

Article

Origin of Fracture-Controlled Conduits in Calcite-Rich Highly Productive Aquifers Impregnated with Diagenetic Silica

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Abstract: The origin of highly permeable flow paths in carbonate-siliciclastic rocks, such as large-aperture fractures in aquifers in the Eastern Bohemian Cretaceous Basin (EBCB), is poorly understood. The karst potential was assessed from the rock carbonate content and the degree of disintegration after leaching in HCl. Surprisingly, dissolution of calcite in EBCB usually did not lead to rock disintegration until calcite > 78%. Instead, porosity increased significantly. High-porosity rock is held together by microns-thick secondary silica cement with a foam-like structure and considerable tensile strength. Three types of conduits occur in the EBCB: (i) bedding-parallel conduits associated with calcite-rich layers, (ii) subvertical fracture swarm conduits that develop on damaged zones of fracture swarms, and (iii) conduits formed by dissolution of calcite veins by groundwater flow. These are ghost-rock karst features where calcite is leached from the rock in the first phase and the residue is washed out by conduits under steep hydraulic gradients in the second phase. Very similar features have been described in Minnesota and Wisconsin, USA. Research has shown that fractures with sharp-edged walls that give the impression of an extensional tectonics origin may actually be ghost-rock karst features in which dissolution and piping have played an important role in their enlargement.

Keywords: karst; groundwater; sandstone; conduit; fissures; piping



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1. Introduction

Karst porosity, as opposed to intergranular and fractured porosity, has specific properties. It is self-organized by the interaction of groundwater flow and dissolution, widening initially narrow fractures and bedding planes into conduits that facilitate flow [1]. Karst porosity is characterized by rapid groundwater flow and contaminant transport over long distances, high susceptibility to groundwater contamination, and a low ratio of karst conduit volume to rock volume, resulting in a low probability that conduits will be encountered by boreholes, e.g., for contamination monitoring [2]. The identification and characterization of different types of karst porosity is, therefore, important for the sustainable use and protection of groundwater resources.

Hydrogeological characteristics and karst evolution have been described in numerous publications in both fractured and/or folded telogenetic and young eogenetic high-percentage carbonates [3]. Less information is available on karst in evaporites [4], quartzites [5], and especially for lithologies at the transition between carbonates and siliciclastics [6–10]. Ghost-rock karst is a specific type of karstification. In the first phase, carbonate is leached from the rock, but the rock structure and appearance are generally preserved. However, the cohesiveness of the rock is compromised. In a second phase, which can occur with a considerable delay after the first phase, the steepened hydraulic gradient causes erosion of the leached rock (residue) and karst conduits are formed [11].

In the eastern part of the Bohemian Cretaceous Basin (BCB) in the Czech Republic, there are highly productive Turonian aquifers with relatively high carbonate content in places. Springs with yields up to 1000 L/s occur in these rocks [12], and the yield of the most productive wells exceeds 200 L/s [13]. This, together with the low density of the surface stream network, indicates an unusually high permeability of the rocks. Wells in the area are fed by large-aperture fractures, often with sharp, fracture-guided flanks. Several hypotheses have been advanced to explain the origin of large-aperture fractures. Hynie [12] proposed the origin of such fractures by extensional tectonics, and some hydrogeologists called them pseudo-karst cavities because they observed that clastic material was flushed out of them [13]. The inflows from these fractures reached up to 90 L/s from a single fracture in one well [14]. Similar large-aperture fractures have been reported from fine-grained siliciclastic-carbonate sediments in Minnesota and Wisconsin, USA [7]. Fractures parallel to the bedding have significantly larger apertures (up to 30 cm) than subvertical fractures. The origin of large-aperture fractures is poorly understood. Some authors consider them to be of karstic origin [8], others of mechanical origin [9]. New insights into the origin of conduits in calcareous sandstones and sandy limestones in the western part of the BCB were provided by Kůrková et al. [10], but these rocks are lithologically different from those in the eastern part of the BCB.

Recently, it has been observed on outcrops in the eastern part of the BCB that large-aperture fractures contain heavily fractured rock residue that is apparently *in situ*, i.e., these fractures were originally filled by fractured rock and thus are not tectonically enlarged. Since these fractures are responsible for a dominant part of the groundwater flow in the aquifers, the study of their characteristics and origin was initiated. Since the origin of highly permeable flow paths in carbonate-siliciclastic rocks, such as large-aperture fractures, is poorly understood, this study focuses on these phenomena.

The aim of this paper is to characterize the karstification potential of the Turonian aquifers in the eastern part of the BCB, to characterize the large-aperture fractures and to explain their origin.

The following steps were taken to achieve the objective: (i) Surface outcrops and borehole cores were sampled and processed to determine the carbonate content and degree of disintegration after acid leaching to test for karstification potential, porosity before and after leaching, and tensile strength. (ii) Lithology and cementing agents in the aquifer were studied using scanning electron microscopy and elemental maps from electron microanalysis. (iii) Fractures with openings were documented on surface outcrops to study their origin. (iv) Fractures with openings were studied on acoustic well logs and downhole camera logs to determine their sizes, dips, and inflow rates to the wells. (v) Finally, a model of fracture-guided conduit formation was constructed.

2. Study Area

The study area is located 120–150 km ESE of Prague (Czech Republic) at an altitude between 250 and 580 m a.s.l. Average annual precipitation and air temperature are 700–800 mm and 7–8 °C, respectively. The average annual groundwater recharge is 2.5–5 L/s/km² (https://mapy.geology.cz/hydro_rajony/ accessed on 15 January 2024). The BCB was formed by transtensional reactivation of NW-trending basement faults [15]. Deposition occurred between Cenomanian and Santonian in a shallow marine strait connecting the Boreal Ocean with the Tethys [16]. The main source of siliciclastics was from the north [15], while a secondary source was located north of the city of Brno in the SE corner of the BCB [17]. Quartz is the most abundant mineral in the BCB, while the second most abundant mineral is calcite [18].

Due to graben and horst structural settings, the BCB consists of a series of individual groundwater basins separated by faults. The study focuses on the Vysoké Mýto and Ústí basins located in the SE corner of the BCB. These basins are structurally grabens, but morphologically resemble synclines. In addition to faults with displacements up to 400 m,

two NW–SE and SSW–SSE systematic fracture sets, which belong to the youngest tectonic phase in the BCB, are present [19].

In addition to the basal Cenomanian aquifer, which is composed of coarse-grained quartz sandstone and is not significant due to poor water quality caused by its very small recharge area, there are 3 Turonian aquifers in the eastern part of the BCB, which are the subject of this study. The Turonian sediments are composed of three sequences, each with an inverse gradation (upward coarsening), representing three regressive trends terminated by transgressions. At the base of each sequence there is a 3–20 m-thick layer of soft calcareous claystone. Above this, the sediments gradually coarsen upward into calcareous sandstone to sandy limestone. There is a frequent admixture of marine spicules [19]. The lower part of each sequence forms an aquitard (claystone), and the upper part of the sequences forms an aquifer. The thickness of the aquifers varies from 10 to 90 m. The aquifers, consisting of the more rigid rocks, form *cuestas* at the surface, and their faces are undermined by erosion of the soft aquitard rocks [20].

Aquifers have negligible intergranular permeability. High permeability occurs due to large-aperture fractures. Therefore, the wells in Turonian aquifers show very different inflows and transmissivities depending on whether the permeable fractures are encountered or not. The average transmissivity of Turonian aquifers varies between 5×10^{-4} and 6×10^{-3} m²/s, based on pumping tests of 282 wells [20]. The maximum transmissivity is up to 5×10^{-2} m²/s in the discharge areas of the aquifers.

While the basal and middle Turonian aquifers are confined or even artesian, with a piezometric surface up to 80 m above ground level, the upper Turonian aquifer is unconfined. The two lower aquifers are recharged only from the edges of the basins where the aquifers emerge to the surface, from losing streams flowing from the surrounding areas and from overflow through the aquitards in the tectonically damaged zones. The upper Turonian aquifer is recharged from extensive outcrops and has a minimum of permanent streams, as most of the water flows underground. The dominant part of the groundwater from the study area of 1400 km² is drained to several localized drainage areas with discharge of 300–1100 L/s [20].

Tracer tests with fluorescein dye and ⁸²Br were performed in the discharge area of the Turonian aquifer in Březová nad Svitavou, where 1100 L/s of groundwater is extracted for the city of Brno's water supply. Three tracer tests showed average flow velocities of 400–650 m/day over distances of up to 2.3 km [21]. In Turonian aquifers, the spread of chlorinated ethene contamination was observed over distances of 2.5 and 9 km [22]. This demonstrated rapid flow and transport of contaminants to distant areas in Turonian aquifers.

3. Methods

3.1. Calcimetry, Dissolution Tests, Porosity, and Tensile Strength

To characterize the karst potential of the Turonian aquifers, small horizontal cylindrical rock plugs were collected from subvertical rock outcrops and cored boreholes using an accumulator drill with a 35 mm-diameter diamond core bit. Plugs were collected from outcrops where conduits occur, from boreholes where fractures with inflows occur, and from other parts of the aquifers to characterize different parts of the aquifers (Figure 1). Each plug was divided into three cylindrical subsamples of 1–2 cm in length. Calcite content was measured by calcimetry on the first subsample, dissolution tests with HCl were performed on the second, and the third was left for scanning electron microscopy (SEM). Because the plugs were drilled parallel to the strata, the same rock layer occurred in each of the three subsamples.

