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CLUSTERED STONE FOREST IN PU DOU CHUN (YUNNAN, CHINA)

GRUČASTI KAMNITI GOZD V FIŽOLJI VASI (PU DOU CHUN, JUNAN, KITAJSKA)

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Abstract UDC 551.435.8(513.21)

Martin Knez, Hong Liu & Tadej Slabe: Clustered stone forest in Pu Dou Chun (Yunnan, China)

One of the unique examples of the development of subsoil karren into a stone forest on the varied geological bedrock of the Lunan surface is revealed to us. Originally of subsoil formation and later denuded, the rounded hills that dissect the karst surface have transformed into a clustered stone forest whose central part usually consists of a larger dissected rock mass with individual stone pillars and teeth at the edge. The geologic profile contains beds of dense, homogeneous and compact fine-grained limestones that alternate with beds of mostly coarse-grained and just as compact dolomitised limestones. These bed properties are also reflected in the exterior of the rock as a diverse relief. The average calcium carbonate content in both types of rocks combined is 97.3%. The rock is thickly bedded to massive; beds are mainly positioned subhorizontally. The contacts between the beds of limestone and dolomitised limestone are sharp and clearly visible, especially in the bottom part of the geologic profile, whereas in the central part, they are often blurred and one type of rock grades continuously into the other. In the areas containing limestone, individual bedding planes are especially visible. As can be inferred, the slightly more porous dolomitised rock, made up of larger particles, disintegrates faster in a more permanently waterlogged acid subsoil environment, where the moisture penetrates it deeper. However, as it takes longer to dissolve, it protrudes from the surface of the dolomitic limestone rock when exposed to moisture from oc-

Izvleček UDK 551.435.8(513.21)

Martin Knez, Hong Liu & Tadej Slabe: Gručasti kamniti gozd v Fižolji vasi (Pu Dou Chun, Junan, Kitajska)

Spoznali smo enega izmed edinstvenih primerov razvoja podtalnih škrapelj v kamnitem gozdu na raznoliki geološki podlagi lunanskega površja. Prvotno podorni in pozneje denudirani zaobljeni griči, ki razčlenjujejo kraško površje, so se spremenili v gručast kamniti gozd, katerega osrednji del običajno sestavlja večja razčlenjena skalna gmota s posameznimi kamnitimi stebri in konicami po robu. V geološkem profilu so plasti gostih, homogenih in kompaktnih drobnozrnatih apnencev, ki se izmenjujejo s plastmi večinoma grobozrnatih in prav tako kompaktnih dolomitiziranih apnencev. Te lastnosti plasti se kažejo tudi na zunanjosti kamnine kot raznolik relief. Povprečna vsebnost kalcijevega karbonata v obeh vrstah kamnin skupaj je 97,3 %. Kamnina je debeloslojna do masivna, plasti so večinoma razporejene subhorizontalno. Stiki med plastmi apnenca in dolomitiziranega apnenca so zlasti v spodnjem delu geološkega profila čisti in dobro vidni, v osrednjem delu pa so pogosto zabrisani, pri čemer ena vrsta kamnine postopno prehaja v drugo. Na območjih, ki vsebujejo apnenec, so še posebej vidne posamezne ploskve kamninske podlage. Kot je mogoče sklepati, se nekoliko bolj porozna dolomitizirana kamnina, sestavljena iz večjih delcev, hitreje raztaplja na trajneje razmočenih kislih tleh, kjer voda prodre globlje. Ker pa se dlje časa raztaplja, izstopa s površine dolomitne apnenčaste kamnine, kadar je izpostavljena občasnim deževnim padavinam. Na obliko stebrov in njihov skalni relief odločilno vplivata sestava in razpokanost

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casional rain. The composition and fracturing of the diverse rock strata decisively influences the shape of the pillars and their rock relief. Larger subsoil rock forms (channels, notches, half-bells) have developed on all rock strata. The diversity of the rock is also reflected by the notches that have formed under the soil along the more rapidly soluble partly dolomite rock strata. Denuded subsoil-shaped pillars are reshaped by rainwater and trickling water. Smaller rock forms carved by rainwater have formed mostly only on evenly composed, fine- grained limestone rock. The tops on such rock are more distinctly conical and blade-like and wider on more slowly soluble rock.

Keywords: stone forest - Shilin, rock, rock relief, complexometry, Yunnan, China.

raznolikih kamninskih plasti. Na vseh kamninskih plasteh so se razvile večje podorne skalne oblike (žlebovi, zajede, polzvonovi). Raznolikost kamnin se kaže tudi v zajedah, ki so nastale pod tlemi ob hitreje topnih delno dolomitnih kamninskih plasteh. Denudirane stebre v obliki podtalnice preoblikujeta deževnica in voda, ki prihaja v drobnem curku. Manjše skalne oblike, ki jih je izdolbla deževnica, so nastale večinoma le na enakomerno sestavljenih drobnozrnatih apnenčastih kamninah. Vrhovi takih skalnih oblik so izraziteje stožčasti in lopataste oblike, na počasneje topnih kamninah pa so zaobljeni.

Ključne besede: kamniti gozd – šilin, skala, skalni relief, kompleksometrija, Junan, Kitajska.

1. INTRODUCTION

The Pu Dou Chun stone forest is one of the unique sites in the network of famous Shilin stone forests (Knez, 1997; Chen et al., 1998; Knez & Slabe, 2001a, 2001b, 2002, 2006, 2007; Knez et al., 2011, 2012, 2017). Its special appearance is dictated by the geological characteristics and the soil erosion of the rounded hills that dissect the karst surface. It develops on diverse limestone and partly dolomitized limestone rock strata. Its development from rounded hills gives it a clustered appearance. In the central part, the clusters are partly dissected larger rock masses, and at the edges they are dissected more distinctly into stone pillars. Between the rounded hills stone teeth protrude from the soil and sediments. The rock relief, which is also dictated by the diverse rock composition, clearly reveals their formation and development.

The beds of limestone and dolomitized limestone alternating with chert beds can be traced throughout the examined geologic column. The rock beds are mainly positioned subhorizontally, rock is thick bedded to massive. Beds of limestone and dolomitized limestone often alternate in the bottom section, which is followed by a section, where we can see dolomitized limestone only exceptionally. This section continues into a section of pure dolomitized limestone, which then abruptly changes into a section of homogeneous and compact limestone that makes up the entire top part of the rounded hill. The contacts between the beds of limestone and dolomitized limestone are mostly sharp and clearly visible.

