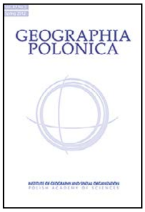

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UNOBVIOUS GEOHERITAGE IN SACRAL BUILDINGS: MILLSTONES IN CHURCHES OF NE POLAND FROM A GEOLOGICAL AND GEOMORPHOLOGICAL PERSPECTIVE

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Abstract

The article highlights the importance of medieval churches with embedded millstones as geocultural objects with a great geotouristic and educational potential. In the lowland areas of Northeastern Poland, 79 millstones and their semi-finished products were inventoried. Their sizes ranged from 70 to 100 cm in diameter. The majority of them were made of erratic boulders, mainly granitoids of Fennoscandian origin. Additionally, gneisses, sandstones, pegmatites, and basaltoid were also identified. An attempt was made to determine the degree of weathering of the millstones over several hundred years of exposure to external conditions. Measurements of moisture content and salinity of the walls surrounding 10 millstones embedded in the walls of 8 churches were taken three times (in spring, summer, and winter). Lower wall moisture was observed in the vicinity of the millstones, but only in the case of three walls, the salinity of the mortar binding the bricks and stones was at a low level. A weak but statistically significant negative correlation was found between the age of the churches and the hardness of the millstones measured with a Schmidt hammer.

Key words

geoheritage • millstones • medieval churches • petrography • weathering

Introduction

Geoheritage encompasses heritage values of significance at various levels, from geological features of global importance to less monumental examples – nonetheless very important at the regional and local scales (Brocx & Semeniuk, 2019). Increasingly, the concept of geoheritage is also applied to specimens found in ex situ positions. Such examples undoubtedly include some geological specimens stored in museums and collections, as well as selected ornamental stones and artworks (sculptures, altars) made from rocks imported sometimes over long distances centuries ago (Dreesen & Dusar, 2004; Barale et al., 2020). Very often, geoheritage sites are also objects of cultural significance, with legends and folk narratives associated with them (Coratza & Hobléa, 2018; Caetano & Ponciano, 2021; Goemaere et al., 2021). Their rank and geotouristic potential then increase radically (Pijet-Migoń & Migoń, 2022). In young glacial areas, erratic boulders play an exceptional role, including those with anthropogenic modifications (Barale, 2024).

For the preservation and promotion of both geoheritage and cultural heritage, the importance of old religious buildings is increasingly highlighted (Górska-Zabielska, 2010, 2016; Sanjurjo-Sánchez et al., 2019; Navarro et al., 2022). The oldest surviving masonry structures in Poland pertain to medieval objects, primarily Christian churches and castles. The main building materials used in their construction were erratic boulders and bricks. The rock material used for the construction of religious objects most often came from the local area (Cedro, 2023; Mazurek et al., 2024). This was due to the availability of such resources in areas devoid of rock outcrops on the surface of the terrain. The use of stone in traditional architecture is one of the most significant connections between geological and cultural heritage (Ballesteros et al., 2021). However, it sometimes happens that imported stones are found in the walls of churches, brought from distances ranging from tens to even thousands of kilometers (Ashley et al., 2011; Bone, 2016, 2022).

Although the oldest buildings in Poland date back to the Middle Ages, their walls often contain so-called *spolia* – artifacts reused during construction. Among them are, for example, pre-Christian statues known as "Prussian Baba" (Szczepański, 2015), ancient tombstones, or penitential crosses (compare: Sánchez-Pardo et al., 2019). A unique object reused in the construction of masonry church and castle walls in the area of the Southern Baltic Lowlands are millstones and quernstones (Herzberg, 1994; Jędryka, 1994; Ostermay, 1998; Brykała et al., 2023; Piotrowski et al., 2024).

These artifacts are the last material remnants of mills that operated for hundreds of years (Brykała et al., 2015; Brykała & Podgórski, 2020; Mosakowski et al., 2020; Szatten et al., 2023). Their placement in the walls of medieval churches indirectly indicates their age. From previous research on the development of milling in Polish territories, it is known that the oldest surviving historical mentions of watermills date back to the 11th century, and windmills to the 13th century (Podgórski, 2004; Święch, 2005). Millstones also possess one exceptional feature – their working surface underwent intensive abrasive processes and was devoid of weathered rock layers. Therefore, their placement in church walls and their unchanged exposure to external conditions over several centuries may be an intriguing "laboratory" for geomorphologists to study the pace of rock weathering (Pope et al., 2002).

Like any building material, millstones are subject to the same weathering processes as any element of walls exposed to external factors. Water and dissolved salts are among the most important factors in physical and chemical weathering (Goudie et al., 1970; Doehne, 2002; Ollier, 1984). Excessive moisture and salinity are also major causes of deterioration in historic buildings (Winkler, 1994; Turkington & Smith, 2000; Sass & Viles, 2010; Oguchi & Yu, 2021). Porous materials with low strength, such as mortars, bricks, and some types of rocks, are particularly susceptible to the destructive effects of water and salts (Vasanelli et al., 2022). As a result of water freezing and the expansion of salt crystals in small pores, cracks, and rock fractures, pressure exceeding the material's tensile strength is created (Kwaad, 1970; Steiger, 2005ab). Experimental studies have shown that even with about 100 cycles of water freezing and thawing, quartz grains can crack (Schwamborn et al., 2012), and crystallization pressure exceeds the tensile strength of most rocks and concrete (Knacke & Erdberg, 1975). These processes result in crumbling, exfoliation, layering, and spalling visible on the surface of rocks and mineral building materials (Arnold & Zehnder, 1989). Groundwater – mainly capillary, atmospheric precipitation, condensation water, and sorptive water – is the main source of moisture in buildings. Crystallizing salts on the surface or beneath the surface of rocks, bricks, or mortars include substances present in groundwater as products of chemical weathering, salts contained in dust, aerosols, and atmospheric pollution, animal excrements, fertilizers, de-icing salt, salts in building materials (Oguchi & Yu, 2021).

Aims of study

The authors assumed that medieval stone churches, where walls contain embedded *spolia* – cultural objects indicating their secondary use in the construction of temples, have the greatest potential for geocultural tourism. Therefore, the primary aim of the study was to determine the distribution of such churches with embedded millstones and the types of rocks they were made from. Subsequently, an attempt was made to assess the degree of weathering of the millstones over several hundred years of exposure to external conditions and to identify the main factors responsible for this process.

It was assumed that the extent of salinity and moisture in the walls built of bricks, mortar, and stones (not only millstones) serves as an indicator of the contemporary activity of weathering processes occurring on the surface of the walls of the studied objects. Therefore, the analysis and evaluation of the moisture and salinity levels in the brick walls surrounding the millstones will allow us to determine the potential impact of frost and salt weathering on the disintegration of church walls in the vicinity of millstones. The results of the conducted research will also help determine whether water migration from the substrate (capillary rise) up the wall is the main cause of its moisture and what influence the exposure and location of the church (e.g. in relation to the sea coastline) have on the degree of wall moisture and salinity.

Study area

The inventory studies covered historic churches listed in the register of monuments in Poland, in the following voivodeships: Masovia, Kuyavia-Pomerania, Podlasie, Pomerania, Warmia-Masuria, and Lodz. This area encompasses nearly 45% of the country's territory. It is a lowland region that was entirely within the reach of influence of the Fennoscandian ice sheets during the Quaternary period, which transported a significant amount of rock material here. After the retreat of the ice sheet, erratic boulders became the primary building material alongside wood.

