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Petrography and provenance of sandstone from Piast Castle and its adjacent chapel in Legnica (SW Poland): implications for medieval and early modern building stone supply

Katarzyna SZADKOWSKA[1*], Wojciech BARTZ[2] and Tomasz STOLARCZYK[3]

[1]Polish Geological Institute – National Research Institute, Lower Silesian Branch, al. Jaworowa 19, 50–122 Wrocław, Poland; ORCID: 0000-0002-1510-8191

[2]University of Wrocław, Institute of Geological Sciences, pl. Maxa Borna 9, 50-209 Wrocław, Poland; ORCID: 0000-0002-7267-2776

[3]Regional Museum in Jawor, ul. Klasztorna 6, 59-400 Jawor, Poland; ORCID: 0000-0003-1490-0483

*corresponding author: katarzyna.szadkowska@pgi.gov.pl

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Abstract

Piast Castle in Legnica (SW Poland) is one of the largest preserved Late Romanesque secular residences in Europe. Constructed and remodelled between the late 12th and 17th centuries, the Castle and its chapel incorporate numerous sandstone architectural details, the provenance and petrographic characteristics of which have been insufficiently documented. We identify the lithological types and probable sources of these sandstones, and investigate their variability in relation to distinct construction phases. A total of 26 samples of historic building stone from Piast Castle and its adjacent chapel, representing the late Romanesque, Gothic, and Renaissance phases, were compared with 24 reference samples of the Cretaceous Quader Sandstones from the North Sudetic Synclinorium. The petrographic analyses encompassed optical microscopy with subsequent grain size distribution and modal analysis, complemented by scanning electron microscopy analyses on reference material. The results of the study indicate that two sandstone types from the North Sudetic Synclinorium were used in the construction of this heritage site: the Coniacian Upper Quader Sandstone and the Turonian Middle Quader Sandstone. This petrographic variability correlates with construction phases: late Romanesque details were carved from both lithological types, whereas Gothic and Renaissance elements predominantly used Upper Quader Sandstone. The findings provide new insights into medieval and early modern material procurement strategies in the Lower Silesia historical area and deliver a petrographic framework for conservation and restoration strategies.

Key words: North Sudetic Synclinorium, cultural heritage, sandstones, petrography, Piast Castle.

Introduction

Stone as a raw material has been used by humans for millennia. Products and buildings made of stone, particularly those related to secular and sacred cultural heritage, attract attention and are the subject of diverse and interdisciplinary analyses (e.g. Gierych, 1955; Labus, 1996, 2008; Skoczylas and Walendowski, 1998; Majerowicz et al., 1999; Wilczyńska-Michalik, 2004; Skoczylas, 2005, 2011, 2013; Götze and Siedel, 2007; Szczepaniak et al., 2008; Marszałek et al., 2014; Skoczylas and Gunia, 2016; Coli et al., 2022; Deniz and Kadioglu, 2022; Franzen and Fischer, 2022; Rescic et al., 2024). Archaeometric investigations are inherently complex and interdisciplinary, combining geology with historical context. They are a valuable source of information for art historians and monument conservators, playing an important utilitarian role. Determining the provenance of the stone material analysed is crucial for selecting the most appropriate material for repairs of historical buildings. Furthermore, analyses of the use of stone in cultural heritage monuments can also reveal broader patterns of technological capability, resource availability and trade networks.

Piast Castle in Legnica (Lower Silesian Voivodeship, SW Poland; Fig. 1) is regarded as one of the most substantial Late Romanesque residential complexes in Europe (Rozpędowski, 2009; Chorowska and Caban, 2016; Chorowska, 2020). The Castle and its chapel are notable examples of stonework art, and the craftsmanship of medieval stonemasons is evident in the decorative architectural details. These elements, composed of light sandstone in hues of yellow, beige and grey, have been the focus of architectural and archaeological research (Rozpędowski, 1971, 2009; Chorowska and Caban, 2016). However, despite its historical significance and over 60 years of archaeological research (Rozpędowski, 1971; Mruczek, 2018), Piast Castle and its chapel in Legnica have not been thoroughly analysed in terms of petrography with respect to the relationship between construction phases and sandstone provenance. The present paper aims to address this gap, aiming to: i) identify the lithological types of sandstones utilised in the architectural details; ii) determine the probable sources of these stones (i.e. the provenance of the sandstones) through comparison of petrographic properties with reference materials; iii) explore correlations between petrographic variability and historically documented building phases.

Piast castle in Legnica and its chapel

Historical notes

Piast Castle in Legnica is situated on a hill, with the Piastowska, Nowa, and Marii Skłodowskiej-Curie streets surrounding it. It was most likely constructed at the end of the 12th century on the site of a wooden Piast stronghold (Bednarek, 2021). In the 15th century, the Castle underwent reconstruction in the Flamboyant Gothic style. The subsequent phase of reconstruction, characterised by the Renaissance style, occurred during the first half of the 16th century, with further modernisations undertaken in the 17th century, among other developments (Rozpędowski ,1971, 2009; Bednarek, 2021). The Castle, which withstood the Mongol invasion in 1241, was partially damaged during the Second World War. Following the war, archaeological excavations in the 1960s revealed the remains of the Chapel of St Benedict and St Lawrence in the inner courtyard. These remains are believed to date back to the first half of the 13th century (1220-1240; Rozpędowski, 1971). The construction of the chapel was overseen by Master Jakub, who had been working for Prince Henry the Bearded (Mruczek, 2018). The chapel was demolished in 1621 (Rozpędowski, 1971). The edifice was originally constructed as a twelve-sided, two-storey structure with numerous architectural details that served to emphasise the elevated status of the Piast princes (Chorowska and Caban, 2016; Mruczek, 2018).

The multi-phase construction of the Castle is reflected in the variety of sandstone details: capitals, window tracery, sculptural ornaments, which offer an opportunity to trace shifts in material supply over more than three centuries. Identifying the provenance of the natural raw material can shed light on patterns of medieval and early modern stone supply, workshop organisation, and material preferences.

Historical analytical material

As part of the work carried out, 26 samples of sandstone were collected from various architectural details from Piast Castle and its adjacent chapel, and subjected to mineralogical and petrographic analysis (Tab. 1; Fig. 2). The architectural details, from which the samples were taken, are damaged fragments of the Castle, originating from various parts and different stages of construction. These fragments are currently stored in the cellars of the Castle chapel. The details included fragments of vault ribs, keystones, rosettes, masonry, columns and capitals. All the samples collected were small (1–4 cm) due to the historic nature of the stone elements sampled and the necessity to minimise intervention in the historic substance of the object. Consequently, the archaeologist (TS) proceeded to collect all the samples of stone material obtained from this cultural heritage site (Tab. 1). The time of construction was determined by TS based on knowledge of previous work carried out by archaeologists and architects. The most numerous fragments are those of the original, Late Romanesque details, which can be dated to the first half of the 13th century (1220-1240), coinciding with the construction of the chapel (Tab. 1). The second construction phase can be traced to the 15th-century rebuilding of the Castle in the Flamboyant Gothic style. During this period, the late Gothic keystones were created, of which samples were obtained. Among the collected fragments of architectural details, three samples were also identified as Renaissance. They are associated with the subsequent reconstruction phase, which was carried out in the first half of the 16th century. This constitutes the third construction phase of the Castle.

Sandstone raw material

Geological background

In south-western Poland, sandstones occur, and are mined in two areas: the first in the Lwówek Śląski and Bolesławiec region (geologically related to the North Sudetic Synclinorium; Żelaźniewicz et al., 2011), and the second in the south and south-west of Kłodzko, with a much less significant area in the vicinity of Krzeszów (all of which are geologically related to the Intra-Sudetic Synclinorium and the Upper Nysa Kłodzka Trench).

Due to the location of Piast Castle in Legnica, from which samples of the analysed historical elements were obtained, and their macroscopic appearance (light, grey, beige and yellow sandstones), Upper Cretaceous sandstones found in the North Sudetic Synclinorium were considered the most likely source of the building material. This assumption was based on the proximity of the sandstone deposits to the monument, historical data on the extraction and use of sandstones in the study area, and published information, where the widespread use of these rocks in architectural details is highlighted (e.g. Michniewicz, 1996; Szczepaniak 2014, 2021; Szczepaniak and Rój, 2019; Zboińska and Bartz, 2019). The historical context is also significant: during the construction of the chapel, the sandstone deposits of the North Sudetic Synclinorium were under the control of the Piast princes. Meanwhile, the Intra-Sudetic Synclinorium – the region of Kłodzko – was historically a separate entity, governed by various dynasties, often constituting a disputed territory between Czech and Polish authorities, despite now lying within the borders of Lower Silesia (Winiarska, 2010).

The North Sudetic Synclinorium (Fig. 1) was formed by the Late Cretaceous-Paleogene inversion of a sedimentary basin (Żelaźniewicz, 2011). Its sedimentary infill ranges in age from the Upper Carboniferous (Stephanian) to the Upper Cretaceous (Upper Cenomanian-Santonian) (Śliwiński et al., 2003). Milewicz (1985) distinguished three formations within the Cretaceous deposits in this area: the Rakowice Wielkie, Czerna, and Węgliniec formations. Within these, he identified six members: the Wilków, Przewóz, Chmielno, Dobra, Żerkowice, and Nowogrodziec members (Fig. 3).

The Rakowice Wielkie Formation comprises marls, clayey marls, and marly claystones. These rocks are predominantly dark grey and laminated. Within this formation, particularly in the western part of the Synclinorium, there is a Lower Turonian Przewóz Member. This unit is composed of marly and marly-sandy limestones, as well as sandstone beds, which in German literature are referred to as *Quadersandstein* (Beyrich, 1849). These are visible in the terrain as a series of hills or dome-shaped elevations (Milewicz, 1997).

The lowest part of the Rakowice Wielkie Formation and simultaneously the oldest (Cenomanian) Cretaceous deposits in the North Sudetic Synclinorium are the Wilków Member sandstones, referred to as the Lower Quader Sandstone (Lwówek-type sandstone; German *Unterquader, Löwenberger Sandstein*; Ehling, 1999). At the base, they are developed as a basal conglomerate up to 40 cm thick, lying unconformably on the bedrock (Milewicz, 1997). In the higher part of the profile, the brown, yellow or light grey Quader Sandstones are coarse- to medium-grained, locally conglomeratic, quartzitic with an admixture (up to several percent) of lithic grains: lydites (cherts) and siliceous schists. The cement in these sandstones is siliceous-argillaceous. These sandstones are classified as quartz arenites. The average grain diameter (mean grain size) in the Lower Quader Sandstone, according to various authors, ranges from 0.42 mm (Ehling, 1999) to 0.53 mm (Milewicz, 1997; Tab. 2).

The sandstones of the Chmielno Member date to the Lower Turonian (Milewicz, 1997). They are also known as Middle Quader Sandstone (Płakowice-type sandstone; Ger. *Mittelquader, Plagwitzer Sandstein*; Ehling, 1999). These are quartz sandstones (arenites), locally containing an admixture of kaolinized feldspars, with the occasional presence of glauconite (Ehling, 1999). The sandstones are predominantly coarse-grained; medium-grained varieties are also common, while fine-grained and conglomeratic sandstones are less frequent (Milewicz, 1962). The grains are generally quite well-rounded. Ehling (1999) states that the mean grain size is 0.38 mm, whereas Milewicz (1997) states that it is 0.42 mm (Tab. 2).

The sandstones of the Dobra Member are several tens of meters thick and not extensively distributed. They are poorly sorted quartz sandstones with variable grain sizes and angular grains (Milewicz, 1997). They are of Upper Turonian age.

