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LITHOLOGIC-PETROGRAPHIC CHARACTERIZATION OF SILURIAN ROCKS IN THE NIESTACHÓW PROFILE (HOLY CROSS MOUNTAINS)

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Abstract: The Niestachów profile is located in the southwestern part of the Holy Cross Mountains and exposes lower Ludlovian greywacke sediments of the Niewachlów Beds that occur above graptolitic claystones of the Prągowiec Beds. Within the sequence of lithologically diversified Niewachlów Beds, more than 400 m thick, 11 characteristic lithologic complexes were identified. The lower and upper parts of the Niewachlów Beds comprise fine- and medium-grained greywacke sandstones with mudstone interbeds, whereas the middle part contains coarse-grained greywacke sandstones and conglomerates. The sediments were transported by "turbiditic currents" from the southwest. Petrographic examination of the upper part of the Prągowiec Beds and the Niewachlów Beds indicates that the greywacke conglomerates and sandstones of the Niewachlów Beds are composed primarily of volcanic and sedimentary lithoclasts, with subordinate metamorphic and scarce plutonic lithoclasts. The sandstones and conglomerates were derived from an orogen containing sandstones and mudstones as well as from the magmatic rocks of a continental volcanic arc, characterized by acidic-intermediate volcanism.

Key words: Holy Cross Mountains, Silurian, lithology, petrography, greywackes.

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INTRODUCTION

In the Kielce region of the Holy Cross Mountains, the lower part of the Silurian succession consists of Llandoverian, Wenlockian and lower Ludlovian graptolitic shales, whereas the upper part is composed of middle Ludlovian greywacke sediments (Tomczykowa and Tomczyk, 1981; Malec, 2006). The occurrence of diverse marine benthonic fossils in these greywackes was seen as an indication of a shallow, marine environment. Poorly-rounded clastic material and the presence of claystone and mudstone lithoclasts may have indicated proximity of the source areas as well as fluvial transport. The sedimentary structures in the greywacke sandstone beds have been attributed to current and wave action in nearshore shelf zones and deltaic environments (Samsonowicz, 1934; Tomczykowa, 1959; Tomczyk, 1962; Kotański, 1968; Łabędzki, 1969; Przybyłowicz and Stupnicka, 1989, 1991; Romanek and Rup, 1989). Only a few authors suggested deposition of the greywackes in a deep marine environment due to the activity of "turbiditic currents" (Łydka *et al.*, 1963).

In the Kielce region, the most complete Silurian greywacke sequence is represented by the Niewachlów Beds that occur in its western part, near Niestachów (Fig. 1). In this area, these sediments rest in stratigraphic continuity on the graptolitic claystones of the Prągowiec Beds (Fig. 2). Despite a thickness of over 400 m of greywackes in this area, only a small part of these sediments is naturally and artificially exposed. In order to fully recognize the lithologic development of the graptolitic shales and the overlying greywacke series of the Niestachów profile, excavations were carried out to expose the unidentified or poorly recognized rock complexes. On the basis of a lithologic-sedimentologic study of the greywackes of the Niewachlów Beds, a deep-marine, depositional environment was determined (Malec, 2002a, 2005, 2006). The detrital material was transported by "turbiditic currents" from the southwest to the southern part of the Holy Cross Mountains (Malec, 2002b; Malec and Kuleta, 2009a; Kozłowski *et al.*, 2014). This paper presents the lithologic-petrographic characterization of the graptolitic claystones of

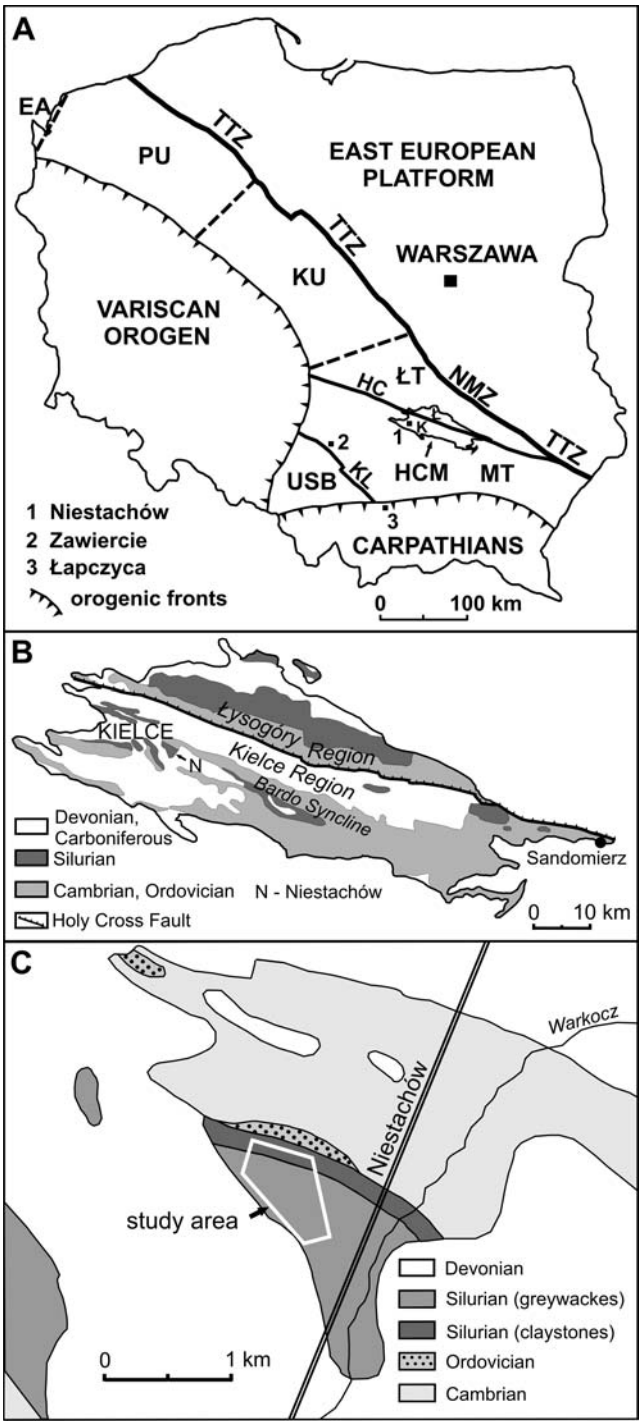

Fig. 1. Location map. **A.** Location of the Holy Cross Mountains in the framework of the main tectonic units of Poland (modified after Narkiewicz *et al.*, 2011); EA – East Avalonia, PU – Pomerania Unit, KU – Kujavian Unit, ŁT – Łysogóry Terrane, MT – Małopolska Terrane, USB – Upper Silesian Block, HCM – Holy Cross Mountains, TTZ – Teisseyre–Tornquist Zone, NMZ – Nowe Miasto–Zawichost Fault, HC – Holy Cross Fault, KL – Kraków–Lubliniec Fault, Ł – Łysogóry Region, K – Kielce Region. **B.** Map of Holy Cross Mountains, with location of Niestachów section. **C.** Geological sketch map of Niestachów area (modified after Czarnocki, 1938).

the Prągowiec Beds and the rock complexes distinguished within the greywacke complexes of the Niewachlów Beds. On the basis of the petrographic study, the geotectonic character of the source area is inferred.

GEOLOGICAL SETTING

The Palaeozoic rocks of the Holy Cross Mountains (Fig. 1) occur in the central part of Europe, close to the Teisseyre–Tornquist Zone (TTZ) that separates the mobile Caledonian and Variscan structures of Central and Eastern Europe from the stable Precambrian East-European Platform (Pożarski and Tomczyk, 1993; Dadlez, 2001). The Palaeozoic formations of the Holy Cross Mountains are located in two areas: the northern (Łysogóry) and the southern (Kielce) regions, separated by the Holy Cross Fault that reflects a distinct discontinuity in the Earth's crust (Guterch *et al.*, 1986; Pożarski and Tomczyk, 1993; Dadlez, 2001). The Łysogóry region belongs to the southern part of the Łysogóry Block, distinguished as the Łysogóry Terrane, whereas the Kielce region constitutes the northern part of the Małopolska Block, formed as the Małopolska Terrane (Pożaryski, 1990; Franke, 1995). The Palaeozoic rock series occur on the opposite side of the Holy Cross Fault and differ in the development of sedimentation and lithology, age of stratigraphic gaps, and tectonic and palaeothermal history (Szulczewski, 1977; Belka, 1990; Pożaryski, 1990; Mizerski, 1991, 1995; Szczepanik, 1997; Malec, 2000b; Belka *et al.*, 2002; Narkiewicz, 2002; Narkiewicz *et al.*, 2011). The deep basement of the Łysogóry Terrane (Guterch *et al.*, 1976) is regarded as a fragment of the mobile part of the East European Platform (Dadlez, 1995; Malinowski *et al.*, 2005; Jaworowski and Sikorska, 2006; Nawrocki, 2006), or a separate part of the Gondwana palaeocontinent (Belka *et al.*, 2002; Krawczyk *et al.*, 2008). The shallow basement of the Małopolska Terrane was considered to be a fragment of the East European Platform, originally located farther to the southeast (Dadlez *et al.*, 1994; Dadlez, 2001). However, it has recently been interpreted as the basement, typical for the Avalonian terranes (Narkiewicz *et al.*, 2011; Malinowski *et al.*, 2013).

The Łysogóry Terrane borders from the northeast on the southwestern margin of the East European Platform along the Teisseyre–Tornquist Zone, which is located in the Nowe Miasto-Zawichost tectonic zone (Narkiewicz *et al.,* 2011). The Małopolska Terrane adjoins from the southwest, along the Kraków–Lubliniec tectonic zone, the Upper Silesian Block of Gondwana provenance (Unrug *et al.,* 1999; Belka *et al.*, 2002; Nawrocki *et al.*, 2004), which is assigned to the northern part of the Brunovistulian Terrane (Buła, 2000; Buła *et al.*, 1997, 2008, 2015; Żelaźniewicz *et al.*, 2009; Buła and Habryn, 2011; Narkiewicz *et al.*, 2011). The Upper Silesian Block and the Małopolska Terrane are interpreted as exotic terranes, separated from Avalonia and connected in the Early Devonian (Belka *et al.*, 2000, 2002; Nawrocki and Poprawa, 2006; Krawczyk *et al.*, 2008). The Małopolska and Łysogóry terranes are supposed to have been docked to Baltica in the late Cambrian (Belka *et al.*, 2000, 2002; Valverde-Vaquero *et al.*, 2000; Winchester *et* *al.*, 2002; Nawrocki, 2006; Nawrocki *et al.*, 2007), or in the Silurian (Pożaryski, 1991; Narkiewicz, 2001; Verniers *et al.*, 2008). The connection of the Małopolska and Łysogóry terranes occurred for a long time, from the Late Proterozoic until the Variscan Epoch (Nawrocki and Poprawa, 2006). According to Nawrocki (2000) and Belka *et al.* (2000), amalgamation of both terranes occurred in the Late Silurian, but according to Narkiewicz (2002), this took place between the late Ludlovian and the Emsian. The results of a palaeomagnetic study conducted by Lewandowski (1993) indicated that the Małopolska Terrane did not dock to the Łysogóry Terrane until the Late Carboniferous. According to this researcher, the Małopolska Terrane during pre-Variscan time was situated in the southeastern corner of the East European Platform, and during the orogeny it was moved dextrally at a distance of about 1,000 km along the platform margin in relation to the present location.

In the Holy Cross Mountains Silurian sedimentary rocks occur fragmentary in the Kielce region and over a substantially larger area of the Łysogóry region (Fig. 1). In both regions, the lower part of the Silurian sequence is developed as graptolitic shales, whereas the upper part consists of greywackes (Tomczykowa and Tomczyk, 1981). In the Łysogóry region, the upper part of the Silurian section also comprises carbonate rocks that in the central part pass continuously into Lower Devonian siliciclastics (Czarnocki, 1950; Pawłowska, 1961; Tomczyk *et al.*, 1977; Kozłowski, 2008).

In a larger area of the Kielce region, where Silurian sediments are preserved, greywacke complexes are overlain by Lower Devonian mudstones and sandstones of the Haliszka Beds, with an upper Ludlow–lower Pragian hiatus between them (Tarnowska, 1981, 1999; Turnau and Tarnowska, 1997) (Fig. 2). The sediments of the upper part of the Silurian profile occur in the northwestern margin of this region, in the northern suburbs of Kielce city. They are represented by upper Ludlovian greywacke mudstones and sandstones of the Kielce Beds and the Miedziana Góra Conglomerate (Malec, 1990, 2001). The lithologic development, thickness and palaeothermometry of the Kielce Beds are similar to those of a coeval sequence in the upper part of the Silurian deposits in the Łysogóry region of the Holy Cross Mountains (Malec, 1993, 2000b, 2001, 2006; Szczepanik, 2002, 2007; Kozłowski *et al.*, 2014).