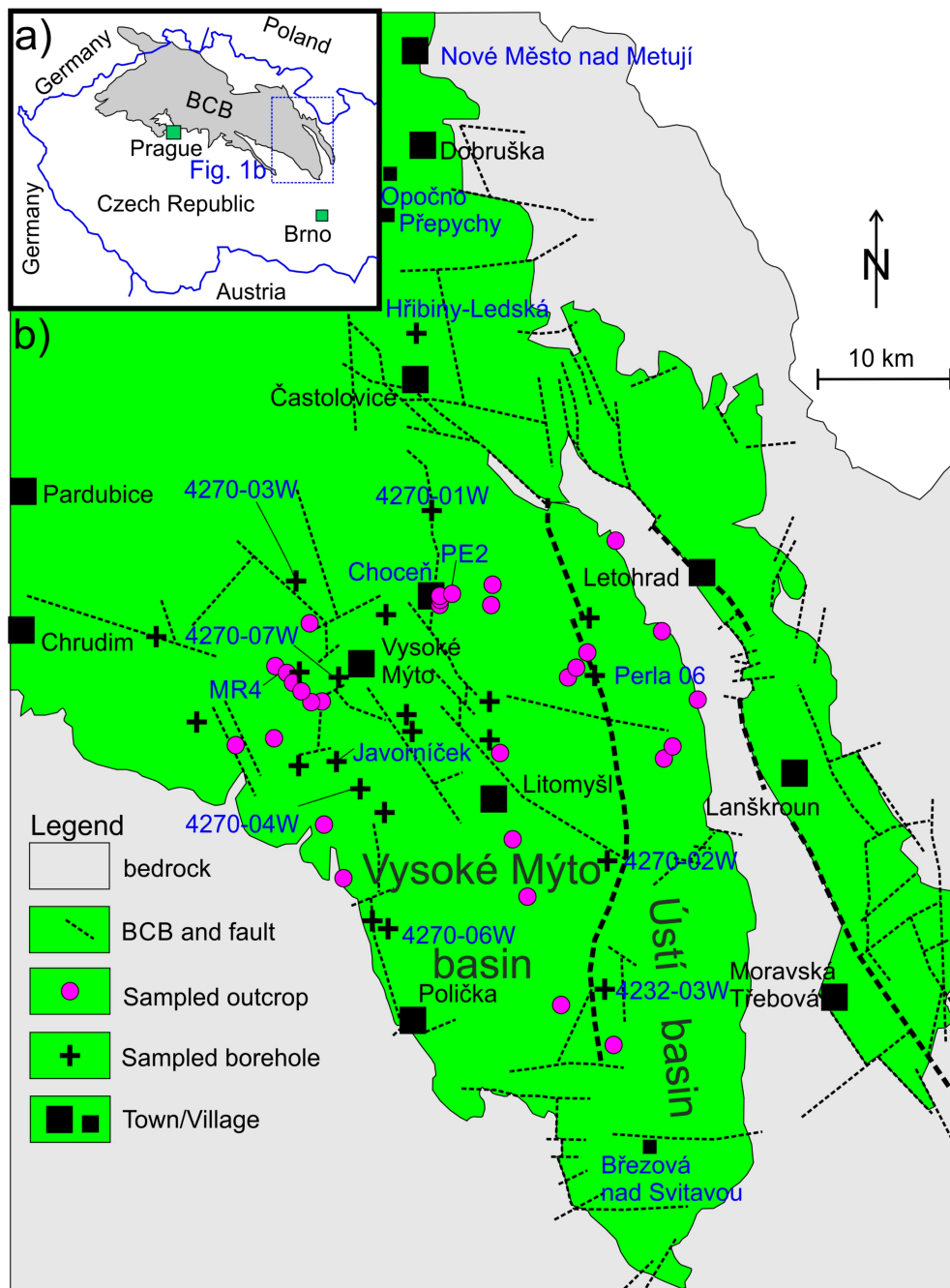


Figure 1. (a) Location of the study area within the BCB and the Czech Republic. (b) Locations of sampled outcrops and boreholes. Geology from Geological Map 1:500,000 obtained from <https://mapy.geology.cz/geocr500/> accessed on 10 January 2024. Blue text represents locations mentioned in the text and figure captions.

For calcimetry (141 samples), the material was ground to a $<63 \mu\text{m}$ fraction, and homogenized. Coulometry was used to measure the CO_2 content. Flame atomic absorption spectrometry was used to measure CaO , MgO , MnO , Fe_2O_3 , and FeO . The calcium carbonate content was determined from CaO and a proportional part of CO_2 [10].

To test if subsamples disintegrated after carbonate dissolution (test if material is karst-prone), dissolution tests with 10% HCl were performed on 228 samples according to [10]. HCl is often used to selectively dissolve carbonate, as it does not dissolve quartz or most aluminosilicates [23]. Subsamples were leached separately in HCl until no reaction of the rock with fresh HCl was observed. The weight of the dried cores was determined before

dissolution (m_{original}). After dissolution, two solid fractions were distinguished: (i) the whole cores or large fragments (m_{large}) and (ii) small fragments and sand grains (≤ 2 mm; $m_{\text{disintegrated}}$). The fractions were washed, dried, and weighed separately.

The disintegration ratio, D , is [10]:

$$D = m_{\text{disintegrated}} / m_{\text{insoluble}} \times 100 (\%) \quad (1)$$

where $m_{\text{disintegrated}}$ is the weight of dry small fragments and sand grains (≤ 2 mm) disintegrated by acid leaching, and $m_{\text{insoluble}}$ is the dry weight of the insoluble solid remaining after acid leaching ($m_{\text{large}} + m_{\text{disintegrated}}$). The disintegration ratio, D , therefore, does not take into account the soluble fraction. The D indicates whether the rock remains intact after acid leaching or disintegrates into fine particles that can be transported by flowing water.

An approximate calcite content has been defined as [10]:

$$\text{Calcite}_{\text{approx}} = (1 - m_{\text{insoluble}}) / m_{\text{original}} \times 100 (\%) \quad (2)$$

where m_{original} is the weight of the dry sample before the leaching test.

The porosity of the rock before and after acid leaching was determined according to the Archimedean principle (measurement of volume, saturated mass, and dry mass). The dry weight of the sample, the weight of the sample immersed in water, and the weight of the sample immersed in water but hanging on a string (buoyancy effect) were measured (Czechoslovak State Standard CSN721010).

Tensile strength (TS) was measured according to [24,25]. Subsamples leached in 10% HCl were glued to large metal plates with their lower circular sides. Then, small metal plates (surface: 2×2 cm) were glued to the upper circular side of each subsample with epoxy resin. After curing, tension was applied by pulling a force gauge attached to the metal plate perpendicular to the subsample surface until the material under the epoxy failed. The pull-off force and area of failure were measured and converted to kPa. Because the tensile strength of rock can be strongly affected by moisture [24,26], measurements were conducted under two different conditions: dried in the laboratory ($\sim 50\%$ relative humidity, 25°C) and wetted for 24 h (field capacity moisture content).

3.2. Scanning Electron Microscopy and Elemental Analysis

The distribution of silica and carbonate was studied in selected subsamples by electron microanalysis. Polished cross-sections of the plugs were coated with gold. The QUANTA 450 (FEI) SEM (Thermo Fisher Scientific Inc. Waltham, MA, USA). was used in high-vacuum mode, with energy-dispersive X-ray spectroscopy using a photomultiplier (Centaurus) backscattered electron (BSE) detector, operating at 15 and 30 kV. An Apollo X EDS detector with EDX Genesis software was used.

SEM imaging of internal parts of subsamples leached in 10% HCl can visualize the internal structure of insoluble material. Therefore, selected samples were examined on a JEOL—6380LV SEM (JEOL, Tokyo, Japan) at the Institute of Geology and Paleontology, Faculty of Science, Charles University at 10 kV. The subsamples were gold-coated and examined in high-vacuum mode.

3.3. Field Documentation and Well Data

Aquifer outcrops were searched for large-aperture fractures and photographed. Available downhole camera records of large-aperture fractures and conduits causing inflows to the wells were obtained from hydrogeologists in the area. Fracture dip and aperture data from an acoustic televiewer were obtained from 7 wells (4270-01W, -02W, -03W, -04W, -06W, -07W, and 4232-3W) [20]. These data were combined with the quantification of inflows to specific well depths derived from the borehole dilution technique [27].

4. Results

4.1. Carbonate Content, Dissolution Tests, and Porosity

Samples were collected from 20 boreholes and 28 surface outcrops to characterize the Turonian aquifers in the eastern part of the BCB. CaO, CO₂, FeO, Fe₂O₃, MgO, and MnO contents were analyzed in 141 samples. CaCO₃ content ranged from 0 to 87 wt.% (mean content 38 wt.%), and MgCO₃ content was low (mean 1 wt.%). Since calcite is the dominant form of carbonate, CaCO₃ will be referred to as calcite in the following text. There was a relatively close relationship between the approximate calcite content (calcite_{approx}) from Equation (2) and the calcite content from calcimetry (Figure 2a; Pearson = +0.96). Calcite content (calcite_{approx}) can thus be derived from samples leached in 10% HCl to avoid the use of expensive calcimetry, which cannot be applied to all samples. Differences between calcimetry and calcite_{approx} content are probably due to inhomogeneities. In the following text, the calcite content determined by calcimetry is preferred and, if not available, the calcite_{approx} content is used.