The Żerkowice Member is the youngest sandstone member within the Rakowice Formation and is estimated to be of Lower Coniacian in age (Milewicz, 1997). These sandstones, known as the Upper Quader Sandstone (Rakowice-type sandstone; Ger. *Oberquader, Rackwitzer Sandstein*; Ehling, 1999), are classified as quartz arenites. They are generally fine- to medium-grained and equigranular. Poorly sorted varieties also occur. The mean grain size according to various authors is: 0.20 mm (Milewicz, 1997), 0.13-0.54 mm (Milewicz, 1998), and 0.11 to 0.31 mm (Ehling, 1999; Tab. 2). In addition to quartz grains, lithic fragments (quartzite and quartzite schist) are present in the sandstones of the Żerkowice Member. Their content ranges from a few to several percent. The content of feldspar grains in these sandstones is negligible (Ehling, 1999). The cement in the sandstones of the Żerkowice Member is argillaceous, kaolinitic (Milewicz, 1997; Ehling, 1999) or ferruginous and quartz-argillaceous (Świętnicka-Goldstein, 1975) with a clayey filling mass. Most grains (almost 90%) are angular (Milewicz, 1998).

According to Milewicz (e.g. 1997, 2006), the Czerna Formation and the Węgliniec Formation are stratigraphically coeval and represent the Lower Santonian. According to this interpretation, the boundary between the Rakowice Wielkie Formation and the Czerna and Węgliniec formations marks the boundary between the Upper Coniacian and Lower Santonian. However, Voigt et al. (2008) place the boundary between the Coniacian and the Santonian within these formations, based on a reinterpretation of the stratigraphic ranges of bivalves belonging to the genus *Inoceramus*.

The Czerna Formation comprises sandstones and mudstones with coal interbeds. It is found in the eastern part of the North Sudetic Synclinorium. At its base, local deposits belonging to the Nowogrodziec Member occur, representing shallow-water sediments and composed of claystones, mudstones, sandstones and thin coal seams (Leszczyński, 2010). The Węgliniec Formation, which occurs in the western part of the Synclinorium, is represented by mudstones (Milewicz, 1997).

Reference sandstone material

Determining the possible provenance of stone material used in the architectural details requires comparison with relevant source material. In addition to historical stone material, reference sandstones that could potentially be used for architectural purposes have also been studied. Various mineralogical and petrographic analyses of sandstones from the North Sudetic Synclinorium have been published (e.g. Ehling, 1999; Labus, 2009; Szczepaniak, 2015; Prell, 2017), which can be used for comparison with the results obtained from the historical samples studied. However, numerical and descriptive data cannot substitute direct microscopic analysis of rock samples and comparison of their microscopic images. This is because any rock characterisation may vary depending on the author's respective observations and interpretations. For this reason, a collection of Cretaceous sandstones samples from the North Sudetic Synclinorium was gathered to determine the origin of the stone material used in the historical sites studied. The samples were collected from former, now abandoned raw material extraction sites and active quarries, as well as natural rock exposures. The rock sampling sites were selected based on published data regarding the historical quarrying of building stone (Ehling, 1999; Walendowski, 2010a-e), as well as on Cretaceous sandstone outcrops portrayed on the Detailed Geological Map of Poland (Badura, 2005; Cymerman et al., 2005a, b; Kozdrój et al., 2005; Przybylski and Ihnatowicz, 2005; Sztromwasser, 1995). The sandstone samples collected served as comparative material, enabling the petrographic and mineralogical characteristics of the reference sandstones to be compared with those of the rocks used in the architectural details of the chapel analysed. To obtain a complete view of the samples, reference sandstones were taken from the

Lower, Middle, and Upper Quader Sandstones. As previously mentioned, not all Upper Cretaceous sandstones from the area were commonly used in construction. From a construction perspective, some of them were probably only of local importance. However, it was decided not to exclude these locations, resulting in a comprehensive review of the Upper Cretaceous sandstones, highlighting the similarities and differences between the various types. Naturally, the set of samples selected does not fully reflect the possible lithological variability, which may vary considerably even within a single deposit. However, the use of microscopic observations of the rock raw material samples enables direct comparison between the most important sandstone types. The sample set collected complements the data widely described in the literature.

The reference sandstones were collected from sixteen locations in the North Sudetic Synclinorium area. A total of 24 reference sandstone samples were obtained (Tab. 3, Fig. 4). Ten samples of the Lower Quader Sandstones came mostly from the Lwówek Śląski region, specifically from the abandoned sandstone quarry within Lwóweckie Skały (Szwajcaria Lwówecka), Wzgórze Kombatantów (formerly *Buchholtz*), and a former quarry on Jaglarz hill north of Płakowice (now part of Lwówek Śląski). Other samples were taken from an abandoned quarry on Twardziel Hill near Radłówka, as well as from a sandstone exposure located south of Warta Bolesławiecka. Six samples were taken from Middle Quader Sandstones at the following locations: an abandoned quarry on Skałka Hill (Płakowice); small quarries near Pielgrzymka; Krucze Skały in Jerzmanice-Zdrój; and exposures in the Warta Bolesławiecka area. Eight samples of the Upper Quader Sandstones were taken from active or recently abandoned quarries in Czaple, Wartowice, Żerkowice, Rakowice Małe, Żeliszów and Zbylutów.

For the purpose of general comparison of the individual rock types, reference sandstone samples were selected that were considered representative of the Lower, Middle and Upper Quader Sandstones of the North Sudetic Synclinorium (Lwówek Śląski, Płakowice, and Żerkowice respectively). These were selected on the basis of historical data on the extraction of sandstone raw material from the quarries, or sample characteristics reflecting the characteristics of the rock formations represented.

Methods of investigation

Optical microscopy and computer image analysis

For the petrographic characterisation, thin sections approximately 40 µm thick were made from all the historical material samples and the reference sandstones at the Institute of Geological Sciences at the University of Wrocław (UWr). The thin sections were then analysed using a Nikon ECLIPS LV100 POL polarising transmitted-light microscope in the Department of Physical Geology at the UWr. Basic microscopic observations enabled the mineral composition of the framework grains to be determined, as well as the morphological characteristics of the grains and the type of cement. Microscopic photographs were also taken of all the thin sections. Computer image analysis was then carried out on the microphotographs, using JMicroVision 1.2.7 software (Roduit, 2007) to measure the diameter (Feret diameter) of the grains crossed by parallel lines drawn on the photographs. The percentage of each component in the rock was also determined using the point-counting method. The number of grains measured in the samples (n) ranged from 300 to 776, enabling the generation of reliable statistical results (Ingersoll et al., 1984). Computer image analysis of the data allowed the geometric and statistical parameters of grain size: median (M_d), mean (M_z) and percentile values – first quartile (Q_1), third quartile (Q_3) – to be determined. These were then ranked according to the respective grain classes, and grain size histograms were developed for all samples according to the phi-Udden-Wentworth scale (Krumbein and Sloss, 1963). Based on the cumulative graphs, graphic sorting was determined (Inclusive Graphic Standard Deviation, σ_I; Folk, 1980).

Scanning electron microscopy

The choice of research methods used to analyse the samples was closely related to the quantity of research material available, while taking into account the possibility of obtaining the most extensive and detailed results. For this reason, three carefully chosen samples from Piast Castle were examined in detail using a scanning electron microscope. These samples, which correspond to the building's different structural phases (Romanesque, Gothic, and Renaissance), were large enough to allow additional analysis. The research was carried out at the UWr Department of Experimental Petrology, using a JEOL JSM IT-100 scanning electron microscope, equipped with an Oxford EDS (SEM-EDS) attachment, in low vacuum (20-30 Pa) at an accelerating voltage of 16 kV. Analyses were performed on vacuum carbon-coated sample fragments up to 1 cm in size. These analyses enabled the observation and identification of mineral phases present in the cement. To determine their mineralogy, the EDS spectra and ZAF-corrected elemental concentrations obtained were compared with the standard spectra provided by Reed (2005). SEM-EDS studies were also applied to samples of the three representative reference sandstones (from Lwówek Śląski, Płakowice and Żerkowice).

Results

Petrography of sandstones from the chapel

All samples analysed from Piast Castle are sandstones with a argillaceous-siliceous cement, which, depending on the sample, is also accompanied by iron-bearing minerals. The pore-filling cement consists of clay minerals (kaolinite), associated with a subordinate ferruginous cement (goethite). Syntaxial quartz overgrowths form a pore-lining cement around the quartz grains. Most of the samples from the chapel can be classified as quartz arenites (Pettijohn et al., 1972; Fig. 5). One sample is a subarkosic arenite (LEG018) and two are sublithic arenites (LEG024 and LEG030).

Among the components of the framework grains, quartz is dominant in all samples, constituting between 87-99% vol. (including polycrystalline quartz; Tab. 4). Lithic fragments such as quartzites and other siliceous rocks are also present, comprising of 1-7%. Alkali feldspars observed in the sandstones analysed are commonly highly weathered and contribute insignificantly to the framework grains, typically not exceeding 1% by volume. Three of the samples analysed from the Castle (LEG018, LEG019 and LEG025) are exceptions, with feldspar contents ranging from 3% (LEG025) to 12% (LEG018). In addition, opaque minerals and sporadic amphiboles (less than 1% vol.) occur in these sandstones. The samples represent fine- to medium-grained sandstones. The mean grain size ranges from 0.18 mm (LEG018 and LEG019) to 0.33 mm (LEG002). The median grain size varies from 0.19 to 0.33 mm. The first quartile ranges from 0.13 to 0.23 mm, and the third quartile from 0.27 to 0.48 mm. The samples are moderately well sorted to poorly sorted (σ_I = 0.67-1.04), with most being moderately sorted. The content of the very fine sand fraction reaches up to 17%. Grains exceeding 1 mm are rare and occur sporadically.

For selected samples, representing the Romanesque (LEG025; Figs. 6-7, 8A), Gothic (LEG028; Figs. 6-7, 8B) and Renaissance (LEG033; Figs. 6-7, 8C) construction phases, additional SEM-EDS observations were carried out, corroborating their overall similarity and the nature of the sandstone cement. A significant proportion of argillaceous pore-filling cement was observed in all of them. The argillaceous cement is dominated by kaolinite, which often occurs in the form of well-developed, booklet-like aggregate packets (Fig. 8). Within the kaolinitic cement, dispersed admixtures of iron-bearing minerals are visible. Additionally, a siliceous cement (poorly crystalline SiO_2, chalcedony) is present. Quartz grains exhibit syntaxial overgrowths, forming pore-lining rims.

Petrography of reference samples

Cenomanian Lower Quader Sandstone of the North Sudetic Synclinorium

Among the Lower Quader Sandstone samples, some show noticeable variations in grain size parameters, though generally they are poorly sorted. They were identified as very fine, medium- and coarse-grained quartz arenites and very fine-grained sublithic arenites (Fig. 9). The framework grains of the sandstones described consist predominantly of quartz (85-99 vol%), relatively small amounts of feldspar, with noticeable differences in the occurrence of lithic fragments (quartzites; up to 15 vol%) and <1 vol% accessory minerals (opaque minerals, amphibole, muscovite and zircon) (Tab. 5). The cement is argillaceous-siliceous (pore-filling, secondary pore-lining), with the presence of ferruginous cement (goethite), associated with clay minerals.

A sandstone sample from Lwówek Śląski (WB1112; Fig. 10-11) was selected as representative of the Lower Quader Sandstones in the North Sudetic Synclinorium. As with the other representative samples identified, detailed petrographic analysis was carried out to characterise the cement more precisely. The nature of the cement in the sample analysed was confirmed through SEM-EDS studies (Fig. 12A). These studies revealed the presence of a siliceous cement in the form of pore-filling, poorly-crystalline SiO_2 and syntaxial quartz overgrowths. Argillaceous (kaolinitic) pore-filling cement is also present. Both siliceous and argillaceous cements are associated with ferruginous cement. Iron-bearing phases also occur as patchy ferruginous coatings on framework grains.