2. THE SHAPE OF THE STONE FOREST

The stone forest dissects rounded hills that stand individually or side by side (Figures 1, 2). The sediment that once covered the rounded hills, the higher parts of the karst surface, has been largely removed but is preserved in the cracks between the stone pillars.

The tops of the rounded hills are most distinctly dissected into a stone forest, that is, into stone pillars. Most often, the stone forests consist of stone pillars at the edges (Figures 3, 4) and larger rock masses or massive stone pillars that are only partially dissected and dominate the central part of the cluster (Figure 1). They can have multiple peaks. The lower parts of the larger rounded hills are often stone walls that are only partially dissected with several peaks. Only individual rounded hills are completely dissected or have stone pillars on their slopes (Figure 5).

The stone pillars reach 20 m in height. Depending on the rock base and its fissuring, the stone pillars are pointed, mushroom-shaped, or elongated. They are found clustered next to each other and rarely stand individually (Figure 3). Individual, mostly smaller rounded hills are more extensive rock masses with dissected tops and slopes (Figure 6). From the surface between the rounded hills, which is covered with thick layers of sediment and soil, stone teeth up to 5 m high protrude (Figure 7). Most of the taller ones are found on the edges of the rounded hills.

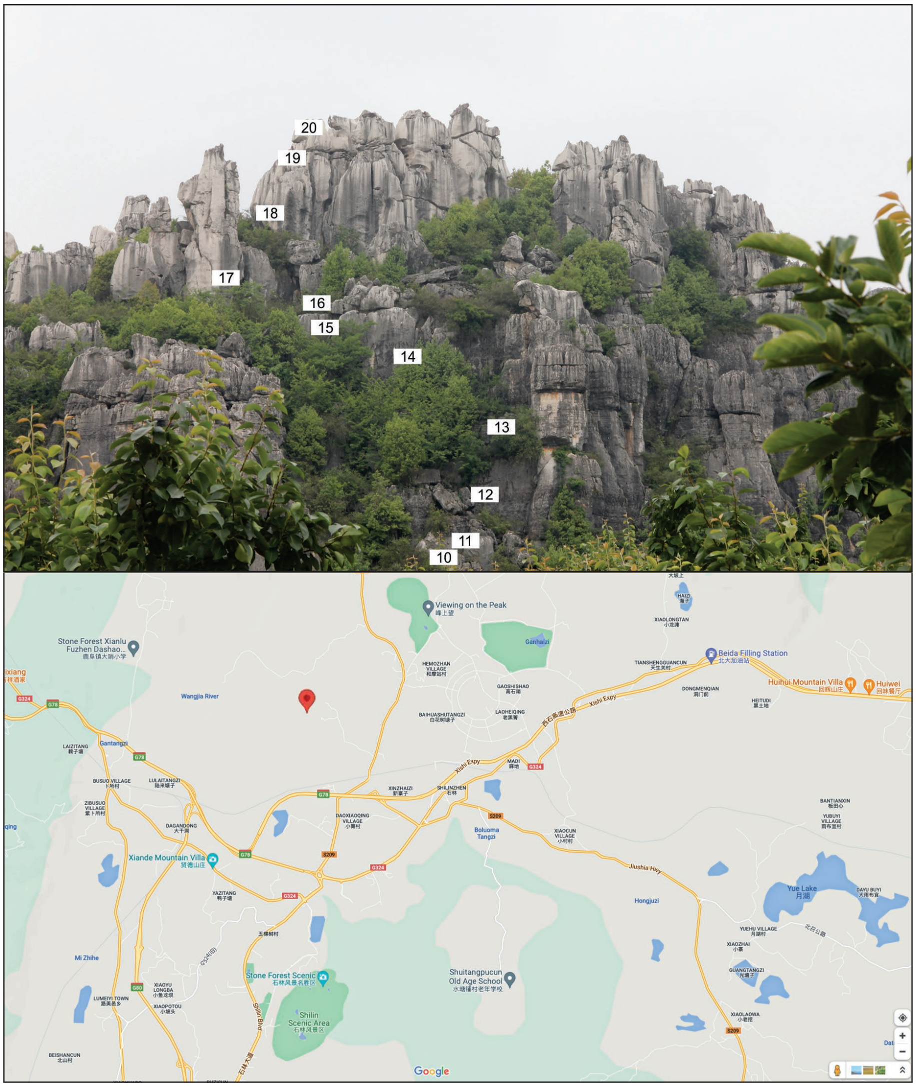

Figure 1: Up, clustered stone forest, down, location (Google Maps, 2022). For sample numbers see also Table 1.

Figure 2: Rounded hills dissected into a stone forest.

Figure 3: Edge of a clustered stone forest.