A total of 228 samples were leached in 10% HCl to determine the degree of disintegration after dissolution, to test whether the Turonian aquifers allow the formation of karst conduits. Disintegration of at least 50% occurred in only 6% of the samples (Figure 2b). Thus, only 6% of the samples were susceptible to karstification (cf. [10]). This number is surprisingly low considering that 19% of all samples had CaCO₃ contents above 50% and, thus, more than half of their mass was calcite. Samples with calcite contents above 80% mostly disintegrated completely. However, most of the samples with calcite contents of 50–80% only partially disintegrated into small fragments or retained their original shape, even though they were predominantly composed of calcite before leaching.

The porosity of the samples prior to leaching ranged from 2% to 40% (average 12%). This indicates that a portion of the samples contained rock from which the carbonate was already partially naturally dissolved, resulting in increased porosity. After leaching in 10% HCl, the porosity of the rock increased significantly to 15–84% (mean 43%). This again shows that calcite leaching tended to increase the porosity to unusually high values rather than causing the samples to disintegrate. Figure 2c shows that the porosity of the samples prior to leaching decreased from about 20% at low calcite contents to only 5% at high calcite contents. Thus, the porosity before leaching had an inverse relationship with the amount of calcite. On the contrary, after calcite leaching, the porosity increased linearly with the original calcite content from about 20% to 80%.

4.2. Disintegration Ratio, Micro-Quartz Cement, and Tensile Strength

There was a surprisingly weak relationship between the disintegration ratio and calcite content (Figure 2b). In general, the samples did not disintegrate when the calcite content was less than 25 wt.%. Partial disintegration could be observed in a small percentage of samples when the calcite content was between 25 and 78 wt.%, but the majority of samples did not disintegrate. On the contrary, most of the samples completely disintegrated when the calcite content was above 78 wt.%. However, two samples with 85–86 wt.% of calcite only partially disintegrated.

It is surprising that rock composed of 78 wt.% of calcite could survive its complete dissolution intact. Thus, only 22% of the original rock mass was sufficient to stabilize the rock structure. To explain this surprising finding, the distribution of calcite and silica on polished cross-sections was studied by elemental mapping (Figure 3). Partially disintegrated samples with moderate calcite content were studied, as well as sample MR4, which showed very little disintegration despite its very high carbonate content.

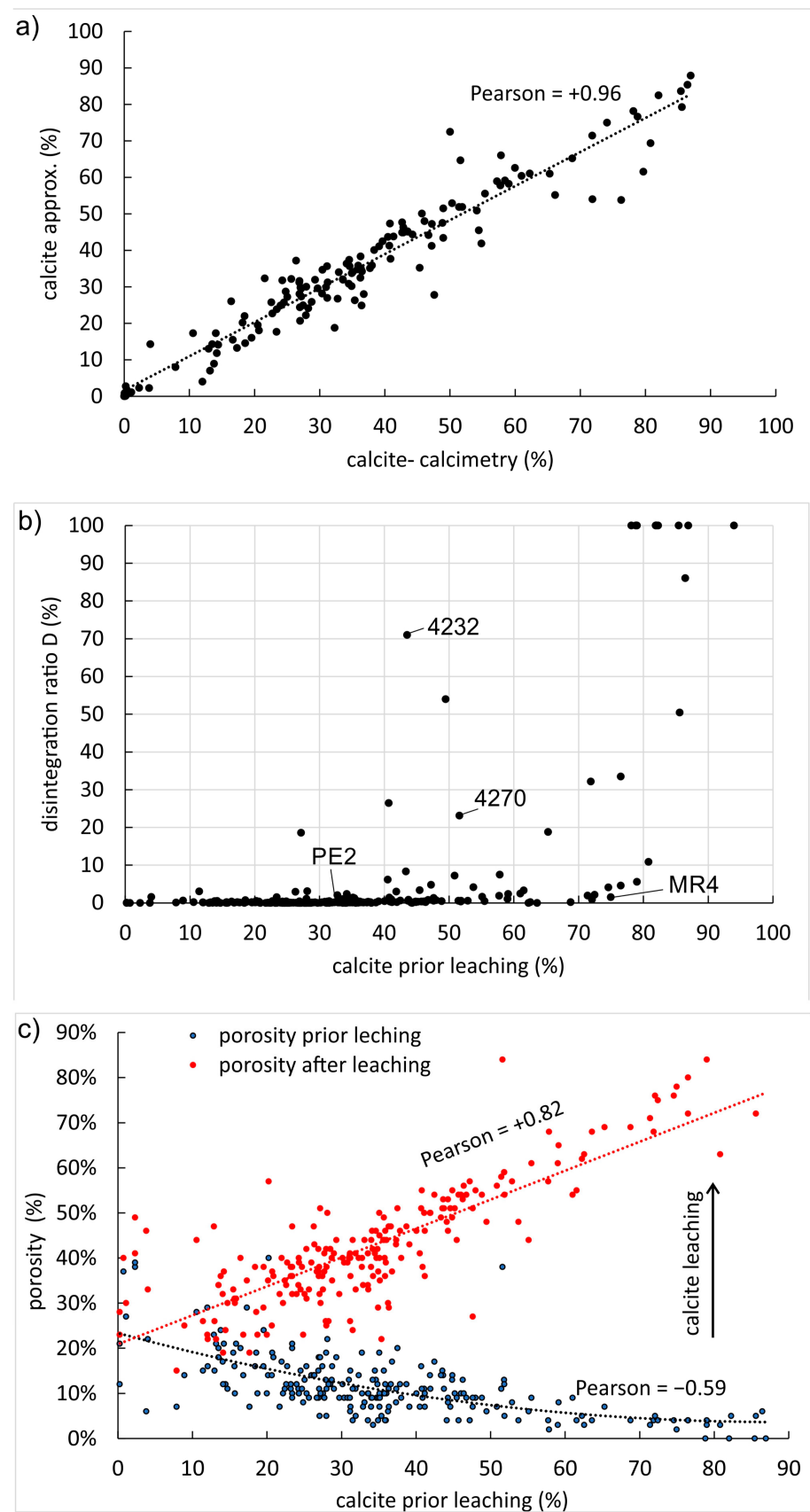


Figure 2. (a) Relatively close correlation between approximate calcite content and precise calcite content from calcimetry. (b) Poor relationship between disintegration ratio and calcite content. (c) Porosity of samples before and after leaching. Samples examined by SEM are highlighted in (b).

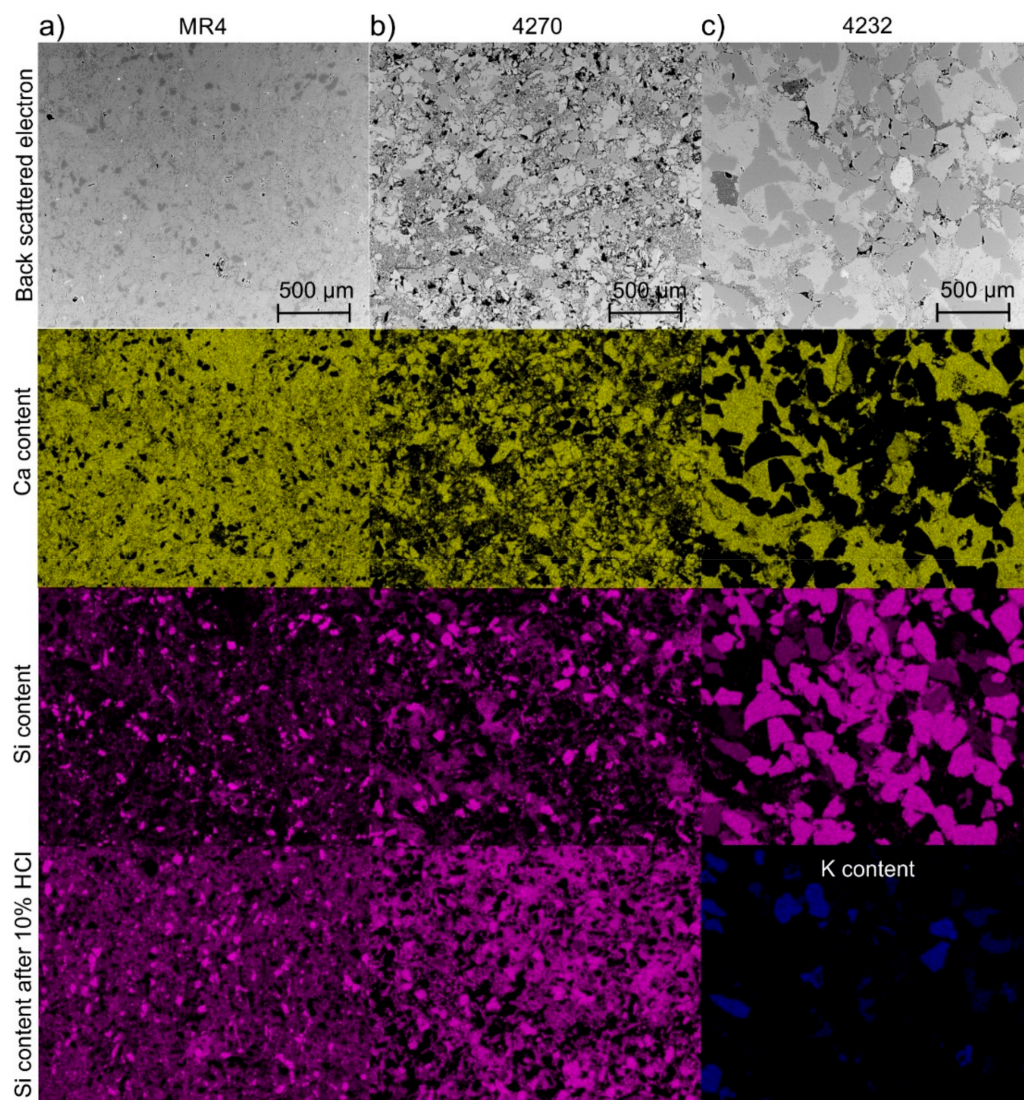


Figure 3. Polished cross-sections of selected rock samples before and after (last row) leaching. (a) Sample MR4, (b) sample 4270-07W, taken from a 213.1 m depth, and (c) sample 4232_03W, taken from a 75.9 m depth. The backscattered electron shows the structure of the rock. Ca content shows calcite content before leaching, and Si content shows quartz and silicate contents before and after leaching. Blue shows the potassium feldspar content for the last sample.

