#### THEMATIC ISSUE



## Weathering phenomena, rock physical properties and long-term restoration intervention: a case study from the St. Johannis Chapel of Lütgenrode (Lower Saxony, Germany)

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#### Abstract

Small historical churches in rural villages are mainly functional buildings, lacking spectacular architectural or ornamental features. This is also true for the St. Johannis Chapel Lütgenrode near Göttingen (Lower Saxony, Germany), which dates back to the 13th century. The use of ca. 10 different natural building stones (Triassic sandstone and limestone, Holocene fresh water carbonate), scattered roof tiles and bricks result in a highly heterogeneous character of the chapel's ascending walls. In addition, various repairs over the last centuries, using inadequate materials, amplified damages and produced critical stability problems, in particular at the southern wall. Here, the suitability of the dimensional stones are evaluated for construction and replacement purposes. A semi-quantitative distribution of lithotypes was performed, and weathering forms were mapped in detail. On-site analyses (micro-drilling resistance, the Schmidt hammer rebound test, capillary water absorption) provide data on the deterioration state of the main lithologies. The petrophysical data show that stratigraphically comparable building stones exhibit different technical characteristics and weathering behavior. All data serve to characterize the state of weathering and provide the data set to plan for future restoration work. The amount needed for restoration work has been estimated to be approximately 435,000–550,000 EUR. Because the local church authorities evaluate the significance of a church based on the frequency of its use, a secular use would be able to save the Lütgenrode chapel, but then the church political leaders would have to act quickly.

**Keywords** Preservation of village churches  $\cdot$  Stone weathering  $\cdot$  Stability assessment  $\cdot$  Petrophysical properties  $\cdot$  Maintenance work

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## Introduction

Many historical monuments made from natural stone are seriously damaged as a consequence of weathering processes, the influence of pollution, insufficient maintenance, application of inappropriate materials and conservation interventions (e.g., Fitzner et al. 1995; Fort et al. 2013; Graue et al. 2013; Siegesmund and Török 2014; Hüpers et al. 2005; Siedel 2013; Amoroso and Fassina 1983). This is particularly true for the numerous small, often medieval village churches in rural areas, where the need of restoration was hampered by the lack of financial support, threatening the persistence of some of the historical buildings significantly. This is unfortunate, because village churches are often not only religious, but also secular centers for a multitude of social events and particularly important for the social cohesion of rural communities. In the case of Lower Saxony (Germany), most of these churches are old, reflecting ages from the 11th to the 18th century, and, during the centuries, natural hazards, wars and feuds, as well as physical and biological deterioration of their building stones demanded repeated repairs or even reconstructions of parts or the entire church (Siegesmund and Snethlage 2014). These (re)constructional activities left their traces in the skin of the buildings, visible by the variable use and handling of natural building stones. Repairs were often done with just the minimum efforts needed and, apparently as in the case of the St. Johannis Chapel in Lütgenrode (end of the thirteenth century, Fig. 1), costs were spared on the building stone quality and sometimes restorations were sometimes performed by unskilled people. The use of ca. 10 different natural building stones-carbonates and siliciclastics plus scattered roof tiles and bricks-impressively shows the highly heterogeneous character of the chapel's ascending walls. Furthermore, several mortar generations, not always compatible with the respective natural building stones and the elevated floor level of the surroundings, resulted in moist walls, where in contact with the soil, leading to a considerable accumulation of a multitude of different physical and biological damages to the natural building stones today. This damage accumulation turned out to be so significant in the Lütgenrode Chapel that the southern facade of the former tower needed to be stabilized by a wooden scaffold.

A systematic mapping of the building stones in the ascending walls in conjunction with the recording and evaluation of weathering damage is a necessary prerequisite for understanding the damage mechanisms and causes of damage. These data serve as an important planning basis for preservation measures appropriate to the monument (Fitzner and Heinrichs 2005).

The structural suitability of ashlars is determined in particular by their resistance to weathering. How and in what way a stone weathers depends not only on the mineral composition and the rock fabric but also on the technical properties of the stone. The most important material properties are, among others, the porosity and the pore radii distributions. Together with water absorption, they control water and moisture absorption and transport in the rock. The strength properties and also the hygric strain or resistance to salt attack are the other important properties.

Based on the mapping of the building stones, the most important rock types were sampled as far as possible from old, abandoned quarries and then investigated with respect to important material parameters. Furthermore, onsite investigations on strength and water absorption were carried out (e.g., Török et al. 2007; Schneider et al. 2008; Pamplona et al. 2007; Pfefferkorn, 2000). The Schmidt hammer, the drilling resistance and the Karsten tube were used for this purpose. The Schmidt hammer can be used to determine a



Fig. 1 The St. Johannis Chapel in Lütgenrode with supporting construction on the south side in 2020

strength down to a depth of about 10 cm, which serves as an indication of the uniaxial compressive strength (Török 2003; Siedel and Siegesmund 2014; Tiano et al. 2000; Viles et al 2011). Drilling resistance measurements provide information on existing zones of weakness based on strength-depth profiles, which were tested on various lithotypes. The capillary water absorption characteristics were also estimated non-destructively on significant ashlars using the Karsten test tube. The knowledge of the capillary water absorption is an important parameter for the stability assessment. All results are documented together with archival research, subsoil investigations, excavations, channel inspections, material investigations regarding used stones and mortars and combined with the findings of the present study. The results of the available investigations are summarized, evaluated and were used to establish a repair concept with a cost estimate.

#### Methods

The methods used in the present study include damage mapping, petrographic analyses, determination of the petrophysical properties and onsite field investigations. To determine the composition of the samples, different methods were used. Minerals were identified by conventional thin section microscopy. Petrophysical properties were carried out to determine the density, porosity and pore size distribution. Density and porosity was measured by buoyancy weighing on cubic samples (DIN 52106) (1972). The pore size distribution was determined using the mercury intrusion porosimetry on cylindrical samples (Brakel et al. 1981) with a Thermo Scientific Pascal 440/140 following DIN 66138 (2008). The capillary water absorption can be expressed by the water absorption coefficient, the so-called w value and is measured following DIN EN 1925. Therefore, a cubic sample with an edge length of 65 mm was fixed at an underfloor balance above a basin filled with water, and the weight was measured every 10 s by a specific computer program. The w value is determined by the relationship of capillary water absorption versus time. The w-values were taken in two directions, parallel and perpendicular to the bedding of the stone if observable. To determine hygric expansion, the cylindric samples were vertically placed in glasses or cups and completely covered with water. Sensors detected the changes of length during a period of 24 h. The ultrasonic P-wave velocity was determined via direct transmission of the ultrasonic travel time through cylindrical specimens (50 mm length, 15 mm diameter) according to DIN 14579 (2005), with a frequency of 350 kHz. It was also used as a non-destructive tool to calculate the dynamic Young's modulus (Edyn), which is proportional to the rock strength (Siegesmund and Dürrast 2014). Surface hardness was determined by the DIN EN 12504-2. For the characterization of the weathering features the drilling resistance on selected lithologies along selected profiles from surface to the depth was applied (Siedel and Siegesmund, 2014).

Fieldwork included mapping of the stone varieties and the type of deterioration visible on the buildings, using the existing classification scheme by Fitzner et al. (1995), Fitzner and Heinrichs (2005) and the Glossary given by ICOMOS (Vergès-Belmin V ICOMOS-ISCS 2010). The first step was to characterize all the stones according to their lithology and to document them by assigning a signature onto a map. Mapping of all surface decay features was documented, classified and represented on a deterioration map. For the data processing (see Hüpers et al. 2005), corresponding computer programs are available, whereby the data collected from well-defined stone surfaces (e.g., individual stone blocks) can be arranged and defined by a chosen color (e.g., multiple weathering forms, the natural stone type or variety).