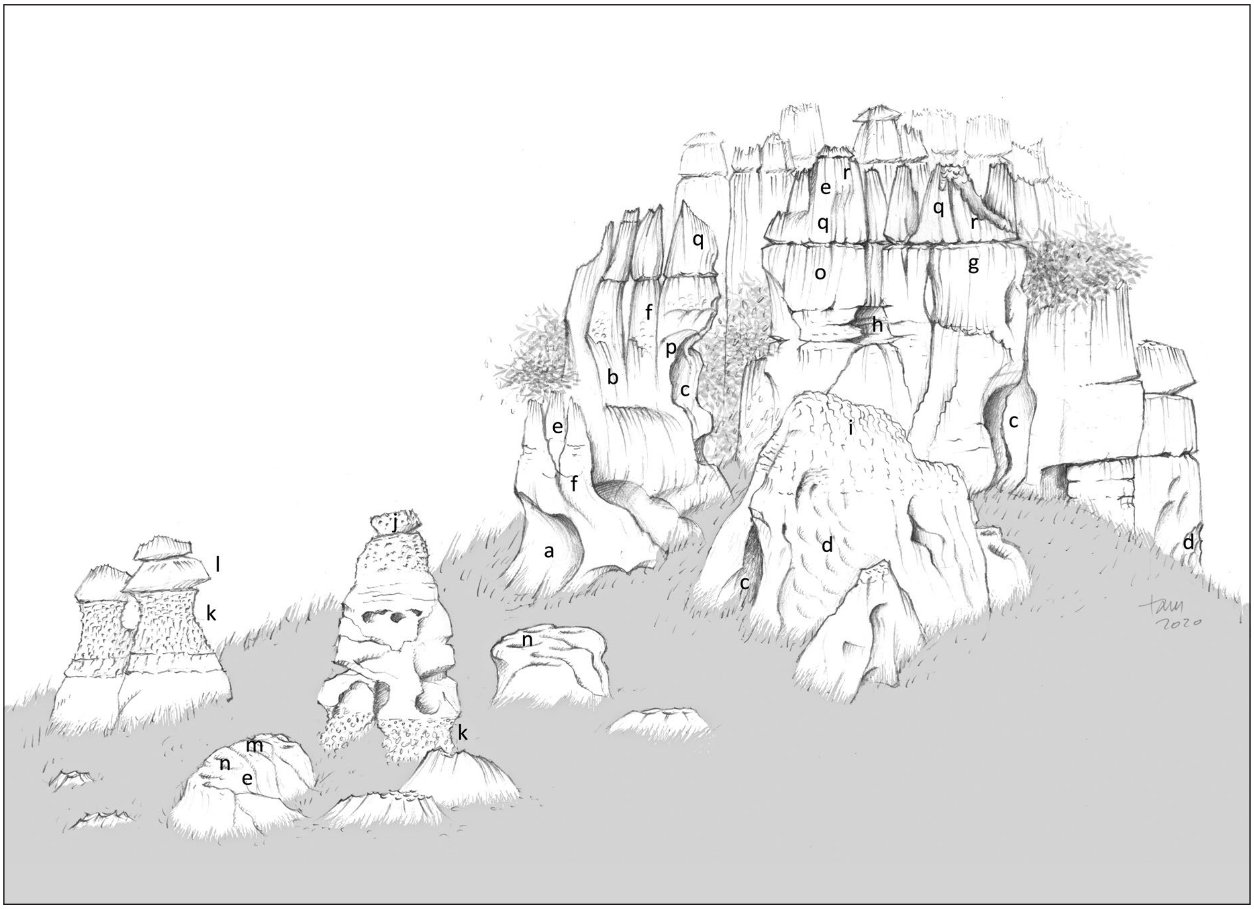

Figure 4: Stone forest with rock relief: a. along-sediment notch, b. old along-sediment notch, c. half-bell, d. subsoil scallops, e. funnel like notch, f. wall channels, g. bedding-plane anastomoses, h. hole at the bottom of a shaft, i. top on partly dolomite rock, j. top on thin-layered rock, k. subsoil notch along limestone-dolomite rock, l. top on limestone rock, m. subsoil channel, n. subsoil cup, o. channels under anastomoses, p. scallops, q. rain flutes, r. rain channels.

Figure 5: Stone pillars on the slope of a rounded hill.

Figure 6: Rounded hill dissected into a smaller stone forest. For sample numbers see also Table 1.

Figure 7: Stone teeth.

3. LITHOSTRATIGRAPHIC AND CALCIMETRIC PROPERTIES OF ROCK

3.1 MACROSCOPIC DESCRIPTION

We began conducting geological research and taking rock samples at the foot of the rounded hills (Figures 1, 6). We took the first rock samples on the stone teeth protruding from the gently undulating to flat cultivable farmland, which is made up of thick layers of soil. As the rock beds are mainly positioned subhorizontally, we were able to continuously sample the rock in the direction of the stone pillars and the central part of the rounded hills. The beds of limestone and dolomitized limestone alternating with chert beds can be traced throughout the examined geologic column.

The rock is thickly bedded to massive. The beds are from 0.5 m to several meters thick; in some places in the upper part of the geologic profile even between 5 and 10 m thick. Most beds are between 2 and 3 m thick. The contacts between the beds of limestone and dolomitized limestone are sharp and clearly visible, especially in the bottom part of the geologic profile; whereas in the central part, they are often blurred and one type of rock grades continuously into the other. In the areas containing limestone, individual bedding planes are especially visible.

The dip angle of the beds varies slightly from the foot to the top; the predominant angle is towards the south and southeast, and ranges from 5 to 10° in the bottom part of the geologic profile, and from 0 to 5° at the top of the rise. The direction of the beds' dip angle is between 160 and 180 °.

The rock has been broken into larger and smaller blocks with subvertical cracks. Cracks and faults are noticeable in all directions; cracks in the directions 340–160, 320–140, 260–80, 230–50 and 200–20 are predominant.

The macroscopic geologic profile can be divided into several sections. Beds of limestone and dolomitized limestone often alternate in the bottom section, 10 m thick. This is followed by a 7 m thick section, where we can see dolomitized limestone only exceptionally. This section continuous into about 20 m thick section of pure dolomitized limestone, which is interrupted approximately in the middle with 1.5 m thick beds of dark grey limestone. This is followed by an abrupt change into about 30 m thick section of homogeneous, compact light grey limestone that makes up the entire top part of the rounded hill.

We took additional rock samples from one of the stone teeth at the foot of the central part of the stone forest (see Figure 21), where we noticed a typical alternation of beds of limestone and dolomitized limestone. We paid special attention to the beds of dolomitized limestone. The dolomitized beds make up the base, which is still partly covered by soil, and the top of the stone tooth. The karstification of limestone or dolomitized areas in the dolomitized limestones takes place differently on the surface and exposed to atmospheric influence than the karstification of dolomitized rocks still covered by soil. The limestone areas karstify faster in the dolomitized limestones on the surface and exposed to atmospheric influence; thus, the relief shows dolomitized areas protruding from the surface of the rock. The subsoil dolomitized areas weather faster in the dolomitized rocks that are still covered by soil; thus, the relief shows limestone areas protruding from the surface of the rock. Notches are forming alongside them.

The rock is mostly grey; the predominant colours (Goddard et al., 1970) are: N 8 (very light grey), 5 YR 8/1 (pinkish grey), 5 YR 7/2 (greyish orange pink), 5 YR 6/1 (light brownish grey) and N5 (medium grey) for limestones; 10 R 8/2 (greyish orange pink), 5 YR 7/2 (greyish orange pink) and 10 YR 6/2 (pale yellowish brown) for the dolomitized limestones; and N 9 (white) and N 8 (very light grey) for chert. The basalt rock found in the form of pebbles in the sediment surrounding the rounded hills is of a brownish grey colour: 5 YR 4/1 (brownish grey) and 5 YR 2/1 (brownish black).

We took 32 rock samples from the profile for microscopic examinations. The rock is Late Permian, of the Maokou Formation (Song et al., 1997).