Sample MR4 had a calcite content of 75% and a porosity after leaching of 78%, but the disintegration ratio, D , was only 2%. Figure 3a shows that sample MR4 consists of limestone with a small admixture of quartz silt. Before and especially after leaching, the foam-like micro-quartz structure was visible, which kept the rock stable after leaching. Sample 4270 had a relatively high porosity (38%) prior to leaching, so the calcite was already partially dissolved by groundwater flow. Calcite content was 51% and the disintegration ratio was 23%. Figure 3b shows that sample 4270 is composed of limestone with a small admixture of quartz sand. The foam-like micro-quartz structure was visible before and especially after leaching. Sample 4232 had a calcite content of 44% and a decomposition ratio of 70%. Figure 3c shows that sample 4270 consists of medium-grained calcareous sandstone. The foam-like micro-quartz structure was not present and, therefore, the material dominantly disintegrated even at a relatively low calcite content. As in other samples, quartz dominated the siliciclastic fraction, but about 10–20% of the silt and sand grains were potassium feldspars (K content on Figure 3).

SEM revealed that micro-quartz is a major cementing agent (Figure 4a,b). The Si was apparently released from marine sponge spicules, which originally consisted of opal, a relatively soluble form of silica [28]. During diagenesis, the opal was dissolved and reprecipitated as micro-quartz, which then provided sufficient strength as a foam-like structure. The structure probably resulted from the precipitation of micro-quartz between carbonate grains. Thus, calcite content as high as 78 wt.% did not warrant rock disintegration after calcite leaching if a foam-like micro-quartz structure was present. A somewhat similar silica structure has been observed in siliceous limestones by Dubois et al. [11].

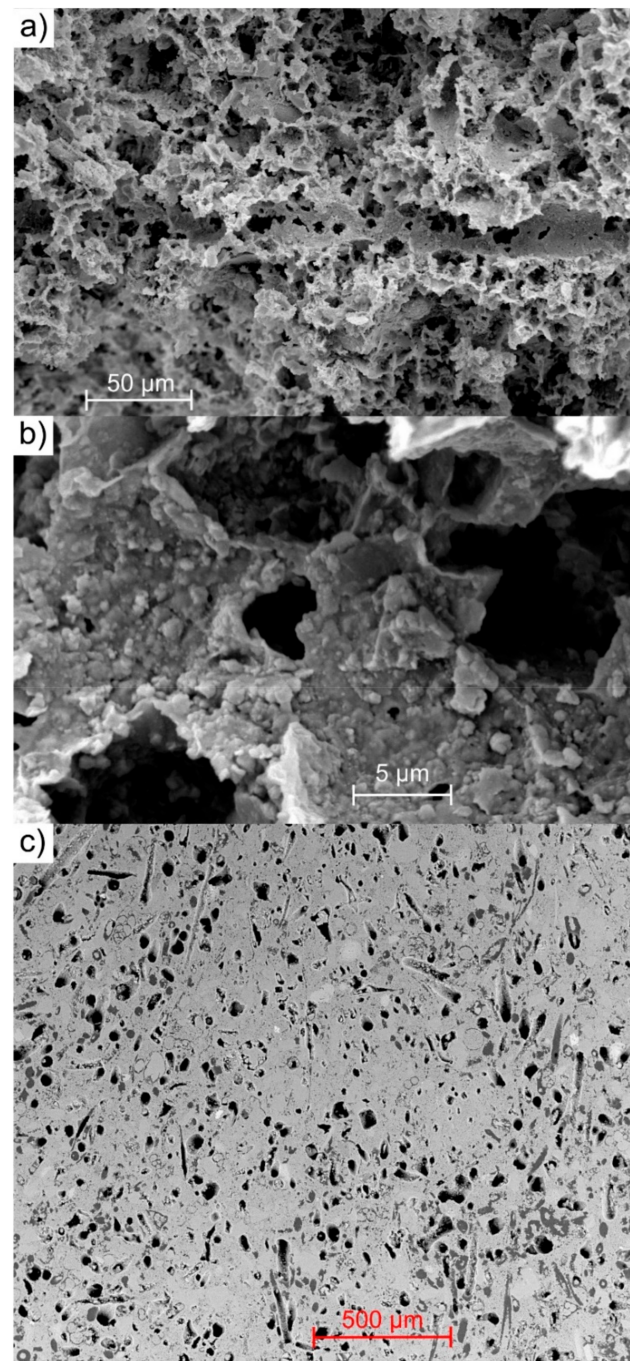


Figure 4. (a,b) Microcrystalline silica structure of sample MR4 with 78% porosity after leaching. The foam-like structure of several-micron-thick silica walls is clearly visible. Prior to leaching, the entire space was filled with calcite. (c) BSE image of the PE2 sample showing very common elongated voids after dissolution of marine sponge spicules.

Tensile strength was measured on subsamples with porosity greater than 50% after leaching in 10% HCl. The mean tensile strength was 440 kPa for dry subsamples with no apparent dependence on porosity. For wet subsamples, the mean tensile strength was 170 kPa, and the tensile strength decreased with increasing porosity (Figure 5). Especially for dry subsamples, the tensile strength was relatively high, considering that more than half of the rock volume was leached. Except for two wet subsamples with negligible tensile strength, the wet tensile strength was sufficient to keep the material stable.

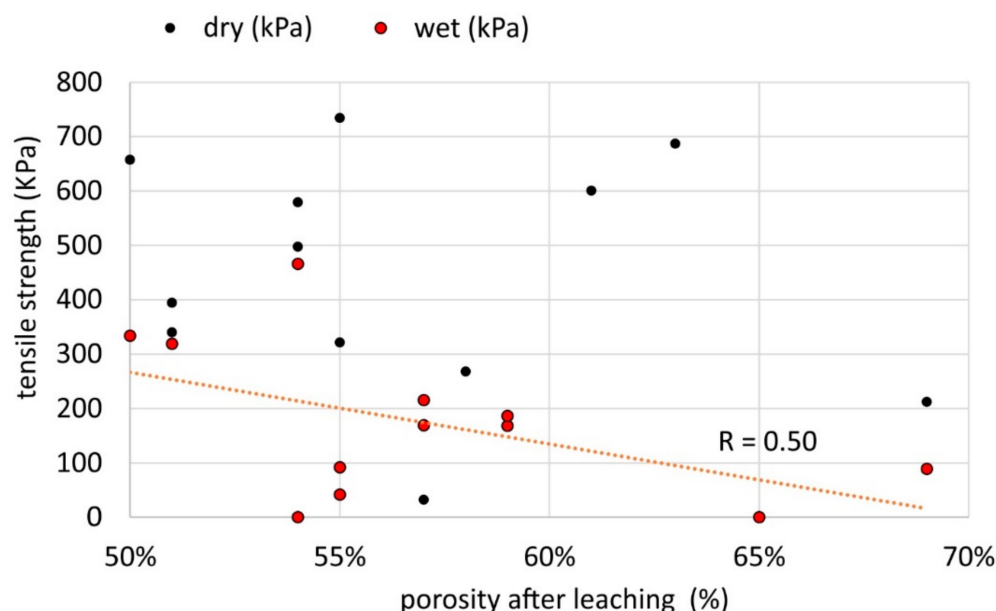


Figure 5. Tensile strength of dry and wet subsamples after leaching in 10% HCl. Black points show dry tensile strength, and red points show the tensile strength in wet conditions. Dashed line shows relationship between wet tensile strength and porosity after leaching. The tensile strength was relatively high considering the high porosity of rock after leaching.

The relatively high tensile strength showed that several-micron-thick foam-like micro-quartz formed a continuous structure, responsible for the cohesion and strength of rock after calcite dissolution. Quartz has a high compressive and tensile strength, so thin but continuous micro-quartz cement is able to keep rock residuum stable even with 80% porosity. In order to allow erosion, such rock must be heavily tectonically fractured into small pieces that can be transported by local groundwater flow due to their low density (1.3 g/cm^3 : considering a quartz density of 2.65 g/cm^3 and pores filled with water). Tectonic fracturing is thus a prerequisite for conduit development in rocks with continuous micro-quartz cement.