## **Building history of the St. Johannis Chapel**

No documents exist, which convey a date of the initial construction of the St. Johannis Chapel. Judging from the beveled window flannings of the slit-like windows in the eastern facade and a comparison with other churches of the area (e.g., Offensen: Stephan and Leuschner 1996), an end of the thirteenth century age for the first construction phasea multistoried tower with at least three stories-is likely. The remnants of its portal are still visible in the southern facade (Fig. 2a). A masonry seam in the southern facade (Fig. 2a) shows that the nave was added later in a second phase. A possible masonry seam occurs in the eastern facade (Fig. 2b), which could also represent a contact between the intact historical structure and later repairs. Müller (1964) suggests that the Lütgenrode Chapel was severely damaged during the destruction of Lütgenrode in 1486. A commemorative stone from 1592 in the southern facade (showing the "Mainzer Rad"-Mainz wheel-the symbol for the archdiocese of Mainz, Fig. 3) dates the completion of the rebuilding phase, during which the nave was added, and tower was shortened to its present-day height. With this step, the Lütgenrode Chapel obtained its present-day outline with an outer dimension of ca.  $15.70 \times 7,60$  m and a nave height of 4,50m, and a total height of the wall of ca. 6,40m. The walls of the nave and the tower were built in a two-shell construction (wall thickness south: 110 cm, north: 95 cm) in uncoursed rubble masonry with well-elaborated edges and embrasures (Fig. 1), using a loam mortar. Possibly in the 18th century, new and larger windows and embrasures were added, capped by a shallow pressure arch. Around 1954, the modern ridge turret was constructed.

The current state of the facade is, in particular on the southern side, in parts desolate and results from a multitude



Fig. 2 a Layout of the Lütgenrode Chapel with masonry seams marked in red and  $\mathbf{b}$  section through the nave and roof structure, multi-layered natural stone masonry made of different dimensional stones

of factors. Because the loam mortar is sensitive to moisture, the wall lost its stiffness, where in contact with the soil and affected by splash water. This resulted in the eye-catching bulge in the southern wall of the former tower, and, to a lesser extent, in the southern wall of the nave. Resulting wall cracks increased humidity in the wall, accelerating the process of destabilization. Cracks and joints were repeatedly repaired/filled with various unsuitable lime and gypsum



**Fig.3** A spolia, depicting the Mainz wheel (width: 56 cm) is located in the southern facade and possibly indicates the date of a reconstruction in 1592

mortars. Where the mortar was too hard, joints formed between mortar and the rubble, resulting in deep, funnel-like gates, where rain and splash water could enter the wall. A recent (1954?) injection of cement suspension further introduced humidity into the walls, causing the development of ettringite and thaumasite in the gypsum mortar and further decreasing the stiffness of the wall. Another problem results from the poor weathering resistance of Keuper siltstones, its strong back-weathering and development of large joints. The process of progressive wall destabilization is further amplified by heavy truck traffic on the nearby national road and the poor quality of the subsoil (Liassic claystone), causing settlement and settlement cracks. The latter problem was solved by the stabilization of the foundation by banquet concrete at the southern side (65 cm wide, 90 cm deep), and, in a second step (1972), the mounting of a reinforced concrete beam, needled to the foundation masonry, a tension rod and injection of concrete suspension into the foundation masonry (see Fig. 2b). Damages by humidity and sagging at the south-eastern corner resulted from a defect main conduit. A general sectional view of the southern wall is given in Fig. 2b.

#### Geological framework

The St. Johannis Chapel in Lütgenrode is located west of the village of Lütgenrode, ca. 10 km north of Göttingen, on an abandoned undercut bank of the small Esolde River, in the center of the N–S-trending Leinetal Graben (Figs. 4, 5), which is interpreted to represent a pull-apart structure (Tanner et al. 2010, 2013; Vollbrecht and Tanner 2011). The graben shoulders and the subsequent areas mainly exhibit Triassic sediments, deposited in the epicontinental Germanic



**Fig. 4** Simplified geological overview map of Göttingen and surroundings of the Leinetal. The chapel in Lütgenrode is marked with a red dot (after Siegesmund et al. 2020)

Basin (Hauschke and Wilde, 1999), while in the central graben, Keuper and Lower Jurassic units are preserved but poorly exposed (Fig. 6). Miocene basalt and Eocene–Pliocene sediments are almost entirely restricted to areas west of the Leinetal Graben, the latter preserved in local subsidence centres. Holocene freshwater carbonate occur randomly distributed in the entire surroundings of Göttingen. A detailed overview on the regional geology is found in Arp et al. (2004) and Siegesmund et al. (2020).

The Buntsandstein Group (950–650 m) consists in its lower parts (Calvörde and Bernburg formations; Indisian) of fine sand, silt and clay, deposited in meandering and braided rivers and in playa lakes (Paul 1982). The Middle Buntsandstein (Volpriehausen, Detfurth, Hardegsen, Solling formations; Olenekian) shows fining upwards cycles of a fluviatile system with conglomeratic intercalations in cross-bedded middle and fine sand deposits and deposits of periodic lakes (Paul and Siggelkow 2004). The Upper Buntsandstein (Roet Formation, lowermost Anisian) consists of cyclical units of silt and fine silt deposits, dolomites, sulfates and halite, the latter two never exposed, because they are surficially leached (Lepper et al. 2014; Dersch-Hansmann et al. 2013).

The Muschelkalk Group (Anisian-lower Ladinium, 210–225 m) consists in its lower parts of wavy limestone ("Wellenkalk") with intercalated tempestites, punctuated by three units of few meters thick, thickly bedded limestone, which are used for regional lithostratigraphic correlation (in ascending order: Oolithbank, Terebratelbank, Schaumkalk bank members). These beds can be



Fig. 5 Simplified cross section through the Leinetal Graben (after Siegesmund et al. 2020)

lithologically very variable (e.g., yellow, dedolomitized limestone: "Gelbkalke", laminated micritic, oolithic and shell-detrital limestone with intercalated hardgrounds; see Kedzierski 2000 for a representative overview). The Middle Muschelkalk (Karlstadt, Heilbronn, Diemel formations; Illyrian?) reflects a regressive episode with the deposition of evaporitic units (gypsum, anhydrite, halite), dolomites and brittle, marly lime and claystone. Solution breccias occur (see section in Dünkel and Vath 1990, pl. 2). The transgressive sediments of the Upper Muschelkalk (Trochitenkalk Formation, 10-16 m) reflect a shallow marine depositional system, and mass accumulations of disarticulated (rarely articulated) Encrinus liliiformis alternate with more oolithic limestone (von Koenen 1908; Stille 1932; Hieke 1967; Nagel et al. 1981; Dünkel and Vath 1990). Progressive flooding of the Germanic Basin is expressed by the Meißner Formation (former "Ceratitenschichten", ca. 40 m), an alternation of dark grey, micritic limestone (up to 40 cm thick) and intercalated, dark marl seams. Characteristic are endemic Ceratitidae (Ammonoidea), which sometimes can occur in great quantities. The most recent data on the Muschelkalk of southern Lower Saxony is found in Farrenschon et al. (2020).

The sediments of the Keuper Group (ca. 550 m, lower Ladinian–Rhaetian) reflect a renewed regression. Mainly fluviatile and flood plain deposits of the Lower Keuper (Erfurt Formation with the Lettenkohlen Sandstone, Anoplophora Sandstone: Bödexen Member; Hauptlettenkohlen Sandstone: Hohehaus Member) are overlain by sabkha deposits (variegated clay, siltstone, dolomitic and sulphatic intercalation: Grabfeld and Weser formations), punctuated by a phase of fluviatile sedimentation and flood plain deposits (Schilfsandstein: Stuttgart Formation; Echle 1961; Arp 2013; Fig. 6) as well as lacustrine episodes (Arnstadt Formation; Arp et al. 2004, Fig. 11). Finally, the Exter Formation of the Upper Keuper (Rinteln, Oeyenhausen, Vahlbruch member; Beutler 2005; Fig. 2), represent first a fluviatile, lateral deltaic/marine depositional system with quarzitic silt and sandstone, dark laminated clay and mica-bearing sandstone (e.g., Jordan 1974; Vath 2005; Barnasch 2010).

The preserved lower Jurassic (Schwarzjura Group, Liassic, 250 m) ranges into the Pliensbachian in the Göttingen area (Stille and Lotze 1933; Arp et al. 2004; Arp 2013) and mainly consists of dark, ammonite-bearing laminated clay with geodia layers intercalated.

Eocene to Pliocene sediments in local subsidence centers consist of fluviatile and limnic sand, gravel, brown coal, and Oligocene marine glauconitic sand (Benda et al. 1968; Nagel et al. 1981; Ritzkowski 1999). Characteristic are large quartzite concretions associated with the brown coal measures. Restricted to the western part of the Leinetal Graben, Miocene basalt (alkali olivine basalt) represent the northernmost extension of the volcanic field of northern Hesse with more than 1000 single occurrences (see Murawski 1951, 1956; Koritnig 1978; Wedepohl 1968, 1987; Schnorrer et al. 2004; Paul 2013 for details). An important Holocene sediment is a freshwater carbonate, referred to as "Duckstein" in the area, which is randomly distributed in the broader vicinity of Göttingen, but Rosdorf and Harste are known as important historical sites with Duckstein quarries.