In the Kielce region, the lower part of the Silurian strata comprises lower Llandover siliceous claystones of the Bardo Beds (Tomczykowa and Tomczyk, 1981; Modliński and Szymański, 2001; Malec, 2006) (Fig. 2). These sediments are distinctly characterized by a relatively large contribution of organic matter (Malec *et al.*, 2010). The upper part of this unit is developed in the form of Llandover and lower Wenlock graptolite-bearing claystones. The thickness of the Bardo Beds is estimated to be in the range of 80–150 m. Upwards, the Silurian beds contain calcareous claystones with syngenetic carbonate concretions, a graptolite fauna, bivalves, and ostracods; the ostracods are planktonic entomozoids, assigned to the upper Wenlock and lower Ludlow. They are represented by the Prągowiec Beds, reaching 150 m in thickness. These sediments pass with sedimentary continuity into medium- and coarse-grained greywacke sandstones

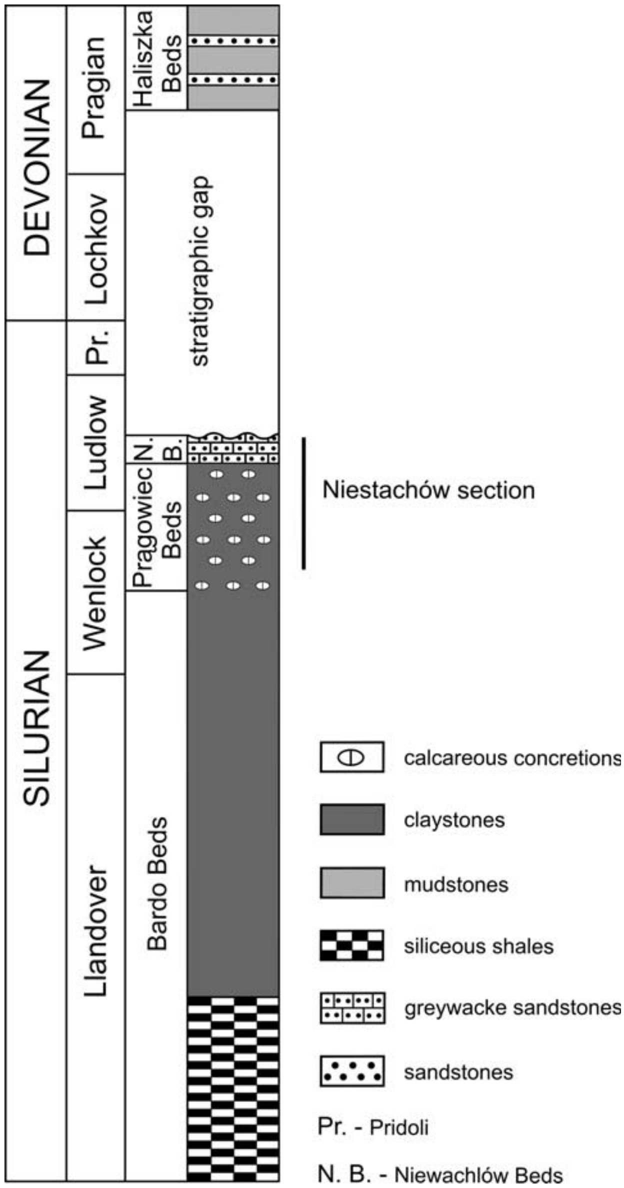

Fig. 2. Niestachów profile compared to the general Silurian succession in the Kielce region of the Holy Cross Mountains.

with subordinate mudstones and fine-pebbled conglomerates of the Niewachlów Beds with a preserved thickness that is estimated to be in the range of 400–500 m. The onset of deposition of the Niewachlów Beds might have occurred in the upper part of the Seatograptus leintwardinensis Zone (Tomczyk, 1956; Tomczykowa and Tomczyk, 1981; E. Porębska – pers. comm., 2005).

The Niestachów Silurian section occurs at a distance of about 5 km from Kielce. This Silurian sequence crops out on the southern flank of the Niestachów anticline, which is a secondary tectonic unit of the western part of the Kielce region (Czarnocki, 1938; Filonowicz, 1973; Fig. 1). In the southern limb of this anticline the Cambrian Series 2 sediments are separated by a sedimentary disconformity and a stratigraphic gap from the sandstones of the Ordovician Bukówka Formation (Bednarczyk, 1981; Trela, 2006). These sandstones, in a tectonic contact, abut against Silurian graptolitic shales that at the top pass with sedimentary continuity into greywacke sediments (Tomczyk, 1956).

PREVIOUS STUDIES

On the basis of the graptolite, bivalve, nautiloid and ostracod fauna, the graptolitic shales at Niestachów were assigned to the Silurian (Gürich, 1896; Siemiradzki, 1922). The stratigraphy of these Silurian sediments was described by Czarnocki (1919), who found large black limestone concretions in the graptolite shales. In the overlying greywackes, several characteristic rock complexes were distinguished:

1. Yellow and yellow-green greywackes with shale interbeds;
2. Yellowish or white thin-bedded sandstones;
3. Yellow-green greywackes;
4. Greywacke conglomerate, 3 m thick, composed of green, rounded, flat shale clasts of lentil size;
5. Conglomerate composed of somewhat rounded pebbles of crystalline rocks, jasper and quartz crystals;
6. Light grey thin-bedded sandstone; and
7. Greywackes similar to the conglomerates (5) described above with the same constituents, but with a fine-grained texture.

According to Czarnocki (1919), the complexes 3 through 7 cover the Silurian–Devonian transition (Dowton).

Sujkowski (1937) performed a petrographic study of limestone–claystone interbeds that occur in the graptolitic shales of the Niestachów profile. Tomczyk (1956) characterized the lithologic development of the graptolitic shales and the lower section of overlying greywacke sediments. He found at the base of the 50-m-thick graptolitic shale complex a tectonic contact with the Lower Ordovician sandstones, whereas at the top it passed gradually into the greywacke sandstones. According to Tomczyk (1956), these sediments occur within the lower Ludlovian Neodiversograptus nilssoni-Saetograptus leintwardinensis zones. Their biostratigraphic position indicates a tectonic reduction in the thickness of the Llandoverian and Wenlockian deposits in the vicinity of Niestachów.

The first petrographic study of the greywackes was done by Dyka (1958) and Taszek (1962). They also stated that the greywacke material was not well sorted and that the thickness of the greywacke beds increased upwards, reaching 80 cm in thickness. In addition, in the upper part of the greywacke sediments, claystone lithoclasts were found in the coarse-grained greywackes with individual ball-shaped landslip structures, up to 40 cm in diameter. Dyka (1958) described selected lithologic greywacke types and performed granulometric, heavy-mineral, DTA and chemical analyses. The Silurian rocks of the Niestachów area were also examined by Filonowicz (1971, 1973) during mapping. The petrographic characterization of the lower and middle part of the greywacke sequence from the Niestachów profile was reported by Przybyłowicz and Stupnicka (1989), while the whole Silurian sequence was sedimentologically and petrographically described by Malec (2000a, 2005) and Malec and Kuleta (2009a).

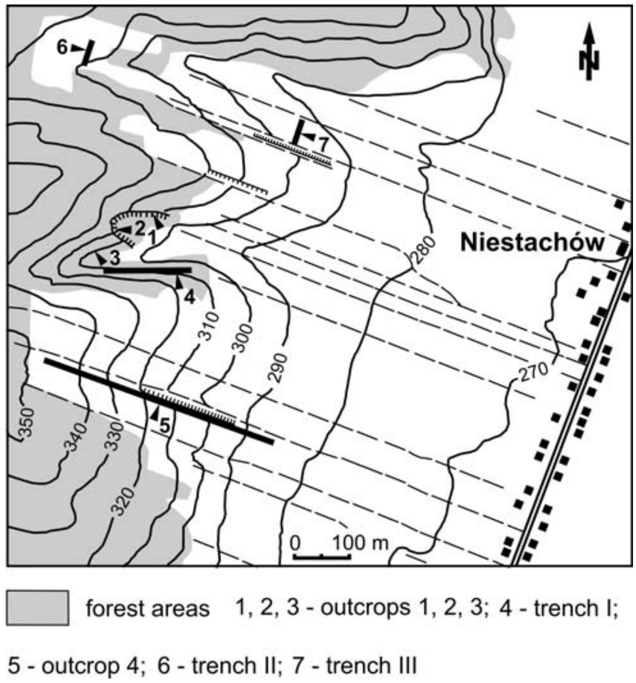

Fig. 3. Location of study sections at Niestachów.

MATERIALS AND METHODS

The rock samples were collected from natural outcrops and trenches (Figs 1, 3). The lower Ludlovian graptolitic shales of the Prągowiec Beds were investigated in a trench over 40 m long (Trench II: 50°50′23″N, 20°43′42″E), in which a section about 20 m thick was exposed (Figs 3, 4). In the northern part of this profile, bed strike and dip are 88/28S. The transition to the Prągowiec Beds and the Niewachlów Beds was exposed in a 40-m-long excavation (Trench III: 50°50′17″N, 20°44′26″E), in which the strike and dip are 80/38S (Figs 3, 5). The top section of the outcropping greywacke series includes small exposures that occur in an abandoned open pit (outcrop 1: 50°50′14″N, 20°44′9″E, outcrop 2: 50°50′14″N, 20°44′5″E), in which the bed strike and dip are 55/30S (Figs 3, 6). The upper part of this section was investigated in a small ravine, located southwest of the open pit (outcrop 3: 50°50′12″N, 20°44′3″E), in which the bed strike and dip are 94/45S (Fig. 3). The stratigraphically younger greywacke sediments were traced in a trench over 140 m long (Trench I: 50°50′11″N, 20°44′6″E), located on the southern slope of the “Zawalicha” ravine, in which a lithologically diverse greywacke series more than 50 m thick is exposed (Figs 3, 7), showing average strike and dip values of 70/35S. The youngest greywacke sediments were identified in the southern part of the study area within a section approximately 160 m long (outcrop 4: 50°50′7″N, 20°44′9″E). There are small discontinuous outcrops of Silurian beds with average strike and dip values of 50/40S, which crop out at a distance of about 450 m near a field pathway (Figs 3, 8). In the Niestachów area, a poorly exposed lower part of the 100-m-thick greywacke series lies between Trench III and outcrops 1 and 3 in the abandoned open pit (Fig. 9).

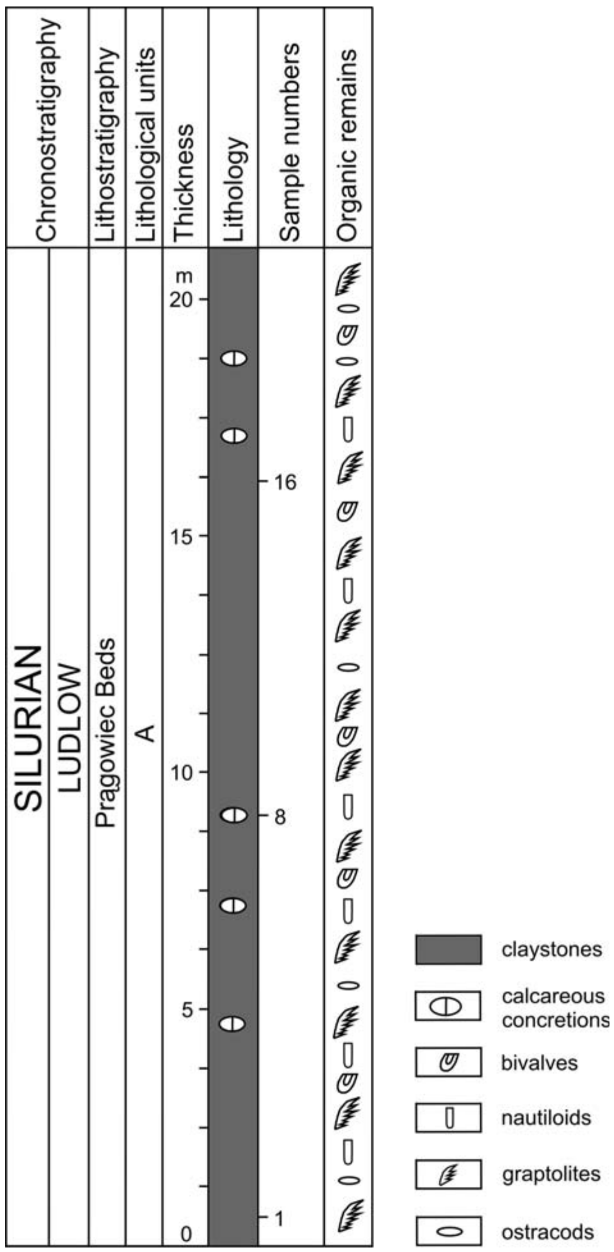

Fig. 4. Profile of the Prągowiec Beds. Niestachów, trench II.