4.3. Characterization of Fracture-Controlled Conduits in Outcrops

Two different types of fracture-controlled conduits have been documented in the outcrops of the Turonian aquifers in the study area. The first type are sub-horizontal, bedding-parallel fractures, which have been strongly widened by corrosion and are partly filled with non-cohesive residue after rock dissolution (Figure 6a,b). They can be traced for tens of meters or more on outcrops and have openings of up to 10 cm. The second type occurs on fracture swarms, which are closely spaced fractures surrounded by unfractured rock [29]. Subvertical fracture swarms form systematic clusters that occur at intervals of tens of meters on outcrops. Individual fractures are subparallel to each other and often only a few centimeters apart (Figure 7). Together with bedding planes, they break the rock into centimeter-sized and larger fragments. Vertically elongated, and more rarely tubular, conduits can be observed at fracture swarms (Figures 6c–e and 7). Vertical calcite veins up to 5 cm-thick have also been observed at some fractures and fracture swarms.

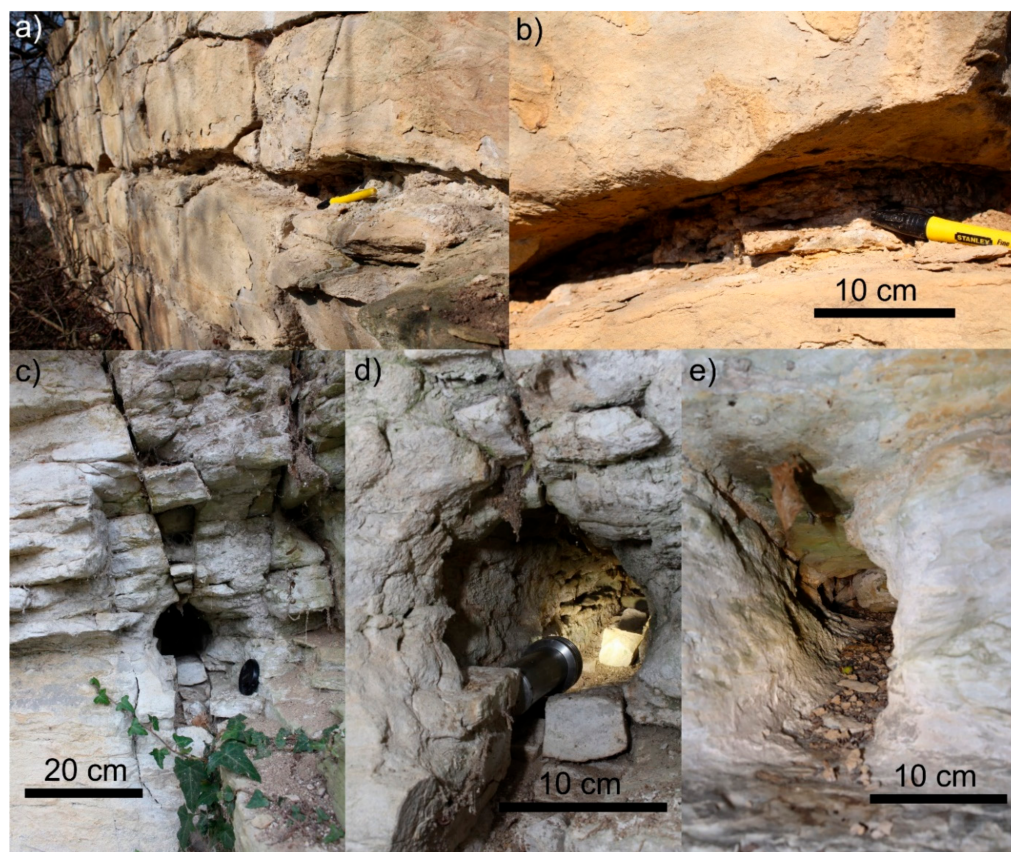


Figure 6. (a) Bedding-parallel conduit (Choceň), (b) detail of the previous figure, (c) tubular conduit (Opočno), (d) detail of the previous figure, and (e) vertically extended conduit (Nové Město nad Metují).

All types of fracture-controlled conduits are filled by remnants of rock dissolution (Figures 6b and 7). In the case of fracture swarms, it is clear that the entire space was originally filled by rock fragments in situ. Thus, it is clear that open spaces are not the result of extensional tectonics, but rather the excavation of small fragments of weathered rock from fracture swarms.

4.4. Characterization of Fracture-Controlled Conduits in Wells Using an Acoustic Televiwer and Downhole Camera

The features documented on the outcrop were identical to the fracture-controlled conduits observed on camera logs in the wells (Figure 8). The largest inflows were observed from bedding-parallel conduits. Fracture dips and apertures from an acoustic televiwer were available from 7 wells (4270-01W, -02W, -03W, -04W, -06W, -07W, and 4232-3W) [20]. These data were combined with inflows to specific depths in the wells, obtained from dilution tests in the wells (Figure 8). Figure 9 shows that the dominant inflows occurred in the upper and middle parts of the aquifers. This is consistent with many hydrogeological reports on individual wells in the area, showing that permeable fractures dominantly occur in the upper part of aquifers, where low amounts of clay occur, favoring rigid deformation. On the contrary, as the admixture increased downward, plastic deformation was favored in the lower part of the aquifer, resulting in less inflows. Figure 9 shows that the dominant part of inflows, and especially inflows >0.1 L/s, was from sub-horizontal fractures, often bedding planes. Sub-horizontal fractures have larger apertures than subvertical fractures and often have wavy edges, showing the effect of dissolution. Subvertical fractures have straight edges with no evidence of dissolution. Few inflows from subvertical fractures were observed. However, the low number of subvertical inflow fractures may be biased by

the fact that boreholes are vertical features, which have a much higher chance of hitting sub-horizontal bedding planes than subvertical fracture swarms.

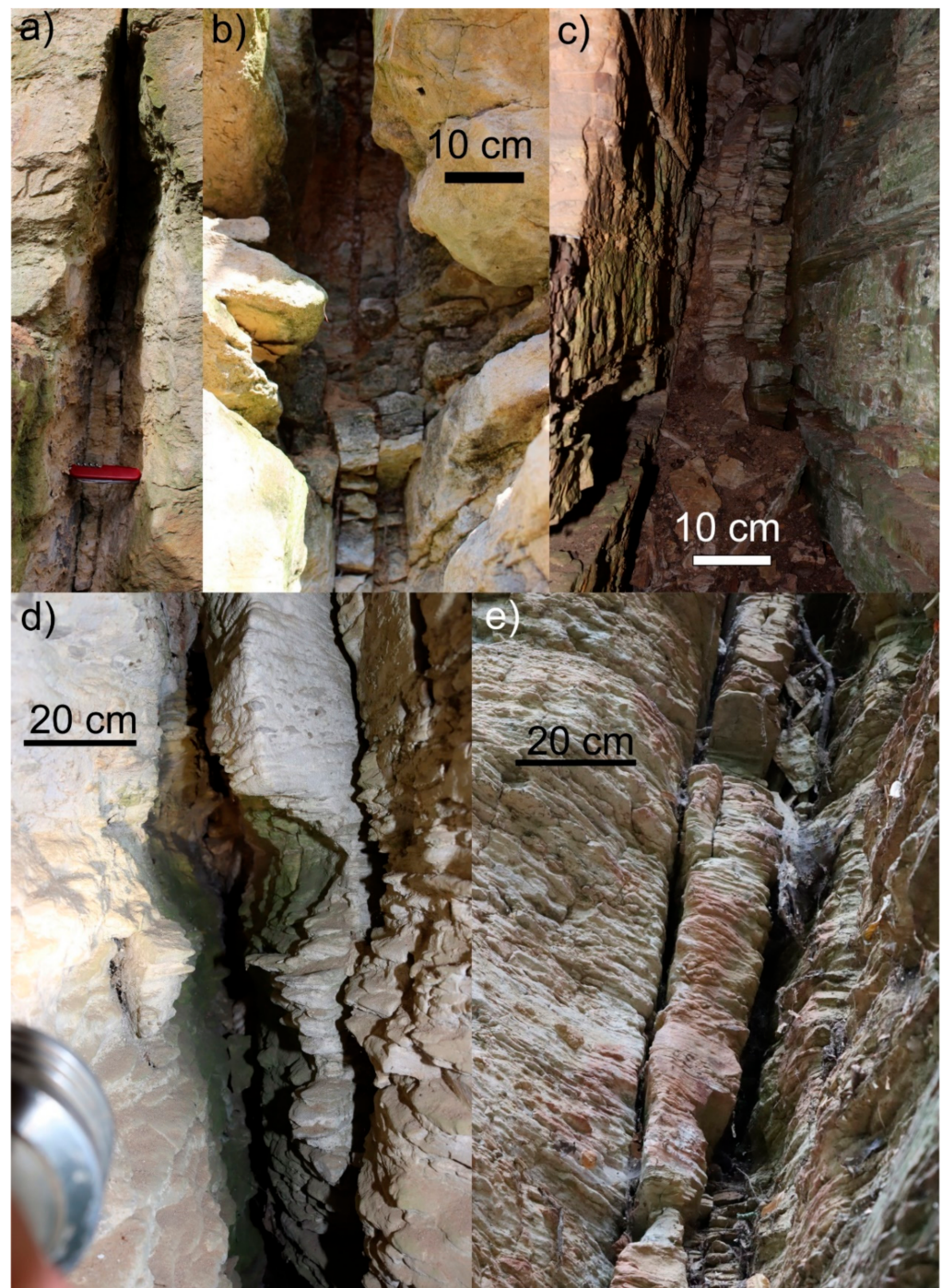


Figure 7. Subvertical fracture swarms with weathered rock fragments in situ. Removal of weathered rock fragments by piping leads to the formation of fracture-controlled conduits. (a) Přepychy, (b) Choceň, and (c–e) Nové Město nad Metují.