Turonian Middle Quader Sandstone of the North Sudetic Synclinorium

The framework grains of the sandstones described consist predominantly of quartz (91-99 vol vol.), alongside smaller proportions of alkali feldspar (up to 4 vol%), lithic fragments (up to 9 vol%), and opaque minerals (less than 1 vol%; Tab. 5). The quartz grains contain inclusions of other minerals, such as tourmaline, rutile and muscovite. The sample from Płakowice (WB1111) is composed almost entirely of quartz, with a few weathered feldspars. The cement in the Middle Quader Sandstone is argillaceous-siliceous and pore-filling, with ferruginous cement present in some areas.

In the samples collected from occurrences near Płakowice, Pielgrzymka and Jerzmanice Zdrój (WB1111, WB1807, WB1808A, WB1808B and WB1809), the predominant fraction is fine sand. Sample WB1809 (sublithic arenite) also shows a significant content of medium and coarse sand. The grain size parameters are generally similar (Tab. 5). They differ only for the WB1802 sample from Warta Bolesławiecka (sublithic arenite), which has a dominant coarse sand fraction (Tab. 5).

The sandstone from Płakowice (sample WB1111; Figs. 10-11) was selected as a representative of the Middle Quader Sandstones of the North Sudetic Synclinorium. The SEM-EDS image (Fig. 12B) revealed argillaceous (kaolinitic) and siliceous pore-filling cement, as well as partially ferruginous cement.

Coniacian Upper Quader Sandstone of the North Sudetic Synclinorium

The framework grains of the Upper Quader Sandstones of the North Sudetic Synclinorium consist predominantly of quartz (88-97 vol%), with generally subordinate contributions from lithic fragments, primarily quartzites (3-12 vol) and sparse accessory minerals (opaque minerals, zircon, tourmaline; Tab. 5). Rutile inclusions are present within the quartz grains. The cement of these sandstones is argillaceous-siliceous (pore-lining, and to a lesser extent pore-filling), with ferruginous cement occurring locally. The samples represents fine- to medium-grained quartz arenites and sublithic arenites; only the sample from the Zbylutów quarry (WB1805) is dominated by a very fine-grained fraction. They are poorly to moderately sorted (Tab. 5).

The sandstone from Żerkowice (WB1403; Figs. 10-11) was selected as a representative sample of the Upper Quader Sandstones of the North Sudetic Synclinorium. SEM-EDS studies (Fig. 12C) also confirmed the presence of siliceous cement in the form of visible syntaxial quartz overgrowths. Pore-filling argillaceous cement is dominated by kaolinite, commonly present in booklet-like aggregates.

Provenance of material used in architectural details: summary of petrographic analysis and discussion

The possible origin of the stone used for the architectural details of the historic Piast Castle in Legnica and its adjacent chapel is informed by the existing literature and by analysis of reference sandstone samples. Given the macroscopic characteristics of the historical samples obtained (light-coloured sandstones) and the location of the monument from which they originated, the Upper Cretaceous Quader Sandstones of the North Sudetic Synclinorium area were considered the most likely source of stone material. This inference is supported by published data on the historical extraction of rock material (e.g. Ehling, 1999; Walendowski, 2010a-e) and known examples of Cretaceous sandstone use in monuments in south-western Poland (e.g. Michniewicz, 1996; Klementowski and Marcinów, 2006; Rembiś and Smoleńska, 2009; Kryza, 2011; Prell and Zagożdżon, 2011; Prell and Kryza, 2014; Szczepaniak, 2014, 2015; Zboińska and Bartz, 2019; Szczepaniak and Rój, 2019). It is, and always has been, a widely used building material. Thanks to numerous quarries, it is readily accessible and does not require long-distance transport with its associated costs. It also has key technical advantages for the construction industry, such as strength, frost resistance and blockiness of the raw material (Labus, 2009; Rembiś and Smoleńska, 2010). At the same time, it is relatively easy to work and aesthetically pleasing. These features are particularly significant in the Castle and chapel's various architectural details, which were intended as decorative elements to enhance the buildings' value and demonstrate the founders' wealth and social status over the following centuries. In the light of the petrographic analyses of the reference sandstones, particularly the investigation carried out on samples assumed to be representative of the Lower, Middle and Upper Quader Sandstones of the North Sudetic Synclinorium, distinct differences can be seen between the individual sandstone types with regard to grain-size parameters, framework grain composition (including the presence of feldspars and lithic fragments) and cement composition.

The Lower Quader Sandstones show the greatest variation in grain size parameters of all the samples taken. A high proportion of grains larger than 0.5 mm is common, unlike in other sandstones from this area. Of all the sandstones analysed, the Lower Quader Sandstones are also the least well sorted (Tab. 5). The content of non-quartz components in the framework grains is also variable. Some samples consist almost entirely of quartz, while in others, the content of lithic fragments was a few to several percent. The proportion of feldspar in the samples analysed did not exceed 1 vol%. The cement is argillaceous (kaolinitic) and siliceous, with a minor proportion of ferruginous cement.

The statistical parameters of grain size in samples of Middle Quader Sandstones are generally lower than those in samples of the Lower Quader Sandstones (Tab. 5). Sorting is also generally better, with most of the samples analysed representing poorly to moderately sorted sediments. In addition to quartz and, in some samples, lithic fragments, the mineral composition of the framework grains also includes alkali feldspar (up to 4 vol%). Published data also suggest the occasional presence of glauconite (Ehling, 1999), but this has not been confirmed in the reference samples analysed. The cement is argillaceous (kaolinitic) and siliceous, with a minor proportion of ferruginous cement.

Of all the Cretaceous sandstones in the North Sudetic Synclinorium, the Upper Quader Sandstones are the best sorted and generally the finest grained (Tab. 5), although the differences from the Middle Quader Sandstones are only slight. However, none of the samples analysed showed a third quartile grain size exceeding 0.5 mm. In contrast, lithic fragments occurred in all of the samples, with a negligible proportion of feldspar (<1 vol%). The cement of these sandstones is argillaceous (kaolinitic) and siliceous, locally ferruginous.

Almost all of the historical samples from Piast Castle and its adjacent chapel are medium-grained quartz arenites; one sample is a sublithic arenite. The mean grain size ranges from 0.22 to 0.33 mm, the median ranges from 0.22 to 0.33 mm, the first quartile ranges from 0.14 to 0.23 mm, and the third quartile ranges from 0.29 to 0.48 mm (Tab. 4). The samples are moderately well to poorly sorted. Their framework grains are composed of quartz (93–99 vol%), with lithic fragments also present (1–9 vol%, depending on the sample). Feldspars and accessory minerals occur singly (Tab. 4). Single grains larger than 1 mm are occasionally present in the framework grains. The cement is argillaceous (kaolinitic) and siliceous, locally ferruginous.

Samples LEG018 (subarkosic arenite), LEG019, and LEG025 (quartz arenite) differ from the dominant sandstone varieties described above in terms of the statistical parameters of grain size and occurrence of alkali feldspars in their framework grains (3-12 vol%) (Tab. 4). All of these fragments have been identified as Romanesque elements and are therefore original architectural details dating from the first half of the 13th century, when the chapel was built (Rozpędowski, 1971).

When considering the possible origin of the stone material used for the architectural details of Piast Castle and its adjacent chapel, two aspects should be taken into account: the petrographic characteristics and the historical context. In terms of their mineralogical and petrographic characteristics, these rocks have been shown to be similar to the Upper Cretaceous Quader Sandstones found in the North Sudetic Synclinorium. This is supported by the composition of the framework grains and type of cement. However, statistical parameters of grain size exclude the involvement of the Lower Quader Sandstones in the monument. This is because they are usually characterised by larger grains and a higher proportion of grains above 0.5 mm. This explains why the Lower Quader Sandstones were not used for the architectural details, some of which feature very rich and subtle ornamentation: coarsergrained material is not suitable for graceful sculpting.

The composition of the framework grains can provide more detailed suggestions regarding the provenance of the material. In most samples from the Castle, the proportion of feldspar is negligible, typically below 1% by volume. However, three samples from Late Romanesque details from the chapel stand out, with feldspar content ranging from 3 to 12 vol%. While quartz dominates the framework grains in both Middle and Upper Quader Sandstones, this higher feldspar content is notable. It suggests that two types of rock were used in the original (Late Romanesque) stonework of the monument: Upper and Middle Quader Sandstones of the North Sudetic Synclinorium. The younger Gothic and Renaissance details from the Castle could have only been made using the Upper Quader Sandstones.

In terms not only of petrography, but also of history, the material most likely used for most of the samples discussed from Piast Castle could be the Coniacian sandstones quarried in the Wartowice or Czaple area. Walendowski (2010a, d) dates the main. period of Upper Quader Sandstone quarrying in Wartowice to the 14th century and in Czaple to the Middle Ages; however, he does not provide supporting evidence for this claim. Conversely, the three samples from the chapel with a higher proportion of feldspars are petrographically similar to the Turonian sandstones. Analysis of the reference samples corroborated the occurrence of up to 4 vol% feldspars in the Middle Quader Sandstone samples from the North Sudetic Synclinorium. This is consistent with Ehling's (1999) observations, which indicate a feldspar proportion of between 1 and 10 vol% in the framework grains of the Turonian sandstones. Labus (2011), on the other hand, highlights the issue of the different grain size of these rocks. Taking into account the survey results and published data, the probable source rock for the Late Romanesque samples identified could be quartz arenites quarried in the Płakowice area (currently a part of Lwówek Śląski). However, the reference sample analysed of this sandstone shows a very low proportion of feldspar; however, rocks within one deposit may vary significantly locally.

The exact origins of the exploitation of the raw material in Płakowice are unknown. However, Walendowski (2010e) describes Płakowice as "one of the oldest sandstone mining sites in the stoneworking district around Bolesławiec and Lwówek Śląski". Gold mining in Płakowice is known to have been practised since at least 1180 (Staffa, 2002), so it was already a mining centre by that time. Further historical-petrographic reports corroborate the mining of Upper Cretaceous sandstones in the vicinity of Lwówek Śląski in the Middle Ages: near Płakowice, in the village of Sobota, a church was built from sandstone blocks as early as the mid-13th century (Adamska, 2020, citing Łużyniecka, 1984; Kozaczewski, 1994), and Walendowski (2010e) and Kryza (2011) highlighted the use of raw material from local quarries in the defensive walls and monuments of Lwówek Śląski. The late Romanesque-Gothic Church of the Assumption of the Blessed Virgin Mary in Lwówek Śląski, one of the oldest churches in Silesia, built on the site of an earlier wooden church, was constructed between 1238 and 1300 from blocks of Cretaceous sandstone. Crucially, during the construction of the Castle chapel, the entire region (and thus the areas of Legnica and Lwówek Śląski) was under the control of Duke Henry the Bearded, who was responsible for numerous economic initiatives, such as the incorporation of Lwówek Śląski into the *Magdeburg Law* in 1217 (Adamska, 2020), as well as the construction of palaces at the castles in Legnica (including the chapel) and Wrocław in the first half of the 13th century (Chorowska, 2020).

In the context of the building stone used for the Legnica chapel, the quarries at Wartowice, Czaple, and Płakowice are all located within approximately 40 km of Legnica, making them close sources of raw material. Using local material for the buildings being constructed therefore seems natural and economically justifiable.

Another observation made during the study was the variation in the degree of sorting of the sediment forming the framework grains between the reference sandstones and the samples from Piast Castle and its chapel. While sorting was predominantly identified as moderate to poor in the reference sandstones, it was found to be moderately good to moderate in the samples from the historical structure. One possible explanation for this is the deliberate selection of better-sorted, more evenly grained raw material for further stoneworking.