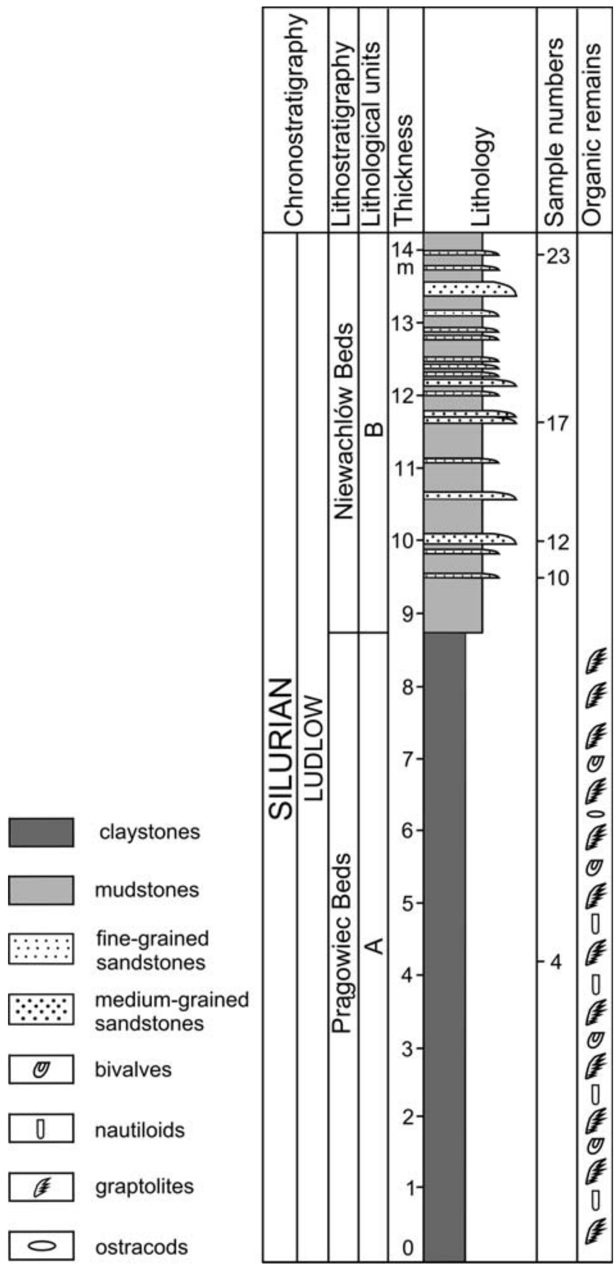

Fig. 5. Boundary profile of the Prągowiec Beds and Niewachlów Beds. Niestachów, trench III.

For the Niestachów Silurian section, the petrographic study included clayey sediments of the Prągowiec Beds and sandstones and fine-pebble conglomerates of the Niewachlów Beds. This study relies on over 80 thin sections used for the polarizing microscopy (Axilolab Carl Zeiss). On the basis of 10 thin sections of conglomerates and 28 thin sections of sandstones, fabric features (that determine the amount of cement in relation to the grain framework), size and shape of grains and pebbles, roundness, orientation and packing were analyzed. In addition, the study of 10 selected rock samples was carried out with a Scanning Electron Microscopy (SEM) LEO 1430 (signal A = SE1, magn. = 200–5000×, EHT = 5.00–20.00 kV, WD = 21 mm) at the Electron Microscopy Laboratory of the Polish Geological Institute in Warsaw.

The classification of the sandstones was based on the Dott's division (1964), modified by Pettijohn and coauthors (1972) with some changes made by Jaworowski (1987). While identifying and determining the structural and textural features of volcanic, sedimentary and metamorphic rocks in the conglomerates, the schemes proposed by Ryka and Maliszewska (1991) were used. The origin of the detrital material of the greywackes and the geotectonic position of their source areas were analyzed with reference to the petrographic composition of the sandstone grain framework, using Dickinson's method (Dickinson *et al.*, 1983).

The main grain constituents, their assemblages and binding agents in the sandstones and conglomerates were labelled by means of the following letter symbols: *Qm* – monocrystalline quartz, *Qp* – polycrystalline quartz, *Q* =

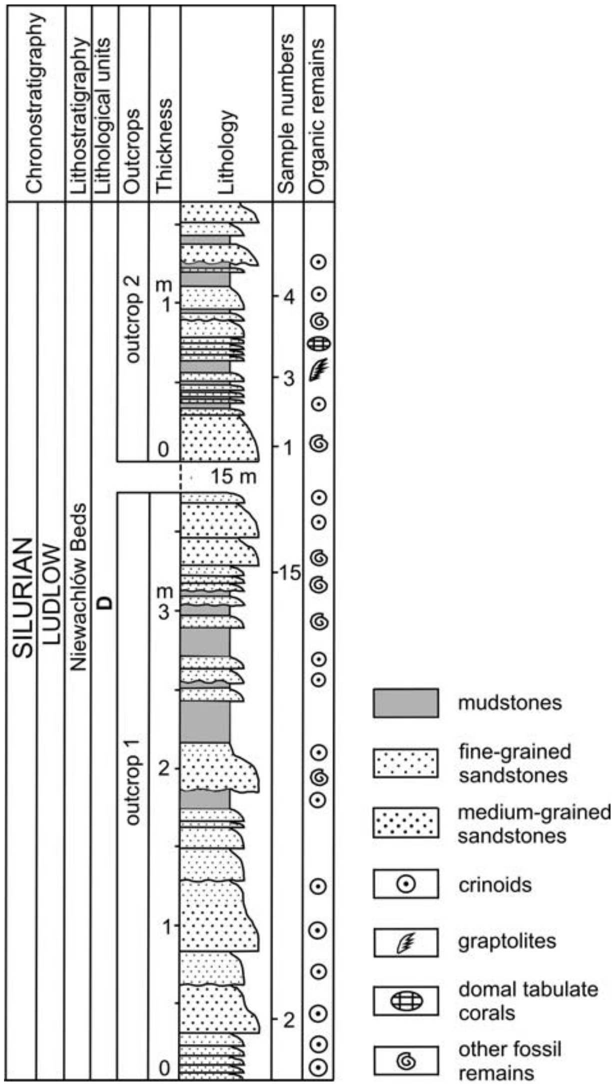

Fig. 6. Profile of the Niewachlów Beds, Niestachów, outcrops 1 and 2.

Qm + *Qp*, *F* – feldspars, *M* – micas, *Lv* – volcanic rocks, *Ls* – sedimentary rocks, *Lm* – metamorphic rocks, *Lp* – plutonic rocks, *L* = *Lv* + *Ls* + *Lp* + *Lm*, *Lt* = *L* + *Qp*, *Mx* – matrix binder, *Cc* – calcite cement, *Qc* – quartz cement. The amounts of particular constituents and their microscopic petrographic features are presented in Tables 1–3 and in Figures 10–13, 15–18.

LITHOLOGIC CHARACTERIZATION

In the Silurian rocks of the Niestachów area, a few lithologically diversified rock intervals ranging from several to a few dozen meters in thickness were distinguished. The intervals constitute in stratigraphic succession twelve characteristic lithologic complexes (A–L; Fig. 9).

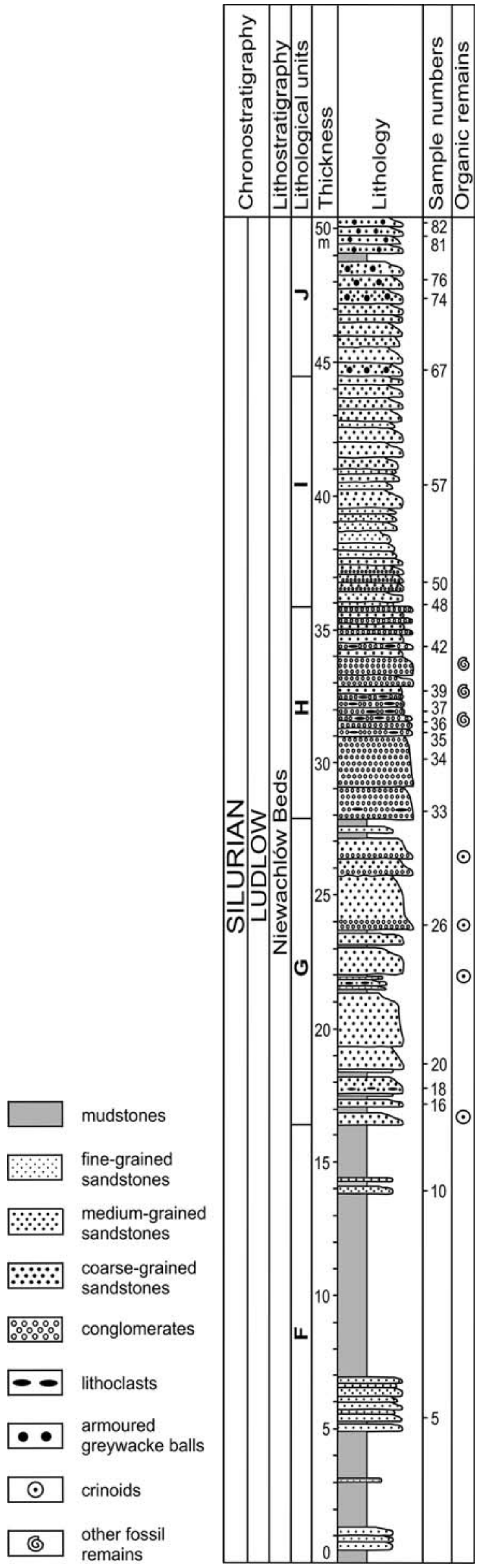

Fig. 7. Profile of the Niewachlów Beds, Niestachów, trench I.

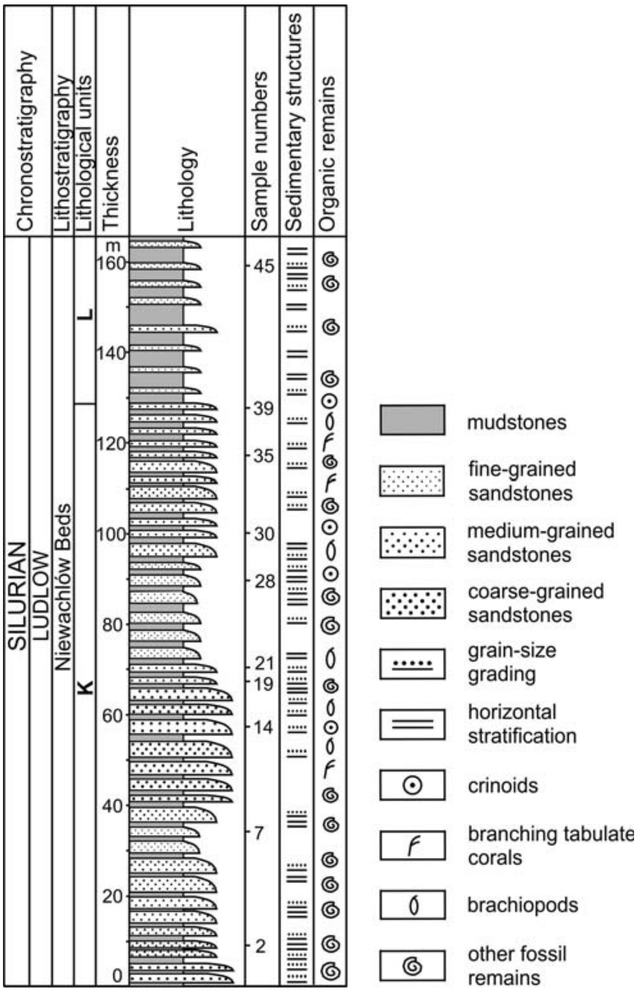

Fig. 8. Profile of the Niewachlów Beds, Niestachów, outcrop 4.

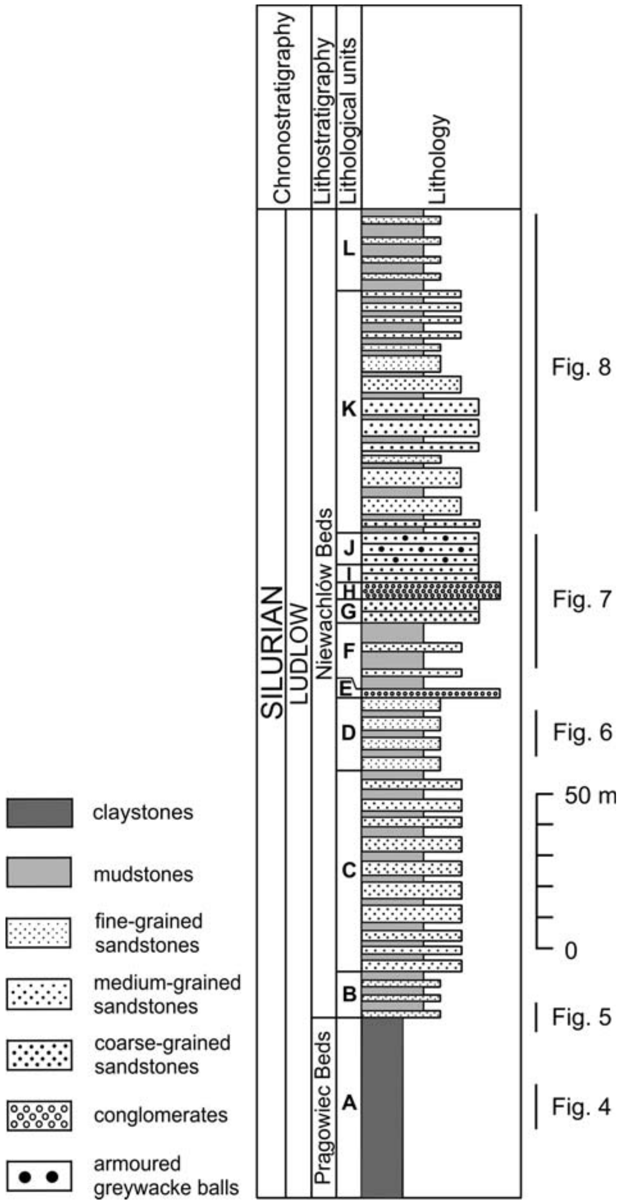

Fig. 9. Simplified profile of Silurian sediments at Niestachów.