#### Natural building stones of the St. Johannis Chapel

The natural building stones of the Göttingen area were described and illustrated in great detail by Siegesmund et al. (2020). In particular, sandstone of the Solling Formation (Middle Buntsandstein), limestone of the Jena and Trochitenkalk formations (Muschelkalk) and the Holocene Duckstein are the most important building stones. The Miocene basalt have been excessively used for pavements in the past, but play a minor role as a building stone in walls. Less important, though locally dominant, is Upper Keuper quartzite, siltstone and sandstone (Exter Formation), other sandstone of the Buntsandstein Group and, very rarely, Middle Keuper sandstone (Stuttgart Formation, Schilfsandstein). Accessory are Oligocene/Miocene quartzites. A compilation of all natural building stones in the broader vicinity of Göttingen is compiled in Fig. 6 with some data on its specific use. Of the 10 stratigraphic intervals with natural building stones listed in the above work, 9 can be found in the walls of the Lütgenrode Chapel (Figs. 7, 8). In addition, two fragments of marine lower Jurassic siltstones occur exclusively here. A short description is given below in a stratigraphically ascending order.

- Brick-red sandstone (Middle Buntsandstein, Hardegsen Formation?). Particularly in the walls below the roof but also randomly distributed, a red-orange to brickred fine to middle sandstone variety occurs, exhibiting horizontal lamination and cross-bedding. Biotite and muscovite are dispersed throughout, and small white patches represent kaolinitized feldspar. From all cooccurring sandstone, it can be readily distinguished by its colour. Its lithostratigraphic position is unclear, but Herrmann (1968) describes such brick-red sandstone from the Hardegsen Formation (Fig. 7e).
- Red sandstone and 3. Green sandstone (Solling For-2. mation, Middle Buntsandstein). The most common working stones in the walls of the St. Johannis Chapel is sandstone of the Solling Formation (Solling Sandstone), referred to as "Wesersandstein" (Weser Sandstone) in the literature (Lepper and Ehling 2018). It occurs in its green and red (dark red to red-violet) varieties here, and the colour change from red to green is gradual and can be observed even in one stone. The laminated and cross-bedded fine to middle sandstone contains biotite distributed throughout, and muscovite can be enriched on the bedding planes. Rip-up clasts occur in some stones. The matrix is calcareous, and small pits (0.5–1.0 cm) result from back-weathering of small carbonate concretions, which are sometimes still preserved. Solling Sandstone rubble was used in the walls, often implemented with bedding vertically oriented. Well-elaborated building stones with smoothed surfaces are used for edges and embrasures (Fig. 7c, d) and were implemented horizontally in relation to the bedding. As shown below, the orientation of the bedding planes have an immediate impact on the degree of rock deterioration
- 3. Grey limestone (Muschelkalk). Small fragments of whitish, micritic limestone with fossil debris are randomly distributed in each wall. It is impossible to relate these stones to any of the Muschelkalk units providing natural building stones (Jena Formation: Lower Muschelkalk, Trochitenkalk & Meissner formations: Upper Muschelkalk; see Fig. 7b).
- 4. Schilfsandstein (Stuttgart Formation, Middle Keuper). An eye-catching lithology is the Schilfsandstein (siltstone to fine sandstone) due to its particular grey–vio-

let to greenish colours (Fig. 7a), often with well-developed ripple laminations. Typically, back-weathering occurs along the lamination, accentuating the internal sedimentary structures.

- 5. Quartzite (Exter Formation, Upper Keuper). The quartzite is beige to grey (Fig. 8c). Sometimes, a faint lamination is visible. When altered, the surfaces are brownish. Due to its hardness, no back-weathering occurs. Bed thickness does not exceed a few tens of cm.
- Rhaetian Sandstone (Rhätsandstein, Exter Formation, Upper Keuper). The often cross-bedded, middle to coarse sandstone can be separated from other sandstone by its brownish to dark brownish surface staining (Fig. 8d). Small biotite and altered feldspar occur.
- 7. Silt to fine sandstone (Exter Formation, Upper Keuper). This unit incorporates poorly cemented and often strongly back-weathered yellowish to greyish-green silt and sandstone, often exhibiting beautiful ripple laminations and convolute bedding (Fig. 8e). Bioturbation occurs sometimes. With increasing cementation, there is a gradational shift towards the quartzites.
- Grey greenish siltstone (probably lower Liassic, Lower Jurassic). Only two fragments of this well-cemented siltstone were discovered. Characteristic is its marine bioturbation (Fig. 8b) and ripple lamination. Due to its cementation, weathering along bedding planes results in sharp ridges.
- 9. Basalt (Miocene). In the Göttingen area, basalt was quarried and manufactured in several large quarries paving stones. Historically, it was an important natural building stone, and in the past it was used excessively in the Göttingen area (Siegesmund et al. 2020). Today, only sparse remains of historical basalt pavements are preserved. The basalt was hardly used for ascending walls, except of very rare exceptions (e.g., the cemetery chapel of Hettensen near Göttingen). Instead, it sometimes occurs in the pedestal of buildings, where basalt was available (comp. Siegesmund et al. 2020). In the walls of the St. Johannis Chapel in Lütgenrode, a single basalt rubble was detected, ca. one metre below the roof in the easternmost part of the southern wall.
- 10. Freshwater carbonate (Holocene). The white to grey Duckstein is characterized by up to several cm-large pores and tubes, resulting from the encrustation of large phytodebris and stalks in situ (Fig. 8a). Microbial lamination and stromatolitic textures are common (see Siegesmund et al. 2020 for detailed discussion). In the walls of the Lütgenrode Chapel, Duckstein was characteristically used to construct the pressure arches—a feature seen in the entire region. Further Duckstein rubble occurs randomly distributed in the walls. Often, Duckstein shows black discoloration as a result of modern air pollution.



**«Fig. 6** Lithostratigraphic overview from the Buntsandstein to the Holocene in the Göttingen area (modified after Siegesmund et al. 2020). B.F. Bernburg Formation, Detf. Fm. Detfurth Formation, Hard. Fm. Hardegsen Formation, K/H/D Fm. Karlstadt/Heilbronn/Diemel Formation, TK Trochitenkalk Formation, Meißner Formation, Erf. Fm. Erfurt Formation, S.F. Stuttgart Formation, MA Middle Ages

## Results

#### Lithological mapping of the St. Johannis Chapel

#### South side

The red and grey-green sandstone of the Solling Formation dominates the visual appearance of the south side not only because of their sheer quantity, but also because the ashlars are significantly larger than the ones of the other lithologies (Figs. 9, 10, 11, 12). While 36% of the masonry is made of the red variety, about 20% consists of ashlars of the greygreenish variety. The lower and side window areas as well as the corner stones are built exclusively from sandstone blocks of the Solling Formation. Subsequently, the quartzites and silt and fine sandstone of the Exter Formation are most represented with 16% and 12%, respectively. These two lithotypes were used particularly often in the eastern part of the south wall. Please note that the percentages refer to the absolute quantity of ashlars and do not represent the proportion of the areal utilization of the individual lithologies, since the size of the ashlars may vary significantly.

The Schilfsandstein was only used sporadically (up to 2% on the south side). Slightly more often, with 7%, Duckstein ashlars are found in the masonry, which were primarily used for the lintels area to build a pressure arch. A brickred sandstone, which could only rarely be mapped in the rest of the area, is mostly found below the roof. Roof tiles and bricks (2%), the limestone of the Muschelkalk Group (<2%) and the sandstone of the Rhaetian Exter Formation (1%) are occasionally dispersed in the masonry. In the upper eastern part of the south wall, a basalt block from the Miocene is used. In the currently statically secured area of the eastern part, the areas, where elongated fragments of silt and fine sandstone are particularly often used are in critical condition.