3.2 MICROSCOPIC DESCRIPTION

We turned the 32 rock samples into 77 microscope slides and examined them using transmitted light microscopy. Prior to the microscopic examination, half of each sample was dyed in alizarin red dye (1.2-dihydroxyanthraquinone, known also as Mordant Red 11; Evamy & Sherman, 1962). Combining the observations with the results of the complexometric titration analysis, we were able to determine the properties of the rock.

The limestone beds in the first *section, where the beds of limestone and dolomitized limestone alternate*, are classified as pelsparite, samples 1 and 4, with sporadic lateral gradings into pelbiosparite (grainstone), sample 7. The peloid grains are distributed without any noticeable sorting; they almost always touch one another within the rock. In some places, the peloids make up smaller groups that are surrounded by larger fields of a sparitic binder. The diameter of the mostly well-rounded, spherical or elliptical peloid grains ranges between 1 and 450 µm; those with 135 µm predominate. They have no internal structure. In light of the fairly uniform size of the peloids, they could be of faecal origin. The fossil remains also contain individual fully micritized whole molluscs or their fragments, and some other bioclasts of unidentifiable shapes that are likewise fully micritized. In addition to other intraclasts in the rock, we also exceptionally notice micritic intraclasts with up to 0.1 mm in diameter. Allochem grains make up between 45 and 50% of the rock. No signs of compaction have been detected; porosity is estimated at 0%. Calcite veins built of sparry calcite and from 1 to 90 μm thick are very rarely present in the rock. Between the cavity structures in the rock, we can exceptionally detect fenestrae, up to 0.5 mm in diameter, whose outer edges are filled with, in some places, almost rhombic crystals with subhedral to euhedral crystal shapes. The inner part of the fenestrae is filled with large drusy mosaic crystals (between 135 and 220 μm).

Another characteristic limestone bed is micritic limestone (mudstone), sample 3. The rock is dense, homogeneous and compact. The grains in the rock have diameters between 1 and 40 μm. The samples contain no fossil remains or other allochems. There is no visible porosity. The rock samples are quite densely crisscrossed by calcite veins from 50 to 180 μm thick, exceptionally even up to 2 mm. All of them are filled with mosaic drusy calcite sparite, mostly transversally to the bedding, and spaced between 0.9 and 3 mm apart.

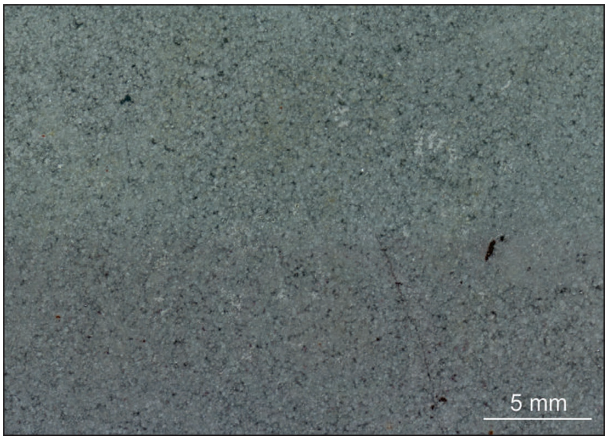

Figure 8: Thin section of entirely dolomitized limestone. Lower half of sample was dyed in alizarin red dye.

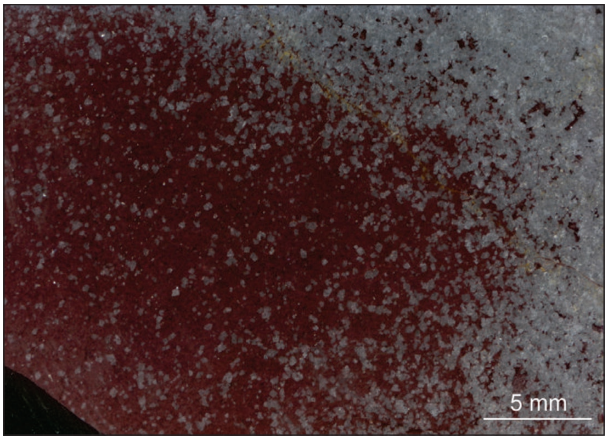

Figure 9: Thin section of dolomitized limestone, visible grading between limestone and dolomitized limestone. Sample was dyed in alizarin red dye.

The dolomitized beds in this section are made up of dolosparite to dolomicrosparite, in some places laterally also dolopelmicrosparite, samples 2 and 9. The rock does not contain any bioclasts or other intraclasts. The rock has an idiotopic texture and dolomite crystals have euhedral to occasionally subhedral shapes with irregular crystal boundaries. The dolomite crystals are well bound. Grains in the samples are mostly of the same size, between 130 and 220 μm in diameter; only individual grains are larger, reaching 0.3 mm in diameter. In some places, the grains are exceptionally smaller than 130 μm and form clusters. In the majority of crystal grains, micritized edges are visible; in some places, their interior has been micritized too. There is no visible porosity along the crystal contacts. The area between the euhedral dolomite crystals is calcitic, changes laterally, and is partly micritized in some places.

The other type of dolomitized limestones in this section is the fully dolomitized beds, i.e., dolosparite, samples 5 and 6 (Figure 8). The rock there has a xenotopic texture and dolomite crystals have anhedral to occasionally subhedral shapes with irregular crystal boundaries. The dolomite crystals are well bound. The grains in the samples are mostly of the same size, between 50 and 250 μm in diameter; the average grain diameter is 120 μm. In the majority of crystal grains, micritized edges are visible and are from 15 to 25 μm thick. Laterally and along the stratigraphic column in these beds we exceptionally detect sporadic individual calcite fills, measuring on average 130 μm in diameter. The rock does not contain any bioclasts or other intraclasts. Moreover, no porosity has been detected.

The third type of dolomitized limestones, i.e., dolobiopelmicrite, contains many bioclasts, other micritized unidentifiable intraclasts and peloids, sample 8. The allochems in the rock take up about 30% of the volume. The bioclasts include many well-preserved molluscs and corals. Most bioclasts are unidentifiable due to intensive micritization. The mollusc shells, around 0.5 mm thick, are well-preserved and up to 5 mm long. As regards porosity, we have noticed partial shelter porosity along the mollusc shells in these samples.