A – Graptolitic claystones

The scope of the study encompassed the upper part of the graptolitic claystone complex of the Prągowiec Beds within a 20-m section in Trench II and the top part (about 10 m) at the boundary between the graptolitic shales and the greywackes of the Niewachlów Beds (Trench III; Figs 3–5). In the section in Trench II, five beds containing carbonate concretions with bitumen-enriched calcite veins were identified. Bivalves, nautiloids and planktonic ostracods (entomozoids) occur in addition to graptolites in these claystones. Graptolites are scarce in an interval at the top of the complex 2.5 m thick. No fossils occur within a 0.5-m section of clayey-mudstone series that lies directly below the oldest greywacke sandstones.

B – Greywacke mudstones and sandstones

These sediments include a 5-m section of the lowermost part of the Niewachlów Beds (Trench III; Figs 3, 5). This complex is characterized by the predominance of clayey-mudstone beds, with thin- and medium-bedded, fine- to medium-grained greywacke sandstones reaching 5–8 cm in thickness. The number of sandstone beds increases at the top. The upper boundary of this complex and its contact with the overlying greywacke sediments are not exposed.

C – Medium- and coarse-grained greywacke sandstones

These sediments are poorly exposed in the Niestachów section and occur only in the lower part of the greywacke series (Fig. 9). They presumably reveal the same lithologic development as the lower part of the Niewachlów greywackes that were found in the Bardo and Zalesie sections (Malec, 2002b; Trela and Malec, 2006). The lower part of the Niewachlów Beds consists of greywacke sandstone beds reaching as much as 1.2 m in thickness, which predominate over mudstone beds. In the greywacke beds, the clastic material shows fractional grading, and parallel and cross-lamination, in places disturbed in convolutions. The majority of greywacke beds exhibit complete Bouma sequences (Bouma, 1962). The sandstone beds contain claystone lithoclasts and armoured greywacke balls. The bottom surfaces of thin- and medium-bedded sandstones show current hieroglyphs. The thickness of this complex in the Niestachów section is about 100 m.

D – Quartz sandstones

They occur in stratigraphic continuity above medium- to coarse-grained greywacke sandstones. These deposits were identified in outcrops 1 and 2 of the abandoned quarry (Figs 3, 6). The section consists of light grey fine- to medium-grained sandstones, mostly medium- and thick-bedded. The sandstones beds are 5 to 80 cm thick and form compact packages up to 2 m thick. They consist of several to a dozen or so beds with erosional boundaries. There are mouldic voids in the sandstones after crinoids and corals. In these sandstones, claystone lithoclasts with graptolite remains occur. The top surfaces of some beds show current ripple marks, whereas at the bottom current hieroglyphs are present. The thickness of this complex is about 25 m.

E – Fine-grained conglomerates

In the outcrop, a few meters above the quartz sandstone complex, a conglomerate of uniform grain size occurs (Fig. 3). The average size of pebbles varies from 3 to 5 mm, reaching a maximum of 10 mm. Pebbles of sedimentary rocks predominate over those of igneous rocks. Most clasts are elongated and are oriented parallel to the bedding. The thickness of this complex is estimated to be up to 3 m.

F – Mudstones and claystones with greywacke sandstones

Sediments of this complex occur directly above fine-pebbled polymictic conglomerates. Its upper part was found in a 17-m section exposed in Trench I (Figs 3, 7). In the lower part in a 5.5 m interval, mudstones with subordinate, medium- and coarse-grained greywacke sandstones occur. Sandstones beds, 5.5 to 35 cm thick, show fractional grading and parallel lamination. Upward, this complex comprises a compact package of medium- and coarse-grained sandstones about 2 m thick, with thin mudstone interbeds. The upper part of the complex a 7-m interval is made up of green grey mudstones with no sandstone interbeds. These mudstones are overlain by a single, medium-grained greywacke sandstone bed separated by mudstones. At the top, there are grey green mudstone beds, 2 m in thickness. The thickness of the whole complex is about 25 to 30 m.

G – Thick-bedded greywacke sandstones

This complex was identified in Trench I (Figs 3, 7). It consists of coarse-bedded greywacke sandstones showing grading and parallel lamination, with subordinate lithoclast-rich sandstones, sandy conglomerates, and sandstones with armoured balls. This complex comprises 9 beds, about 45–200 cm thick, separated by single thinner sandstone beds and very few mudstone beds. They form two compact sandstone packages without shale interbeds, about 3.0 to 4.5 m thick. The lower part of the beds contains claystone lithoclasts, cavities left after the leaching of crinoid skeletons, and armoured greywacke balls of spherical to oval shape, 15 cm and 8 cm across. The thickness of this complex is about 11 m.

H – Varigrained conglomerates

In the lower part of this complex, within a section about 4 m thick, conglomerate beds varying from 26 to 190 cm in thickness occur (Fig. 7). In the upper part of this complex, conglomerate beds, 15–20 cm thick, are separated by sandstone and sandy conglomerate beds. The average size of pebbles in the conglomerates is 5 mm. The lower part of these beds comprises claystone and quartz sandstone lithoclasts, up to 14 cm across, and spherical armoured greywacke balls, up to 5 cm in diameter. Igneous rock pebbles occur in a similar amount or slightly predominating over sedimentary rock pebbles. The thickness of this complex is about 8 m.

I – Calcareous greywacke sandstones

This complex is made up of medium- and thick-bedded greywacke sandstones varying from a few centimeters to 60 cm in thickness, with no mudstone interbeds (Fig. 7). The greywacke material consists of fine to medium and scarce, coarse grains of igneous and sedimentary rocks, showing a composition similar to that of the underlying conglomerates. These grains are strongly cemented by carbonate. In the lower part of the beds, graded bedding occurs, whereas parallel lamination of fine-grained detrital material predominates upwards. The thickness of this complex is about 9 m.

J – Greywacke sandstones with armoured balls

This complex is represented by medium- to coarse-grained greywacke sandstones with armoured greywacke balls (Fig. 7). In an interval about 4.5 m thick, in the lower part of this complex, greywacke beds lack mudstone interbeds. The thicknesses of sandstone beds are similar to those in the underlying greywacke complex. These sandstones contain numerous spherical greywacke balls, varying from 2 to 26 cm in diameter. The central parts of these balls are accentuated by the presence of claystone lithoclasts. This complex is exposed within a 6-m section. However, its total thickness is unknown.

K – Medium-grained greywacke sandstones

Sediments of this complex occur in outcrop 4 and primarily consist of greywacke sandstones with subordinate mudstones. The grain size of the constituents decreases upwards (Figs 3, 8). In the lower part of this complex, coarse-grained greywacke sandstones with claystone lithoclasts occur. There are many cavities in the greywacke sandstones. They were formed as a result of leaching of organic remains, referable to crinoids, brachiopods and branching tabulates. The thickness of this complex is about 120 m.

L – Mudstones with greywacke sandstones

This complex occurs at the top of outcrop 4 (Fig. 3). It consists of mudstones with subordinate thin- and medium-bedded, fine- to medium-grained greywacke sandstones (Fig. 8). Upwards, the proportion of greywacke beds gradually decreases. The graded-bedded sandstones contain cavities left after the solution of unidentified organic remains. The thickness of the exposed bottom part of this complex is about 40 m.

The upper part of greywacke sediments in the Niestachów profile is overlain by Lower Devonian terrigenous deposits.

COMMENTS ON THE STRATIGRAPHIC SUCCESSION OF SEDIMENTS

The succession of greywacke sediments that form lithologic complexes in the Silurian Niestachów profile confirm the stratigraphic scheme proposed by Czarnocki (1919). Units 1 to 3, distinguished by this author, correspond to the complexes B through F and units 4 and 5 are equivalent to complex H, whereas units 6 and 7 are identical to complexes I through L (Fig. 9).

In a different succession scheme of Silurian sediments, presented by Przybyłowicz and Stupnicka (1989) and Stupnicka (1995), three lithostratigraphic units are distinguished in a stratigraphic succession: the Niewachlów Greywacke Formation (corresponding to complexes B and C), the Widełki Shale Formation and the Niestachów Sandstone Formation. The latter is equivalent to complex D. According to Stupnicka (1995), the Widełki Shale Formation is separated from the Niestachów Sandstone Formation by a stratigraphic gap of tectonic origin. The next subsequent stratigraphic gap was placed higher in the profile by this author, between the Niestachów Sandstone Formation and Lower Devonian Old Red Sandstones.

In the Niestachów section, the late Ludlovian–early Pragian stratigraphic gap occurs at the top of greywacke series, in which the erosional upper surface of Silurian sediments is unconformably overlain by Lower Devonian (upper Pragian–Emsian) sandstones (Fig. 2), similar to that in the Bardo Syncline area, located east of Niestachów (Czarnocki, 1939; Kowalczewski and Tomczyk, 1981) (Fig. 1).

The Niewachlów greywacke series does not contain the Widełki Shale Formation, i.e. the additional lithostratigraphic unit distinguished by Stupnicka *et al.* (1991) at the top of Silurian greywacke sediments in the Widełki area, in the western part of the Bardo Syncline. In the Widełki section, Silurian sediments assigned to this unit represent mainly graptolitic claystones, which correspond to the top of lower Ludlovian Prągowiec Beds (Malec, 2004, 2006, 2014). There is no reason to distinguish in the Niestachów Silurian profile a new lithostratigraphic unit, the Niestachów Sandstone Formation (Przybyłowicz and Stupnicka, 1989). This unit corresponds to complex D or to unit 2 of Czarnocki (1919). It occurs in sedimentary continuity with greywacke sediments of complex C. According to Przybyłowicz and Stupnicka (1989), the Niestachów Sandstone Formation ends Silurian sedimentation in the Niestachów profile. In fact, these sediments end vertically upwards in stratigraphic continuity with greywacke sediments, about 250 m thick, assigned to complexes E through L (Figs 7–9).

PETROGRAPHIC STUDY

The petrographic study of Niestachów Silurian sediments focused on greywacke conglomerates and sandstones of the Niewachlów Beds, and to some extent the graptolitic claystones of the Prągowiec Beds.

Conglomerates

Conglomerates and sandy conglomerates occur primarily in the middle part of the Niestachów profile, in which they form bed assemblages in complexes: E (outcrop 3) and H (Trench I; Figs 2, 7, 9). A major contribution of gravel occurs in the lower sandstone beds, assigned to complex G (Fig. 7).

The conglomerates of the Niewachlów Beds are referable to fine-grained and polymictic varieties. Those rocks with a compact grain framework were assigned to orthoconglomerates and those with a dispersed grain framework to paraconglomerates.

The main constituent is represented by lithoclasts (*L*). Grains of monocrystalline quartz are substantially fewer, but occur in variable amounts (*Qm*). Accessory minerals of this fraction are feldspars (*F*). The binding agent is an arenaceous-silty-aleuritic matrix (*Mx*), which underwent chloritization and locally calcitization (Table 1).

Lithoclasts (L) are represented mainly by fragments of volcanites (*Lv*) and sedimentary rocks (*Ls)*, which in variable proportions reach over 70% of the whole rock. Fragments of metamorphic rocks (*Lm*) are subordinate, and plutonic rocks (*Lp*) are scarce (Table 1, Fig. 10).

Volcanite lithoclasts (*Lv*) are commonly semirounded, isometric or somewhat elongated rock fragments of porphyric fabric, from the group of rhyolites, dacites and trachytes (Fig. 11A–C, E). Phenocrysts are represented by (i) quartz of different shapes, the grains of which are usually melted with corrosion voids and commonly fractured, (ii) feldspars (albite), and (iii) differently chloritized biotite and subordinate other mafic minerals, usually substituted by iron oxides and hydroxides (Figs 11A–C, E, 12E, F). These clasts are embedded in a groundmass that shows a microcrystalline or felsic structure and an unoriented and also trachytoid texture. Particular clasts are made up of all these mineral types or only feldspars or mafic minerals. Phenocryst-free fragments of the groundmass are common. Among them, clasts showing a micropoikilitic structure and a characteristic perlitic texture can be distinguished. The groundmass consists of tiny, elongated feldspar and quartz microlites, in unoriented, oriented and pseudotangential arrangements. The background of the microlites takes the form of major, isometric feldspar crystals that preserve mostly a pellet-shaped primary glass nature. These lithoclasts often underwent concentric-crustal disintegration and form the psammitic grain constituents of the conglomerates and sandstones. The conglomerates also contain characteristically rounded fragments of chloritized perlitic glass (Fig. 12A). Among the volcanites, lithoclasts showing diabasic structural features also occur. The groundmass, which is made up of tiny feldspar laths of microcrystalline and intersertal structure and unoriented and oriented texture, locally contains albite phenocrysts. The presence of glass or pyroxenes is documented as chlorite (Fig. 11D). The volcanites are also represented by rock fragments, exhibiting a felsitic-vitrophyric structure and a fluidal texture. They consist of parallel-oriented, elongated microlites of feldspars, or mafic minerals and a variable content of glass, altered to chlorites. The proportions of these volcanic rock groups vary in the profile.