Methods

Inventory and basic parameters of millstones

The first stage of the conducted research was an inventory of historic churches to identify millstones embedded in their walls. For this purpose, the database of immovable monuments of the National Institute of Cultural Heritage of Poland was utilized. From this database, temples were selected where at least part of the church's structure created until the end of the 16th century has been preserved to our times. Additionally, other millstones and quernstones identified during field research were also taken into account – they served as a comparative material for specimens dating from the late Middle Ages.

For comparative purposes, documentation of individual millstone specimens was carried out through photography and measurements of their dimensions (as shown in Fig. 1), as well as descriptions of characteristic features, such as: stage of production (from semi-finished product to stone worn out during mill operation), degree of preservation (fragment or intact), diameter of the eye of the stone, form of the trough for the handle, thickness of the stone, type and depth of furrows. Additionally, the exact placement position of each millstone within the building structure was determined, considering the height from ground level and orientation relative to the cardinal directions (exposure).

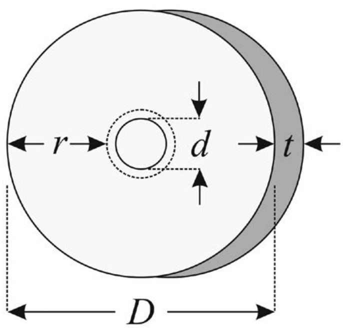

Figure 1. Parameters describing the size of the millstone. Explanations: D – diameter of the millstone, d – diameter of the eye of the millstone, r – radius of the millstone, t – thickness of the millstone

Petrographic studies

The millstones or their semi-finished products subjected to examination are architectural/decorative elements of churches under legal conservation protection. This precludes the use of invasive methods such as sampling for microscopic analysis. Therefore, the study was limited to non-destructive macroscopic field methods. Minerals constituting the rock were identified, and its textural characteristics were described. Observations were made on the dry surface of the rock and then after moistening it with water, which facilitated the proper recognition of features, including the coloration of individual rock components, especially on weathered surfaces. Based on this, the type of rock used as a raw material for the millstones was determined. Photographic documentation of the entire stones (in dry and wet conditions) was also performed, including their location within the church walls, as well as selected macro-scale fragments to facilitate comparisons with the reference collection of Scandinavian rocks stored in the collections of the Department of Geology and Geomorphology at the University of Lodz. Numerous atlases (e.g. Zandstra, 1999; Smed, 2002; Schulz, 2003; Rudolph, 2008ab) and the website of M. Bräunlich (www.kristallin.de), containing detailed descriptions and numerous photographs of Fennoscandian rocks occurring as erratics in the Central European Lowland, were also useful for identifying Scandinavian rocks.

Physicochemical measurements of walls with millstones

It was assumed that for detailed research on the role of millstones in the process of capillary rise of water from the substrate up the walls of churches and the deposition of salts on the surface, a group of 10 millstones located in various locations would be selected – both in different parts of the country (at different altitudes above sea level, distances from the sea, etc.) and with different wall exposures. The lithological and hydrogeological conditions of the areas where the churches were built were characterized based on maps from the resources of the Central Geological Database, developed at the Polish Geological Institute – National Research Institute in Warsaw. Meanwhile, the characteristics of the thermal and precipitation conditions will be presented based on publicly available data from the Institute of Meteorology and Water Management – National Research Institute for measurement stations located closest to the selected objects for detailed research.

The assessment of moisture content in millstones and building materials used for the walls of churches was conducted three times (spring and summer 2022, and winter 2023). For historic buildings, non-invasive methods are used to measure wall moisture

(Hola, 2017). In-situ measurements were performed using the resistance method with a Laserliner MultiWet-Master Compact Plus moisture meter. Measurements were taken at grid intersections with a square side length of 0.2 m, with the millstone located at the center. The results of moisture measurements for bricks and lime mortar were expressed in absolute values as a percentage of water content. Additionally, to determine spatial variations in moisture across the entire wall, measurement results were presented using index values, which express the relative level of moisture content.

The degree of salinity was determined in mortar samples collected at each location from three points in the joints where the brick contacts the millstone. The mixed sample, weighing approximately 100 g in total, was packed into plastic bags to minimize moisture loss and potential salt recrystallization. The collected material was ground in an agate mortar and sieved to particle size <0.063 mm. To wash out water-soluble substances from the tested sample, the mixture was left for 48 hours, stirring every 12 hours (10-15 min. each time). The aqueous suspension was filtered through a Millipore filter (pore size 0.2 μm) and subjected to analysis (Stryszewska & Dudek, 2020). Anions were determined by ion chromatography, and cations by atomic absorption spectrometry (AAS). The results obtained were expressed in mg/dm^3; subsequently, they were converted relative to the sample mass and expressed as percent of the mass. The specific electrolytic conductivity (SEC) at 20°C and pH were measured using a multifunctional device CPC-411 by Elmetron.

The degree of wall moisture was determined according to a five-level classification used for brick walls in historic buildings (Adamowski, 2005), and the degree of salinity according to the guidelines of the WTA (WTA-Merkblatt 2-9-04/D Sanierputzsystem) and Austrian standards, which also indicate specific repair actions for each level of salinity (Ö-Norm B 3355: 2017 03 01 Trockenlegung von feuchtem Mauerwerk).

Study of rock surface hardness and micro-roughness

Two methods were used to determine the degree of weathering of millstones:

1. Measurement of rock surface hardness (rebound) or compressive strength using a Schmidt hammer (SH) N-type.
2. Measurement of the micro-roughness of large feldspar crystals (mainly microcline or orthoclase) exposed on the millstone surfaces, using the portable Handysurf+ electronic micrometer (Dąbski, 2014, 2015).

The SH measurements were based on 10 impacts performed in the most representative places, avoiding any discontinuities, unevenness, cracks, and stone edges. Low rebound values (R-values) indicate a softer rock surface, typically interpreted as advanced weathering.

Handysurf+ was used for the first time (to our best knowledge) in assessing the weathering degree of plutonic and metamorphic rocks. Therefore, the findings should be considered preliminary. Only crystals with a diameter of at least 7 mm and a smooth surface could be measured due to instrument limitations (Dąbski, 2014, 2015), resulting in a limited number of measurements. The Rz parameter was chosen to visualize changes in micro-roughness because it directly informs about mean micro-denivelations (distance between convexities and concavities). High Rz values can cautiously be interpreted as a result of advanced weathering, but spalling can rejuvenate measured surfaces, so inferring about weathering processes must be done carefully.

Only millstones embedded vertically in the unplastered (no roughcast) external walls of churches were considered. It was assumed that progressive exposure to subaerial weathering would result in decreased millstone hardness (SH rebound value) and increased micro-roughness of feldspar crystals. The aspect of the rock surfaces was registered, with walls facing S and W noted as warm, while those facing N and E were noted as cold.

Results

Distribution of churches with embedded millstones in NE Poland

In the study area, out of 703 churches examined, a total of 63 millstones embedded in the walls of 32 churches were identified (Fig. 2). Additionally, 16 millstones were identified, either embedded in the wall of a castle (Olsztyn) or currently deposited in churchyards and museum areas. These specimens were used as comparative material. Besides the millstones identified visually, our database was supplemented with objects described in ethnographic sources (Bartoszewicz, 1855; Makowiecki, 1876; Kolberg, 1885), archaeological research findings (Grzeszkiewicz-Kotlewska & Kotlewski, 1997; Krzysiak, 2001), geological and architectural studies (Czernicka-Chodkowska, 1990; Kunkel, 2006; Strużyński, 2014; Bętkowski, 2019; Grzegorz Osowicki – personal communication in 2022).