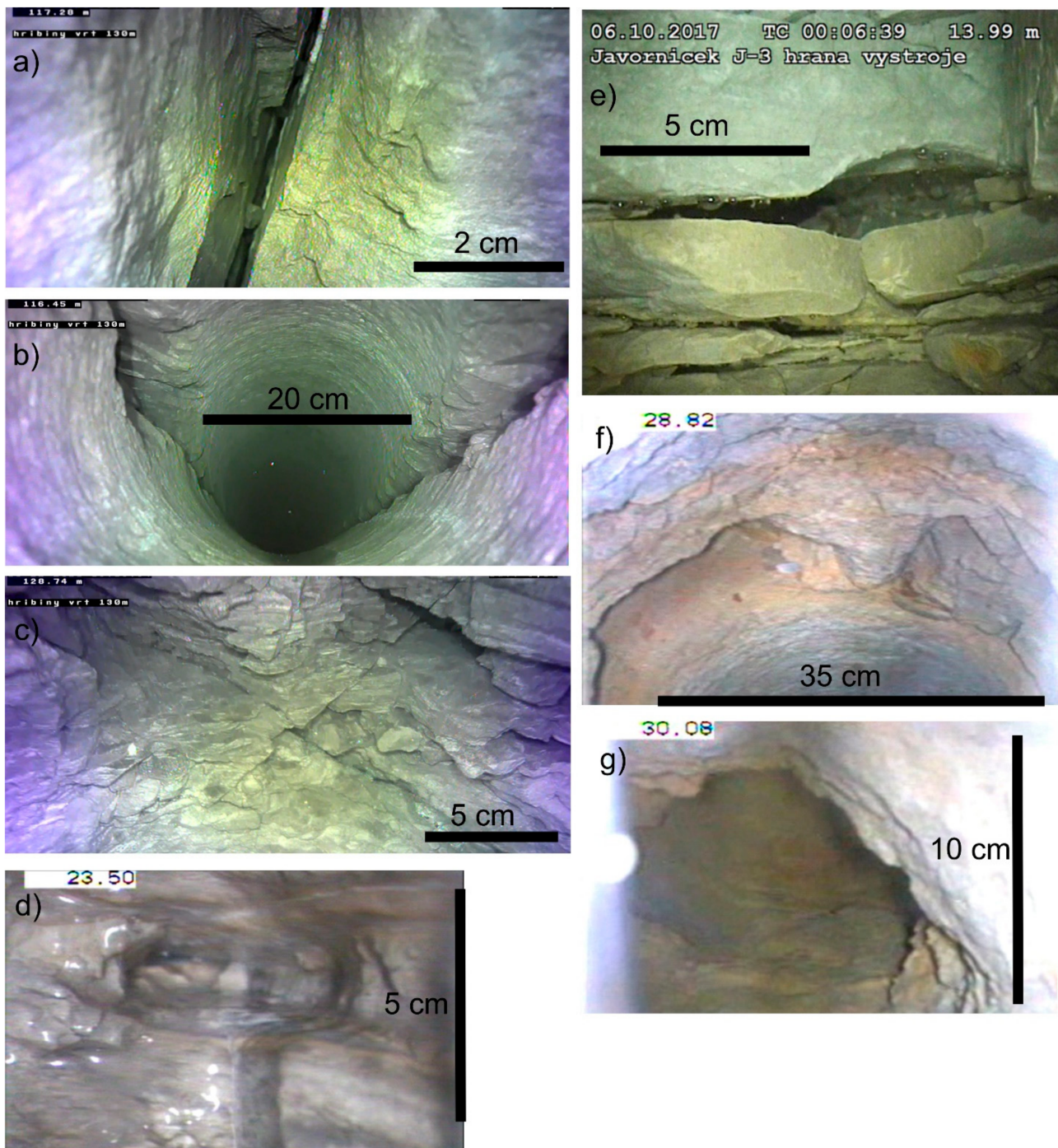


Figure 8. Conduits with inflows to wells. (a,b) Inflow of the Hřibiny–Ledská well (5–10 L/s): depth of 117 m, and subvertical fracture swarm with remnants of a white calcite vein. (c) Hřibiny–Ledská well: depth of 128 m, and crossings of subvertical fractures with a bedding plane. (d) Conduit with small inflow from the vadose zone of the well 4470_06W. (e) Bedding plane conduit in the well Javorníček, with a depth of 13 m. (f,g) Inflow of the well Perla 06 (36 L/s), with a depth of 28–30 m.

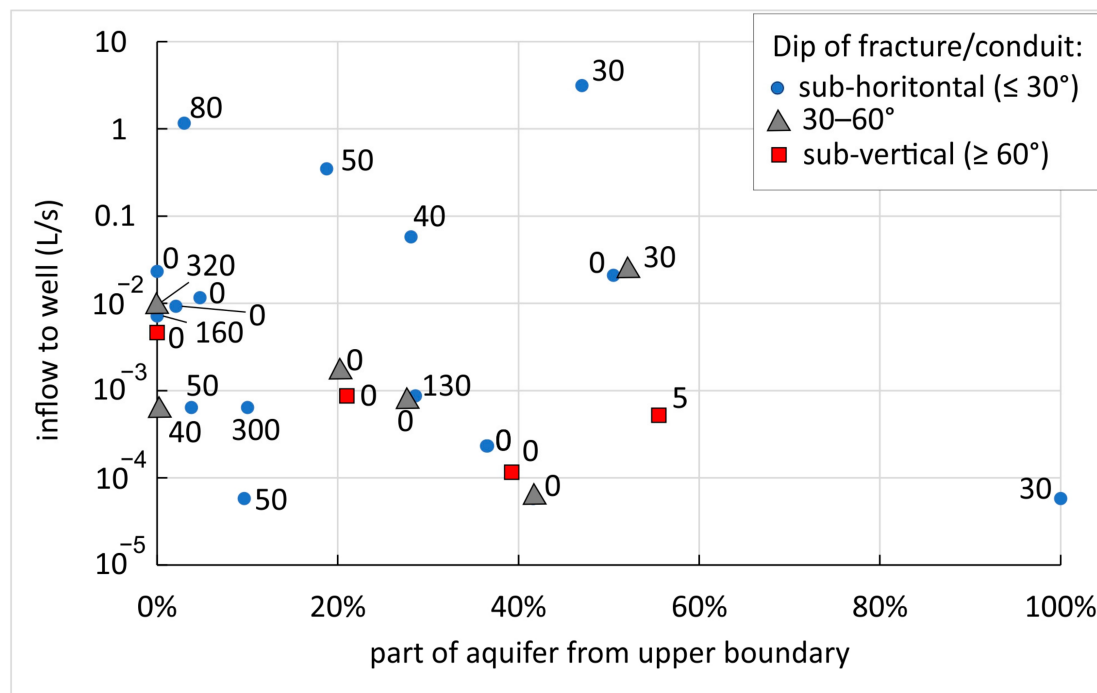


Figure 9. Characterization of fractures/conduits from an acoustic televiwer with inflows of wells, based on the dilution technique. The horizontal axis shows the vertical position in the aquifer (0% is the top, 100% is the bottom). The vertical axis shows the inflow intensity from a given fracture (determined by the dilution technique). Numbers in the figure indicate the fracture/conduit opening in mm.

5. Discussion

Based on analyses and observations, we have presented a conceptual model for the origin of fracture-controlled conduits causing localized groundwater inflow to wells in Turonian aquifers in the eastern part of the BCB. Bedding-parallel conduits were connected to layers with a high calcite content (>80 wt.%) or low secondary silica impregnation. Groundwater dissolved the calcite, leaving a non-cohesive residue, which was later washed out when a high flow velocity was induced by steep hydraulic gradients. Only a very small part of the aquifer thickness had sufficient calcite content to allow the formation of such features (a very small part of the samples had a disintegration ratio $D > 50\%$). Other type of conduits were formed by the dissolution of calcite veins by groundwater flow.

Fracture swarm conduits have a more complicated origin (Figure 10). In the first phase, tectonic forces created numerous vertical fracture swarms, where the distance between the closest parallel fractures was often only a few centimeters. These damaged zones were preferentially used for groundwater flow, which leached calcite from the calcite-rich layers. This process is very slow (Paleogene-recent). Since the material contained silica cement (foam-like structure), it did not disintegrate even when the calcite content reached ≤ 80 wt.%, but the density and cohesion of the rock decreased significantly after leaching. Later, when the hydraulic gradient in the fracture zone increased (e.g., in the vicinity of a valley due to intensive groundwater drainage, or as a result of lowering the water table in a well due to groundwater pumping), small rock fragments from fracture swarms were flushed out by rapid groundwater flow, resulting in the formation of fracture-controlled conduits with extreme permeability and flow rates up to 90 L/s. This second phase can be much shorter (hours to days in the case of intensively pumped wells) and is controlled by the hydraulic gradient and flow rate. The conduits can have sharp-edged walls along the fracture surfaces, creating the false impression that they were formed by extensional tectonics (Figure 10c). However, their preserved fills on rock outcrops, formed by damaged rock in situ, clearly demonstrated that they are the product of erosion of rock residua from fracture swarms

(Figure 7). Erosion of residues from “pseudo-karst cavities” around the well was observed, for example, during the Cl1 Čistá well test, when up to 210 L/s spontaneously flowed out of the well due to artesian overflow [13]. Fracture swarm conduits can develop in a higher vertical proportion of Turonian aquifers than bedding-parallel conduits. It is possible that rocks with a higher porosity after calcite leaching are more likely to form fracture swarm conduits. These conduits connect individual bedding-parallel conduits.