In the stratigraphically younger section, where we see dolomitized limestone only exceptionally, the

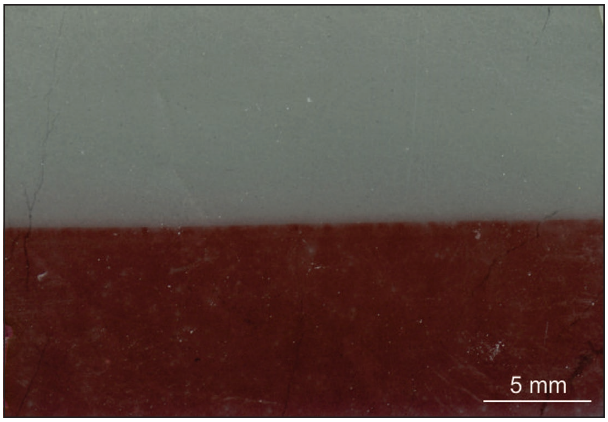

Figure 10: Thin section of limestone. Lower half of sample was dyed in alizarin red dye.

properties of the limestones and dolomitized limestones are basically the same as those described in the previous paragraphs. The samples were taken at a macroscopically visible grading between the limestones and dolomitized limestones; these gradings are clearly visible in the microscope slides too (Figure 9). In the part that is still composed of limestone, individual sparite fields between the peloids have been dolomitized; these dolomitized fields become increasingly common towards the other end of the slide and eventually predominate (sample 10). The beds of limestone, biopelmicrosparite and grainstone have similar properties as those in the previous section, only that the peloids here are more numerous, slightly bigger, around 180 μm on average, and mostly in close contact with one another (sample 11).

The about 20 m thick section of macroscopically fully dolomitized limestone, which is interrupted approximately in the middle with 1.5 m thick beds of dark grey limestone, demonstrates the properties of dolomitized limestone; samples 12, 13, 15 and 16 are all dolosparite to dolomicrosparite, similarly as samples 2 or 10. As planned during sampling, we captured more limestone pelsparite in some microscope slides, and more dolosparite in others.

The limestone beds, 1.5 m thick within this section, i.e., sample 14, are identical to sample 3 and are micritic limestone (mudstone). The rock is dense, homogeneous and compact. The grains in the rock have diameters between 0.5 and 40 μm. The samples contain no fossil remains or other allochems. There is no porosity in the rock. Likewise, there are no calcite veins (Figure 10).

The 30 m thick section of homogeneous, compact light grey limestone begins with several beds that contain chert nodules, sample 17. In the dense, homogeneous and compact micritic limestone (mudstone), the chert is barely noticeable and partly calcified. This is followed by thick beds of pelbiomicrite (wackestone), samples 18 and 19. Practically the only allochems we see on the microscope slides are numerous crinoids – most likely, as the rock is almost fully micritized. In most cases, the crinoids, with diameters between 90 and 180 μm, touch one another. The rock is dense, homogeneous and compact; there is no visible porosity. Calcite veins, up to 1.8 mm thick, appear only exceptionally and are built of drusy mosaic sparite. Another exception is smaller dolomitized fields, mostly with diameters up to 6.5 mm, with a xenotopic texture and dolomite crystals with anhedral to occasionally subhedral shapes, which partly grade into an idiotopic texture and dolomite crystals with euhedral shapes.

The top of the stone forest is built of dense, homogeneous and compact beds of pelbiosparite (grainstone), sample 20. The rock is heavily micritized. It contains many peloids, bioclasts and other intraclasts. The allochems in the rock take up about 90%. The only clearly identifiable bioclasts are gastropods with shell diameters up to 4.5 mm, smaller fragments of molluscs, and fragments of unidentifiable foraminifers and corals. Most of the space is taken up by peloids with no internal structure. The rest of the rock is made up of heavily micritized sparite cement.

Slides 21 and 22 are made up of samples of basalt and chert taken from the soil at the foot of the rounded hill and will not be described in detail.

The stone tooth (see Figure 21) at the foot of the stone forest, to which we paid special attention, is built of alternating beds of limestone and dolomitized limestone with the same properties as described above.

3.3 COMPLEXOMETRIC ANALYSES

Using the dissolution method (Engelhardt et al., 1964), we performed 20 complexometric analyses on 20 rock samples (Table 1). It has been determined that 11 profile samples exceed 98% of total carbonate content, and two even 100%. The highest calcite content in the limestone beds amounts to over 98%, while almost all the beds contain over 95%.

The average value amounts to 85.4%. The dolomite content in the limestones does not exceed 2%, on average. The highest dolomite content in the dolomitized limestone beds amounts to over 96%, while almost all the beds contain over 90%. The average value amounts to 86%. The calcite content in the dolomitized limestones does not exceed 9%, on average. Sample 17 is chert. The average insoluble residue value amounts to 2.7%. If we exclude the two high values in samples 5 and 6, the average insoluble residue value amounts to just 1.6%, which means that the rock beds in the stone forest are made up of very pure carbonates.

Table 1: Complexometric analyses of rock samples.

Rock sample	CaO (%)	MgO (%)	Dolomite (%)	Calcite (%)	Total carbonate (%)	CaO/ MgO	Insoluble residue
PDC 1	55.57	0.16	0.74	98.76	99.51	347.31	0.49
PDC 2	41.12	11.00	50.34	46.05	96.39	3.74	3.61
PDC 3	55.18	0.40	1.84	97.47	99.31	137.53	0.69
PDC 4	56.13	0.64	2.95	97.05	100.00	87.7	0.00
PDC 5	30.22	15.12	69.15	16.40	85.55	2.00	14.45
PDC 6	31.63	16.13	73.76	16.42	90.18	1.96	9.82
PDC 7	54.90	0.44	2.95	96.36	99.31	85.78	0.69
PDC 8	40.26	12.57	57.53	43.47	100.00	3.20	0.00
PDC 9	0.88	53.44	93.75	4.06	97.21	0.02	2.79
PDC 10	46.15	7.46	34.12	63.84	97.96	6.19	2.04
PDC 11	54.73	0.40	1.84	96.67	98.51	136.82	1.49
PDC 12	1.57	52.88	90.47	7.19	97.66	0.03	2.34
PDC 13	0.40	54.79	96.77	1.84	98.61	0.01	1.39
PDC 14	54.22	0.32	1.47	95.97	97.44	169.37	2.56
PDC 15	0.36	54.51	96.38	1.66	98.04	0.01	2.62
PDC 16	3.31	50.47	81.80	15.12	96.92	0.07	3.08
PDC 17	26.61	0.32	0.74	47.08	47.82	166.31	52.18
PDC 18	54.84	0.40	1.84	96.86	98.70	137.10	1.30
PDC 19	55.07	0.12	0.55	97.98	98.53	458.91	1.47
PDC 20	54.28	0.96	4.43	94.45	98.88	56.54	1.12

3.4 IMPACT ON KARSTIFICATION

Despite the often macroscopically similar rock where we also took samples, it has turned out that the rock changes constantly along the examined geologic profile: dense, homogeneous and compact fine-grained limestones alternate with mostly coarse-grained, yet compact, dolomitized limestones. These bed properties are also reflected in the exterior of the rock as a diverse relief.