Analyzing the spatial distribution of the examined objects, three clear groupings are evident: 1) in Płock Mazovia, 2) in Warmia and Masuria, and 3) in Pomerania. At the current stage of research, the functions that the millstones were intended to serve in the churches have not been determined. They were most often embedded in the external facade walls, at various heights: from the ground level (Winnica) to high above the portal (Purda) or in the tower (Garbno). In a few cases, millstones were found inside the church: embedded in the floor or threshold (the church in Charnowo and the ruins of St. Nicholas' Church in Toruń), and in one case, displayed near the altar mensa (the church in Nowica). No dominant location within the church structure was noticed. They can be found on all walls: in the tower, chancel, main nave, and side nave.

Stones embedded in the walls are predominantly found in medieval Gothic churches. In younger churches, millstones were found sporadically – these included: the 18th-century Baroque churches in Wyszogród and Nowica, the 19th-century belfry of the church in Głuchów, and the early 20th-century church in Zagroba. Typically, only one millstone was found in the walls of a church. However, in a few cases, up to seven millstones were embedded, as in the church in Pułtusk. 33% of the stones are semifinished products at various stages of production. The rest are millstones showing signs of use in mills, sometimes with furrows still visible on the working surface of the stone. The thickness of the millstones could only be determined in a few cases.

Rock material used for the production of millstones

A total of 53 finished millstones (complete or preserved only in fragments) and 26 semi-finished products, whose processing was interrupted at various stages, underwent macroscopic petrographic analysis. Among them, millstones and semi-finished products with diameters ranging from 70 to 100 cm dominate. Only a few exceed this range.

The raw material used for the production of millstones was almost exclusively various types of Scandinavian granitoids present throughout Poland as erratic boulders (Fig. 3; Czubla, 2015). Among these, rapakivi granites (both viborgites and pyterlites) were relatively numerous. Revsund, Siljan, Småland, Sala, Uppsala granites, as well as Bornholm granitoids, were also identified. Generally, these rocks exhibit coarse- and medium-crystalline textures and are relatively poor in dark minerals susceptible to weathering, such as biotite.

Exceptionally, other types of rocks were also utilized, such as gneisses (one specimen each in Bodzanów and Rogiedle), sandstones (in Głuchów and semi-finished products in Wyszogród and Sulejów), pegmatites (semi-finished products in Bodzanów, Ostrołęka, and Kraskowo), and in only one case (Wocławy in Żuławy) volcanic rock, identified macroscopically as basaltoid – Fig. 4. Basaltoid undoubtedly originated from outside Poland, the sandstone in Sulejów originated from the northern Mesozoic margin of the Holy Cross Mountains, while all other rocks were obtainable in the form of erratic boulders in the immediate

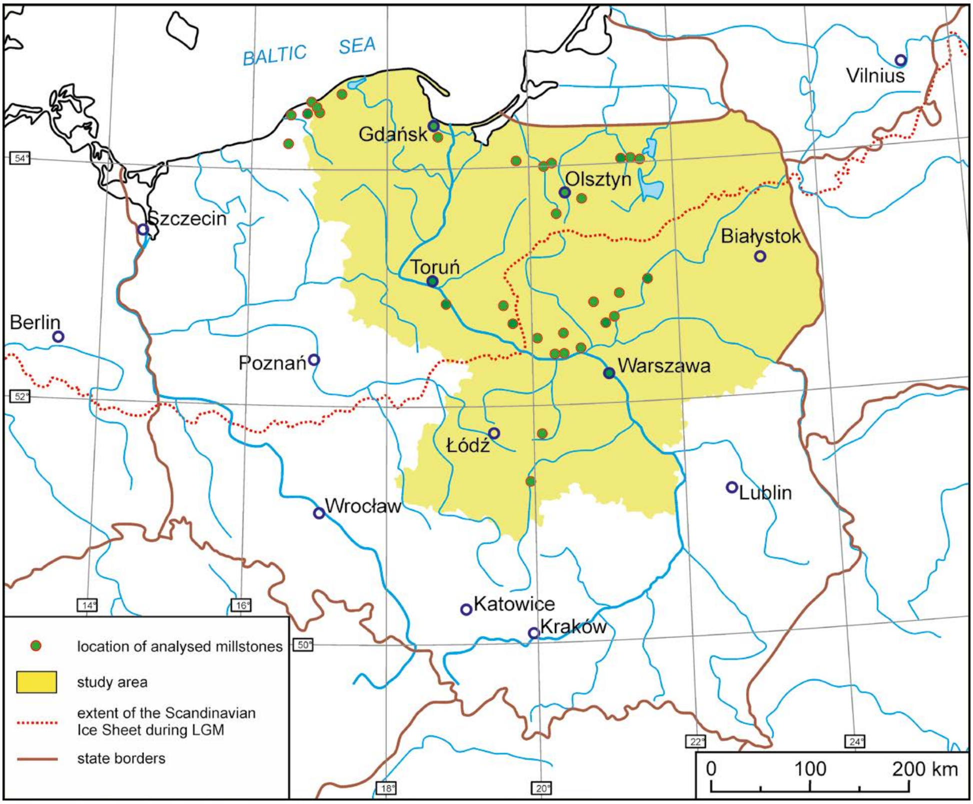

Figure 2. Location of sites with millstones and semifinished products

vicinity of their current utilization. A significant portion of them are so-called indicator erratics (Milthers, 1909), i.e., rocks that can be attributed to a specific source area in Scandinavia (e.g. Meyer & Lüttig, 2007), but in relation to millstone production, this is not of significant importance.

Moisture and salinity conditions in the vicinity of millstones

Moisture and salinity measurements were conducted in the vicinity of 10 millstones embedded in the walls of 8 sacred buildings (Tab. 1). Six of them are located in the postglacial area covered by the last glaciation, and two (Zakroczym and Pułtusk) on denuded uplands from the old glacial period within the limits of the Warta glaciation. The structures in Cisowo, Zimowiska, and Dąbrowa were built on fluvioglacial sandy and silty deposits, usually of small thickness, lying on glacial till. The churches in Krasków and Rogiedle were founded on glacial till and sandy clay soils, respectively, while in Nieszawa, they were situated on sandy-gravelly alluvial terraces of the Vistula. In these locations, the groundwater level is typically 2-5 m below the ground surface. Only in Cisowo, groundwater lies deeper (>20 m), and its table is under tension. The church in Zakroczym was built in the edge zone of the Vistula Valley on sandy-silty alluvium covering glacial till. The groundwater level here is deeper than 20 m. The last object in Pułtusk was erected on the level surface of the Narew floodplain. It is situated on an anthropogenic embankment covering sandy-gravelly alluvial deposits. Groundwater in the vicinity of the church lies at a depth of about 2 m.

Figure 3. Millstones made of Scandinavian granitoids; A, B – stone embedded in the southern wall of the former church in Pułtusk, Revsund granite (erratic), C, D – stone embedded in the southern wall of the church in Gryźliny (Warmia), Finnish or Åland rapakivi granite (erratic), E – stone embedded in the eastern wall of the former church in Pułtusk, Scandinavian granitoid – Småland granite (erratic), F – two halves of a large millstone embedded in the wall of the castle in Olsztyn, coarse crystalline Finnish rapakivi granite (erratic). (Photos by P. Czubla)

Figure 4. Millstones in church walls; A – millstone or semi-finished product in Bodzanów in Mazovia, leucocratic gneiss (erratic), B – semi-finished product at the entrance to the church in Kraskowo (Masuria), coarse crystalline pegmatite (erratic), C – worn millstone or semi-finished product in Rogiedle (Warmia), gneiss with small crystals (erratic), D – semi-finished product used as building material in the monastery church in Sulejów, sandstone from the vicinity of Wąchock (northern Mesozoic margin of the Holy Cross Mountains), E, F – worn millstone in the ruins of the church in Wocławy in Żuławy, porous volcanic rock, most likely imported from the Eifel massif (?). (Photos by P. Czubla)