#### West side

As on the south side, the two sandstone varieties of the Solling Formation are the most common with 36% (red variety) and 25% (grey–green variety). Red sandstone occurs more often in the lower area and the grey-greenish variety in the upper area (Figs. 9, 10). Most of the brick-red to fleshcolored Hardegsen Sandstone can be found in the top layer of the masonry. In terms of surface area, the siltstone and fine sandstone of the Rhaetian (Rhätsandstein) make up only a very small part of the western wall of the chapel. Nevertheless, they are available in quite a large number of ~9%. The Holocene Duckstein cobbles are inserted above the lintel and at moderate to high altitudes of the masonry wall. Roof tiles and bricks (3%), quartzite (~7%), Schilfsandstein (4%) and the sandstone of the Rhaetian (<3%) are applied irregularly. Two grey siltstone can be found, one in the lower southern part of the west side, one in the eastern wall: they probably belong to the Schwarzjura Group (Liassic).

#### North side

The red and grey-green sandstone blocks of the Solling Formation account for almost two thirds (61%) of the masonry on the north side. Apart from the areas below the roof and the lintel, they clearly dominate the western part of the north side (Fig. 12). As on the south and west sides, the flesh-colored Hardegsen Sandstone and the Duckstein have been used sporadically (< 3% each). In the eastern part, less sandstone of the Solling Formation have been used. Instead, the application of quartzite and Rhätsandstein is increased. Between the lower and upper window opening, a rather wide area is noticeable, which largely consists of Schilfsandstein. This area ends abruptly in the center of the north wall, where the seam between the older and newer parts of the chapel is located. The construction joint is not as pronounced as on the south side, given that the former corner blocks are no longer there. This goes back to the destruction of the north wall at the end of the 15th century. Due to their increased use in the eastern part of the north side, the Schilfsandstein, Rhätsandstein and quartzite reach percentages of 11%, 4% and 12%, respectively. The limestone of the Muschelkalk as well as roof tiles and bricks are only sporadically scattered in the northern facade. The western part of the north side is the only larger and contiguous area in which remnants of plaster have remained on the outer walls of the chapel.

#### East side

A unique feature of the east side is the more frequent use (31%) of quartzite from the Exter Formation. The red sandstone of the Solling Formation and the siltstone and fine sandstone of the Rhaetian follow with 24% and 15%, respectively. The grey–green Solling Sandstone is comparatively rarely used (6%), mainly below the roof and as a corner stone (Fig. 13). Characteristic for the east side are the walled-up embrasures, which are surrounded by Rhätsandstein. Probably in the course of a reconstruction in 1592, a former window opening in the lower half of the facade has been bricked up with Duckstein, Schilfsandstein, rocks of the Exter Formation and red Solling Sandstone. Duckstein blocks make up around 10% of the lithology on the east side and are often



◄Fig. 7 The building stones of the Lütgenrode Chapel. a Schilfsandstein (Stuttgart Formation, Middle Keuper; picture width: 25 cm). b Limestone (Muschelkalk; width of the figure: 8 cm). c Red Solling Sandstone (Solling Formation, Middle Buntsandstein; width: 31 cm). d Grey Solling Sandstone (width: 37 cm). e Red Sandstone of the Hardegsen Formation (Middle Buntsandstein; width 25 cm)

located in the area around the notches. The Schilfsandstein ashlars are distributed throughout the masonry and correspond to 6% of the rocks used on the east side facade. All other lithotypes are only occasionally used. In Table 1, all mapped rock types are presented with their respective occurrence within the four outer walls of the chapel and their most important identifying features. Figure 14 illustrates the most common lithologies on the respective sides of the building in the form of pie charts.

#### Damage types and weathering features

The main types of damages were classified according to the "Illustrated Glossary on Stone Deterioration Patterns" of the International Scientific Committee for Stone (ICOMOS-ISCS) (Vergès-Belmin 2010) and divided into the groups: cracks and deformations, detachment, forms of material loss and discoloration/deposit (Figs. 15, 16, 17). The discoloration and deposit group as well as the biological colonization of the glossary were combined in the discoloration/deposit category.

#### **Cracks and deformation**

The St. Johannis Chapel suffers from numerous hairline cracks and fractures in the masonry (Fig. 12). Hairline cracks are narrow cracks less than a millimeter wide and can be found in almost all types of rock (Vergès-Belmin 2010). Fractures are cracks that completely cross the rock. These are partly due to larger crack systems in the masonry.

#### Detachment

Bursting is the local loss of the rock surface due to internal pressure. In general, these occur in the form of an irregularly defined crater. Chipping describes the breaking out of pieces from the edges of a rock. Both types of damage have been combined for the damage mapping. In Fig. 16 for example, the upper area of the inscription stone has broken out over a larger area. Examples of minor spalling features are displayed in Fig. 17. Sanding is a special term for the granular disintegration of, i.e., sandstone and granite. It is the result of a lack of grain bonding that leads to a superficial loosening of individual grains in the grain size class of sand. It usually leaves a rough surface and the loosened rock material is often deposited below the affected stone. Sanding often occurs in conjunction with the rounding of sandstone (Fig. 16). The formation of scales is driven by surface parallel detaching of rock material with a shell-shaped appearance. In doing so, it does not follow the rock texture, and the thickness of the scale is smaller than its area (Vergès-Belmin 2010). The scales on the St. Johannes Chapel range from a few millimeters to a few centimeters in thickness (Fig. 16a, c, d). Flaking is a subtype of scaling and defined as detachment in the form of thin, flat or curved flakes. These are usually in the millimeter range and have a similar arrangement to fish scales (Fig. 16f). The detachment of sharp, slender pieces that split off or break off from the rest of the stone, is known as splintering. At the St. Johannis Chapel, this damage phenomenon occurs mainly on siltstone, and therefore, the detached pieces of rock are less sharp than fragments from other lithologies.

#### Features induced by material loss

The loss of stone material on the St. Johannis Chapel can be characterized by a variety of weathering features. Among them are variable erosion forms like the loss of less resistant components (e.g., clay lenticles, pumice clasts or fossil fragments) or the loss of matrix material, which results in protruding of the more compact stone components (Fig. 17c). A special form of back-weathering of less resistant components can be observed on many sandstone ashlars of the Solling Formation. Small cavities of around 5-10 mm diameter result from the back weathering of small carbonate concretions (Fig. 17b). In addition, larger cavities, which were probably created by weathered rip-up clasts (<3 cm in diameter), can be observed. In these notches, clayey residues can be found. For the damage mapping, both weathering phenomena were combined as one. A frequently observed weathering phenomenon on sedimentary rocks is fabric controlled back-weathering. Some silt and fine sandstone of the Exter Formation, as well as some ashlars of the Schilfsandstein and the Solling Formation show clear back-weathering along the same layers, which leads to a striped appearance (Fig. 17d). Another feature is the rounding of originally angular stone edges, leading to a distinctly rounded profile (Fig. 16e). Rounding can especially be observed on stones, which preferably deteriorate through granular disintegration, like sandstone.

#### **Discoloration and deposit**

In the base area of the St. Johannis Chapel, many stones are covered with salt crusts and efflorescence (Fig. 15e). These are formed in the presence of high concentrations of soluble salts as a result of wet–dry cycles. Soiling is a very thin deposit of foreign particles that give the rock surface a dirty appearance. It can be the result of industrial or traffic-related



Fig. 8 The building stones of the Lütgenrode Chapel. a Duckstein (Holocene; width of the window: 120 cm). b Grey siltstone (Lower Liassic, Lower Jurassic; width: 31 cm). c Rhaethian Quartzite (Erfurt

Formation, Upper Keuper) as river gravel (width: 11 cm). **d** Rhaethian Quartzite (width 30 cm). **e** Rhaetian silt- and fine sandstone (width: 30 cm)



Fig. 9 Lithological mapping of the western part of the south side of the St. Johannis Chapel in Lütgenrode (width of the mapped wall ca. 8.10 m; comp. Fig. 2)

pollutants (e.g., soot). Increasing adhesion and compaction can cause crusts (in this case black crusts) to form. Such crusts arise primarily in areas that are protected from precipitation and run-off water. In contrast to soiling, the crusts adhere more strongly to the rock and rock material is often separated off when it is detached. Chemically, they consist of a matrix of gypsum that fixes the foreign particles. Figure 16c shows black crust on calcareous rocks. Brownish and reddish iron crusts are often present on quartzites, as well as on siltstone and fine sandstone. Due to their coloration, they differ significantly from dirt and black crusts. Furthermore, yellowish to orange iron accumulations are present on the Schilfsandstein and the grey–green Solling Sandstone (Fig. 16b). Hereafter, the two phenomena under iron accumulation are considered together. Bird droppings are a frequent type of deposit observed on the stones' surface. In addition, sand grains were accumulated by the sanding of the sandstone. The St. Johannis Chapel is subjected to a wide range of biological colonization. It ranges from microorganisms such as bacteria, cyanobacteria, algae, fungi and lichens up to higher plants and the construction of nests or housing for animals. Grey and orange lichens, that form patches of millimeters to centimeters in size, are common. Green algae and higher plants occur most often in the base area (Fig. 16c, e).