Table 1

Petrographic composition of conglomerates (in %)

	Litho-logical units	Locali-zation	Litho-clastic size: mostly/ largest (in mm)	Litho-clastic rounded and shape	Qm	Qp	F	Lv	Ls	Lm	Lp	Remains	Cement Mx	Rock name
1		trench IV/2	3.0/6.0	o, p; w, i	13.9	0.0	0.8	26.2	27.0	2.5	0.0		29.5	polymictic paraconglomerate
2	H	trench I/42	2.2/4.0	p; i.w.	13.2	0.0	0.0	23.7	15.8	0.0	0.0		47.3	
3		trench I/37	3.5-<13.0	p; i.w.	5.3	0.0	0.0	31.6	17.1	0.0	0.0		46.1	
4		trench I/36b	5.0/9.0	p, o; i, w	7.1	0.0	0.0	43.9	19.4	1.0	0.0		28.6	polymictic orthoconglomerate
5		trench I/36a	5.0/15.0	p, o; i, w	2.2	1.1	0.0	42.7	19.1	1.1	0.0		33.7	polymictic paraconglomerate
6		trench I/36	3.0-<17.0	p, o; w, i	0.0	0.0	0.0	23.5	33.3	0.0	0.3	4.8 bioclasts	38.1	
7		trench I/35	5.0/7.0	o, p; w, i	7.1	0.0	0.0	32.7	38.8	1.0	0.0		20.4	polymictic orthoconglomerate
8		trench I/34	3.0/5.0	p, o; i, w	15.2	0.0	1.9	33.3	22.9	2.9	0.3		23.5	
9		trench I/33	7.0/11.0	p, o; i, w	5.6	1.6	0.0	37.3	7.9	0.8	0.3		46.5	polymictic paraconglomerate
10	E	outcrop 3/2	3.0/6.0	o, p; w, i	2.0	1.0	0.0	27.6	44.9	1.0	0.0		23.5	polymictic orthoconglomerate
11		outcrop 3/1	2.5/4.0	o, p; w, i	2.2	1.1	0.0	21.8	43.2	3.3	0.6		27.8	

Qm – monocrystalline quartz, Qp – polycrystalline quartz, Qc – quartz cement, F – feldspar, Lp – plutonic lithoclasts, Lm – metamorphic lithoclasts, Ls – sedimentary lithoclasts, Lv – volcanic lithoclasts, Mx – matrix cement; grains: rounded (o), semirounded (p), izometric (i), elongated (w)

The structural observations and chemical analyzes of conglomerate thin sections using a scanning electron microscope (SEM) confirmed that the feldspar phenocrysts are albite. This also indicates that the feldspar microlites of the groundmass are represented by prismatic, idiomorphic and hypidiomorphic plagioclase grains that are exclusively albite. The background of these minerals is a K-feldspar overgrown with quartz and in places with albite-orthoclase perthite. The background of the albite microlites in individual grains is also represented by chlorite, formed as a product of glass devitrification and alteration of tiny mafic mineral microlites. The biotite phenocrysts are partially or completely chloritized. The SEM study revealed numerous pseudomorphs of chlorites after biotite that consist of thick neoformational flakes, characterized by the predominance of iron over magnesium. Many inclusions of prismatic apatite and subordinate zircon were documented in the large biotite flakes as well as irregular grains of magnetite, titanomagnetite, ilmenite and chromite in groundmass.

This petrologic study indicates a classification of the volcanites described. The prevailing albitic composition of the feldspars examined enables assignment of these rocks to albite varieties, i.e. albitic rhyolites, dacites, trachytes and diabases. However, it is impossible to determine to what extent these are primary albites or feldspars, affected by albitization. Therefore, this issue requires further detailed study.

Sedimentary lithoclasts (*Ls*) are represented by rounded and mostly elongated fragments of claystones, mudstones and mixed claystone-mudstone rocks (Fig. 13A, B). Fragments of fine-grained quartz arenites and mudstones are scarce. Greywacke-arkose sandstones are among the characteristic clasts. They are light grey with a large amount of muscovite and an illitic-sericitic matrix. The other characteristic constituents are sandstone and mudstone lithoclasts with phosphate cement and fragments, composed totally of collophane with an admixture of iron oxides and hydroxides. In the conglomerate fraction, they occur in individual grains and more commonly among psammitic grains. Among the accessory constituents, cherts and lydites were distinguished. The lydites consist of microcrystalline and aphanitic silica, which is pigmented with a carbonaceous substance, in places with visible traces of biogenic structure. Fragments of bituminous shales and carbonate rocks are scarce.

Metamorphic lithoclasts (*Lm*) are represented by fragments of quartzites, quartz, quartz-mica and chlorite schists and gneisses (Fig. 13B). They are subordinate in all of the rocks examined (Table 1).

Plutonic rocks (*Lp*) were found only in four samples in the form of individual grains, composed of feldspars, micas and other mafic minerals. These grains were affected by calcitization (Fig. 11F).

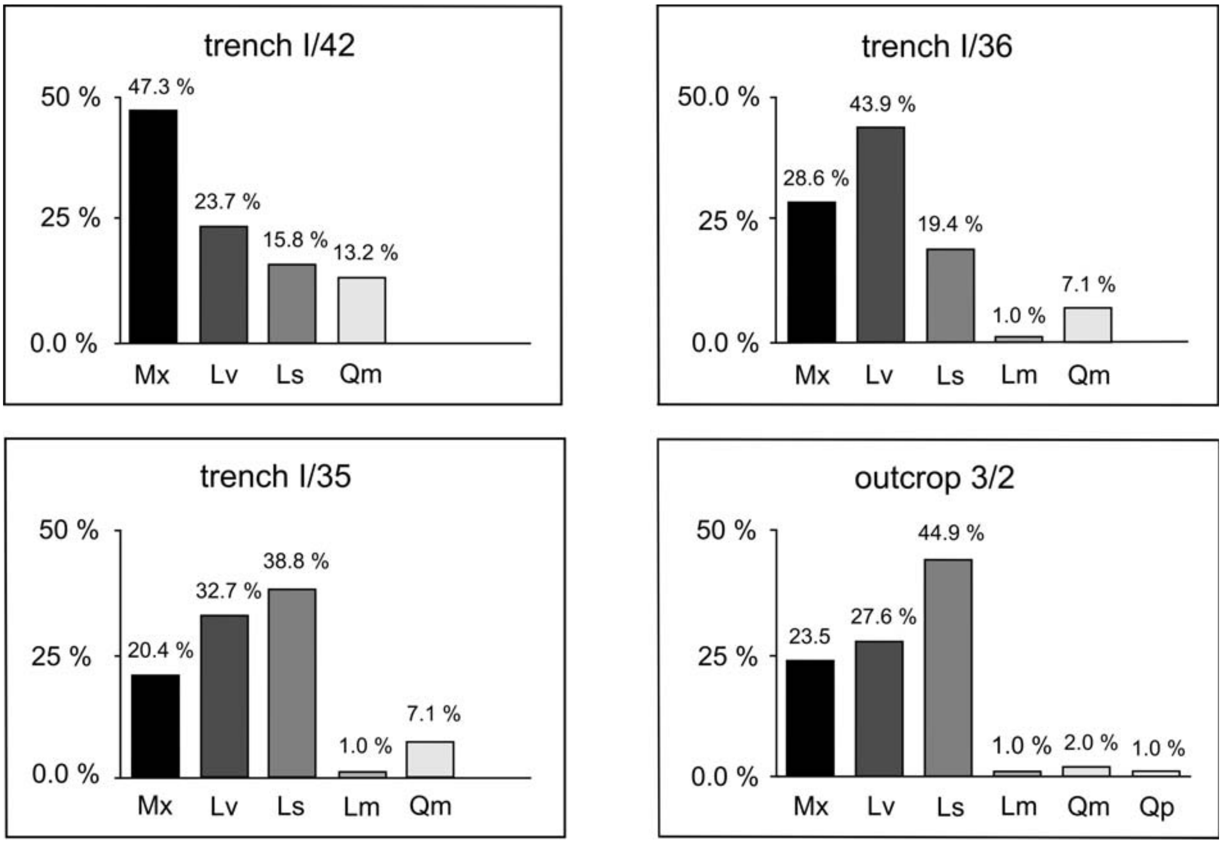

Fig. 10. Petrographic composition of conglomerates in the Niewachlów Beds at Niestachów. Qm – monocrystalline quartz, Qp – polycrystalline quartz, Lm – metamorphic lithoclast, Ls – sedimentary lithoclast, Lv – volcanic lithoclast, Mx – matrix cement.

Quartz (*Q*) is represented mostly by monocrystalline grains (*Qm*), 2 to 4.5 mm in size. Polycrystalline quartz (*Qp*) was noted in several samples as single grains (Table 1). Quartz and rhyolite grains are characterized by deep corrosion voids, which point to their volcanic origin (Fig. 12B). Angular and semirounded grains with concave rims may indicate a primary pyroclastic origin.

Feldspars (*F*) were recorded in the form of psephitic grains in one sample, in which the largest amount of quartz occurs (Table 1). They are represented by semirounded, in places angular, twinned plagioclases (albites). The latter ones are affected to varying degree by kaolinitization and locally by calcitization (Fig. 12C).

Considering lithologic features of the sediments examined, the quartz, feldspars and volcanic clasts described are classified as epiclastic material.

The constituents of the conglomerates contain fragments of intrabasinal sediments. These are reworked calcitic bioclastic material (Fig. 12D) and intraclasts of carbonate rocks, claystones and mudstones. Intraclasts of larger size than the basic, epiclastic conglomerate material have not been included in the quantitative petrographic evaluation of the conglomerates.

The binder of matrix type (Mx) forms mostly a basal background and also a porous one for the constituents of the psephitic fraction, described above. Within a particular thin section, the transitional character of the binding agent can be traced. The matrix consists of rock and mineral grains of psammitic and aleuritic fraction that are similar in composition to the conglomerates with distinctly larger amounts of quartz and feldspar cement. Biotites and glauconites are scarce. In addition, mafic grains were noted; they probably represent ferruginous pseudomorphs after mafic minerals that can be assigned to biotites or maybe to pyroxenes or amphiboles. These are supplemented by illitic-chloritic-quartzose aggregates stained yellow-brown by iron oxides and hydroxides. These are partly altered to clay minerals and tiny chloritized grains of feldspars, micas and volcanic glass grains. Calcite cement (*Cc*) locally replaces irregular primary matrix binder (Table 1).

The common occurrence of clayey-ferruginous rims on lithoclastic grains of rocks, quartz and feldspars were related to diagenetic processes (e.g., Figs 12B, 13A, B). Locally recorded mechanical compaction led in places to tight grain packing and the formation of pitted grain contacts. The formation of clayey-ferruginous coatings that preceded compaction is distinctly visible.

The analysis of conglomerate and sandstone binder by SEM indicates that both chips and slides show an advanced alteration of biotite to chlorite. Thick chlorite flakes locally envelope the remains of relict biotite. Very fine-grained, rosette-shaped chlorite, scattered on the surfaces of feldspar fissures and poorly altered biotite flakes, were also observed. The rock cement is also considerably chloritized; hence chlorite aggregates with quartz make up most of fine-grained binding material.