Table 1. Regional characterization of precipitation and thermal conditions

Millstone localization	Weather station	Annual precipitation [mm]		Average air temperature [°C]		
		average	range	annual	minimum	maximum
Cisowo	Darłowo	663.7	387.6-912.1	8.0	4.9	11.1
Zimowiska	Ustka	684.9	422.1-1019.1	8.3	5.3	11.3
Dąbrowa	Jeżyczki/Darłowo	775.7	286.6-1185.9	8.0	4.9	11.1
Rogiedle	Lidzbark Warmiński	636.9	409.1-908.5	7.4	3.3	11.6
Kraskowo	Kętrzyn	592.6	373.1-841.9	7.7	3.8	11.6
Nieszawa	Głodowo	588.8	362.4-957.2	8.2	3.9	12.5
Zakroczym	Zakroczym/Legionowo	556.2	365.2-869.5	8.5	4.3	12.7
Pułtusk	Pułtusk	556.3	316.5-824.0	8.1	3.6	12.5

The presented characterization of thermal and precipitation conditions (Tab. 1) indicates that annual precipitation totals decrease noticeably from the north to the center of the country. The highest totals of 775 mm were recorded in Dąbrowa, located approximately 10 km from the sea coast, while the lowest were in Pułtusk and Zakroczym at 556 mm. The mean air temperature values are less varied. They are slightly lower for the objects located in NE Poland. Also notable are the higher values of over 1°C for the mean maximum air temperature in the localities situated in Central Poland, and the mean minimum temperature in the coastal zone.

Walls in which millstones were embedded exhibit varying exposure and the position of the lower edge relative to the ground surface (Tab. 2). With the exception of the church in Kraskowo, the ground along the walls where millstones were embedded was hardened with cobblestone or concrete. Biological corrosion marks and moderate signs of weathering were commonly visible on the surface of the stones and bricks, along with mortar losses (Tab. 2).

Table 2. Characteristics of walls and substrate surrounding the millstones selected for moisture and salinity measurements

Millstone localization	Exposure	Millstone location relative to ground [cm]	Character of the ground	Wall condition
Cisowo	S	30	pavement	signs of biological corrosion
Zimowiska	W	60	stone revetment	mortar fragments on bricks, slight signs of biological corrosion on bricks and millstone
Dąbrowa	N	15	concrete	slight signs of biological corrosion on millstone
Rogiedle	N	0	concrete	signs of brick weathering, visible biological corrosion
Kraskowo	NW	55	sandy on clay	visible weathering of bricks, loss of mortar
Nieszawa	N	80	pavement	at 60-80 cm height visible biological corrosion
Zakroczym	W	30	pavement	at 0-30 cm visible biological corrosion
Pułtusk 1	E	0	pavement	visible weathering of bricks, loss of mortar
Pułtusk 2	S	0	pavement	visible weathering of bricks, loss of mortar
Pułtusk 3	N	85	pavement	visible weathering of bricks, loss of mortar, visible biological corrosion

The measurement results indicated a varied degree of moisture in the walls of the churches surrounding the millstones (Tab. 3). The brick sections of the walls were more humid. The moisture content in the bricks also showed significant variability not only within the same wall, but also between locations. In some locations such as Rogiedle, Dąbrowa, and Zakroczym, it was relatively low compared to other places where moisture levels reached even a few dozen percent (Nieszawa, Pułtusk 2), and even above 20% as in the case of Kraskowo. Against this background, the moisture content of the mortar binding the bricks showed much less variation (0.55-2.21%), except for the walls of churches in Nieszawa and Kraskowo, where water content reached locally 4-6%. Referring to the obtained moisture measurement results to the classification of moisture in brick walls in historic buildings, it should be noted that the permissible moisture level (3%) of lime mortar was exceeded only in some parts of the wall of the church in Nieszawa and Kraskowo. In the case of bricks, exceeding the permissible moisture level was observed on small areas of the church walls in Zimowiska, Pułtusk, and Kraskowo, as well as on a larger area of the wall of the church in Nieszawa (Fig. 5, 6). Based on the extent of moisture, these wall sections should be classified as moderately moist (8-12%) and wet (>12%), while the entire wall of the church in Nieszawa should be considered as having elevated moisture levels.

Index moisture values indicate that millstones, as well as other materials used in the construction of church walls, not only exhibit lower moisture levels, on average by around 30 units, but also less variability in moisture compared to the moisture content of bricks and mortar (Fig. 6).

The mortar solutions binding bricks and stones exhibit a slightly alkaline pH (7.47-7.65) and electrical conductivity values ranging from 157 to 423 $\mu S \cdot cm^{-1}$. The variation in salinity of the tested solutions is well expressed by the values of their overall mineralization determined based on the sum of ions. In this regard, they can be divided into two groups (Fig. 7). The first group consists of objects whose solutions are characterized by lower salinity. This group includes Cisowo, where the lowest overall mineralization was found to be 146 $mg \cdot dm^{-3}$, as well as Nieszawa, Zimowiska, Rogiedle, and Pułtusk 3. The second group with higher salinity includes the remaining objects, with Dąbrowa at the forefront, where

Table 3. The moisture level in % of water content in brick and mortar part of the church wall around the millstones

Location	Brick				Mortar			
	n	avg.	range	cv	n	avg.	range	cv
Cisowo	22	0.13	0-2.87	469	35	0.72	0.60-1.07	15
Zimowiska	45	0.71	0-5.91	225	89	0.74	0.55-1.88	31
Dąbrowa	70	0.09	0-1.49	344	62	0.73	0.57-1.06	16
Rogiedle	37	0.04	0-0.51	275	63	0.87	0.62-2.21	24
Kraskowo	83	1.74	0-21.02	271	109	0.96	0.63-3.99	45
Nieszawa	139	4.72	0-17.41	82	93	1.30	0.68-6.10	82
Zakroczym	92	0.10	0-1.67	300	63	0.71	0.61-0.96	10
Pułtusk 1	107	0.75	0-6.80	163	45	0.72	0.56-1.10	17
Pułtusk 2	90	1.60	0-14.38	188	56	0.74	0.57-2.04	34
Pułtusk 3	44	0.84	0-5.68	146	32	0.69	0.55-1.03	19