Fig. 10 Lithological mapping of the eastern part of the south side of the St. Johannis Chapel in Lütgenrode (width of the mapped wall ca. 7.40 m; comp. Fig. 2)

## Damage mapping of the St. Johannis Chapel

## South side

Due to the fact that the eastern part of the south side was covered by construction measures for static reinforcement,

only the western part could be reliably mapped (Fig. 18). The most common damage is minor chipping and spalling (35%), pollution and black crusts (30%) as well as smaller cavities through back-weathering (26%). These three damage groups are distributed over the entire side of the build-ing. However, the intensity of damage that the rocks have



Fig. 11 Lithological mapping of the west side of the St. Johannis Chapel in Lütgenrode (width of the mapped wall ca. 7.60 m; comp. Fig. 2)

suffered from the three phenomena is quite low. Black crusts are quite rare. Most of the stones are soiled. All other weathering phenomena are significantly less present (< 10%).

Particularly noticeable are scaling with 9%, rounding with 8% and sanding with 7%. They mainly occur in the lower parts of the building. Sanding and rounding occur almost exclusively on the red sandstone of the Solling Formation. Scaling also occurs in higher areas of the masonry and, in addition, on the grey–green variety of the Solling Formation.

In parts, the intensity of damage caused by scaling, sanding and rounding is enormous. Due to the strong rounding of some ashlars, cavities are created in the former corner areas, which can reach down to a decimeter and ultimately may have a potential negative impact on the static of the building. Salt crusts and flaking in the base area damage the masonry. In addition, the replacement and filling of the masonry by silt and fine sandstone of the Exter Formation, which weather back strongly, create additional extensive cavities. On less weathered siltstones and fine sandstone, the weathering phenomenon of splintering can be observed frequently.

The biological colonization is to be considered subordinate, since less than 4% of the stones are affected by it. In all areas of the facade, isolated ashlars with usually greyish



Fig. 12 Lithological mapping of the north side of the St. Johannis Chapel in Lütgenrode (width of the mapped wall ca. 15.40 m; comp. Fig. 2)

lichen can be found. White deposits have been mapped underneath the roof, which are presumably bird droppings. Cracks and deformations occur scattered on around 6% of the stones. Equally frequent are iron enrichments and iron crusts (7%), which especially can be found on the quartzite of the Exter Formation. Matrix back-weathering is a rarely occurring form of material loss, with < 1% of the stones affected. In the critical areas of the statically secured eastern part, the silt and fine sandstone often show vertical fractures, with opening widths in the centimeter range. Rounding and partly strong back weathering are common features and, in some areas, the superficially applied mortar is already completely decayed.

#### West side

The damage mapping on the western facade is shown in Fig. 19. As on the south side, the highest damage intensity occurs in the lower area of the masonry, where rounded and sanding sandstone dominates. However, also in the higher parts of the facade, some ashlars show the same weathering phenomena. Salt crusts, biological colonization and sometimes very intensive scaling and flaking can be observed near the ground. Cracks and deformations also occur preferentially in the lower area and affect almost 10% of the masonry. Smaller chipping and spalling are the most common weathering phenomena (48%), but do not result in high damage intensities. They are followed by soiling and few

black crusts (42%). Around 4% of the stones show yellowish-orange to brownish iron accumulations or iron crusts. The holes of the sandstone varieties that were created by the back-weathering of carbonate concretions characterize a third of the total surface (34%).

#### North side

Soiling and black crusts (63%) as well as smaller spalling and chipping (46%) determine the damage pattern on the north side (Fig. 20). The presence of high amounts of black crusts could originate from the north-facing position. As the wind predominantly comes from the west or south all year round, the resulting lower exposure to precipitation leads to an undisturbed adhesion of atmospheric particles that form these crusts.

The sandstone varieties show characteristic cavities as well as clear rounding and sometimes heavy sanding in the lower to middle parts of the facade. In some of the sandstone ashlars of the Solling Formation, weathered rip-up clasts can be found. The red sandstone show particularly high damage intensity due to scaling, when the bedding is oriented parallel to the surface. Looking at the entire north face, scaling has been mapped on around 5% of the ashlars.

Only 1% of the stones were affected by biological colonization. Cracks and deformations as well as chipping and bursting were found in 6% and 1% of the ashlars,



Fig. 13 Lithological mapping of the eastern side of the St. Johannis Chapel in Lütgenrode (width of the mapped wall ca. 7.60 m; comp. Figure 2)

respectively. Pidgeon droppings can be found below the roof. In the base area of the north side, some sandstone and quartzite ashlars show salt loads that range from weak salt efflorescence to pronounced salt crusts.

## East side

The damage pattern of the masonry of the east side is less diverse than on the other sides of the building. Especially soiling and black crusts dominate the appearance (66%) (Fig. 21). In contrast to the south and west sides, black crusts

Lithotype	Abbr	Color code	Stratigraphy	Perc	entage	e frequ	en
				N	W	Е	S
Sandstone red	SSr		Lower Triassic (Solling Fm)	42	36	24	3
Sandstone grey–green	SSg		Lower Triassic (Solling Fm)	18	25	6	1
Siltstone	SL		Lower Jurassic (Schwarzjura Group)	_	0.1	0.1	C

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Sandstone red	SSr	Lower Triassic (Solling Fm)	42	36	24	36	Red to dark red	Carbonaceous matrix, weath- ered carbonate concretions
Sandstone grey-green	SSg	Lower Triassic (Solling Fm)	18	25	6	19	Grey-green to beige	Carbonaceous matrix, weath- ered carbonate concretions
Siltstone	SL	Lower Jurassic (Schwarzjura Group)	-	0.1	0.1	0.1	Grey-green	Ripple bedding, marine bioturbation
Limestone	МК	Middle Triassic (Muschelkalk Group)	0.1	4	2	2	Light grey to grey	Micritic matrix, fossil detritus
Travertine	Trv	Holocene	3	6	10	7	White to grey	Very porous, a lot of black, gypsum crusts and soiling
Schilfsandstein	SSt	Upper Triassic (Stuttgart Fm)	11	4	6	2	Grey-purple to green	Ripple bedding, cross-bedding
Rhätsandstein	RS	Upper Triassic (Exter Fm)	4	3	3	1	Beige to light brown	Medium to coarse sand, cross- bedding
Quartzite	Qzt	Upper Triassic (Exter Fm)	12	7	31	16	Beige-grey to dark grey	Conchoidal fracture, fine lamination
Silt- und fine sandstone	SF	Upper Triassic (Exter-Fm)	5	9	15	12	Yellow-beige to grey-green	Convolute lamination, strong back weathering
Sandstone (Hardegsen)	SH	Lower Triassic (Hardegsen Fm)	3	5	2	3	Reddish-orange (flesh- colored)	Parallel and cross-bedding, many biotites and kaolinised feldspars
Bricks and roof tiles	Dz	Anthropogene	2	3	1	2	Reddish-orange	-

Rock color

Characteristic features

are more common than soiling. Most of the rocks have dark crusts, especially in the lower parts. This is probably because a neighboring residential building protects huge parts of the east facade from precipitation. Minor spalling and chipping have been mapped on almost every second ashlar (45%). Iron enrichment and iron crusts are common (12%). The rather high occurrence of iron crusts is due to the increased number of quartzites applied on this side, which are more susceptible to this type of damage. Cracks and deformations occur on around 6% of the ashlars. Elongated cuboids of the silt and fine sandstone and quartzite of the Exter Formation are often broken vertically. In addition, there are vertical crack systems that have resulted in fractures in the mortar and ashlars (Fig. 21). Breakouts and chipping, like the cracks and deformations, are scattered throughout the facade.