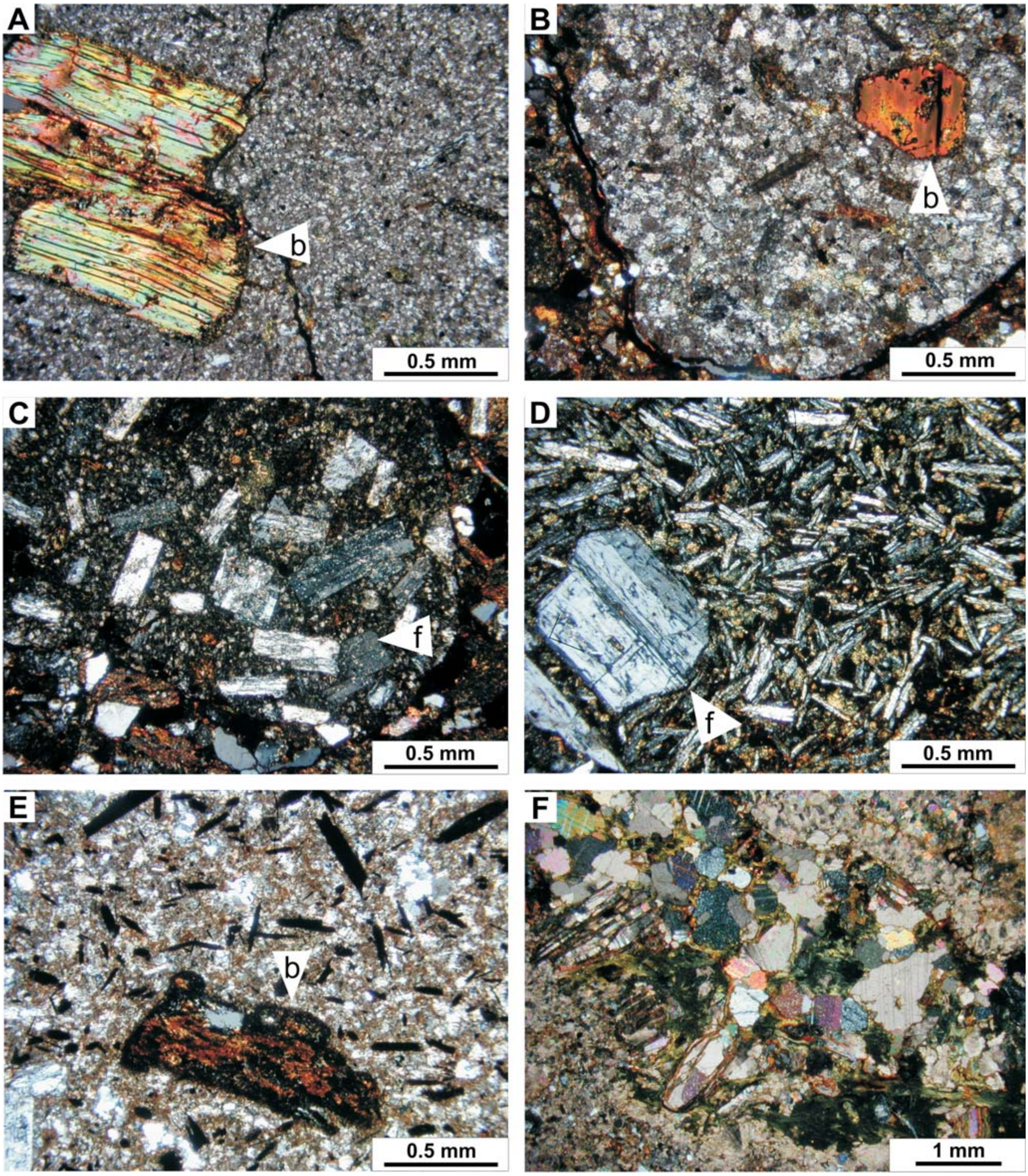

Fig. 11. Igneous rock clasts in polymictic conglomerates. Niewachlów Beds. Niestachów, trench I. Crossed nicols. **A.** Volcanite clast of rhyolitic type with biotite phenocrysts (b), sample 33. **B.** Volcanite clast of dacitic type with biotite phenocrysts (b) and perlitic groundmass, sample 37. **C.** Clast of dacitic type ? with feldspar phenocrysts (f), sample 50. **D.** Clast of diabasic type with a feldspar phenocryst (f), sample 36. **E.** Rhyolite clast with a biotite phenocryst (b), sample 33. **F.** Calcitized clast of feldspathic-micaceous plutonic rock (?), sample 36.

The variation in conglomerate composition within the profile of the Niewachlów Beds examined is expressed as different proportions of volcanic and sedimentary lithoclasts. Two stages of this variability can be noted. The first one encompasses the conglomerates of complex E, whereas the other relates to the conglomerates of complex H (Fig 7, 9). The former is characterized by the predominance of sedimentary lithoclasts, the latter by the predominance of volcanoclasts over sedimentary lithoclasts (in places equal amounts are present) (Table 1; Fig. 10).

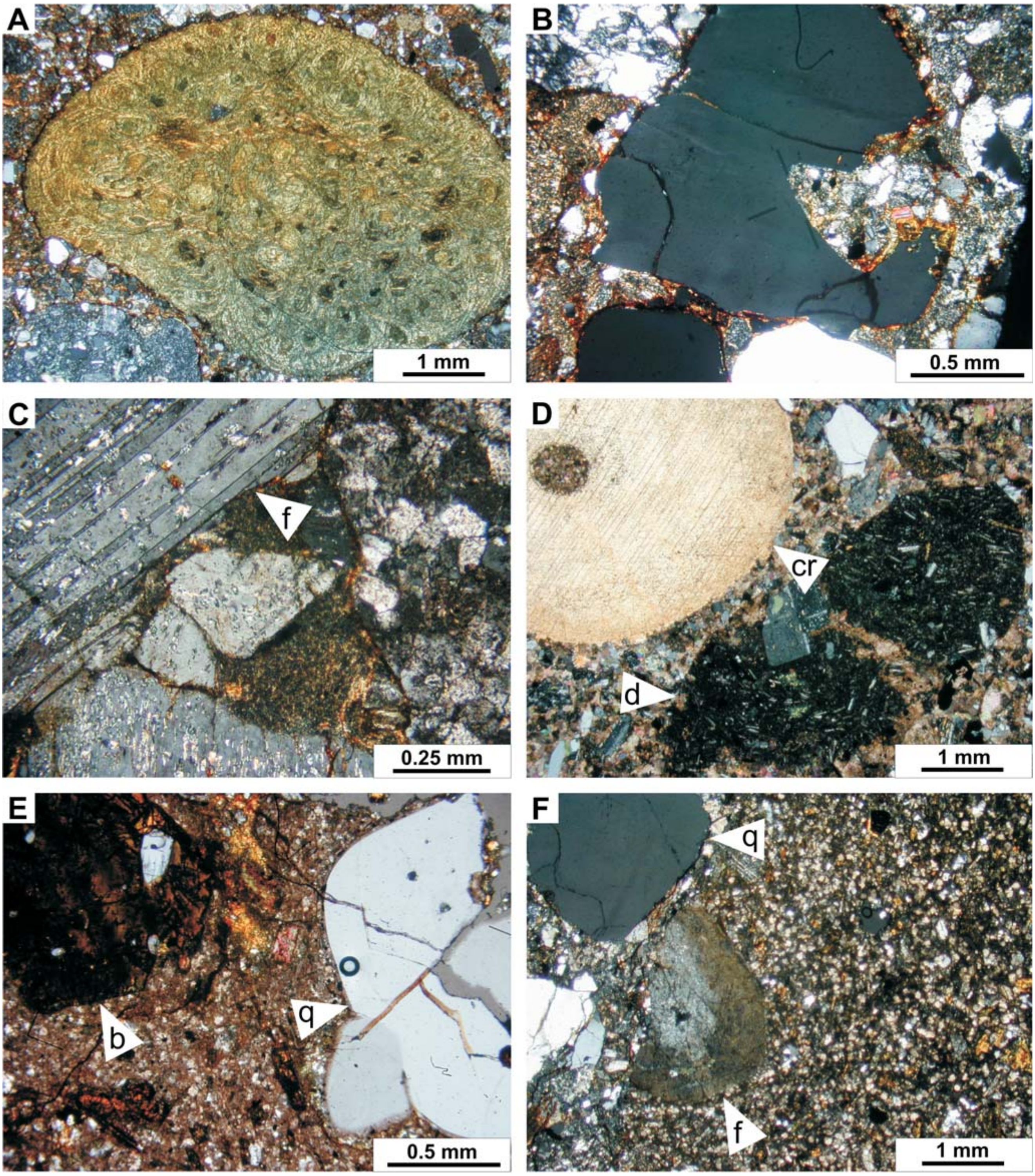

Fig. 12. Clasts in polymictic conglomerates. Niewachlów Beds. Niestachów, trench I. Crossed nicols. **A.** Chloritized clast of perlitic glass, sample 26. **B.** Monocrystalline quartz with deep corrosion voids and clayey-ferruginous rims, sample 33. **C.** Feldspars – albite (f) and a fragment of rhyolitic groundmass, sample 34. **D.** Crinoid bioclast (cr) and a diabase clast (d), sample 36. **E** (sample 33), **F** (sample 37). Quartz phenocrysts (q), biotite (b) and feldspars (f) in rhyolite.

Sandstones

The sandstones in the profile of the Niewachlów Beds at Niestachów show diversity in the composition of the grain framework and binding agents as well as differences in grain size and degree of roundness. Three groups of sandstones were distinguished.

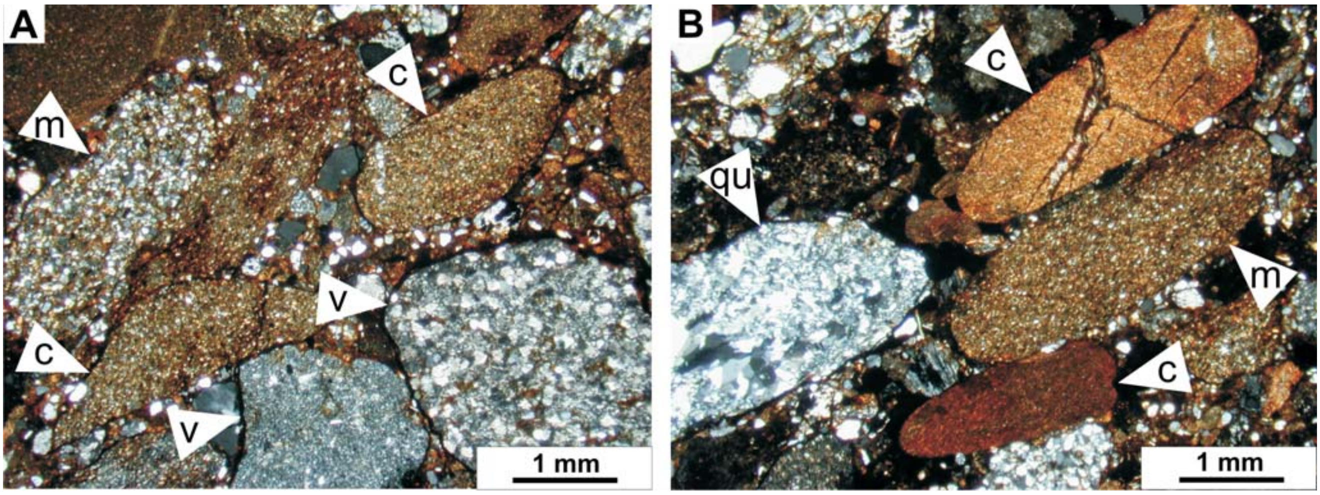

Fig. 13. Polymictic conglomerates with the predominance of sedimentary rock lithoclasts. Niewachlów Beds. Niestachów, outcrop 3. Crossed nicols. **A.** Elongated claystone (c) and mudstone (m) clasts and isometric volcanite (v) clasts with clayey-ferruginous rims, sample 1. **B.** Quartzite clast (qu) and elongated clasts of claystones (c) and mudstones (m) with clayey-ferriginous rims, sample 2.

Poorly sorted greywacke sandstones with a clayey-chloritic-quartzose binder

The petrographic composition of these sandstones is qualitatively similar to that of conglomerates. They correspond primarily to lithic wackes and to fine-grained varieties of sublithic wackes (complex B), with scarce sublithic and lithic arenites (lower part of complex K; Tables 2, 3; Figs 14A, 15A–F).

Noticeable differences mainly are related to the amounts of individual constituents. Most distinct is the increase in feldspars (*F*) at the expense of volcanic (*Lv*) and sedimentary (*Ls*) lithoclasts. The contribution of monocrystalline (*Qm*) and polycrystalline (*Qp*) quartz grains was also larger than in the conglomerates. The only difference is in the roundness of quartz grains, which apart from angular forms (Fig. 15C, D) implies good mechanical processing (Table 2; Fig. 15E, F). The binding agent of matrix type consists of aleuritic grains of quartz, feldspars, lithoclasts, and ferruginous illitic-chloritic-quartzose groundmass. Iron oxides and hydroxides form distinctly elongated oriented streaks (Fig. 15F), patches and spots. As in the conglomerates, diagenetic processes are documented by the formation of clayey-ferruginous coatings on grains and tightly-packed and deformed grains, as well as the subordinate calcitization of binder, feldspars and lithoclasts.

Greywacke sandstones of varying grain size with clayey-chloritic and calcitic binder

These sandstones occur in complexes I and J and in the form of individual intercalated beds in conglomerate complex H. The petrographic composition of the grain framework does not differ from that of the previously described lithic wackes. The difference is due to an admixture of carbonate lithoclasts, but especially to a considerable contribution of carbonate binder (Table 2). A decrease in the amount and size of quartz in relation to feldspars is evident. The most common size of quartz grains corresponds to the fine-grained fraction, whereas feldspars occur mainly in a medium-grained fraction, and lithoclasts appear in a coarse fraction. The degree of grain roundness is diverse (Fig. 16A). The calcite binder is affected to different degrees by aggrading neomorphism. This process is associated with the replacement of primary matrix, lithoclasts and feldspars, and etching of quartz grains. The grain framework of these sandstones may have contained a large amount of carbonate, currently included in the binder. Only carbonate and carbonate-chlorite bioclasts up to 5 mm in size stand out from the calcite binder (Fig. 16B). The sandstones of complex J comprise characteristic, well-rounded, spherical clasts, varying from 2 to over 20 cm in diameter; they reveal the features of armoured balls. In the microscope image, they show a similar composition to that of their host sandstones. These sandstones (calcitic lithic wackes) have not so far been recorded in the profile of the Niewachlów Beds.