It has been determined that the karstification of limestone or dolomitized areas in the dolomitized limestones takes place differently on the surface and exposed to atmospheric influence than the karstification of the rocks still covered by acid soil. The limestone areas karstify faster in the dolomitized limestones on the surface and exposed to atmospheric influence; thus, the relief shows dolomitized areas protruding from the surface of the rock. The subsoil dolomitized areas weather faster in the dolomitized rocks that are still covered by soil; thus, the relief shows limestone areas protruding from the surface of the rock.

4. ROCK RELIEF

The rock relief reveals the characteristic development of denuded subsoil karren into a stone forest (Figure 4), that is, the reshaping of exposed subsoil rock forms by rainwater and water creeping along the walls of stone pillars and teeth.

The **subsoil rock forms** that uniquely dissect the diverse rock strata, provide an important stamp. We divide them into those that are completely underground or subsoil and those that have already been more or less reshaped by rainwater and creeping water. Along-sediment notches (Figures 4a, 11) that have formed and continue to form at long- term levels of sediment and soil that surrounds or previously surrounded (Figure 4b) stone pillars and teeth (Slabe & Liu, 2009) can be found throughout the entire height of the pillars (Figure 12). The higher on the pillars the notches are found, of

Figure 11: Along-sediment notch.

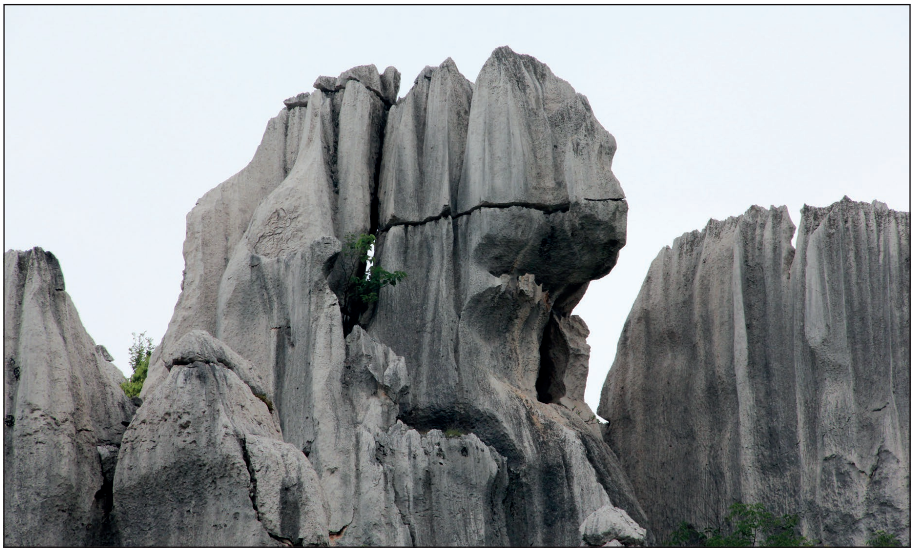

Figure 12: Stone pillar on which subsoil rock features are being reshaped by rainwater and trickling water.

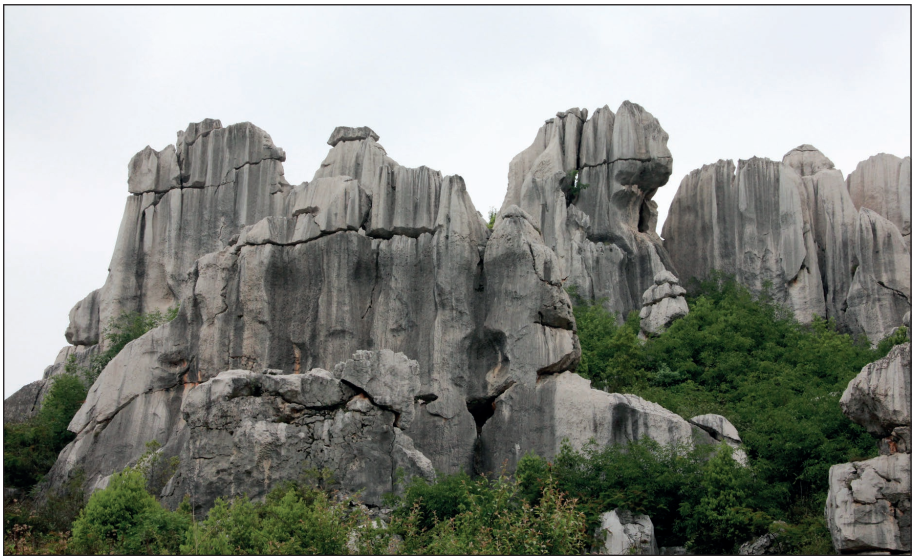

Figure 13: Half-bells.

Figure 14: Subsoil scallops.

course, the more markedly reshaped they are (Figure 4b). Subsoil notches have also formed at the mouth of bedding planes and cracks where water flowed into contact with the sediment.

Subsoil half-bells (Slabe & Liu, 2009) that develop due to the spreading of a larger amount of water trickling down a wall when it reaches the soil widen the wall channels in places. Those that have already been largely reshaped by trickling water are clearly visible (Figures 4c, 13). They indicate long-term levels of sediment and soil that surrounded the stone pillars. They are therefore found in adjacent channels at the same level (Figure 13). Subsoil scallops have formed on rock where water flowed fairly evenly over the entire contact surface (Figure 14; Slabe & Liu, 2009).

The tops of the larger stone teeth are dissected by (subsoil) funnel-like notches (Figures 4e, 12) below which channels are found. They have formed independently as the mouths of vertical subsoil channels or at the end of the subsoil channels (Figures 4f, 15) that dissect the larger tops.