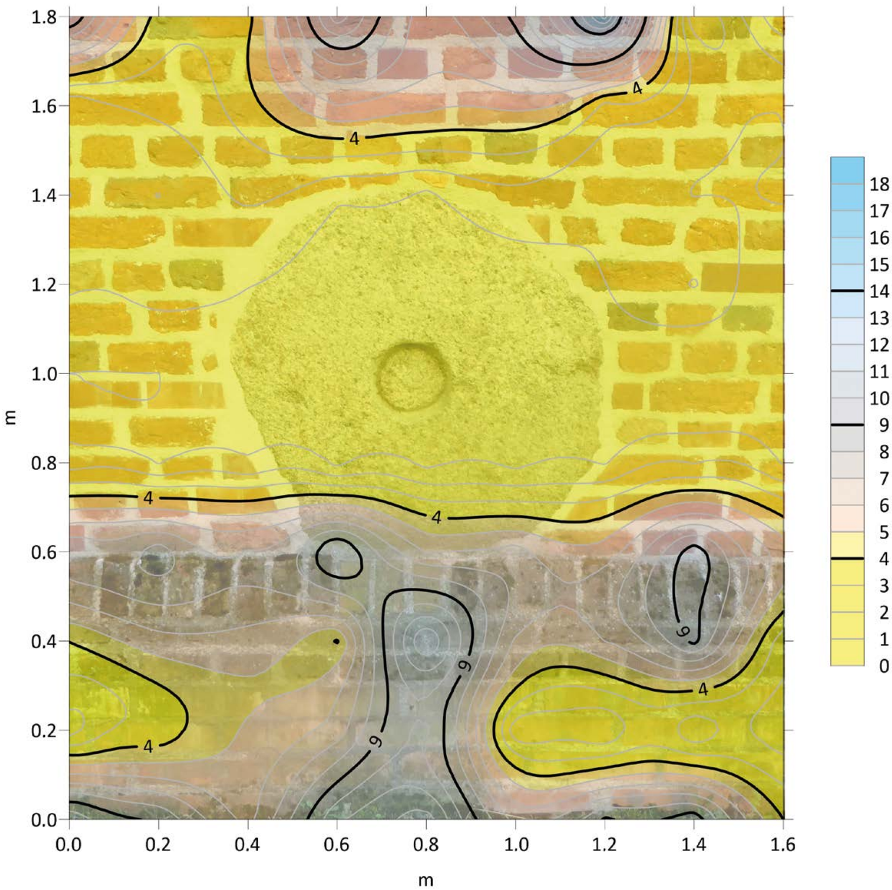

Figure 5. Moisture [%] of the northern wall of the church in Nieszawa in the vicinity of the millstone on April 21, 2022

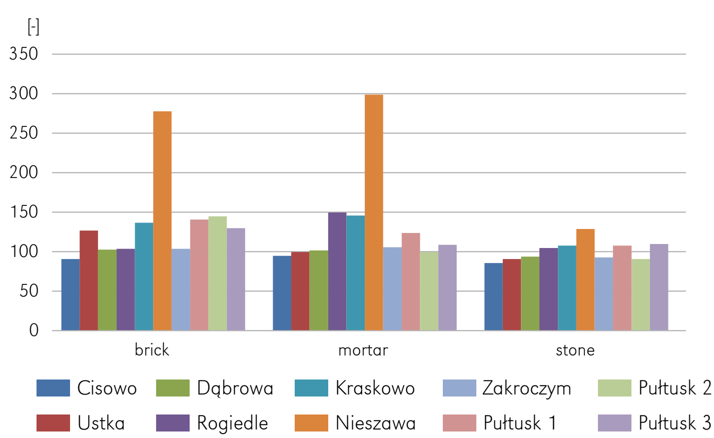

Figure 6. Variability of the average index moisture content of building elements forming the walls of churches in the vicinity of millstones

the overall mineralization was 337 mg·dm^{-3}. In the tested solution samples, the dominant ions are Ca^{2+}, HCO^{3-}, and SO_4^{2-}, which together account for over 90% of the ions (Fig. 7). The remaining ions, except for the sites in Dąbrowa and Kraskowo, account for less than 5%. Therefore, these are bicarbonate-calcium type solutions, and sulfate-calcium type solutions for the Dąbrowa, Kraskowo, Pułtusk 1, and Pułtusk 2 sites.

Comparison between warm and cold walls shows that weaker rocks as well as more rough feldspar crystals are found on colder sides (Fig. 10); however, the difference obtained is not statistically significant (at the 0.05 significance level). This can be explained by moisture conditions that may facilitate hydrolysis of minerals and more frequent freezing and thawing, which must lead to quicker rock weathering.

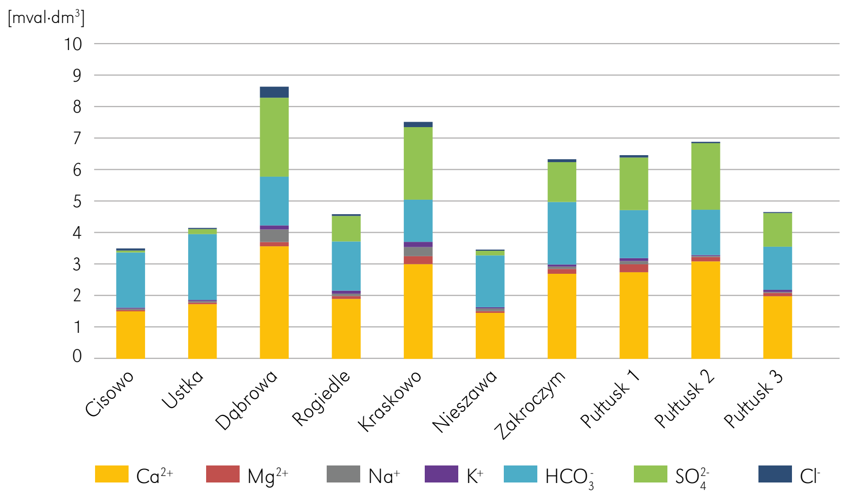

Figure 7. Variation in salinity of the mortar binding bricks and stones in the walls of the examined churches

Study of rock surface hardness and micro-roughness

The limited number of measurements requires caution in drawing conclusions, but there is a weak negative correlation (although statistically significant) between the age of the churches and the SH rebound values of millstones' surfaces (Fig. 8). This can be explained by the growing weathering rind, which is the outermost subtle layer of rock where physical, chemical, and microbiological alterations of rock structure and minerals occur. On the other hand, the correlation between the age of churches and the micro-roughness of feldspar crystals is puzzling, as older millstones do not exhibit more rough crystals (Fig. 9). However, the correlation is even weaker than in the former case and is not statistically significant.

Discussion

Since Roman times, it has been acknowledged that the optimal characteristics of raw materials for millstone production include high hardness, porosity, and easy workability facilitating subsequent stone sharpening or "dressing" (Bachman & Kitamura, 1987). Particularly significant were the porosity and/or graininess of the rock, which enabled the cutting of grains of ground cereals. The uniformity and resistance of the rock to cracking (compactness) reduced the risk of accidents (Czysz, 2015). Only certain types of sandstones, quartzites, basalts, and porphyries were supposed to meet such conditions (Wolfram, 1833; Bachman & Kitamura, 1987). Therefore, the selection of the optimal

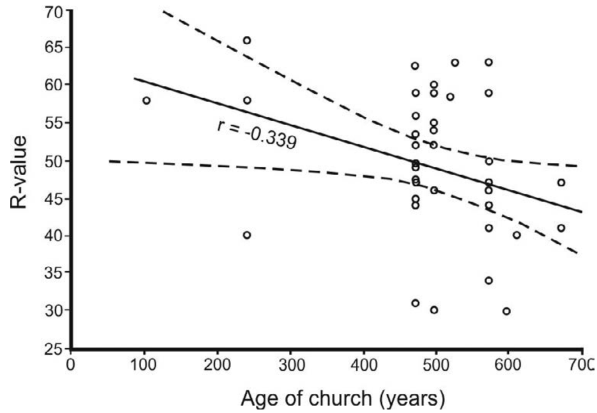

Figure 8. Correlation (and 0.95 confidence interval) between the age of churches and hardness of millstones (R-values)

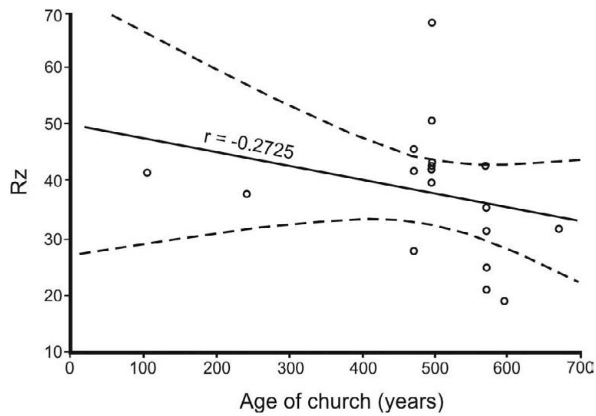

Figure 9. Correlation (and 0.95 confidence interval) between the age of churches and micro-roughness of feldspar crystals of millstones (Rz)