Fine-grained quartz sandstones

These sandstones occur in complex D. They differ from those described above because of their petrographic composition that corresponds to quartz and sublithic arenites and sublithic wackes (Fig. 17A, B). The grain framework is characterized by the predominance of semirounded and isometric quartz grains (Table 2). They consist primarily of monocrystalline quartz with several percent of polycrystalline quartz. Feldspars, micas, volcanic and sedimentary rock lithoclasts reach several percent. The individual grains contain glauconite. The binder is represented by matrix; this is clayey-chloritic with a substantial admixture of iron oxides and hydroxides. The arenites contain several percent of regenerated, rimmed and porous quartz binder. The petrographic features of these sandstones were described by Przybyłowicz and Stupnicka (1989), who assigned them to quartz and sublithic arenites.

The quantitative petrographic composition of these sandstones was a basis for defining the geotectonic position of the source areas of the grains. The contents of particular components were marked on the triangular genetic diagrams pro-

Table 2

Petrographic composition of sandstones (in %)

	Lithol ogical unit	Localization	Size Q mostly/ largest mm	Rounded and shape Q	Qm	Qp	F	M	Rock fragments				Re-mains	Cement			Classifi-cation
									Lv	Ls	Lm	Lp		Mx	Cc+Mx	Qc	
1	L	outcrop 4/45	0.25/0.35	p,k,o; i,w	26.1	0.9	18.9	0.9	4.5	17.1	2.7	0.0	G	27.1		1.8	lithic wacke
2	K	outcrop 4/39	0.25/0.7	p,k,o; i,w	19.8	1.9	19.8	0.0	14.2	13.2	0.9	0.0	G	30.2			
3		outcrop 4/35	0.15/0.7	p,k,o; i,w	23.8	2.0	17.8	0.0	10.9	18.8	3.0	0.0	G	23.8			
4		outcrop 4/30	0.08/1.1	p,k; i,w	30.4	2.4	7.2	0.8	15.2	21.6	2.4	0.0	G	18.4		1.6	
5		outcrop 4/28	0.1/0.4	p,k; i,w	19.8	1.0	8.9	1.0	17.8	17.8	3.0	0.0	G	28.7		2.0	
6		outcrop 4/21	0.9/1.9	p,k,o; i,w	15.5	2.9	13.5	0.6	24.4	20.6	1.1	0.0	G	21.5			
7		outcrop 4/19	1.2/1.95	p,k; i,w	13.6	2.3	8.2	0.0	23.7	21.4	3.1	0.0	n	27.6			
8		outcrop 4/14	0.6/1.5	p,o,k; i,w	18.6	0.8	18.6	0.8	36.4	11.9	1.7	0.0		11.0			lithic arenite
9		outcrop 4/7	0.12/0.25	p; i	60.2	2.0	5.1	0.0	4.1	4.1	0.0	0.0		14.2		10.2	sublithic arenite
10		outcrop 4/2	0.15/0.5	p; i,w	42.7	2.0	8.7	1.3	10.0	16.0	1.3	0.0		14.7		3.3	lithic arenite
11	J	trench I/81	0.12/0.7	k,p; w,i	7.9	1.0	11.9	2.0	27.7	21.8	1.0	0.0		15.8	10.9		calca-reous lithic wacke
12		trench I/74	0.15/1.2	k,p; i,w	13.3	2.0	6.1	1.0	17.3	19.4	2.0	0.0	G 1.0 b	10.2	27.6		
13	I	trench I/67	0.1/0.25	k,p; i,w	11.0	1.0	5.0	2.0	13.0	21.0	0.0	0.0	2.0 b	13.0	32.0		
14		trench I/57	0.15/0.5	k,p; i,w	15.1	2.2	13.7	3.6	10.8	18.0	1.4	0.0	0.7 b	20.1	14.1		
15		trench I/48	0.15/0.35	k,p; i,w	13.7	0.9	11.1	2.6	11.1	17.1	0.0	0.0	0.9 b	17.1	25.6		
16	H	trench I/39	0.3/0.7	k,p; i,w	9.8	1.6	18.9	1.6	14.8	13.9	0.0	0.0	0.8 b	9.0	29.5		
17	G	trench I/26	0.15/2.5	k,p; i,w	11.3	0.9	12.2	3.5	19.1	13.0	1.7	0.0		36.5	1.7		lithic wacke
18		trench I/20	1.5/2.3	k,p; i,w	17.4	1.2	6.2	2.2	15.0	14.6	3.7	0.0	n	39.6			
19		trench I/18	1.2/2.5	k,p; i,w	21.2	1.1	10.6	1.7	15.1	22.3	1.1	0.0	G	26.8			
20	E	trench I/5	0.2/1.6	k,p; i,w	14.3	0.7	13.9	5.2	5.2	8.7	1.2	1.0	G	49.8			
21	D	outcrop 2/4	0.12/0.4	p; i	73.0	4.5	0.9	0.9	0.9	3.6	0.0	0.0	n	7.2		9.0	quartz arenite
22		outcrop 2/1	0.08/0.15	p; i	47.1	2.0	2.0	2.9	2.9	6.9	0.0	0.0	G	32.4		3.9	sublithic wacke
23		outcrop 1/15	0.12/0.55	p; i	58.8	5.9	3.9	1.0	2.0	2.9	0.0	0.0		19.6		5.9	
24		outcrop 1/2	0.1/0.25	p; i	64.5	3.6	4.5	1.8	1.8	2.7	0.0	0.0		11.8		9.1	sublithic arenite
25	B	trench III/23	0.1/0.25	p,k; i,w	42.9	1.8	5.4	0.9	7.1	6.3	0.0	0.0	G	33.9		1.8	sublithic wacke
26		trench III/17	0.12/0.3	p,k; i,w	41.5	3.8	4.7	0.9	10.4	5.7	0.9	0.0		29.2		2.8	
27		trench III/12	0.12/0.4	p,k; i,w	37.3	3.6	4.5	0.0	10.0	4.5	0.0	0.0		40.0			
28		trench III/10	0.1/0.25	p,k; i,w	35.9	0.9	6.0	3.4	6.8	10.3	0.9	0.0	n	35.9			

G – glauconite, n – undistinguishable grains, b – bioclasts; grains: rounded (o), semirounded (p), angular (k), izometric (i), elongated (w); Q – quartz, Qm – monocrystalline quartz, Qp – polycrystalline quartz, Qc – quartz cement, F – feldspar, Lp – plutonic lithoclasts, Lm – metamorphic lithoclasts, Ls – sedimentary lithoclasts, Lv – volcanic lithoclasts, Mx – matrix cement, Cc – calcite cement, M – mica. For the other explanations see the text.

posed by Dickinson and co-authors (1983). They included the proportions of mono- and polycrystalline quartz, feldspars and lithoclasts, converted to 100% (Table 3). The triangle apices are occupied by mono- and polycrystalline quartz (Q), feldspars (F) and lithoclasts (L). The sandstone samples of the Niestachów area cover the fields of a reactivated orogen and a magmatic arc.

A similar position is taken up by samples on the triangle determined by Qm (monocrystalline quartz), F and Lt (lithoclasts + polycrystalline quartz) with the localization of several samples at the contact of a reactivated orogen with a continental block. The triangle with Lm, Lv i Ls in the apices indicates that the source area was a magmatic arc (Fig. 14B, C, D).

Claystones and mudstones

In the Niestachów profile, these sediments occur in complex A, which belongs to the Prągowiec Beds (Figs 4, 5, 9). The basic variety of rocks is laminated illitic claystones with an admixture of aleuritic quartz grains and tiny muscovite (hydromuscovite) flakes, which are arranged parallel to the bedding. These constituents are evenly distributed in illitic groundmass, then lamination is enhanced by the presence of thin, commonly discontinuous, bituminous laminae enriched in framboidal pyrite (Fig. 18B). This mineral is also scattered throughout the entire groundmass. In some places, selective, parallel and streaky clayey and silty laminae were

Table 3

Percent participation of grained components in sandstones

	Lithological units	Localization	Q	F	L	Qm	F	Lt	Lv	Ls	Lm
1	L	outcrop 4/45	38.5	26.9	34.6	37.2	26.9	35.9	18.5	70.4	11.1
2	K	outcrop 4/39	31.1	28.4	40.5	28.4	28.4	43.2	50.0	46.7	3.3
3		outcrop 4/35	33.8	23.4	42.9	31.2	23.4	45.5	33.3	57.6	9.1
4		outcrop 4/30	41.4	9.1	49.5	38.4	9.1	52.5	38.8	55.1	6.1
5		outcrop 4/28	30.4	13.0	56.5	29.0	13.0	58.0	46.2	46.2	7.7
6		outcrop 4/21	23.5	17.3	59.2	19.9	17.3	62.9	52.8	44.7	2.5
7		outcrop 4/19	22.0	11.3	66.7	18.8	11.3	69.9	49.2	44.4	6.5
8		outcrop 4/14	22.1	21.2	56.7	21.2	21.2	57.7	72.9	23.7	3.4
9		outcrop 4/7	82.4	6.8	10.8	79.7	6.8	13.5	50.0	50.0	0.0
10		outcrop 4/2	60.4	11.7	27.9	57.7	11.7	30.6	36.6	58.5	4.9
11	J	trench I/81	12.5	16.7	70.8	11.1	16.7	72.2	54.9	43.1	2.0
12		trench I/74	25.4	10.2	64.4	22.0	10.2	67.8	44.7	50.0	5.3
13	I	trench I/67	23.5	9.8	66.7	21.6	9.8	68.6	38.2	61.8	0.0
14		trench I/57	28.2	22.4	49.4	24.7	22.4	52.9	35.7	59.5	4.8
15	H	trench I/48	27.0	20.6	52.4	25.4	20.6	54.0	39.4	60.6	0.0
16		trench I/39	19.4	31.9	48.6	16.7	31.9	51.4	51.4	48.6	0.0
17	G	trench I/26	20.9	20.9	58.2	19.4	20.9	59.7	56.4	38.5	5.1
18		trench I/20	32.1	10.7	57.2	29.9	10.7	59.4	44.9	43.9	11.2
19		trench I/18	31.3	14.8	53.9	29.7	14.8	55.5	39.1	58.0	2.9
20	F	trench I/5	33.3	31.0	35.7	31.8	31.0	37.2	54.3	39.1	6.5
21	D	outcrop 2/4	93.9	1.1	5.0	88.0	1.1	10.9	20.0	80.0	0.0
22		outcrop 2/1	80.6	3.3	16.1	77.3	3.3	19.4	30.0	70.0	0.0
23		outcrop 1/15	88.0	5.3	6.7	80.0	5.3	14.7	40.0	60.0	0.0
24		outcrop 1/2	88.2	5.9	5.9	83.5	5.9	10.6	40.0	60.0	0.0
25	B	trench III/23	70.4	8.5	21.1	67.6	8.5	23.9	53.3	46.7	0.0
26		trench III/17	68.6	7.1	24.3	62.9	7.1	30.0	61.1	33.3	5.6
27		trench III/12	68.2	7.6	24.2	62.1	7.6	30.3	68.8	31.3	0.0
28		trench III/10	60.6	9.9	29.6	59.2	9.9	31.0	38.1	57.1	4.8

Q – quartz, Qm – monocrystalline quartz, Qp – polycrystalline quartz, F – feldspar, L – lithoclasts, Lm – metamorphic lithoclasts, Ls – sedimentary lithoclasts, Lv – volcanic lithoclasts, Lt – (L + Qp).

observed. They also contain individual carbonate clasts (bioclasts) and feldspar grains, which may be of pyroclastic origin (Fig. 18C). There are carbonate concretions within claystones in the middle part of this complex. The origin of these concretions is probably similar to that of the carbonate concretions, described from the Lower Carboniferous deep-sea greywackes and mudstones of the Sudetes (Bojanowski *et al.*, 2014). Their micritic groundmass is distinctive because of sparitic biogenic constituents, probably of algal origin (Fig. 18D).