Conclusions

1) Despite originating from different construction phases of the building (from the 13th to the 16th century), the sandstones used in the architectural details of Piast Castle in Legnica and its chapel mostly represent quartz arenites with an argillaceous-siliceous cement, while sublithic arenites and subarkosic arenites occur only occasionally.

2) Due to slight variations in the composition of the framework grains, observed in some historical samples, particularly in their feldspar and lithic fragment content, it can be inferred that the sandstones probably originated from two sources. Petrographic variability of the rock material is also evident across the different construction phases of the chapel. The Gothic and Renaissance details analysed are similar to the Upper Quader Sandstones from the North Sudetic Synclinorium, which are currently extracted from deposits near Wartowice, Czaple and Żeliszów. The original (Late Romanesque) architectural details from the chapel were made not only of Coniacian Upper Quader Sandstones, but also of Turonian Middle Quader Sandstones from the North Sudetic Synclinorium, which are mined near Płakowice (now part of Lwówek Ślaski).

3) Given the lack of rocks representing the Lower Quader Sandstones, and the observed differences in the degree of sorting between reference sandstones and historical samples, it can be concluded that the former stonemasons deliberately selected better-quality raw material (equigranular and better sorted) for stoneworking and architectural use.

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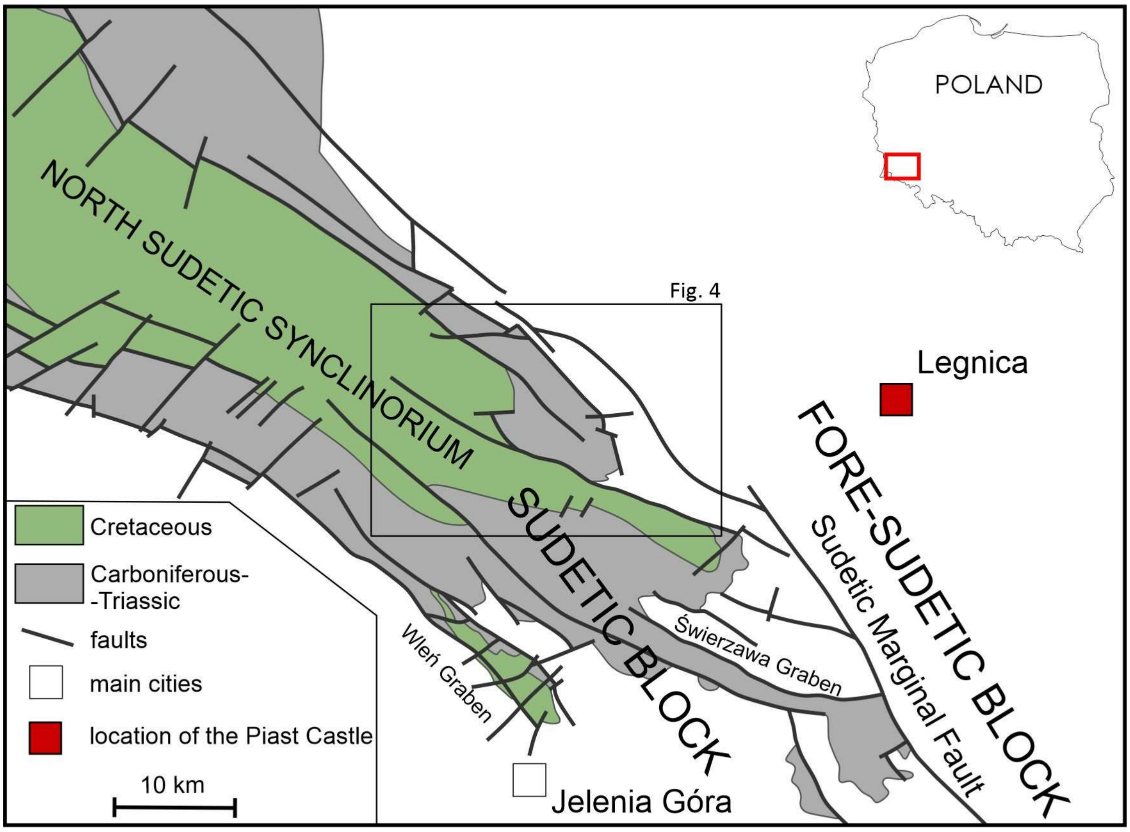


Fig. 1. Simplified geological map of the North Sudetic Synclinorium (based on: Stępień and Grabowski, 2002; modified by the authors) with the location of Piast Castle in Legnica marked.

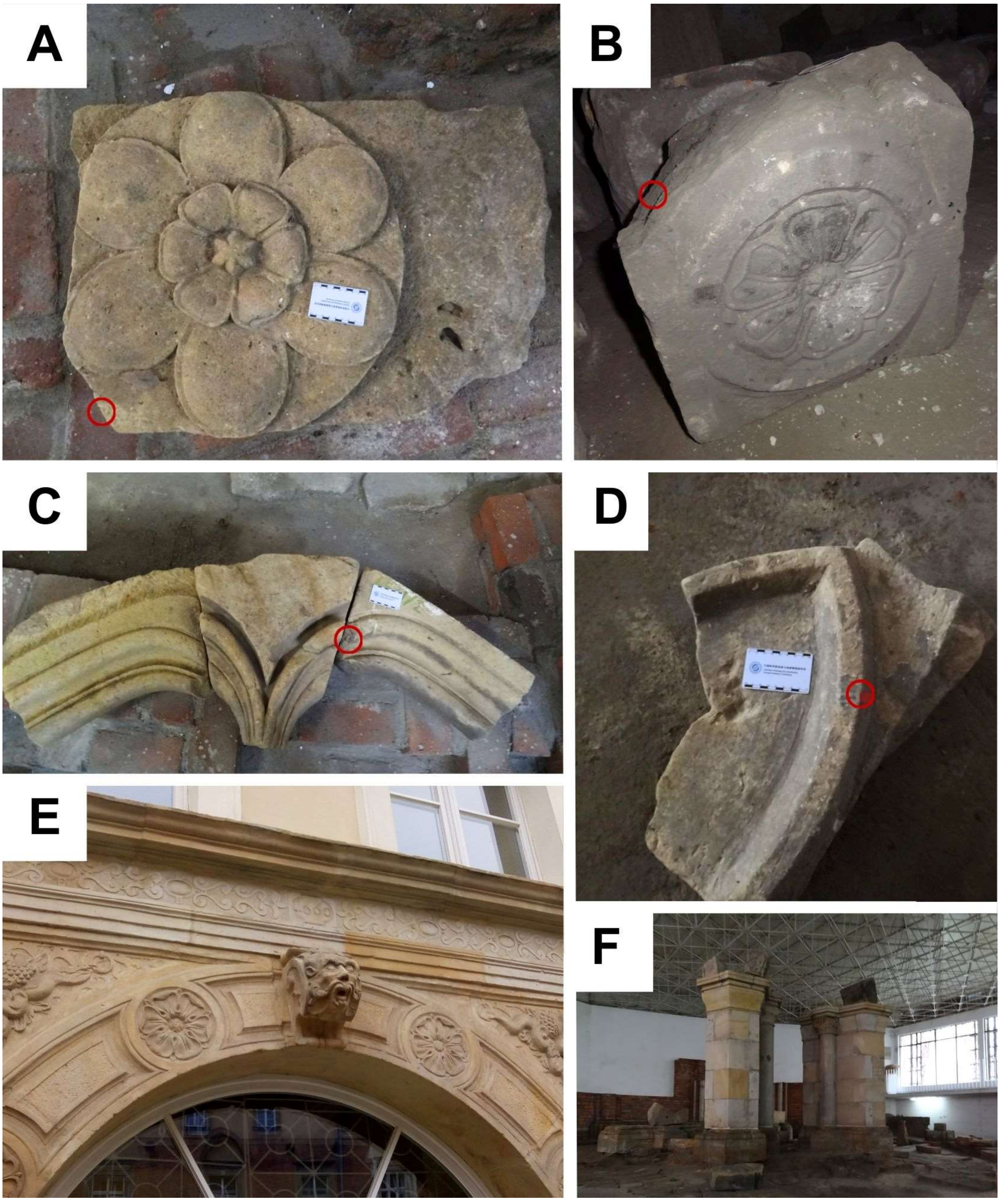


Fig. 2. Examples of architectural details from Piast Castle in Legnica and its adjacent chapel, from which samples of historical stone material were obtained. Red circles indicate sampling locations.
A – element with rosette from triforium; B – detail with rosette from window reveal; C – fragments of vault ribs with keystone; D – fragment of blind tracery; E – example of architectural details from Piast Castle in Legnica: stone window reveal with rosettes (see Fig. 2B); F – the remains of the Castle chapel are currently covered with a pavilion and are open to visitors during the summer season (all photos by KSz).

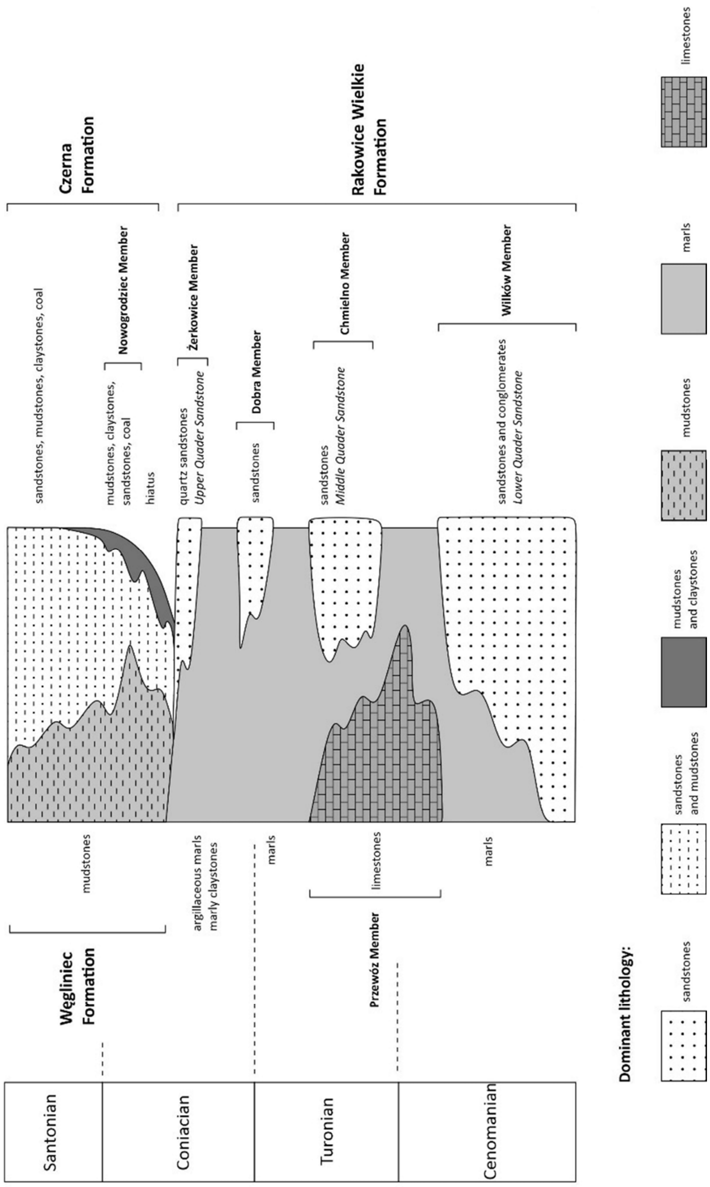


Fig. 3. Lithostratigraphy of Cretaceous deposits in the North Sudetic Synclinorium (based on: Milewicz, 1985; Voigt et al., 2008; Leszczyński et al., 2022).