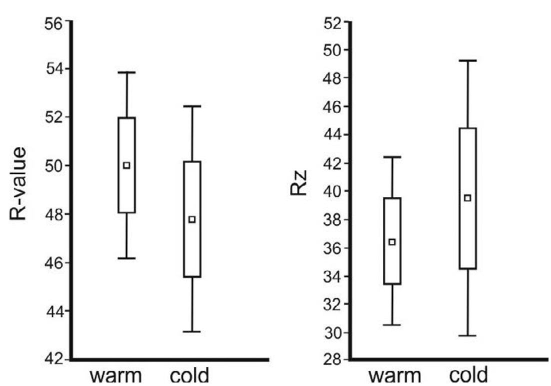

Figure 10. Influence of millstones aspect on their hardness and micro-roughness of feldspar cryslats

type of rock had a decisive importance in millstone production. Already in antiquity, millstones and quernstones made from the best raw materials were objects of trade between very distant regions; for example, millstones made from phonolites (alkaline rocks similar to basalts) from the Orvieto region on the Apennine Peninsula reached the areas of present-day Libya, Tunisia, southern France, and even northern Spain (far-away provinces of the Roman Empire such as Gallia, Iberia, Tunisia, Tripolitania, and Cyrenaica) (Santi et al., 2003; Antonelli et al., 2005; Santi et al., 2021). Similarly extensive was the trade in so-called "Rhenish millstones", i.e., those made from volcanic rocks, macroscopically similar to basalts (tephrites and basanites – Gluhak & Hofmeister, 2011), exploited in the vicinity of Mayen in the Eifel massif (Major, 1982; Hockensmith, 2009; Gluhak & Hofmeister, 2011; Hannibal, 2019; Wenzel, 2020).

Ready-made millstones or semi-finished products made from the best raw materials were very expensive. In the 16th century, the production of a large millstone in Mayen required about 30 working days, and the price of the same millstone in Andernach – the Rhineland center of trade in this product – was around 5 thalers (Reichsthaler), which meant that the stonemason's labor constituted about half of the cost of the finished product (Hörter, 2003). In the 17th century, in Bavaria, the cutting of a millstone was said to take two weeks of hard work by a stonemason and cost 6 guilders, but in trade, the same stone cost 15 guilders (Czysz, 2015). In the case of deliveries to the areas of Pomerania, Warmia, or Mazovia, the costs of long-distance transport, customs duties, and the profits of intermediaries would also need to be taken into account, further raising the final price. Even assuming that the average lifespan of a millstone ranged from about 8 to even 50-60 years (Hejnosz & Gronowski, 1963; Trebeß & Ludwig, 2019), the cost of investment was very high. It is therefore not surprising that cheaper substitutes were sought.

The geological structure of the Central European Plain, where outcrops of solid rocks are rare, seems to be unfavorable for local millstone production. However, this area was repeatedly within the reach of the Fennoscandian glaciation during the Pleistocene. Subsequent ice sheets left thick sequences of glacial and fluvioglacial deposits, including erratics of very coarse fraction, which could be used as raw material for querns and millstones. The widespread occurrence and relatively large petrographic diversity of glacial erratics (e.g. Czubla, 2001, 2015; Czubla et al. 2006; Chachlikowski, 2013; Górska-Zabielska, 2015; Szydłowski, 2017) allow for the selection of raw materials with the most favorable technical parameters. This vast resource base enabled the substitution of expensive millstones imported from present-day Germany and France with local products (Dahms, 1917; Kuczkowski, 2013).

From the conducted studies, it can be concluded that Scandinavian granitoids were most commonly used for millstone production – 69 stones, accounting for 89.6% of the analyzed set. Among them, granites from the rapakivi group from eastern Fennoscandia, rocks from Småland and central Sweden were well represented, but the majority consisted of rocks with characteristics that did not allow them to be attributed to a specific source area in Fennoscandia, but were commonly found in the form of erratics in the Central European Plain.

Granitoid erratic boulders were used for millstone production for a very long time, even in the 19th century (Wolfram, 1833). Milling manuals from this period even contain guidelines on what to consider when choosing the type of rock with the most favorable characteristics for the grinding process. Granites low in mica and rich in evenly distributed quartz grains were particularly suitable for this purpose. The most perfect material for millstone production was supposed to be rocks in which quartz and feldspar occurred in balanced proportions. An excess of feldspar makes millstones too soft, while an excess of quartz makes them too hard (Wolfram, 1833). In the analyzed millstones and semifinished products, usually only the first condition was met, i.e., a small proportion of micas. The proportions of quartz and feldspar were not usually taken into account during this period.

The very high proportion of granitoids may partly result from their favorable technical parameters, but it also reflects their abundant occurrence in the form of large erratic boulders suitable for processing. This hypothesis is confirmed by exploratory studies of erratics collected from fields in the Kołbaskowo municipality south of Szczecin, which showed that granitoids account for 41% of the >0.5 m fraction (Cedro, 2023). Almost identical results were obtained on the Wolin Island coast between Międzyzdroje and Wisełka, with >41% of boulders exceeding 1 m in diameter (Cedro, 2023). Among the erratics (erratic boulders) used for the construction of a megalithic tomb in Wietrzychowice in Kuyavia, granitoids constitute as much as 79% of the utilized materials (Pawlikowski et al., 2020). Similar data (granitoid share approximately 50%) were also obtained in studies of megalithic structures in Krępcewo (Stargard County), Karsko (Pyrzyce County), and Wollschow (Landkreis Uckermark, Germany) – Cedro, 2023. Granite erratics commonly found in the Western Pomerania region were also used in the construction of medieval churches. Their share ranges from about 19 to nearly 43% of the utilized rock material (Cedro, 2023). Observations conducted by the authors of erratics used as building material for Gothic churches with embedded millstones confirm the high proportion of granitoids, but metamorphic rocks are also quite well represented, while sandstones are much less common.

In the finer fraction (>5 cm, suitable for the production of Neolithic tools) examined in Kuyavia, granitoids no longer have such a huge advantage as in the aforementioned megalithic structures, but still constitute the dominant component with a share of 39% (Chachlikowski, 2013, 2018). On the Wolin Island coast, in the 60-128 mm fraction, the proportion of granitoids was only 21% (Lityński, 2018; cited in Cedro, 2023).

Occasionally, attempts were made to use pegmatites, or more precisely, granitoids with pegmatitic veins, for the production of millstones. In all three cases of such millstones identified in the walls of churches in northeastern Poland, processing was presumably discontinued upon noticing defects in the raw material. The most advanced processing was found in the stone from Kraskowo. This is surprising because a coarse crystalline pegmatite with potassium feldspars up to 10 cm in size was used there, and drilling even began (work was only abandoned after reaching a depth of 12 cm). However, even assuming modest experience and knowledge of medieval stonemasons, it is difficult to accept that a rock with significantly inferior characteristics was deliberately chosen for millstones. It can be speculated that the raw material was selected based solely on aesthetic considerations and was intended from the beginning to serve only as decoration in the church wall (Piotr Kittel, 2023 – oral suggestion). Similar imitations of valuable and sought-after items, such as coins, prestigious jadeite greenstone axes, are known from various epochs (including Sheridan & Pailler, 2012; Heymann et al., 2013; Klassen, 2014; Horoszko, 2021), and they are not uncommon even today. In the case of the other two pegmatitic millstones (Bodzanów and Ostrołęka), work was discontinued at a much earlier stage, i.e., before drilling the hole began.

