is reshaped by rainwater, by the water flowing across karren, and by biocorrosion. The first two examples of karren differ mostly because of the dip and thickness of the strata of similar rock, while the third example is unique, as karren form on a completely different type of rock.

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