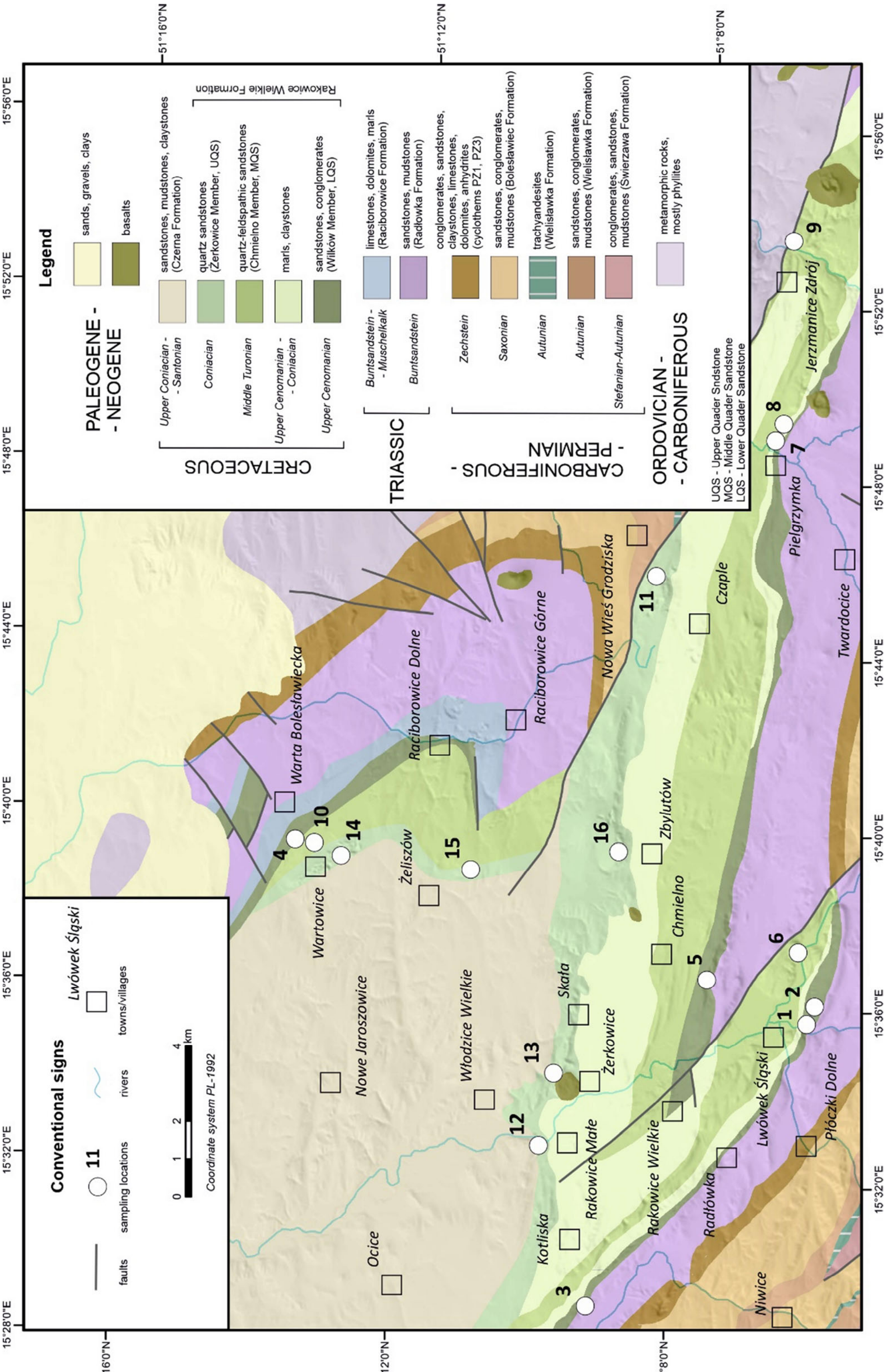


Fig. 4. Simplified solid geological map of the North Sudetic Synclinorium with reference sample locations.
The location numbers on the map, indicating individual sandstone sampling sites, are explained in Tab. 3. The geological image was drawn on the basis of geological maps (Milewicz et al., 1979; Sztromwasser, 1995; Badura, 2005; Cymerman et al., 2005a, b; Kozdrój et al., 2005; Przybylski and Ihnatowicz, 2005; modified by authors). The digital terrain model is part of the state geodetic and cartographic resource maintained by the Surveyor General of Poland pursuant to the provisions of the Act of 17 May 1989 on Geodetic and Cartographic Law (Journal of Laws of 2010, No. 193, item 12).

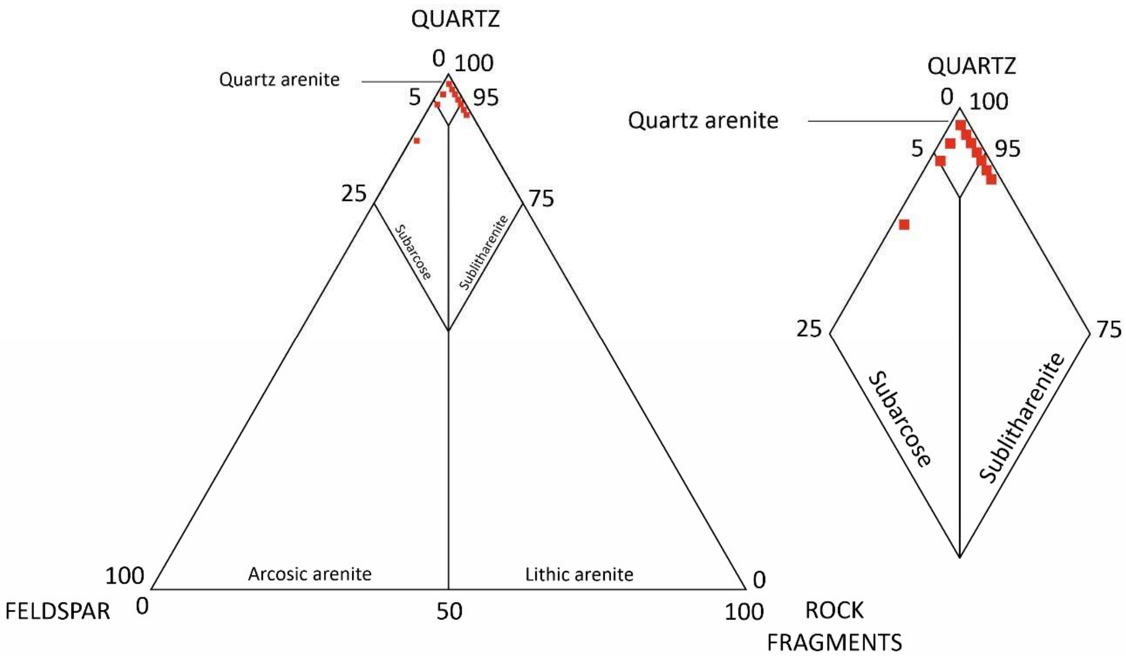


Fig. 5. Classification of historical samples analysed from Piast Castle in Legnica and its chapel (based on Pettijohn et al., 1972).

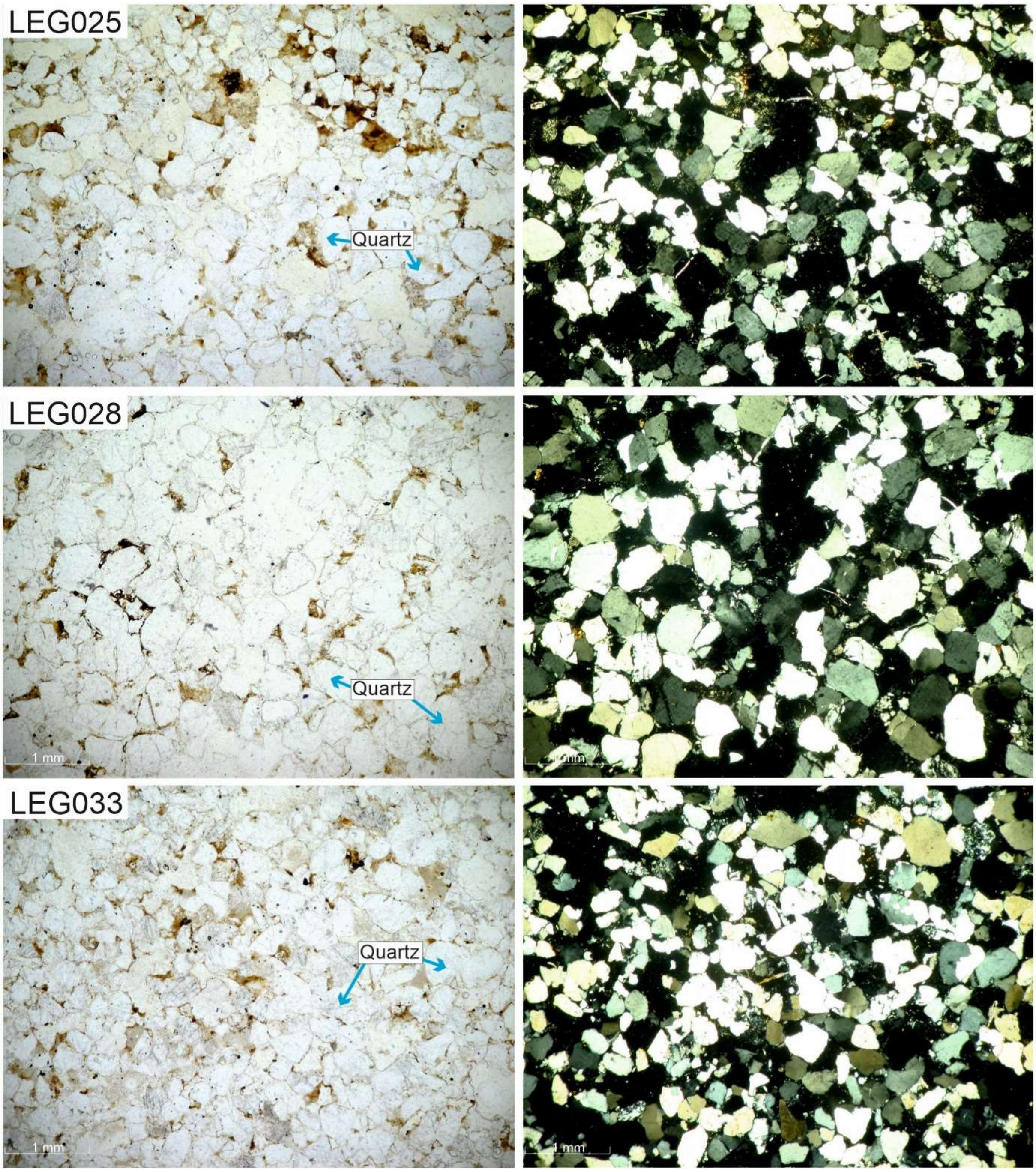


Fig. 6. Microscope images of samples LEG025, LEG028 and LEG033 in plane-polarized (left) and crossed-polarized light (right).