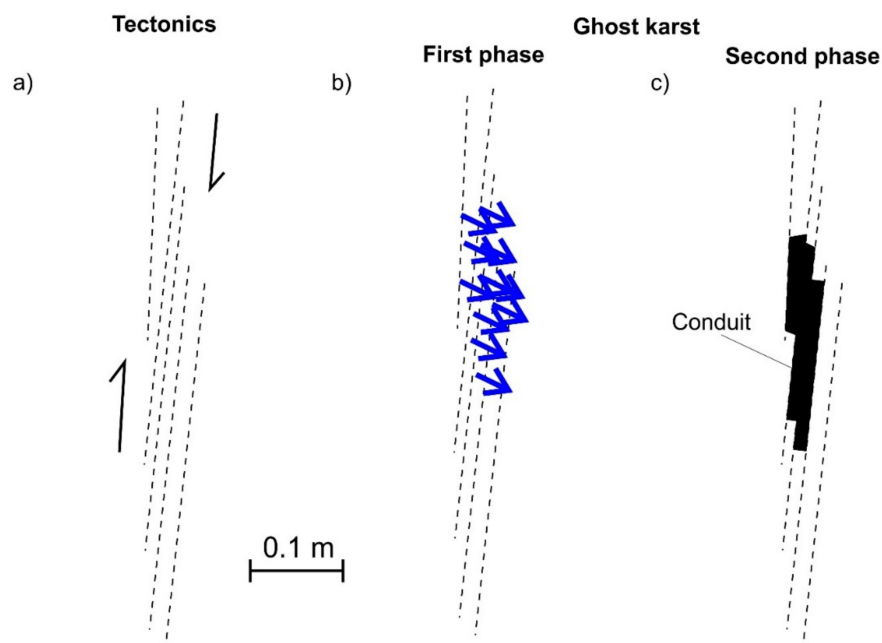


Figure 10. Model for the formation of highly permeable fracture-swarm conduits. (a) A cluster of subparallel vertical fractures (dashed lines) is formed by tectonic forces (fracture swarm). (b) Ground-water flowing intensively across the damaged zone (blue arrows) of the fracture swarm dissolves the calcite and transforms the rock into residue. (c) As the hydraulic gradient steepens, the low-density small fragments of residue are washed out of the fracture zone and a fracture-controlled conduit is formed.

Since dissolution played a major role in all these phenomena, they are karstic in origin. This is a two-phase process, with the first phase producing a residue by calcite leaching, and the second phase producing a conduit by washing out the residue under elevated hydraulic gradients. As such, it is typical of ghost-rock karst phenomena [11]. There can be a considerable time lag between the first and second phases. On many fractures, the residua are never washed out due to the lack of steep hydraulic gradients (lack of a second phase). Extreme values of porosity due to calcite dissolution (up to 66%) and extreme reductions in rock strength have been described from ghost karst residua in the UK and Belgium in [30–32].

Interestingly, in fine-grained siliciclastic-carbonate sediments in Minnesota and Wisconsin, as in the BCB, conduits parallel to bedding planes have significantly larger apertures (up to 30 cm) than subvertical conduits (up to 5 cm [7]). In the UK in arkose sandstone with some carbonate cement, the most permeable conduits were found at the intersection of bedding planes and vertical fractures [33]. Thus, it is evident that fracture-controlled conduits in the BCB are very similar to the phenomena in Minnesota and Wisconsin, USA, and the rocks of the Turonian aquifers in the eastern part of the BCB have properties that fall under the typical characteristics of ghost-rock karst.

The results of tracer tests in the Březová nad Svitavou spring area clearly showed that the fracture-controlled conduits did not form only short, isolated segments, but an extensive interconnected network through which 1100 L/s flows at a velocity of 400–650 m/day over a distance of several kilometers to the largest springs in the BCB, which now supply

the second largest city in the Czech Republic with groundwater [21]. Comparable flow velocities have been found in open fractures in siliciclastic-carbonate rocks in Minnesota and Wisconsin, USA (35–750 m/day [8,9]), in conduits in Sherwood sandstone with intergranular carbonate cement in the UK [34], and in fissures in sandstone with carbonate beds in Luxembourg (2–8400 m/day [35]).

As conduits are formed by the washing out of residua from weathered zones, they will especially occur where water flows intensively, i.e., in drainage areas. This is consistent with the distribution of transmissivities from pumping tests, which is highest in the largest drainage areas. Therefore, wells in drainage areas often have much higher transmissivity ($5 \times 10^{-2} \text{ m}^2/\text{s}$) than the average transmissivity in the area (5×10^{-4} – $6 \times 10^{-3} \text{ m}^2/\text{s}$).

The existence of a continuous network of ghost-rock karst conduits strongly changes the conceptual model of the eastern part of the BCB. The existence of rapid groundwater flow capable of transporting contaminants over km distances must be considered in groundwater modeling to properly capture flow velocities in conduits, and the catchment of losing streams should be better protected to avoid groundwater contamination. Modeling concepts in ghost karst and sandstones with conduits have already been presented in [36,37]. When new water supply wells are constructed, deep drawdowns and the resulting steep hydraulic gradients can cause erosion of residua from fractures and thus increase the inflow to the well.

In other siliciclastic-carbonate sediments, it should be investigated whether conduits are present and what their origin is. The present study, as well as [34,36], showed that even thin carbonate-rich beds can host highly permeable conduits that can localize groundwater flow from the entire aquifer to a few-decimeter-thick zone. Fracture swarms may allow flow between individual bedding-parallel conduits. If the presence of conduits and rapid groundwater flow is demonstrated in the area, protective measures similar to those used in regular karst should be applied to protect groundwater from contamination.

6. Conclusions

In addition to the well-characterized karst hydrogeology of high-percentage limestones, there are a number of other lithologies at the transition between carbonates and siliciclastics where the formation of highly permeable flow paths is poorly understood. To assess the susceptibility to karstification, the carbonate content and degree of disintegration after leaching in HCl were determined on samples taken from cores and outcrops from highly productive Turonian aquifers in the eastern part of the BCB.

Surprisingly, dissolution of calcite from fine siliciclastic-carbonate rocks usually did not result in rock disintegration until the calcite content exceeded 78%. Instead, calcite dissolution resulted in a significant increase in porosity, with 26% of the rock samples having 50–84% porosity after calcite dissolution. Scanning electron microscopy revealed that high-porosity rock is held together by micron-scale secondary silica with a continuous foam-like structure that is light but relatively strong, based on tensile strength tests. This structure was obscured by the calcite and was only visible after calcite dissolution.

Camera logs in boreholes and the study of rock outcrops showed that aquifers contain three different types of conduits: (i) bedding-parallel conduits associated with calcite-rich beds, (ii) subvertical fracture swarm conduits formed on damaged zones of fracture swarms, and (iii) conduits formed by dissolution of calcite veins by groundwater flow. These are typical features of ghost-rock karst, where calcite was leached from the rock in the first phase, and the residue was washed out by piping under steep hydraulic gradients only in the second phase.

Based on rapid flow velocities (400–650 m/day) over km distances (tracer tests), it was evident that these fracture-controlled conduits formed a continuous network in the drainage areas of the Turonian aquifers in the BCB. Very similar features have been described in aquifers of Minnesota and Wisconsin, USA, in a platform Lower Paleozoic sequence of siliciclastic-carbonate rocks, so other siliciclastic-carbonate aquifers may also host such high-permeability features.

Research has shown that the karstification of siliciclastic-carbonate rocks cemented by secondary silica is complex, and that the results of dissolution tests must be combined with scanning electron microscopy, borehole logging, and the study of surface outcrops to understand the formation of high-permeability features, such as conduits and fissures. It has also been shown that fractures with sharp-edged walls, which create a clear impression of tectonic origin, may in fact be ghost karst features in which dissolution has played an important role.