Since less sandstone ashlars were used in the east wall compared to the other sides of the building, the rate of holes due to back weathering is comparatively low (6%). In the center of the east side, many siltstone and fine sandstone components are located, which are characterized by fabriccontrolled back weathering. Salt crusts, biological colonization, rounding and sanding are only found sporadically on the east side. Matrix back-weathering, splintering and flaking do not occur. As on the south and north sides, deposits of bird droppings can be found on a few rocks of the upper part.



Fig. 14 Comparison of the most common lithologies of the respective building sides of the chapel. The percentages of the lithotypes corresponds to the values given in Table 1



Fig. 15 a Crack formation and rock fragmentation in the grey-green Solling Sandstone (width: 50 cm). b Superficial iron enrichment (width: 30 cm). c Soiling, iron enrichment and biological colonization (width 20 cm). d Vertical fractures as a result of larger crack

structures in the Holocene Duckstein (widht: 50 cm). e Soiling and gypsum crusts on calcareous rocks (width: 10 cm). f Salt efflorescence and loss of material (width: 25 cm)

# Overview and graphical representation of the distribution of the damage types

Table 2 shows all mapped damage and weathering phenomena with their respective frequencies on the four sides of the chapel. Figure 22 compares the incidence of damage phenomena on the respective sides of the building. Ashlars that showed no damage were not taken into account.

#### **Rock physical properties**

To evaluate the construction suitability of the individual building stones, their petrophysical properties were determined in laboratory experiments and onsite measurements. Representative samples of all lithologies were sampled from the immediate vicinity. In addition, three sandstone varieties from the Solling Formation, namely, Weser grey (WG), Weser red (WR) and Uder (UD), were evaluated, as they could potentially be considered as regional exchange material for the predominantly used Solling Sandstone (SSr).

Many rocks show a pronounced anisotropy, expressed by a directional dependence in their technical properties. Therefore, the test specimens were oriented with regard to a Cartesian X-Y-Z coordinate system. The XY plane represents the bedding plane, with the X direction set parallel to the lineation. The Z direction is oriented perpendicular to the bedding plane. The petrophysical properties determined for the individual rocks can be found in Table 3.

#### Pore space properties

A majority of the technical parameters of stone are directly or indirectly influenced by the pore space, as they are controlled by the type and shape of pores, their size and distribution, as well as their cross-linking. The effective porosity (accessible to fluids and gases) as well as the bulk and matrix densities were determined on sample cubes of 65 mm edge length by hydrostatic weighing according to DIN EN 772–4. The pore radii distributions were determined on sample fragments according to DIN 66133 by mercury intrusion porosimetry (MIP).

Extraordinary high porosity is shown by the Duckstein (Trv), with 39.7 vol% and an accordingly low bulk density of 1.58 g/cm<sup>3</sup> (Table 3). The rest can be divided into two groups according to their porosity: (1) very porous rocks with porosities between 10 and 20 vol% (RSc < SSr < SF < SH < SSt < UD in ascending order) and (2) intermediate to less porous rocks with porosities between 2 and 10 vol% (MK < MK–TK < WG < QZ1 < WR < RSf < TK < QZ2 < QZ4 < QZ3 in ascending order). With the exception of RSf, the less porous rocks of group 2 are characterized by mean pore radii < 1 µm. The highly porous rocks show mean pore radii up to 9.69  $\mu$ m (SSr), but not exclusively, as smaller radii are also observed (QZ3, SSt). In most of the investigated rocks the fraction of capillary pores clearly dominates (up to 90%) (Fig. 23). Only the less porous MK, MK–TK and WR exhibit higher fractions of micropores.

#### Water absorption and transport

Water is recognized as the main driving factor for inducing deterioration processes in natural stones (Mirwald 1997; Siegesmund and Dürrast 2011; Snethlage 1984), for example by inducing clay swelling mechanisms or the distribution of harmful salts into the pore space. Therefore, the overall capability and intensity of water absorption as well as the connectivity of the pore network were determined.

The total water absorption was determined under voluntary (atmospheric) and forced (vacuum) conditions by total immersion. The quotient of both values is described by the dimensionless saturation coefficient S and allows for the estimation of the frost resistance of the stone after Hirschwald (1912). The S value ranges between 0 and 1. Values < 0.75 point to a weathering and frost resistant rock, while the frost resistance is uncertain until further investigations with values between 0.75 and 0.9. Rocks with S values > 0.9 are classified as not weathering and frost resistant. The capillary water absorption coefficient (*w*) describes how much water the material can absorb due to capillary forces over a certain area and time and was determined according to DIN EN ISO 15148 on sample cubes of 65 mm edge length in a closed cabinet while weighing over time.

The majority of the investigated rocks absorb between 0.7 and 6.5 wt% water under atmospheric conditions and up to 9.3 wt% (UD) under forced conditions (vacuum). Lithologies that obtain a lower fraction of capillary pores, typically absorb less. The Duckstein is an overall exceptional case, with an extraordinary high water absorption of up to 25 wt% (vacuum). With an S value of 0.65, it is, however, classified frost resistant according to Hirschwald (1912). As most of the other lithologies SSr, MK, QZ2, QZ3 and QZ4, however, show values between 0.75 and 0.9, and their frost resistance is according to Hirschwald (1912), uncertain until further investigation. The w values range between almost no capillary water uptake (e.g., MK and MK-TK with 0.2 kg/  $m^2\sqrt{h}$  to extremely high capillary water uptake of up to 18.7 kg/m<sup>2</sup> $\sqrt{h}$  (Trv), whereby lithologies with higher porosity and fractions of capillary pores show the highest values (Table 3). The water uptake is generally higher in the X direction parallel to the bedding, indicating a better pore connectivity in this direction. The in situ measurements with the Karsten tube illustrate these different water absorption capacities and directional dependencies very clearly (Fig. 24).



◄Fig. 16 a Scaling of red Solling Sandstone (width 45 cm). b Different orientation of sandstone ashlars; bedding parallel to the surface (left) or vertical to the surface (right) (width: 60 cm). c Large scales are often present if the ashlars are installed parallel to the bedding (width: 19 cm). d Progressive weathering into the core of the stone results in surface parallel scales and cracks (width: 42 cm). e Rounding and sanding of red Solling Sandstone on the southern facade (width 90 cm). f Spalling and flaking phenomena are present on many sandstone surfaces (width: 7 cm)

#### **Mechanical properties**

The mechanical properties define how long a material can withstand stress before it yields, and, therefore, characterize its strength. In this study, several destructive and non-destructive techniques were applied onsite and in the laboratory.

The ultrasonic P-wave velocity was determined via direct transmission of the ultrasonic travel time through a respective travel distance according to DIN 14579 (2005) (with a frequency of 350 kHz). As a non-destructive technique, it allows for the estimation of the rock strength (Sharma and Singh 2008). The ultrasonic velocities of the investigated lithologies range widely between 2.2 km/s (UD) and 5.2 km/s (MK), with the highly porous rocks typically showing lower velocities than the low porous rocks (Table 3). Many rocks show anisotropic behavior, with higher values parallel to the bedding (X direction). The often used Hardegsen Sandstone (SH) exhibits particular low ultrasonic velocities (2.5 km/s) that are only undercut by the Uder Sandstone (UD) (2.2 km/s). The low values indicate a reduced strength in both rocks. This has to be evaluated critically, especially for the Uder Sandstone (UD), since it is considered a potential exchange material.

Another non-destructive technique that allows for the strength characterization of rock material, is the surface hardness (Desarnaud et al. 2019; Wedekind et al. 2016). It was conducted via a Schmid hammer of the Equotip3 type from the Proceq Company. The values are expressed in Leeb Hardness (HL) and range from 265 to 799 HL. The highest values are achieved by the quartzite, the Weser Sandstone (WG, WR) as well as the Muschelkalk limestone and represent high rock strength (Table 3). The increased surface hardness of the Weser Sandstone coincides with their increased ultrasonic velocities and point to an overall higher rock strength than the Solling Sandstone. The surface hardness of the Uder Sandstone (UD) is slightly increased compared to the Solling Sandstone. However, together with the results from the ultrasonic measurements, it seems that UD is characterized by a lower overall rock strength.