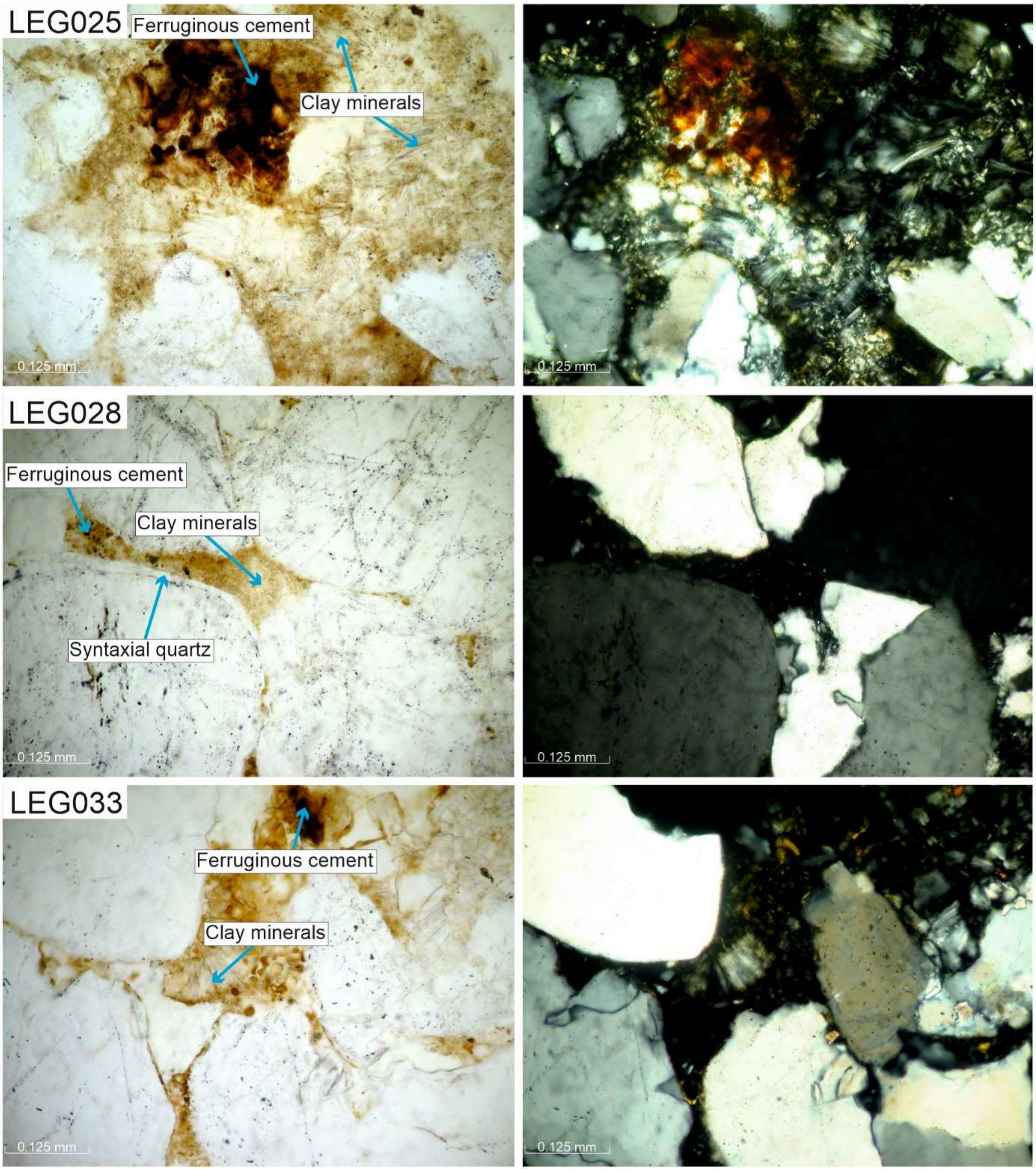


Fig. 7. Microscope images of samples LEG025, LEG028 and LEG033 in plane-polarized (left) and crossed-polarized light (right), illustrating detailed views of cements.

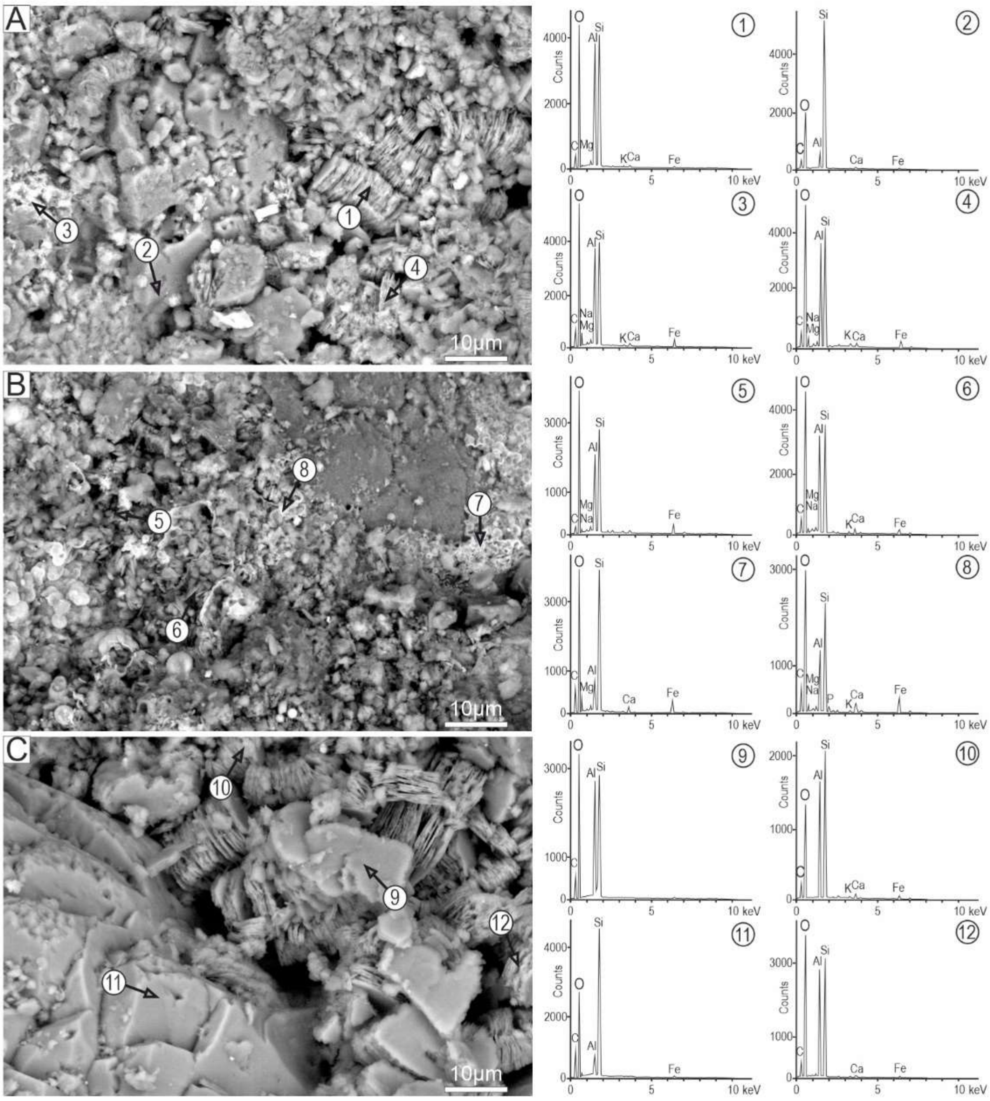


Fig. 8. Backscattered electron (BSE) images of samples: (A) – LEG025; (B) – LEG028; (C) – LEG033 and EDS spectra. Spectra 2 and 11 – syntaxial quartz; spectra 7 and 8 – siliceous cement (poorly crystalline SiO_2) containing Al and Fe; spectrum 9 – kaolinite (single flake).

The remaining spectra correspond to kaolinitic cement (booklet-like aggregates) with variable amounts of Fe-bearing minerals dispersed between the flakes of the aggregates.

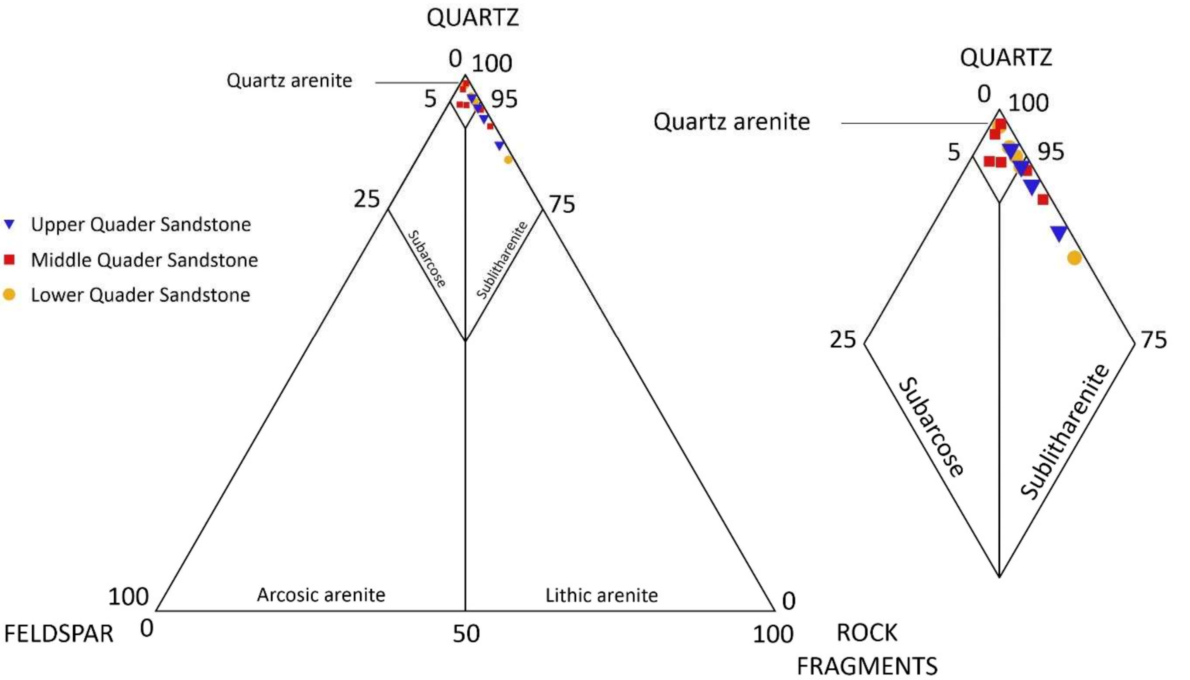


Fig. 9. Classification of reference sandstones analysed from the North Sudetic Synclinorium (based on Pettijohn et al., 1972).