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References

1. Worthington, S.R.H.; Ford, D.C. Self-organized permeability in carbonate aquifers. *Ground Water* **2009**, *47*, 326–336. [[CrossRef](#)] [[PubMed](#)]
2. Worthington, R.H.; Ford, D.C.; Beddows, P.A. Porosity and permeability enhancement in Unconfined carbonate aquifers as a result of solution. In *Speleogenesis, Evolution of Karst Aquifers*; Klimchouk, A.B., Ford, D.C., Palmer, A.N., Wolfgang, D., Eds.; NSS: Huntsville, AL, USA, 2000; pp. 77–90.
3. Florea, L.J.; Vacher, H.L. Springflow hydrographs: Eogenetic vs. telogenetic karst. *Ground Water* **2006**, *44*, 352–361. [[CrossRef](#)]
4. Bruthans, J.; Kamas, J.; Filippi, M.; Zare, M.; Mayo, A. Hydrogeology of salt karst under different cap soils and climates (Persian Gulf and Zagros Mts., Iran). *Int. J. Speleol.* **2017**, *46*, 303–320. [[CrossRef](#)]
5. Mecchia, M.; Sauro, F.; Piccini, L.; DeWaele, J.; Sanna, L.; Tisato, N.; Lira, J.; Vergara, F. Geochemistry of surface and subsurface waters in quartz-sandstones: Significance for geomorphic evolution of tepui table mountains (Gran Sabana, Venezuela). *J. Hydrol.* **2014**, *511*, 117–138. [[CrossRef](#)]
6. Runkel, A.C.; Tipping, R.G.; Alexander, E.C., Jr.; Green, J.A.; Mossler, J.H.; Alexander, S.C. Hydrogeology of the Paleozoic Bedrock in Southeastern Minnesota. In *Minnesota Geological Survey Report of Investigations*; Minnesota Geological Survey: Saint Paul, MN, USA, 2003; p. 105.
7. Runkel, A.C.; Tipping, R.G.; Alexander, E.C.; Alexander, S.C. Hydrostratigraphic characterization of intergranular and secondary porosity in part of Cambrian sandstone aquifer system of the cratonic interior of North America: Improving predictability of hydrogeologic properties. *Sed. Geol.* **2006**, *184*, 281–304. [[CrossRef](#)]
8. Green, J.A.; Runkel, A.C.; Alexander, E.C. Karst conduit flow in the Cambrian St. Lawrence Confining Unit, southeast Minnesota, USA. *Carbonates Evaporites* **2012**, *27*, 167–172. [[CrossRef](#)]
9. Barry, J.D.; Green, J.A.; Steenberg, J.R. Conduit flow in the Cambrian lone rock formation, Southeast Minnesota, USA. In *Proceedings of the 14th Sinkhole Conference NCKRI Symposium*; Doctor, D.H., Land, L., Stephenson, J.B., Eds.; National Cave & Karst Research Institute: Carlsbad, NM, USA, 2015; Volume 5, pp. 31–41.
10. Kůrková, I.; Bruthans, J.; Balák, F.; Slavík, M.; Schweigstilllová, J.; Bruthansová, J.; Mikuš, P.; Vojtíšek, J.; Grundloch, J. Factors controlling evolution of karst conduits in sandy limestone and calcareous sandstone (Turnov area, Czech Republic). *J. Hydrol.* **2019**, *574*, 1062–1073. [[CrossRef](#)]
11. Dubois, C.; Quinif, Y.; Baele, J.M.; Barriquand, L.; Bini, A.; Bruxelles, L.; Dandurand, G.; Havron, C.; Kaufmann, O.; Lans, B.; et al. The process of ghost-rock karstification and its role in the formation of cave systems. *Earth-Sci. Rev.* **2014**, *131*, 116–148. [[CrossRef](#)]

12. Hynie, O. *Hydrogeology of ČSSR: Ground Waters*; Czechoslovak Academy of Sciences: Prague, Czech Republic, 1961. (In Czech)
13. Pavliš, R. *Final Report on Čistá C11 and C12 well 101 p. Vodní zdroje, Chrudim*; Geofond P035952; Vodní Zdroje: Chrudim, Czech Republic, 1981. (In Czech)
14. Žižka, V. *Final Report on Wells Lo 15/4 Pekla and Lo5/3 Choceň-Peliny*; Geofond P045435; Vodní Zdroje: Prague, Czech Republic, 1984. (In Czech)
15. Uličný, D.; Laurin, J.; Čech, S. Controls on clastic sequence geometries in a shallow-marine, transtensional basin: The Bohemian Cretaceous Basin, Czech Republic. *Sedimentology* **2009**, *56*, 1077–1114. [\[CrossRef\]](#)
16. Wiese, F.; Čech, S.; Ekrt, B.; Košťák, M.; Mazuch, M.; Voigt, S. The Upper Turonian of the Bohemian Cretaceous Basin (Czech Republic) exemplified by the Úpohlavy working quarry: Integrated stratigraphy and palaeoenvironment of a gateway to the Thetys. *Cretac. Res.* **2004**, *25*, 329–352. [\[CrossRef\]](#)
17. Čech, S.; Klein, V.; Kříž, J.; Valečka, J. Revision of the Upper Cretaceous stratigraphy of the Bohemian Cretaceous Basin. *Věstník Věstník Ústředního Ústavu Geologického* **1980**, *55*, 277–296.
18. Štaffen, Z. Chemostratigraphic correlation of beds and formation in Bohemian Cretaceous Basin. *Acta Mus. Richnoviensis Sect. Nat.* **1999**, *6*, 7–152. (In Czech)
19. Skácelová, Z.; Mlčoch, B.; Čech, S. Geological interpretation of a seismic reflection profile in the eastern part of the Bohemian Cretaceous Basin. *J. Geosci.* **2022**, *67*, 1–17. [\[CrossRef\]](#)
20. Burda, J.; Grundloch, J.; Kůrková, I.; Bruthans, J.; Bůzek, F.; Čech, S.; Herčík, F.; Kadlecová, R.; Kondrová, L.; Kůrková, I.; et al. Hydrogeology district 4270. In *Evaluation of Groundwater Resources*; Final Report; MS Geofond: Prague, Czech Republic, 2016; p. 249. (In Czech)
21. Pavliš, R.; Tůma, W. *Final Report on Hydrogeology Survey in Březová nad Svitavou—Hladové prameny*; Vodní Zdroje s.p. Chrudim: Chrudim, Czech Republic, 1983. (In Czech)
22. Lachman, V. Groundwater Flow and Highly Permeable Zones in Aquifers of Eastern Part of Bohemian Cretaceous Basin based on Litá Area and Surroundings. Ph.D. Thesis, Faculty of Sciences, Charles University, Prague, Czech Republic, 2010; 69p. (In Czech).
23. Ray, S.; Gault, H.R.; Dodd, C.G. The separation of clay minerals from carbonate rocks. *Am. Min.* **1957**, *42*, 681–686.
24. Bruthans, J.; Světlík, D.; Soukup, J.; Schweigstillová, J.; Válek, J.; Sedlackova, M.; Mayo, A.L. Fast evolving conduits in clay-bonded sandstone: Characterization, erosion processes and significance for origin of sandstone landforms. *Geomorphology* **2012**, *177*–178, 178–193. [\[CrossRef\]](#)
25. Bruthans, J.; Soukup, J.; Vaculíková, J.; Filippi, M.; Schweigstillová, J.; Mayo, A.L.; Mašín, D.; Kletetschka, G.; Řihošek, J. Sandstone landforms shaped by negative feedback between stress and erosion. *Nat. Geosci.* **2014**, *7*, 597–601. [\[CrossRef\]](#)
26. Lin, M.L.; Jeng, F.S.; Tsai, L.S.; Huang, T.H. Wetting weakening of tertiary sandstones-microscopic mechanism. *Environ. Geol.* **2005**, *48*, 265–275. [\[CrossRef\]](#)
27. Pitrák, M.; Mareš, S.; Kobr, M. A simple borehole dilution technique in measuring horizontal ground water flow. *Groundwater* **2007**, *45*, 89–92. [\[CrossRef\]](#)
28. Čáp, P. Microscopic study of the silicified rocks and spongolites of the Bohemian Cretaceous basin. *Geosci. Res. Rep.* **2006**, *39*, 107–108. (In Czech)
29. Gabrielsen, R.H.; Braathen, A. Models of fracture lineaments-joint swarms, fracture corridors and faults in crystalline rocks, and their genetic relations. *Tectonophysics* **2014**, *628*, 26–44. [\[CrossRef\]](#)
30. Kaufmann, O.; Deceuster, J. Detection and mapping of ghost-rock features in the Tournaisian area through geophysical methods—An overview. *Geol. Belg.* **2014**, *17*, 17–26.
31. Rowberry, M.D.; Battiau-Queney, Y.; Walsh, P.; Blazejowski, B.; Boutroumazeilles, V.; Trentesaux, A.; Křížová, L.; Griffiths, H. The weathered Carboniferous limestone at Bullslaughter Bay, South Wales: The first example of ghost-rock recorded in the British Isles. *Geol. Belg.* **2014**, *17*, 33–42.
32. Dubois, C.; Quinif, Y.; Baele, J.-M.; Dagrain, F.; Deceuster, J.; Kaufmann, O. The evolution of the mineralogical and petrophysical properties of a weathered limestone in southern Belgium. *Geol. Belg.* **2014**, *17*, 1–8.
33. Medici, G.; West, L.J.; Mounney, N.P. Characterization of a fluvial aquifer at a range of depths and scales: The Triassic St Bees Sandstone Formation, Cumbria, UK. *Hydrogeol. J.* **2018**, *26*, 565–591. [\[CrossRef\]](#)
34. Medici, G.; West, L.J. Review of groundwater flow and contaminant transport modelling approaches for the Sherwood Sandstone aquifer, UK; insights from analogous successions worldwide. *Quarterly J. Eng. Geol. Hydrogeol.* **2022**, *55*, qjeh2021-176. [\[CrossRef\]](#)
35. Meus, P.; Willems, L. Tracer tests to infer the drainage of the multiple porosity aquifer of Luxembourg Sandstone (grand-Duchy of Luxembourg): Implications for drinking water protection. *Hydrogeol. J.* **2021**, *29*, 461–480. [\[CrossRef\]](#)
36. Runkel, A.C.; Tipping, R.G.; Meyer, J.R.; Steenberg, J.R.; Retzler, A.J.; Parker, B.L.; Green, J.A.; Barry, J.D.; Jones, P.M. A multidisciplinary-based conceptual model of a fractured sedimentary bedrock aquitard: Improved prediction of aquitard integrity. *Hydrogeol. J.* **2018**, *26*, 2133–2159. [\[CrossRef\]](#)
37. Dubois, C.; Goderniaux, P.; Deceuster, J.; Poulain, A.; Kaufmann, O. Hydrogeological characterization and modelling of weathered karst aquifers. Applicability to dewatering operations in limestone quarries. *Environ. Earth Sci.* **2019**, *78*, 99. [\[CrossRef\]](#)

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