Subsoil holes are very distinctive. They have formed as bedding plane anastomoses (Figure 12) and along cracks (Figures 16, 17), especially where shafts have also formed along vertical cracks. Subsoil bedding plane anastomoses are mostly intertwining channels a few centimeters in diameter that have only rarely developed into larger holes. They are mainly found along bedding planes between rock strata of different compositions (Figures 4g, 12). The holes reach 0.5 metre in diameter. They generally have round cross-sections but along bedding planes and cracks, they are elliptical (Figure 17). Above-sediment channels in individual holes testify that they have formed in a local phreatic zone and were therefore paragenetically elevated. In

Figure 15: Subsoil channels in funnel-like notches.

Figure 16: Subsoil holes.

some places their network is very dense and the holes have merged (Figure 16). Larger holes often form at the tops of subsoil half- bells, where the dissolution of the rock is faster or the inflow of water through them has caused the formation of a half-bell (Figure 18).

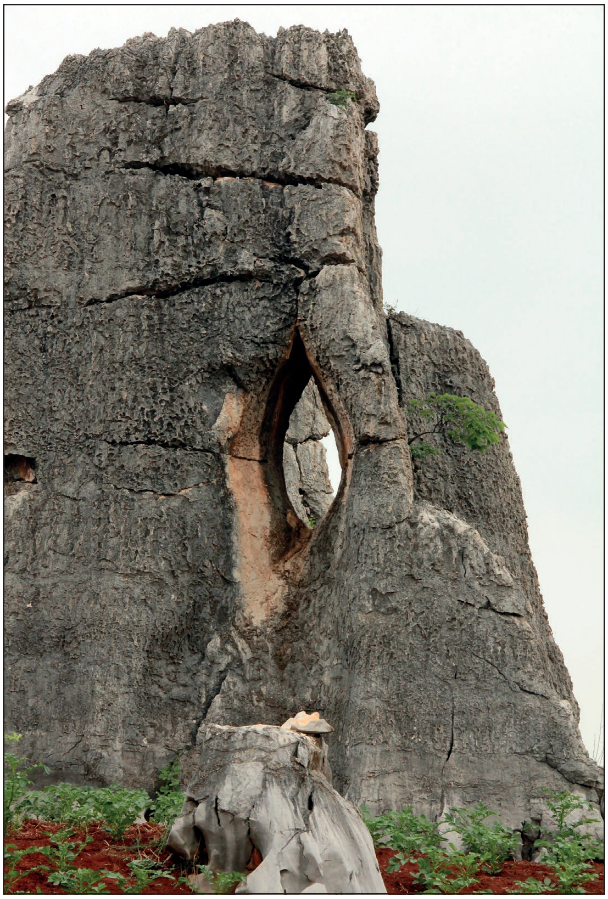

Figure 17: Reshaped subsoil holes.

Another special feature of stone forests is strongly illustrated here. These are subsoil shafts with diameters of up to 75 centimeters (Figure 19).

Downwards they often end in a flat hole along a bedding plane, especially along thin rock strata. They therefore form along more distinct vertical cracks. At their bottom there is a subsoil cup with wall notches. A channel leads from them (Figures 4h, 20). The walls of the shaft, which is often multi-legged, are rounded and, if not reshaped by trickling water, smooth. Some are found under larger and flatter subsoil holes, which indicates a changed pattern in the flow of water. Shafts are the result of the predominant vertical percolation of water downward through the rock and channels in contact with sediment. In local phreatic zones, there are flat holes that are reshaped when denuded.

The impact of the composition of the rock and its stratification and fissuring on the formation of the stone forest is clearly evidenced in the shape of a selected stone tooth (Figures 4, 21). This three-meter tall stone tooth has formed in the strata of diverse rock. At the top, which is relatively broad and has developed on partly dolomite rock, large subsoil rock forms, funnel-like notches and subsoil channels dominate. As a rule, stone teeth on partly dolomite rock are broader and the tops are relatively rounded (Figure 4i) and only individual teeth are pointed. Also the tops on thinner strata of denuded decomposing rock are wider when denuded (Knez & Slabe, 2001b). At the top of this stone tooth is also a thinner rock strata (Figure 4j). The surface is rough because the more slowly soluble parts protrude from it. The middle part of limestone strata shows distinctly three-dimensional subsoil perforation. The diameter of the largest holes reaches many tens of centimeters. The surface of the rock that has not been denud-

Figure 18: Half-bell.

ed for long is subsoil smooth, while there are rain flutes on the rock that has been exposed to rain for a long time. The densest system of subsoil holes has formed at the contact with the rock above, and individual large holes are also found on the contact with the rock below. On the latter, partly dolomite rock similar to that above a distinctive notch has formed, half a meter deep (Figure 4k). Such rock is thus the most rapidly soluble in subsoil conditions, particularly dolomite parts that are concave (Figure 21 bottom). However, when such rock is exposed to rain, as seen at the top of the stone tooth, the dolomite parts of the rock are convex (Figure 21 top). This is true of all stone forests and is a common feature of their formation.

On neighbouring low stone teeth, however, the tops are formed of limestone rock. The stone teeth therefore have wider and brighter tops that are sharper on the thicker rock strata (Figure 4l). The partially dolomite rock below them dissolves more rapidly under the soil (Figure 22). Chert also protrudes from the subsoil formation of the rock surface. In places where the wider tops of stone pillars are covered with soil and sediment, subsoil channels (Figure 4m, 15) and subsoil cups (Figure 4n) are found. Channels, mostly reaching to half a meter in diameter, often form from subsoil holes, especially bedding plane anastomoses, when they become uncovered by the denudation of the upper rock strata. In some places, a branched network of subsoil channels has developed across the entire flat tops. On finely fissured rock the network has an angular shape. The cups are found standing individually or in channels. Some are multi-storey. Subsoil channels and cups divide the tops into meandering and sharp longitudinal rock tops and rock points, which are in all cases their final form.

Figure 19: Subsoil shaft.

Figure 20: Hole at the bottom of a shaft.

Figure 21: Stone teeth on limestone and limestone and dolomite rock. Samples from 21 to 32 (because of big similarities of already described samples) are not separately and additionally described in this chapter.

Figure 22: Stone teeth, down in dolomite rock.

Figure 23: Bedding-plane anastomoses and wall channels beneath.