To visualize the weathering profile from the stone surface into its core, the drilling resistance was measured insitu on two selected ashlars from the mainly used Solling Sandstone. The drilling machine drives a 3 mm drilling bit into the stone surface, keeping the rotation and the pressing force constant. A coupled chart recorder continuously registers the penetration depth by drawing a line on a paper running perpendicular to it with a speed of 5 mm/s. Figure 25 illustrates very well the difference in drilling resistance on a healthy and a deteriorated Solling Sandstone. The difference between both ashlars is enormous. A scale of several millimeters on the deteriorated Solling Sandstone could be clearly illustrated. However, even behind the scale the weathering into the core of the stone appears to be progressive, as the increase in drilling resistance is lower compared to the unweathered example.

#### Weathering behavior—hydric expansion

The hydric expansion was measured on cylindrical samples of 50 mm length and 15 mm diameter under conditions of complete immersion in demineralized water following DIN 13009. A displacement transducer with a resolution of 0.1  $\mu$ m measured the linear expansion as a function of time.

Except for the Duckstein (Trv), all samples react with an expansion process to water immersion. The expansion values range from barely anything (0.04 mm/m for RSf) up to 0.49 mm/m (SH) (Fig. 26). The maximum values are typically reached perpendicular to the bedding (Z direction), indicating anisotropic behavior. Increased hydric expansion often coincides with high porosity and capillary water absorption capacity (seeTable 3). From the potential exchange material, Weser red (WR) shows an increased hydric expansion potential (up to 0.34 mm/m), which is more than double the amount of the Solling Sandstone. Both Weser grey (WG) and Uder (UD) exhibit significantly lower expansion potential and may be evaluated more positively in this regard.

### **Conclusions and discussion**

"Leave the church in the village" is the slogan with which the residents of Lütgenrode are fighting to preserve the historic St. Johannis Chapel of Lütgenrode. Especially the rural churches are of central importance for the history and future of small communities. Churches have always been political, social and cultural spaces, which in modern times, especially in rural areas, represent an important public community space, with which the people also connect parts of their own life. The church, which can be seen from far away, continues to provide identity and a sense of home. Unfortunately, many of these rural cultural monuments are in a critical state, because urgently required (expensive) restorations



◄Fig. 17 a Surface parallel flaking and scaling on the Schilfsandstein (width: 45 cm). b Selective dissolution of carbonatic concretions (width 13 cm). c Loss of matrix leading to protruding of more resistant components (width 7 cm). d Extreme example of fabriccontrolled back-weathering in the form of splintering (height: 60 cm). e Formation of salt crusts on rocks in the base area of the chapel (width: 55 cm). f Expansion processes leading to scaling parallel to the bedding (width 33 cm) were postponed in favor of cheaper punctual repairs. Often enough, architectonically and historically the most valuable among them are located in structurally weak regions. If such objects are listed as an important cultural heritage, there is hope that something will be done to preserve them. However, the St. Johannis Chapel in Lütgenrode is not the only church which needs an urgent reconstruction belonging to the church office Göttingen–Münden. The funds of the church office for the preservation of all churches, which



Fig. 18 Damage mapping of the eastern part of the south side of the St. Johannis Chapel in Lütgenrode



Fig. 19 Damage mapping on the west side of the St. Johannis Chapel in Lütgenrode



Fig. 20 Damage mapping on the north side of the St. Johannis Chapel in Lütgenrode

includes about 80 churches and chapels, are limited. A conflict exists, because the "value" of a church is measured by the size of the Christian community and the expected visitors of the church. This approach does not consider the architectural value, nor does it support the political attempts to stop the rural exodus. Because numerous rural churches have also become centers for secular activities-concerts, readings, open churches for anybody who wants to rest etc .-- its meaning reaches often far beyond pastoring and worship services in many communities. Because the Church in Germany is directly funded by a church tax, and taking into consideration that numerous rural churches have been administered in the past but not maintained, it could be argued that there exists a general moral commitment and a liability towards society to compensate for this negligence. In particular, where an 800-year-old chapel is about to lose its structural integrity and restoration is urgently required to save the historical monument, the taxpayer must expect action and the protraction as experienced is hardly comprehensible.

Because the St. Johannis Chapel in Lütgenrode is in a desolate state due to its acute structural defects, it was closed for a time and provisionally structurally secured. The massive damage, especially to the south wall of the chapel, is mainly due to moisture penetration and a weakening stiffness of the outer wall. This considerably damages the existing gypsum, clay and lime mortar. Together with the existing cement-containing injection mortar, this leads to an increasing and significant state of decay. As a result of the many different mortars, there are also salt formations and salt migrations, whereby the natural stones in lower areas also develop considerable forms of damage. For an effective repair concept, this means that the water ingress must be significantly reduced to eliminate the cause of the damage. After the structural repair or plastering the south and west sides can be an effective moisture protection. However, the repair is subsequently described via a qualitatively executed jointing to maintain the quality of an exposed masonry. Stone damage in the base area can predominantly only be repaired by stone replacement or material supplementation. For dealing with less damaged stone surfaces, restorative measures can be considered, such as the strengthening of stone surfaces by the addition of binding agents, the reworking of stone surfaces or the binding of detached stone material.

Due to the very long history of damages and repairs in the ascending walls of the Lütgenrode Chapel, many different natural stones have been used. The goal must be to largely secure and save the historical inventory through repair work. In this context, it seems particularly desirable to minimize the progressive and sometimes critical weathering of the natural stone. It is often necessary to replace historic



Flaking

 $\diamond$ 

Splintering

Fig. 21 Damage mapping on the east side of the St. Johannis chapel in Lütgenrode

Cracks and deformation

N

Table 2 Overview of the used symbols and the percentage of the individual damage phenomena related to the ashlars

Damage phenomena	Legend/color	Abune	dance in %		
		N	W	Е	S
Cracks and deformation	M	6.0	9.0	5.0	6
Bursting/chipping	В	1.0	3.0	3.0	1.0
Sanding	$\bigcirc$	7.0	6.0	0	7.0
Scaling	S	5.0	16.0	2.0	9.0
Flaking	$\blacklozenge$	2.0	1.0	-	3.0
Spalling	Ă	45.0	48.0	45.0	35.0
Loss of matrix		0.5	1.0	_	1.0
Rounding		11.0	8.0	1.0	8.0
Fabric controlled back-weathering		0.2	2.0	2.0	2.0
Holes due to back-weathering		19.0	34.0	6.0	26.0
Biological colonization	***	1.0	5.0	0.5	3.0
Iron rich patina		8.0	4.0	12.0	7.0
Soiling/black crust		63.0	42.0	66.0	30.0
Salt crust		1.0	1.0	0.1	1.0
Back-weathering		0.1	1.0	0.1	1.0
Splintering		2.0	1.0	_	2.0

**Fig. 22** Comparison of the frequencies of damage phenomena on the four sides of the building (for details see Table 2)



natural stone material for structural and safety reasons, and the effort is usually to reuse the same stone material. When looking for possible replacement stones, it is not only the comparability with the original stones to be replaced that is decisive, but also their compatibility with all other natural stones in the building.

Renovating the outer masonry requires uncovering the base of the wall at a depth up to approximately 1.0 m and up to 1 m in width. Renewal of the jointing with moisture resistant and compatible mortar is essential. Plastering in the area in contact with the ground to reduce moisture penetration, clay sealing close to the surface at least on the south and west sides, renewal of the main conduit are in question.

The renovation of the southern masonry is not only necessary for structural reasons. The usual injection techniques with needling are not suitable because of the high water ingress. The aim is to completely remove the injection mortar and consolidate the masonry by rebuilding it, with the aid of the emergency support, which was already designed as an assembly support at the time. The goal is to retain as much of

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the historic building surface as possible. This requires smallscale work under the daily supervision and instruction of the specialist site management. In the area of emergency support, step-by-step deconstruction and full-depth masonry reconstruction will be required. De-jointing, removal of the injection mortar under assembly securing, reconstruction, stone replacement up to 20% of the total facade and the replacement of corroding needling from 1972 are under discussion.

For the masonry of the east facade, west facade and north facade, complete de-jointing, masonry protection and reconstruction is inevitable. To prevent the complete exchange of the masonry a stepwise injection method for different cracks widths must be applied. Different resins, resin modified mortars or crack bridging by adhesives are important tools for the reconstruction. Stone replacement or the use of stone replacement mortars are also under discussion. The resulting replacement material has to show similar properties, aesthetics and weathering behavior like the original rock.