Metamorphic rocks, due to the dominance of directional textures, often emphasized by mica, had technical parameters that were not conducive to their use in the production of millstones. Only two such unequivocal cases were identified in the studied area – in Bodzanów and Rogiedle. The millstone in Bodzanów was made of leucocratic (very poor in dark minerals) gneiss. In Rogiedle, a typical gneiss with quite numerous dark minerals was used. Among erratic boulders, the proportion of metamorphic rocks (mainly gneisses, migmatites, quartzites, and amphibolites) is relatively high, and their fairly frequent use as building materials for Gothic churches and other structures is emphasized (from 29 to

>50% in stone churches in the Kołbaskowo municipality – Cedro, 2023). In preliminary surveys of large (>0.5 m) erratics in the aforementioned municipality and on the island of Wolin (>1 m), the proportion of metamorphic rocks (mainly gneisses) was found to be 40% (Cedro, 2023). In the megalithic tomb in Wietrzychowice, 10% of erratics were classified as granitic gneisses (Pawlikowski et al., 2020), while in Krępcewo, Karsko, and Wollschow, metamorphic rocks accounted for 30 to 35% of the erratic boulders used for tomb cladding (Cedro, 2023). In the finer fraction (>5 cm) in Kuyavia, gneisses accounted for as much as 20% of the examined erratics (Chachlikowski, 2013, 2018). The mere 2.5% share of gneisses in the production of millstones in the surveyed area clearly indicates a deliberate avoidance of this raw material in the selection process by stonemasons.

The significantly lower number of preserved millstones or semi-finished products made of sandstones is much harder to explain. These rocks are usually considered good raw material for the production of millstones (Wolfram, 1833; Bachman & Kitamura, 1987; Grunert, 2007; Trebeß & Ludwig, 2019), although during milling, there is contamination of the produced flour or grits with fine grains of quartz. In modern times, sandstones, alongside so-called artificial stones, were the primary type of rock used for this purpose. However, it turned out that only two millstones (possibly flawed semi-finished products) survived in Gothic churches, and the third, used as part of the pavement in front of the entrance to the church in Charnowo, is rather a modern grinding stone.

In the boulder fraction of erratics, sedimentary rocks are rare, almost exclusively comprising quartzitic sandstones with highly recrystallized cement. In northern Germany, they collectively constitute only 1.3% of the total boulders in the >63 cm fraction (Schulz, 1999). The largest known sedimentary erratic in the Central European Plain is likely the Jotnian sandstone/argillite measuring 4 × 3 × 2 meters, found in Labenz bei Lauenburg (Łebieniec about 5 km south of Łeba) in 1927 and unfortunately almost immediately crushed into gravel (von Bülow, 1927; cited in Schulz, 1999). On the coast of Hiddensee Island, sedimentary erratics are scarce, but some of them reach sizes suitable for use as raw material for millstones (Buchholz, 2014). Research in NW Poland has shown the presence of sandstone and limestone erratics at a level of 6-10% (Cedro, 2023). In the description of the raw materials of the megalithic tomb in Wietrzychowice, sandstones were not identified, but a category of quartzites appeared, presumably including the mentioned quartzitic sandstones. This category accounts for 7% of the total erratics (Pawlikowski et al., 2020). Similar proportions, i.e., a few percent of sandstones and quartzites, were identified in the cladding of tombs in Krępcewo, Karsk, and Wollschow (Cedro, 2023). A significantly higher proportion of these rocks was noted in the >5 cm fraction in Kujawy – up to 30% (Chachlikowski, 2013; 2018). Studies conducted by the author in the >2 cm fraction at dozens of sites (totaling around 150 samples) from the Gdańsk Pomerania through Kujawy, Mazovia, Podlasie, to Greater Poland and Lower Silesia showed that sandstones and quartzites typically account for 4 to 12% of Fennoscandian erratics in glacial deposits. Higher values were obtained for highly weathered (decalcified) clays, where these rocks accounted for between several and 29%, but this apparent increase resulted from the elimination of carbonate rock erratics and mainly concerned the fine fraction. However, it should be noted that the original layering of clastic sedimentary rocks and the variability of fractions, cement, and other textural characteristics facilitate the breakdown of these rocks into smaller fragments – too small to be used for the production of millstones.

The scarcity of sufficiently large sandstone erratics does not seem to be the sole factor influencing the minimal number of millstones made from this raw material preserved in the surveyed area. Stones were likely available from Silesia or from the territory of present-day Germany (Grunert, 2007; Kubicki, 2012), as later accounts suggest (Długokęcki et al., 2004; Bartz & Prarat, 2020). The question arises as to whether the scarcity of millstones made from sandstones is because this rock was rarely used, or whether other applications were found for the originally more abundant worn millstones made from this raw material, such as for stepping stones or grinding plates.

Among the examined millstones and semi-finished products, there were no items made from carbonate rocks, which in the boulder fraction (>63 cm) of glacial deposits in northern Germany have a similar proportion to sandstones, i.e., about 1.3% (Schulz, 1999). An exception is the bedstone of a small hand quern, originating from the wreck F53.15 "Rudowiec" (Bednarz, 2021), stored in the collections of the National Maritime Museum in Gdańsk. It was made from reddish Ordovician limestone, occurring, among others, on Öland, and in the form of erratics also in Poland. In the past, large erratics of carbonate rocks may have been more numerous on the surface than today, but most of them have long been used for lime production or as flux (e.g. Klöden, 1832; cited in Schulz, 1999). The reason for avoiding carbonate rocks in the production of millstones may have been the low hardness of limestones and dolomites, and in the case of potential secondary use, their susceptibility to weathering, which would result in their limited visual attractiveness after being incorporated into the facade of a building. It is also possible that remnants of limestone millstones did survive in the walls of Gothic churches, but only as a component of the mortar.

In historical records, including records from customs offices, a significant number of millstones owned in warehouses in places like Hamburg, Lübeck, and Gdańsk were emphasized, indicating the extent of imports to the Prussian region (Sattler, 1887; Ziesemer, 1913; Forstreuter, 1951; Huiskes, 1980). A relatively young inventory from 1740 of the Great Mill in Gdańsk – the largest watermill in medieval Europe – listed 36 installed millstones. Among them, 20 were identified as Pirna stones (sandstones!), 8 were designated as Silesian stones (also sandstones), and 4 were Rheinish stones and another 4 so-called field stones – meaning, made from erratic boulders. The inventory also mentioned 6 Pirna stones and 1 Rheinish stone undergoing processing at the time, and 1 damaged (cracked) Rheinish stone (Trzoska, 1975). This would indicate that in the 18th century, millstones made from local materials had a small share in the Great Mill in Gdańsk – 9 or 11%, depending on whether the full inventory or only currently installed stones are considered. There is a lack of data to determine the raw material structure of millstones exploited in the Great Mill in medieval times, but studies of stones embedded in the walls of Gothic churches indicate the absolute dominance of local products at that time, i.e., made from erratics. Only one imported historical stone has been identified in the surveyed area, and no Pirna sandstones were identified at all. Data from Bavaria also do not confirm the significant role of long-distance trade in millstones in the medieval and early modern periods (Czysz, 2015). In the foothills of the Alps (Dasing), almost every available rock within a radius of several tens of kilometers was used for millstone production, and expensive millstones were exploited until completely worn out (some preserved fragments were ground down to a thickness of only 2 cm – see Czysz, 2015). Interestingly, some metamorphic rocks used for this purpose from the Alps may have been previously transported from original outcrops by local mountain glaciers (it allows them to be called erratics) (Czysz, 2015).

The high status (perhaps even sacralization) of worn millstones is a spatially and temporally limited phenomenon (Brykała & Lamparski, 2021, 2022, 2023). Even in the early Middle Ages, millstone remnants were treated as waste, used alongside other rock fragments to harden the substrate, as evidenced by findings from Rotbachtal from the Carolingian period (Rünger, 2012).