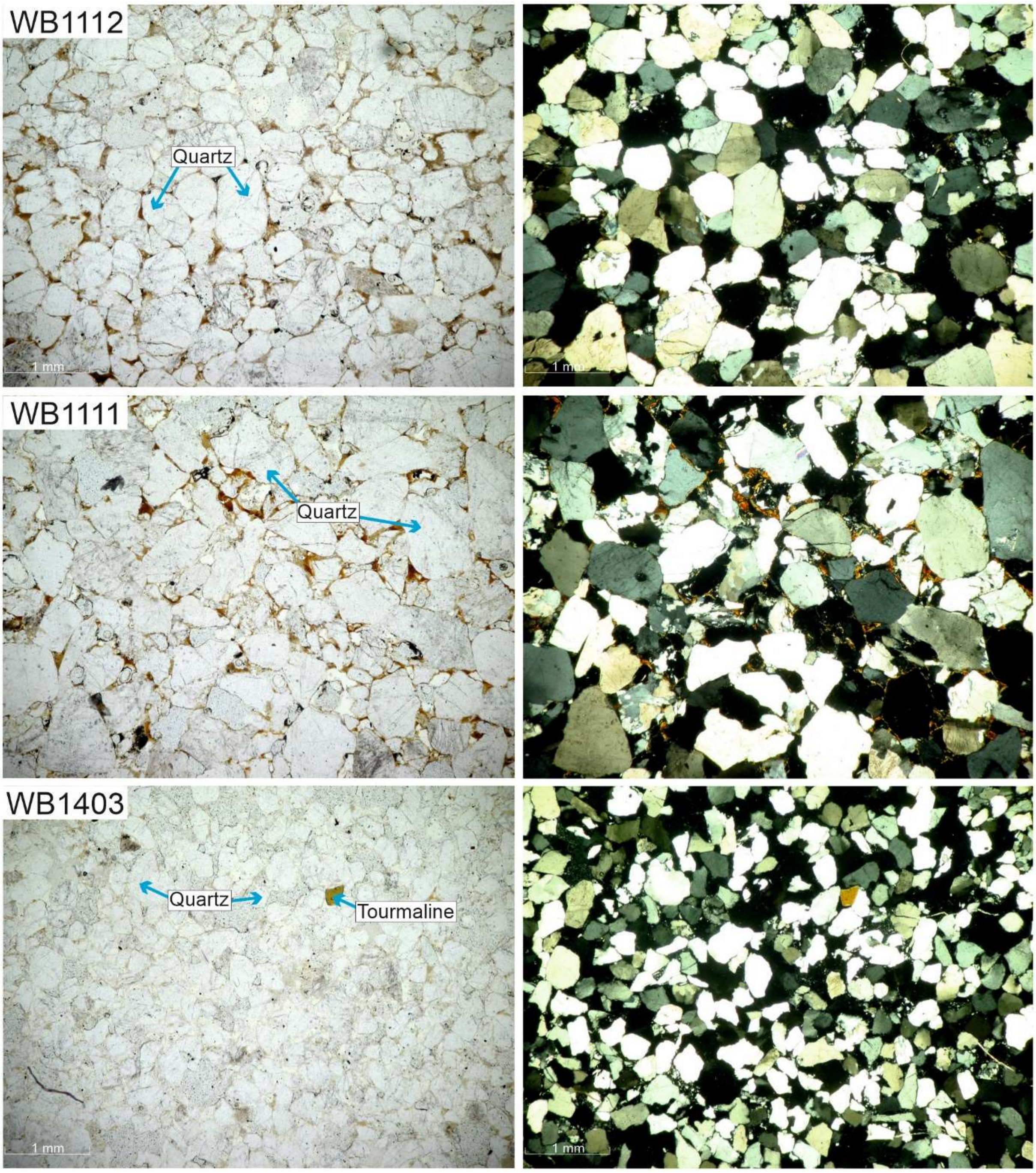


Fig. 10. Microscope images of samples WB1112, WB1111 and WB1403 in plane-polarized (left) and crossed-polarized light (right)

Additional microscope images for other samples (WB1116, WB1809, WB1110) are provided in the supplementary material (Appendix 1).

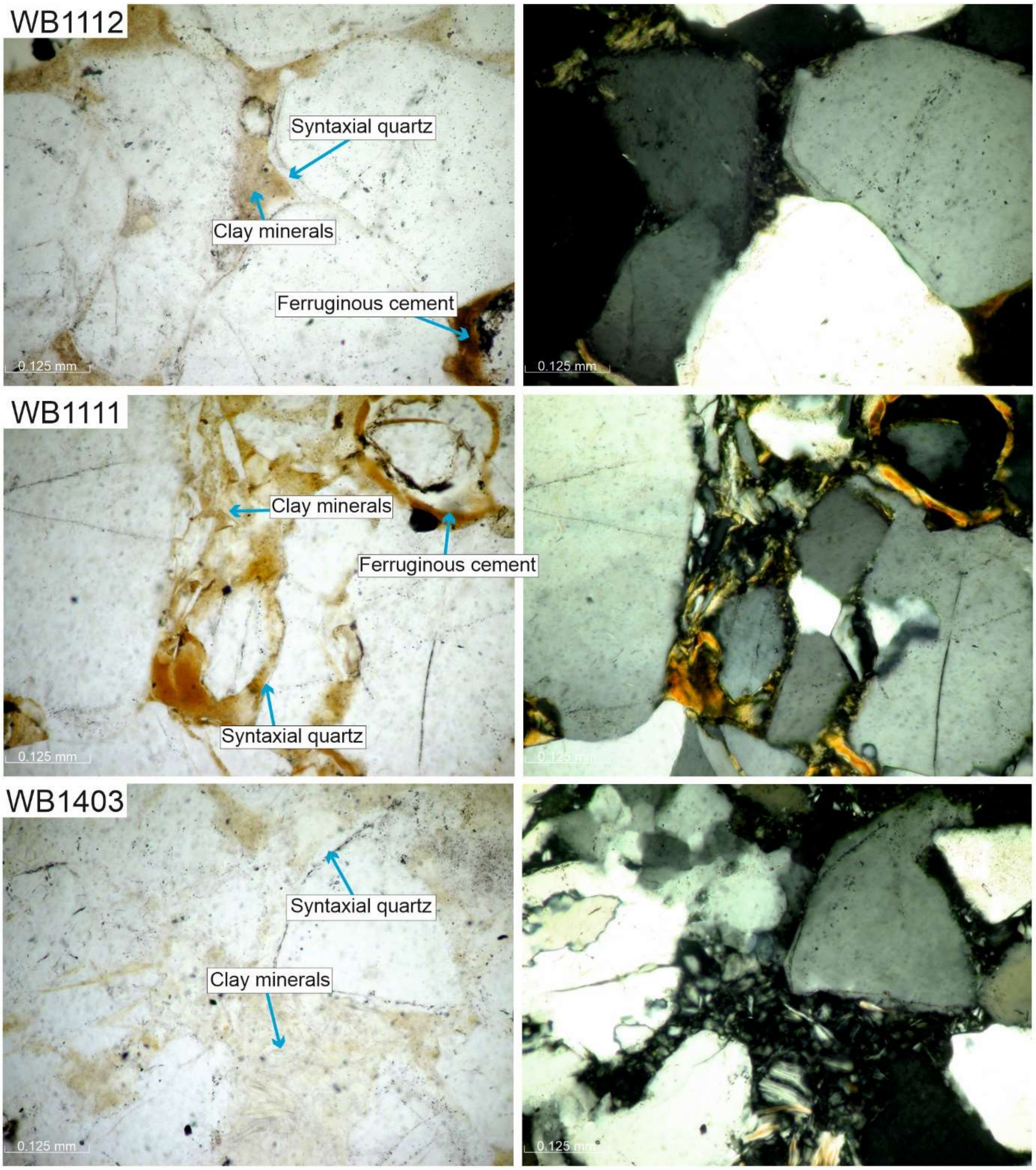


Fig. 11. Microscope images of samples WB1112, WB1111 and WB1403 in plane-polarized (left) and crossed-polarized light (right), illustrating detailed views of cements.

Additional microscope images for other samples (WB1116, WB1809, WB1110) are provided in the supplementary material (Appendix 2).

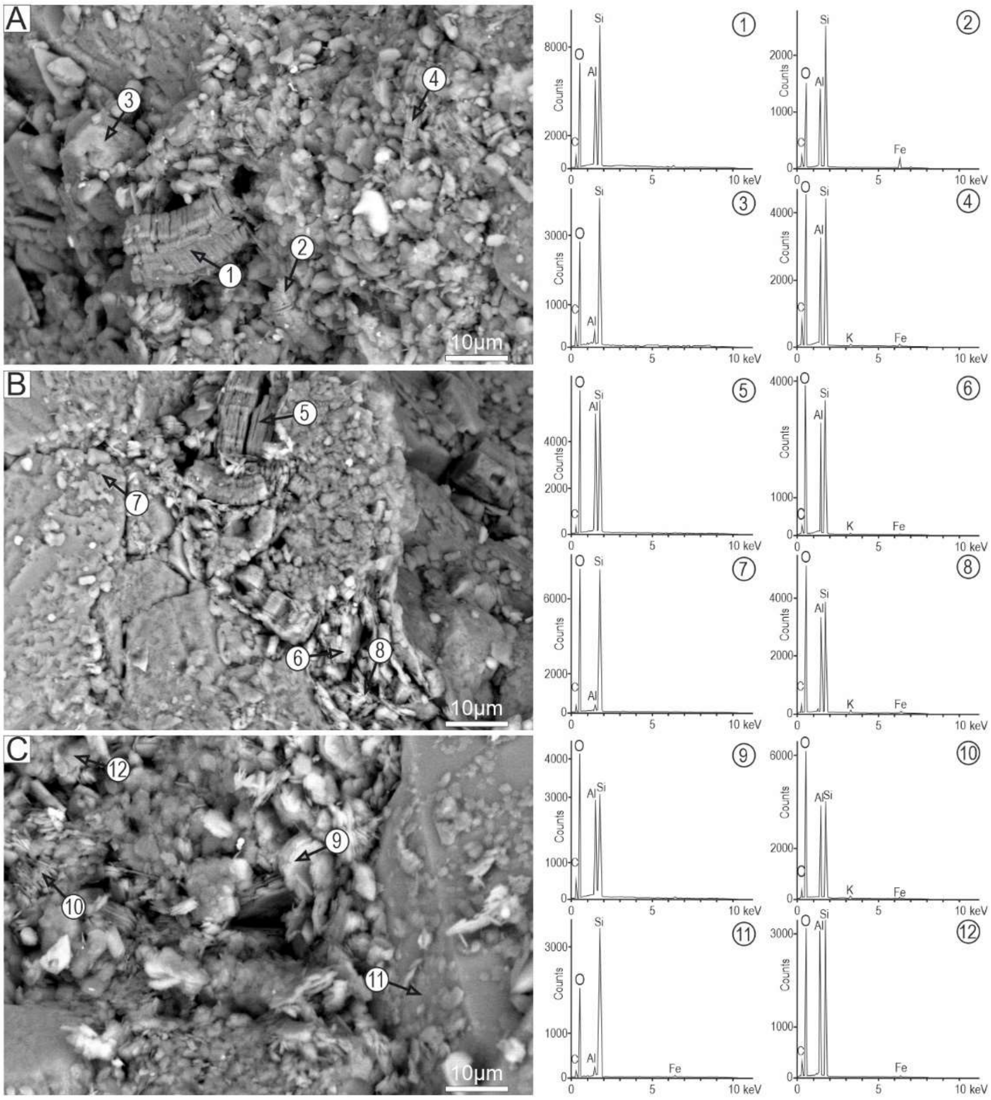


Fig. 12. Backscattered electron (BSE) images of samples: (A) – WB1112 (Lwówek Śląski); (B) – WB1111 (Płakowice); (C) – WB1403 (Żerkowice) and EDS spectra.
Spectra 3, 7 and 11 – syntaxial quartz. The remaining spectra correspond to kaolinitic cement (booklet-like aggregates) with variable amounts of Fe-bearing minerals dispersed between the flakes of the aggregates.

Table 1

Architectural details from Piast Castle in Legnica and its adjacent chapel, from which the samples were obtained for analysis. Italics indicate an unconfirmed (presumed) time of creation of each architectural element.

Sample	Architectural detail	Time of creation
LEG002	unspecified	*1st half 13th c.*
LEG003	element with rosette from triforium	
LEG004	vault rib element with keystone	
LEG005	rib element with tracery	*15th c.*
LEG006	tracery	
LEG007	unspecified	*1st half 13th c.*
LEG009	arch	
LEG010	unspecified	
LEG011	fragment of a buttress	
LEG013	tracery	*15th c.*
LEG014	frieze element	*1st half 13th c.*
LEG015	fragment of a column	
LEG017	exterior wall of the chapel	1st half 13th c.; Romanesque
LEG018	chapel element from the shaft (internal)	
LEG019	fragment of a column	
LEG020	rib	
LEG021	rib	
LEG022	rib/keystone	
LEG024	rib	
LEG025	column finial	
LEG028	fragment of a gothic keystone	15th c.; Gothic
LEG029	fragment of a gothic keystone	
LEG030	fragment of a gothic keystone	
LEG031	window reveal	1st half 16th c.; Renaissance
LEG032	rosettes at window reveal	
LEG033	rosettes at window reveal	

Table 2. Basic grain size parameters of the Upper Cretaceous Quader Sandstones of the North Sudetic Synclinorium: examples according to Milewicz (1997, 1998) and Ehling (1999).