In the past, guidelines in the preservation of historic buildings usually focused on examination, action and

Sample ID	SSr	MK	MK-TK	ΤK	Trv	HS	QZ1	QZ2	QZ3	QZ4	RSf	RSc	SF	SSt	MG	WR	IJ
Porosity [vol%]	15.4	2.3	4.1	9.4	39.7	16.8	6.9	9.5	10.4	9.8	9.0	11.8	16.7	17.4	5.5	7.6	19
Bulk density [g/cm <sup>3</sup> ]	2.14	2.61	2.56	2.34	1.58	2.12	2.40	2.33	2.30	2.32	2.34	2.21	2.21	2.20	2.41	2.47	6
Matrix density [g/cm <sup>3</sup> ]	2.53	2.67	2.66	2.59	2.62	2.55	2.58	2.57	2.57	2.57	2.57	2.51	2.66	2.67	2.55	2.68	5.0
Water absorption vac. [wt%]	7.2	0.9	1.6	4.0	25.0	7.9	2.9	4.1	4.5	4.2	3.9	5.3	7.5	7.9	2.3	3.1	6
Water absorption atm. [wt%]	5.5	0.7	1.2	2.1	16.4	6.5	2.1	3.2	3.8	3.5	2.9	3.9	5.0	5.5	1.5	1.8	6.0
Saturation coefficient S	0.77	0.80	0.72	0.53	0.65	0.83	0.73	0.78	0.84	0.84	0.74	0.73	0.66	0.70	0.67	0.57	0
Micropores [%]	10	89	54	27	16	10	21	30	20	19	16	11	18	31	24	58	Ξ
Capillary pores [%]	06	11	46	73	84	90	79	70	80	81	84	89	82	69	76	42	8
Mean pore radius [µm]	9.69	0.03	0.13	0.80	1.51	2.16	0.44	0.14	0.20	0.25	1.44	4.16	0.40	0.14	0.59	0.06	Э.
SSA via MIP [m²/g] <i>w</i> value [kg/m² √(h)]	2.8	2.2	3.4	2.4	2.6	2.2	1.6	2.4	2.3	2.3	2.3	2.3	3.4	4.5	1.6	4.8	ć.
X	9.9	0.2	0.2	0.6	18.7	10.4	0.8	1.5	1.6	1.4	3.1	4.0	Ι	Ι	0.3	0.4	17
Ζ	9.0	0.2	0.2	0.4	16.5	7.6	0.8	1.1	1.3	0.9	3.0	4.8	I	I	0.3	0.4	4
ø hydric exp. [mm/m]																	
X	ı	ı	0.05	0.08	ı	0.40	0.10	ı	0.25	0.18	0.03	0.10	I	I	I	I	0.
Ζ	0.15	0.08	0.05	0.07	0.28	0.49	ı	0.20	0.37	0.21	0.04	0.14	0.17	0.46	0.11	0.34	0.
MAX	0.15	0.08	0.05	0.08	0.28	0.49	0.10	0.20	0.37	0.21	0.04	0.14	0.17	0.46	0.11	0.34	0.
P wave velocity [km/s]																	
X	3.5	5.2	5.1	4.3	3.3	2.6	3.7	3.5	3.3	3.4	3.4	3.8	3.4	3.3	4.2	4.3	сi
Ζ	3.6	5.1	4.4	4.0	3.2	2.5	3.7	3.4	3.3	2.8	3.3	3.4	3.1	3.1	3.9	4.8	5
Surface hardness	395	649	608	490	265	538	767	756	721	799	757	594	425	596	720	722	4

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Fig. 23 Pore radii distributions of selected building stones of the Lütgenrode Chapel, as well as the potential replacement material

material instructions. Today one decides either for a reconstruction of the former repair interventions or the stabilization of the historically grown appearance. The question arises whether the preservation of the substance is in the foreground or whether the structural repair is distinguished from the historical substance. In addition to the urgently required static safeguarding, stone replacement will be very important for the planned restoration.

The suitability of a potential exchange material for the mainly used Solling Sandstone depends on several factors. In general, the exchange material should exhibit similar petrophysical properties to the original stone, since strongly deviating material behavior may induce stress into the adjacent material, like jointing mortar or neighboring ashlars. As the construction of the Lütgenrode Chapel is somewhat disordered and plenty of inadequate material was utilized in inadequate ways, this factor may be of secondary importance in this specific case.

From the three potential replacement sandstones, the Uder Sandstone (UD) may come closest to the petrophysical properties and weathering behavior of the Solling Sandstone. Uder is likewise a relatively porous sandstone with a similar pore structure that enables water absorption to the degree of the Solling Sandstone. The Weser Sandstone



Fig. 25 Drilling resistance on a deteriorated (left) and unweathered (right) example of Solling Sandstone

Fig. 26 Hydric expansion of selected samples. SSr Solling Sandstone red, MK Limestone Muschelkalk, Trv Duckstein, SH Hardegsen Sandstone, QZ Quartzite, RSf = Rhätsandstein fine, SF silt- and fine sandstone, SSt Schilfsandstein, WG Weser grey, WR Weser red, UD Uder



is characterized by significantly lower porosity and mean pore radii, that cause a far lower (capillary) water absorption potential. The reduced ability of water absorption and distribution into the stone is a big plus. The damage mapping identified many damage phenomena in the base area of the building connected to hydric expansion or salt weathering processes that are strongly influenced by water absorption, distribution and retention. In this regard, the Weser Sandstone may slow down the respective deterioration processes and may prove to be suitable replacement stones. Weser red (WR), however, shows moderate expansion potential upon water immersion and should not be applied in the base area or in water runoff areas. The non-destructive strength characterization by ultrasonic velocity and surface hardness measurements clearly point to the Weser Sandstone as material with higher strength, compared to the less resistant Uder Sandstone (UD).

Considering the specific environmental conditions at the Lütgenrode Chapel, the Uder Sandstone can be considered to be the least suitable exchange material out of the three sandstones investigated. Both Weser Sandstone varieties proved to be the more suitable alternative. The Weser red (WR), however, may potentially suffer from its increased hydric expansion potential. In the laboratory, Weser grey (WG) did not give any indications on future damage potentials and should, therefore, be considered the most qualified replacement material.

Triassic limestone (Muschelkalk), if this group of rocks should be used for the reconstruction, is more difficult to obtain (Siegesmund et al. 2010). The closest quarries are located in Thuringia. Quite a number of limestone comes from the Kirchheim area near Würzburg, all from the Upper Muschelkalk Subgroup (Middle Triassic). The Kirchheim Muschelkalk is a light-brown grey, dense-looking limestone, which is rich in shell fragments that are aligned in shell beds. The weathering resistance is good. Kirchheim Muschelkalk itself has two varieties, Blaubank (blue grey) and Goldbank (grey-brown). The local Duckstein is not available anymore in the Göttingen area, but alternatively, the travertine from Bad Langensalza is still available, and it is an excellent building stone.

According to existing estimates, approximately 435,000 EUR will be necessary for the complete repair work (Göttinger Tageblatt, 09.07.2020). Due to the current price increases in constructions, a total cost of 550,000 EUR seems to be a realistic estimate. The largest share will be for the restoration of the south facade and the interior, where the greatest damage prevails. The emergency protection on the south side will stop the collapse of the already extremely warped facade for a few more years. The dramatic situation with regard to the state of the building does not make it necessary to close the church at this time, as was done several years ago.

As a result of the mapping, the current distribution of natural building stones in the walls of the St. Johannis Chapel is precisely documented. The data base reflects the state of the art, and it enables the recognition of lithotype distribution in the walls, which conveys information about historical phases of restoration. Our mapping preserves, therefore, the potential historic information, which the walls still might carry. To finalize a precise documentation of the status quo, a 3D scan of the entire walls is desirable, and the cost for such a scan plus analyses and depiction should be well below 10,000 EUR. This record of the status quo is important, because any restoration efforts-in our case large scale changeswill inevitably obliterate any historic information. A further aspect may be a conceptual/esthetical issue. Because the repairs in the walls of the St. Johannis Chapel are fundamental, the choice of material for the restoration may enter two paths. First, a restoration could attempt to preserve the historical habitus of the building using natural building stones resembling those needed to be removed. Alternatively, a modern reconstruction could use various materials-steel, concrete, bricks, wood etc.--to fuse the historic core with modern architectural concepts, which would give the building a very unique character.

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## Declarations

**Conflict of interest** The authors declare that there are no conflict of interest.

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