The most commonly encountered water-soluble salts in building structures are sulfates, nitrates, chlorides, and carbonates. Among the most prevalent in the environment are calcium, sodium, and magnesium sulfates, as well as sodium and potassium chloride (Oguchi & Yu, 2021). From the perspective of the destructive impact of salts on structures, chlorides, nitrates, and sulfates are the most important (Peřinková et al., 2021). The content of these salts in the mortar binding millstones with bricks ranged from 0.01% to 0.12% for chlorides, from 0.003% to 0.26% for nitrates, and from 0.07% to 1.2% for sulfates (Tab. 4). These values indicate that the degree of salinity in the tested mortar samples, according to the WTA guidelines, was low concerning chlorides and nitrates, except for the Dąbrowa and Kraskowo sites, where a moderate level of salinity was observed. However, half of the samples showed a moderate level of salinity due to the presence of sulfates (Tab. 4). According to the Austrian standard (Ö-Norm B 3355), a low level of salinity in the churches in Cisowo, Zimowiska, and Nieszawa indicates that there is no need for preventive or corrective measures. In the remaining structures, the sulfate content corresponding to Level III indicates an urgent need for remedial action. Additionally, salinity at Levels II or III was observed in the churches in Dąbrowa, Kraskowo, and Zakroczym due to the presence of the other two groups of salts (Tab. 4).

Interpretation of the data obtained from SH and micro-roughness analyses is problematic, because of uncertainty with assessment

Table 4. Degrees of salinity of mortar according to (A) WTA-Merkblatt 2-9-04/D standard and (B) Ö-Norm B 3355: 2017 03 01 Trockenlegung von feuchtem Mauerwerk, and values of mortar salinity in weight percentage

Chlorides	A	low	<0.2	B	I	<0.03
		medium	0.2-0.5		II	0.03-0.1
		high	>0.5		III	>0.1
Nitrates		low	<0.1		I	<0.05
		medium	0.1-0.3		II	0.05-0.15
		high	>0.3		III	>0.15
Sulphates		low	<0.5		I	<0.1
		medium	0.5-1.5		II	0.1-0.25
		high	>1.5		III	>0.25

	Chlorides		Nitrates		Sulphates	
	A	B	A	B	A	B
Cisowo	0.02	0.02	0.00	0.00	0.03	0.03
Zimowiska	0.01	0.01	0.00	0.00	0.08	0.08
Dąbrowa	0.12	0.12	0.22	0.22	1.20	1.20
Rogiedle	0.02	0.02	0.03	0.03	0.39	0.39
Kraskowo	0.06	0.06	0.26	0.26	1.11	1.11
Nieszawa	0.01	0.01	0.02	0.02	0.07	0.07
Zakroczym	0.03	0.03	0.05	0.05	0.61	0.61
Pułtusk 1	0.03	0.03	0.03	0.03	0.80	0.80
Pułtusk 2	0.01	0.01	0.02	0.02	1.02	1.02
Pułtusk 3	0.01	0.01	0.01	0.01	0.51	0.51

of weathering time acting on the millstones. Firstly, in many cases, the age of the studied churches was uncertain. Usually, historical sources provided only rough information about the time of the church's erection. If only a century was known, the middle of the century was used as a rough approximation (e.g. 15th century = 1450 AD). Secondly, it was impossible to assess the time that passed between the onset of weathering (end of rock abrasion in the process of grain grinding) and the emplacement of the millstone in the wall of a church. Despite these uncertainties, the obtained negative correlation (weak but statistically significant) between millstone hardness and the age of churches supports our research hypothesis.

On the other hand, the results of micro-roughness measurements are not easy to interpret. The small number of samples does not allow us to draw firm conclusions; however, it is possible that declining micro-roughness of feldspar crystals with increasing age of churches results from micro-scale spalling. Detachment of loose, weathered fragments most likely occurs along cleavage planes and therefore leads to declining micro-roughness of crystals (rejuvenation of their walls).

The Schmidt hammer was used in studies of a variety of heritage sites. Fort et al. (2010) conducted an interesting research on the provenance of building blocks used in the Church of the Assumption of Our Lady in Valdemorillo (Spain). The blocks were predominantly monzogranite followed by granitic porphyry, porphyritic monzogranite, gneiss, and leucogranite. The age of their exploitation and emplacement in the church walls was uncertain as the building underwent subsequent developments and renovations (between the 8th century and 16th century). The rocks from the church's walls exhibited lower R-values (and ultrasonic values), and higher porosity and water saturation values compared to the original quarry rocks, which resulted from rock decay processes. The authors inferred spalling of homogeneous monzogranite and grain disintegration in granitic porphyries.

Salvatici et al. (2020) utilized the SH test (together with ultrasonic tests) to assess the weathering degree of sandstone elements on Renaissance buildings. Debailleux (2019) proved that SH tests can also be successfully used in the assessment of the weathering degree of ancient fired clay bricks sampled from historical masonry and help to distinguish between exposures and locations within a wall.

Micro-roughness measurement for the study of building material surface properties is usually based on optical devices. Weinhold et al. (2007) used The OptoSurf instrument to assess the quality of laser cleaning of building walls. Recently, Tsigarida et al. (2021) performed a very interesting study of rock surface-water interaction influenced by rock micro-roughness. They used confocal microscopy, and conclusions were drawn about the influence of a protective film applied on building walls to increase water-repellency and resistance to weathering. Our study proved that colder, therefore more moist walls of churches, possess more rough feldspar crystals which probably perpetuate further weathering by decreasing water-repellency.

Conclusions

Medieval sacral buildings constitute one of the oldest and most valuable groups of monuments subject to conservation protection in Poland. They are often the main tourist attractions, serving as destinations for tourist traffic. Due to the fact that one of their main building materials is glacial erratic boulders, such buildings have great potential as geoheritage objects. Embedded in the walls, these boulders indicate the types of rocks that were once found in the immediate vicinity of the church under construction. They also often point to the source areas of these rocks in Fennoscandia.

Even higher geotouristic significance is attributed to *spolia* – cultural objects reused in the construction of churches alongside „ordinary" erratics. Among them, millstones undoubtedly hold a prominent place. They testify not only to the former economic development of a given area, the use of water and wind energy for mills, but also undoubtedly to some mysterious, symbolic significance within the church walls. Searching for answers to questions regarding the reasons for their placement in sacred buildings should be continued by representatives of the humanities (historians, theologians, cultural anthropologists, ethnologists, art historians).

At present, none of the churches have an information board about the millstones embedded in their walls. Even the priests of these churches were surprised by our findings. Besides their obvious cultural functions, such objects have the potential to propagate information about geology and geomorphology. Information about glaciations, minerals forming the rock, their origin, or exogenic processes should be exhibited in such places. This will contribute not only to the increased geotouristic attractiveness of the site, but also to geological and geographical education (compare with: Baug & Løland, 2011).

There is a weak, but statistically significant correlation between millstone surface hardness and the age of churches, despite uncertainties concerning the weathering duration, which support the research hypothesis. The limited number of measurements precludes conclusions about the influence of weathering duration on feldspar micro-roughness. The aspect of the millstone surface seems to play an important role, although results are not statistically significant, in the rate of weathering (colder sites facilitate rock decay).

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Unless otherwise stated, the sources of tables and figures are the author's, on the basis of their own research.

Authorship contribution statement
DB central to the conception and project administration. PC, DB, MD and PG prepared the draft version of the manuscript. All authors carried out the inventory works, field measurenments and laboratory analysis. PC, DB, MD, PG and PL prepared the final version of figures and DB reviewed and edited the final version of manuscript. DB ensured the funding acquisition. All authors finally approved the version for publication.

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