Fully or partially denuded subsoil-shaped pillars and the subsoil rock forms on them are reshaped by **rainwater and trickling water**. These forms include the larger funnel-like notches (Figure 4e) on the edge of the tops, the large subsoil channels below them (Figures 4f, 12, 13), and the notches (Figure 4b) that reflect previous levels of sediment that surrounded the rock. Channels also form at the tops at the end of subsoil channels. The water that penetrates through the rock also reshapes empty holes and shafts that initially formed as subsoil forms. Channels lead from them (Figure 20). The first periods of such reshaping can be traced on the recently denuded stone teeth in the fields. A large number of smaller channels up to 5 centimeters in diameter are usually found below bedding plane anastomoses (Figures 4o, 23). In the initial part on the edge, they are deeper and, as a rule, subsoil in origin. On the thinner rock strata, deep channels are found on their upper parts, shallow and wide ones in the middle vertical sections, and farther down on the overhang formed above the next bedding plane, they merge into scallops. This pat-

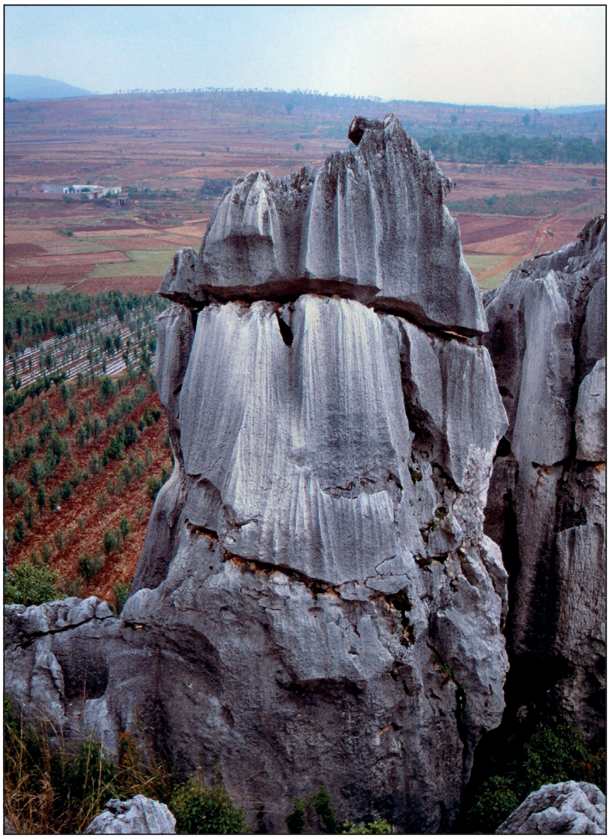

Figure 24: Rain flutes and channels.

Figure 25: Solution pans in denuded subsoil channels.

tern can repeat across several rock strata (Figure 20). Large channels run across their network, starting at the tops or smaller channels have broken through the rims of larger subsoil channels.

Scallops are found on overhanging surfaces that are evenly washed by water trickling down the walls (Figures 4p, 12).

Rock forms that are created directly by the action of rainwater are also distinctive. Rain flutes are found on the walls of subsoil channels and holes initially formed under partially covered rock (Figures 4q, 6, 12, 13, 24). These also dissect the walls of the funnel-like notches at the edge of the tops, the exposed parts of subsoil channels, and the walls of the wider parts of stone pillars (Figures 6, 12, 13).

On walls that are not distinctly dissected under the soil or on the walls of larger subsoil channels and funnel-like notches, the flutes unite into channels (Figure 4r) that reach up to 10 centimeters in diameter. In particular, they distinctly dissect thin tops.

The composition of the rock decisively influences the development of small rock forms. The most distinct forms are found on limestone rock. The pointed tops of stone teeth on this rock are smooth, which indicates their recent denudation. As a rule, pointed tops are not found or are less distinct on partly dolomite rock (Figure 4i). The rock is composed of larger nodules of dolomite.

The water that flows from flutes on the wider and more dissected tops carves channels that lead to their edges. Branched networks have formed in some places.

The lower parts of subsoil holes are shaped into solution pans (Figures 4n, 25). These also form in subsoil channels and in some places at the bottom of funnel-like notches. Solution pans are therefore of various shapes and dissected depending on the original subsoil forms.

The rock surface beneath vegetation is characteristically dissected. It is quite dense in the cracks between the pillars, in subsoil channels and cups, at the bottom of funnel-like notches, and in subsoil holes filled with soil. The rock is dissected into a network of tiny notches. Beneath the leaves of trees and shrubs, cups have formed on flat surfaces from which water trickles along the sloping parts. There are no rain flutes here.

5. CONCLUCION

The stone forest's geologic profile contains beds of dense, homogeneous and compact fine-grained limestones of the pelsparite type with lateral gradings into pelbiosparite (grainstone) with a high calcium carbonate content. Fine-grained limestones alternate with beds of mostly coarse-grained and just as compact dolomitized limestones of the dolosparite type (in some places laterally also of the dolopelmicrosparite type), and with a high calcium carbonate content. The average calcium carbonate content in both types of rocks combined is 97.3%. Due to the diverse types of rock, we can clearly see diversely karstified and weathered rock sections on the surface of the rock and in the profile of the stone forest, which has resulted in the development and emergence of tiny rock features. As can be inferred, the slightly more porous dolomitized rock, made up of larger particles, disintegrates faster in a more permanently waterlogged acid subsoil environment, where the moisture penetrates it deeper. However, as it takes longer to dissolve, it protrudes from the surface of the dolomitic limestone rock when exposed to moisture from occasional rain.

Originally of subsoil formation and later denuded, the rounded hills that dissect the karst surface have transformed into a clustered stone forest whose central part usually consists of a larger dissected rock mass with individual stone pillars and teeth at the edge.

The composition and fracturing of the diverse rock strata decisively influence the shape of the pillars and their rock relief. Larger subsoil rock forms (channels, notches, half- bells) have developed on all rock strata. However, limestone is more distinctly perforated in three dimensions. Subsoil holes and subsoil shafts have formed in it. The diversity of the rock is also reflected by the notches that have formed under the soil along the more rapidly soluble partly dolomite rock strata.

Denuded subsoil-shaped pillars are reshaped by rainwater and trickling water. Smaller rock forms carved by rainwater have formed mostly only on evenly composed, fine-grained limestone rock. The tops on such rock are more distinctly conical and blade- like and wider on more slowly soluble rock.

Another unique example of the development of subsoil karren into a stone forest on the varied geological bedrock of the Lunan surface is thus revealed to us.

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