	Milewicz, 1997		**Milewicz, 1998**		**Ehling, 1999**	
	mean/ median[1] [mm]	sorting coefficient	mean [mm]	inclusive graphic standard deviation	mean [mm]	sorting coefficient
Lower Quader Sandstone	0.53	1.8	-	-	0.42	1.75
Middle Quader Sandstone	0.42	1.8	-	-	0.38	1.68
Upper Quader Sandstone	0.20	1.2 (to 1.13)	0.13-0.54[2]	0.3-1.4	0.11-0.31	1.28-1.55

[1]Milewicz (1997) uses the terms mean and median interchangeably to refer to the same parameters.

[2]Samples from the western part of the Synclinorium, where Milewicz (1998) claims the coarsest sandstones are found, were also considered. Milewicz (1997) and Ehling (1999) focused on the eastern part of the Synclinorium, where fine- and medium-grained sandstones are found. In the original work (Milewicz, 1998), the values are given on a phi scale and have been converted to millimetres here.

Table 3. Locations of sandstone sampling sites in the North Sudetic Synclinorium. Sampling site numbers correspond to the map (Fig. 4).

No	Location	Sample	
1	Lwówek Śląski, Szwajcaria Lwówecka	WB1112	Upper Cenomanian, Lower Quader Sandstone
		WB1113	
		WB1114	
		WB1115	
2	Lwówek Śląski, Wzgórze Kombatantów	WB1806	
3	Radłówka, Twardziel hill	WB1116	
		WB1117	
4	Warta Bolesławiecka 1	WB1801	
5	Jaglarz hill, quarry	WB1118	
		WB1119	
6	Płakowice, Skałka hill	WB1111	Middle Turonian, Middle Quader Sandstone
7	Pielgrzymka 1, quarry	WB1807	
8	Pielgrzymka 2, quarry	WB1808A	
		WB1808B	
9	Jerzmanice Zdrój, Krucze Skały	WB1809	
10	Warta Bolesławiecka 2	WB1802	
11	Czaple, Gruszecki quarry	WB1108	Coniacian, Upper Quader Sandstone
		WB1109	
		WB1110	
12	Rakowice Małe, quarry	WB1402	
13	Żerkowice, quarry	WB1403	
14	Wartowice, quarry	WB1803	
15	Żeliszów, quarry	WB1804	
16	Zbylutów, quarry	WB1805	

Table 4. Statistical parameters and modal composition of samples from Piast Castle in Legnica and its chapel.

Sample	[mm]				[phi]	[%]			
	M_d	M_z	Q_1	Q_3	σ_I	Otz	Fs	L	A
LEG002	0.32	0.33	0.23	0.48	0.82	98	<1	2	<1
LEG003	0.31	0.30	0.21	0.42	0.76	99	<1	1	<1
LEG004	0.27	0.24	0.17	0.37	0.94	99	<1	1	<1
LEG005	0.28	0.27	0.19	0.38	0.80	97	<1	3	<1
LEG006	0.27	0.26	0.18	0.37	0.73	97	<1	3	<1
LEG007	0.23	0.22	0.14	0.38	1.02	99	<1	<1	<1
LEG009	0.32	0.28	0.18	0.45	0.92	97	<1	3	<1
LEG010	0.24	0.23	0.16	0.35	1.04	96	<1	4	<1
LEG011	0.28	0.27	0.18	0.40	0.85	97	<1	3	<1
LEG013	0.26	0.25	0.19	0.36	0.77	97	<1	3	<1
LEG014	0.25	0.25	0.17	0.36	0.78	99	<1	<1	<1
LEG015	0.27	0.27	0.19	0.39	0.89	96	<1	4	<1
LEG017	0.28	0.26	0.17	0.41	0.92	97	<1	3	<1
LEG018	0.19	0.18	0.13	0.27	0.87	87	12	<1	<1
LEG019	0.21	0.18	0.13	0.30	0.95	95	5	<1	<1
LEG020	0.32	0.29	0.21	0.42	0.84	96	<1	4	<1
LEG021	0.27	0.25	0.16	0.39	0.96	95	<1	5	<1
LEG022	0.28	0.26	0.17	0.42	0.93	97	<1	3	<1
LEG024	0.25	0.25	0.17	0.38	0.91	93	<1	7	<1
LEG025	0.25	0.22	0.16	0.34	0.96	97	3	<1	<1
LEG028	0.32	0.29	0.21	0.44	0.86	99	<1	1	<1
LEG029	0.26	0.23	0.17	0.33	0.75	97	<1	3	<1
LEG030	0.33	0.30	0.23	0.44	0.88	93	<1	6	<1
LEG031	0.29	0.29	0.22	0.38	0.67	99	<1	<1	<1
LEG032	0.26	0.24	0.19	0.33	0.68	99	<1	<1	<1
LEG033	0.22	0.20	0.15	0.29	0.81	97	<1	3	<1

Parameters M_d, M_z, Q_1, Q_3 are given in mm, σ_I in phi units, content of individual rock components is expressed in volume percent (% vol.). M_d - median, M_z - mean, Q_1 – first quartile, Q_3 – third quartile, σ_I - graphic sorting, Qtz - quartz, Fs - feldspars, L - lithic fragments, A - accessory minerals.

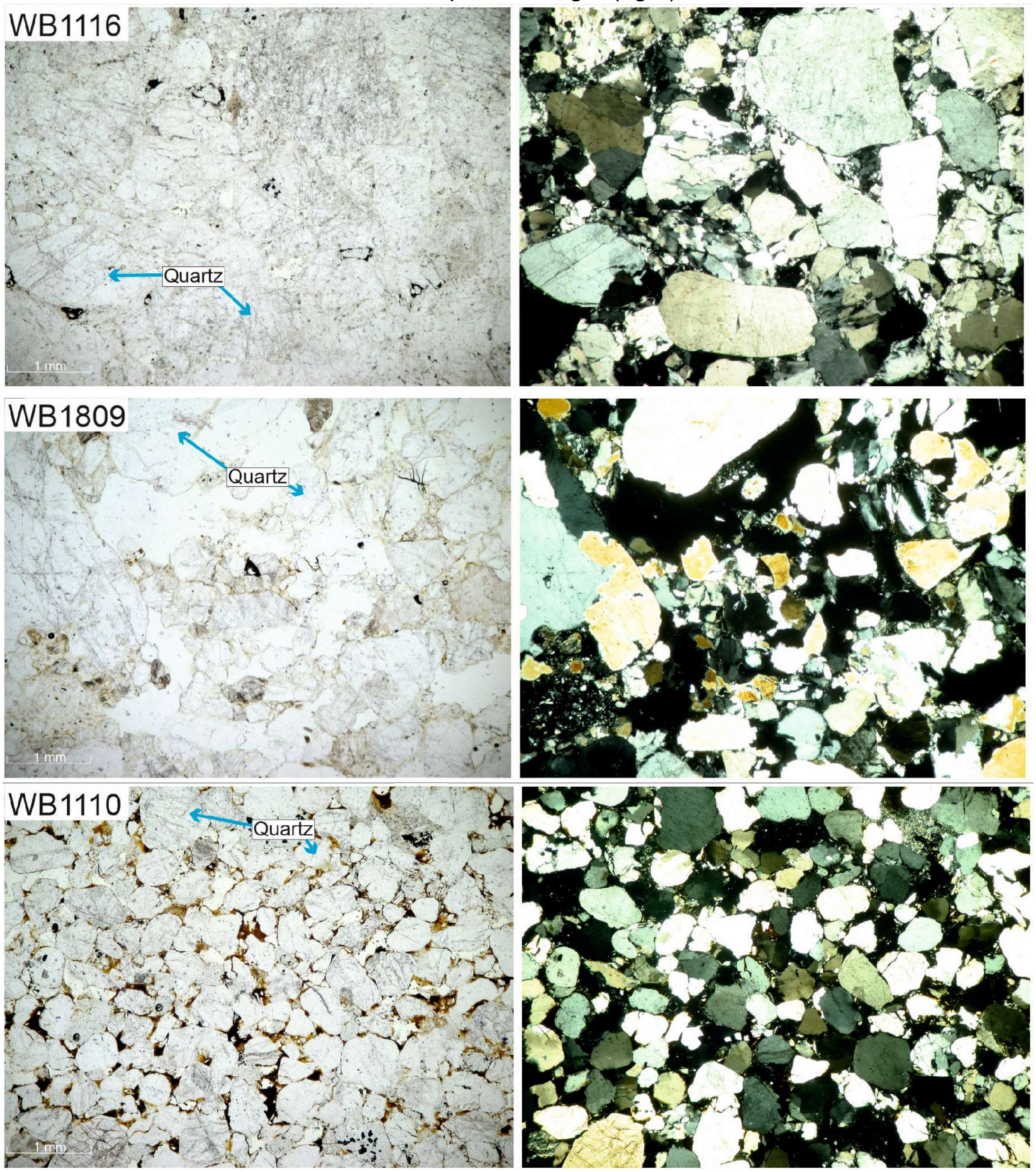
Table 5. Statistical parameters and modal composition of sandstone samples from the North Sudetic Synclinorium.

Sample	[mm]				[phi]	[%]			
	M_d	M_z	Q_1	Q_3	σ_I	Otz	Fs	L	A
WB1112	0.34	0.27	0.15	0.61	1.53	95	<1	5	<1
WB1113	0.21	0.18	0.10	0.32	1.24	99	<1	<1	<1
WB1114	0.31	0.26	0.17	0.47	1.17	99	<1	1	<1
WB1115	0.34	0.29	0.16	0.58	1.34	97	<1	3	<1
WB1806	0.30	0.30	0.17	0.55	1.16	99	<1	<1	<1
WB1116	0.15	0.16	0.06	0.36	1.59	85	<1	15	<1
WB1117	0.15	0.14	0.06	0.32	1.53	96	1	3	<1
WB1801	0.15	0.17	0.07	0.36	1.48	99	<1	<1	<1
WB1118	0.27	0.25	0.12	0.60	1.54	99	<1	1	<1
WB1119	0.26	0.23	0.14	0.53	1.53	96	<1	4	<1
WB1111	0.17	0.19	0.10	0.36	1.18	99	<1	<1	<1
WB1807	0.17	0.16	0.11	0.27	1.09	97	1	<1	1
WB1808A	0.16	0.15	0.10	0.22	0.92	95	3	2	<1
WB1808B	0.15	0.13	0.08	0.20	1.02	95	3	2	<1
WB1809	0.25	0.27	0.15	0.53	1.34	93	1	6	<1
WB1802	0.36	0.31	0.15	0.70	1.64	91	<1	9	<1
WB1108	0.28	0.25	0.13	0.48	1.25	88	<1	12	<1
WB1109	0.26	0.24	0.14	0.41	1.09	95	<1	5	<1
WB1110	0.20	0.17	0.10	0.33	1.15	95	<1	5	<1
WB1402	0.25	0.19	0.14	0.31	1.34	93	<1	7	<1
WB1403	0.25	0.19	0.11	0.36	1.25	97	<1	3	<1
WB1803	0.16	0.13	0.10	0.20	0.86	97	<1	3	<1
WB1804	0.17	0.15	0.11	0.21	0.79	95	<1	5	<1
WB1805	0.15	0.16	0.08	0.32	1.25	96	<1	3	1

Parameters M_d, M_z, Q_1, Q_3 given in mm, σ_I in phi, content of individual rock components in vol%. M_d - median, M_z - mean, Q_1 – first quartile, Q_3 – third quartile, σ_I - graphic sorting, Qtz - quartz, Fs - feldspars, L - lithic fragments, A - accessory minerals.

APPENDIX 1

Microscope images of samples WB1116, WB1809 and WB1110 in plane-polarized (left) and crossed-polarized light (right).



Appendix 2

Microscope images of samples WB1116, WB1809 and WB1110 in plane-polarized (left) and crossed-polarized light (right), illustrating detailed views of cements.