SOURCE AREA OF GREYWACKE MATERIAL

The continuous profile of greywackic sediments exposed in the Niestachów area allows the authors to indirectly trace the chronological sequence of tectonic and orogenic activities in the source area during the early Ludlovian. The lower part of the greywacke series of Niewachlów Beds (complexes B, C) consists mainly of fine- and medium-grained greywacke sandstones, linked to the beginning of orogenic activity. Complex D of fine- and medium-grained quartz sandstones represents in turn sediments presumably derived from the secondary erosion of previously deposited siliciclastic sediments of the source area. The presence of bioclasts, corals and crinoids in these sandstones points to original deposition within a shallow zone, where carbonate sediments presumably were laid down. The pyroclastic interlayers that occur in these sandstones indicate volcanic activity in the source area. Short-lived, intensive, tectonic upthrusting is evidenced by the conglomerates assigned to complex E. The predominance of sedimentary lithoclasts in these conglomerates points to the erosion of lithologically diversified sedimentary cover. The presence of mudstones with subordinate greywacke sandstones in complex F indicates weaker tectonic activity in the source area. In contrast, the deposition of coarse-grained sandstones and conglomerates of complexes G and H is linked to the maximum intensity of orogenic activity in the source area during sedimen-

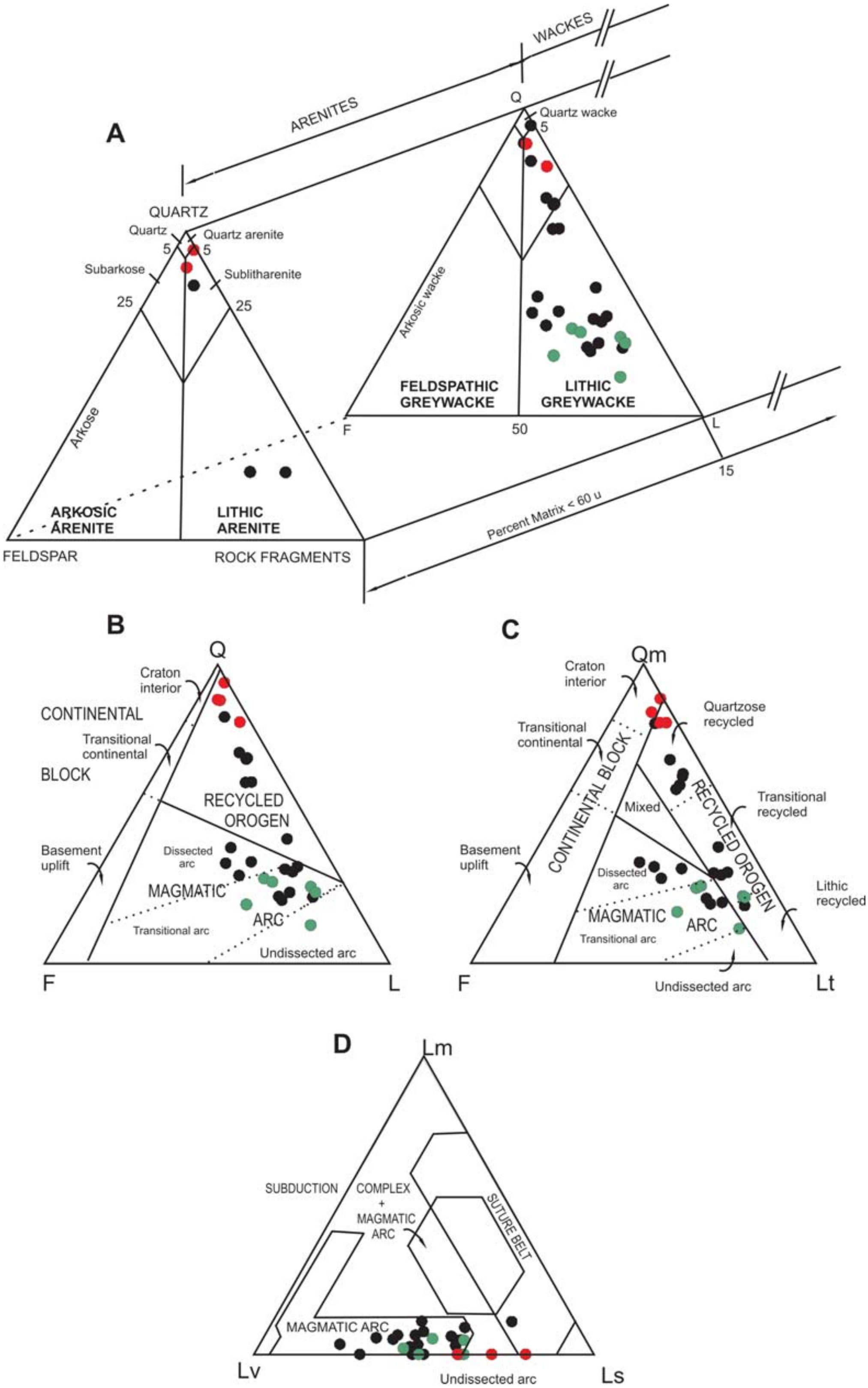

Fig. 14. Classification diagram **A**. Classification diagram for sandstones of the Silurian Niewachlów Beds at Niestachów (after Dott, 1964 modified by Pettijohn *et al.*, 1972 and Jaworowski, 1987). **B**, **C**, **D.** Genetic diagrams of source areas of detritic constituents (B, C. after Dickinson *et al.*, 1983; **D.** After Ingersoll and Suczek, 1979). Black circles – varigrained and fine-grained greywacke sandstones with clayey-chloritic-quartzose binder. Green circles – varigrained greywacke sandstones with clayey-chloritic and calcitic binder. Red circles – fine-grained quartz sandstones. Q – quartz, L – lithoclasts (Lv + Ls + Lp + Lm), F – feldspar, Qm – monocrystalline quartz, Qp – polycrystalline quartz, Lt – (L + Qp), Lm – metamorphic lithoclasts, Ls – sedimentary lithoclasts, Lp – plutonic lithoclasts, Lv – volcanic lithoclasts.

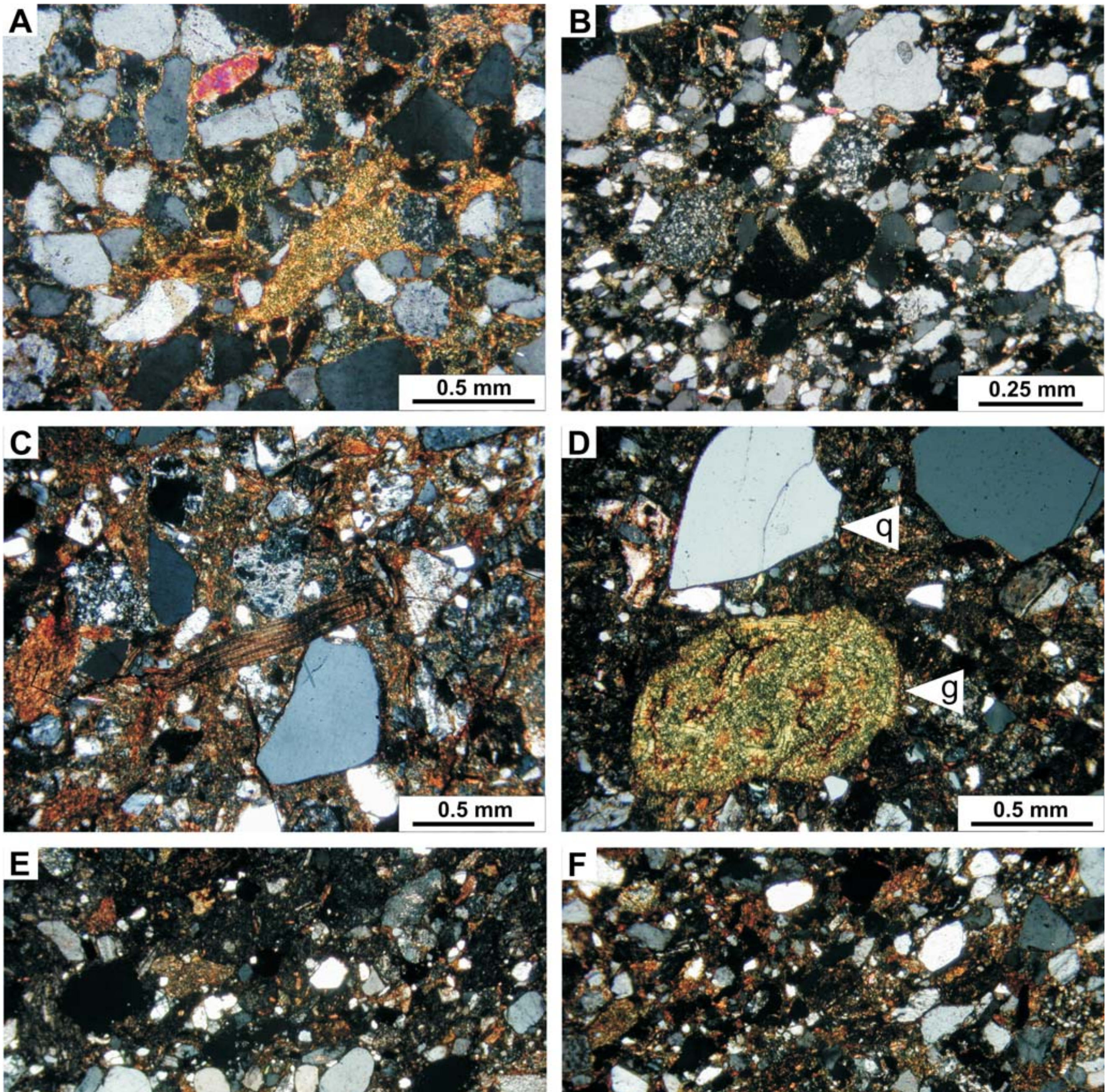

Fig. 15. Greywacke sandstones. Niewachlów Beds. Niestachów. Crossed nicols. **A**, **B.** Fine-grained sublithic wackes. **C**, **D**, **E**, **F.** Varigrained lithic wackes. Angular quartz (q) and rounded chloritized glass (g) grains (C, D) and diverse roundness of quartz, feldspar and lithoclast grains (E, F) as well as streaky enrichments of iron oxides and hydoxides (F) are visible. **A**, **B.** Trench III; A. Sample 12; B. Sample 17. **C**, **D.** Trench I; C. Sample 5; D. Sample 20. **E**, **F.** Outcrop 4; E. Sample 19; F. Sample 46.

tation of the greywackes assigned to the Niewachlów Beds. At that time the volcanic cover with subordinate sedimentary rocks and a partly metamorphosed basement were affected by intensive erosion. Pronounced tectonic activity also lasted in the source area during the deposition of the overlying medium- and coarse-grained greywacke sandstones of complexes I, J and K. A distinct decrease in orogenic activity is evidenced by the deposition of mudstones with minor greywackic sandstones assigned to complex L at the top of the Silurian Niestachów profile.

The determination of the origin of the grains in the Silurian greywackes of the Niewachlów Beds was based primarily on the coarse-grained part of the greywacke sequence. The main reason for this focus is the richest inventory of grain constituents composed of a variety of rocks, namely sedimentary, igneous (including effusive, veined and plutonic) and metamorphic (gneisses) (Dyka, 1958; Taszek, 1962; Łydka *et al.*, 1963; Łabędzki, 1969; Chlebowski, 1978; Przybyłowicz and Stupnicka, 1989, 1991; Romanek and Rup, 1989; Stupnicka *et al.*, 1991; Migaszewski, 1998). Owing to the diverse petrographic composition of greywackes, different potential source areas of the material were considered. Most researchers were in favour of localization of these areas outside the Palaeozoic block of the Holy Cross Mountains. These source areas would have been situated in the Silesian-Cracovian area (Znosko, 1974), in the southeastern (Jaworowski, 1971), southern and eastern margins of the Holy Cross Mountains, beneath the Carpathians, or in the Slovakian area (Kowalczewski, 1974; Chlebowski, 1978; Znosko, 1983; Romanek and Rup, 1989), as well as the north, north-east (Jaworowski, 1971; Stupnicka, 1992; Stupnicka and Przybyłowicz, 1998) or the north-west (Znosko, 1983) of the Holy Cross Mountains. The other hypothesis assumes that the grains of the greywackes were of local origin and were delivered to the basin from the eruptions of volcanoes, located in the Bardo and Daleszyce synclines (Przybyłowicz and Stupnicka, 1989, 1991; Stupnicka *et al.*, 1991; Migaszewski, 1998). The presence of igneous (effusive and plutonic) and metamorphic lithoclasts in the greywacke material, not encountered in the Holy Cross Mountains, excludes this area as a potential area of greywackes. The alimentary source for the Upper Silurian greywackes may have been located at a considerable distance from the Palaeozoic block of the Holy Cross Mountains and outside the current margins of the Małopolska Block. According to Malec (1996), the Upper Silurian greywacke sediments that occur in the area of the Holy Cross Mountains were transported from the south and southwest in the form of turbidites and were laid down in a basin (Teisseyre–Tornquist sea), situated along a subduction zone. The oceanic plate of this basin also underwent subduction. This sea extended between Baltica in the east and probably a volcanic island arc and terranes that restricted the sea from the south and southwest. The presence of lithoclasts of sedimentary and igneous (mainly effusive) rocks in the greywacke series of the Holy Cross Mountains points to detrital source material, derived from an eroded orogen and a volcanic arc composed of sandstone-mudstone and volcanic rocks (Malec, 1996, 2000a, 2001, 2002b, 2005; Kozłowski *et al.*, 2004, 2014; Malec *et al.*, 2005; Malec and Kuleta, 2009a). The analysis of current indicators on the bottom surfaces of the greywacke sandstones of the Niewachlów Beds implies that the detritic material was delivered to the Holy Cross Mountains from the southwest (Malec, 2000a, 2001, 2002b), or that the detrital material of greywacke sandstones of the Niewachlów Beds and the Wydryszów Beds was delivered to these areas from the west (Kozłowski *et al.*, 2004, 2014), outside the boundaries of the Małopolska Block.

In the area of the Małopolska Block (Terrane), outside the Kielce region of the Holy Cross Mountains, the Silurian siliciclastic sediments have been documented in its southwestern marginal zone. In this area, these deposits consist of mudstones and sandstones assigned to the Mrzygłód Formation and overlying sandstones and greywacke conglomerates of the Łapczyca Formation (Piekarski *et al.*, 1980; Buła, 2000). The last mentioned were drilled between Łapczyca and Zawiercie (Fig. 1; Wdowiarz, 1954; Turnau-Morawska, 1957; Cebulak, 1958; Myszka and Parachoniak, 1958; Łydka *et al.*, 1963; Roszek and Siedlecki, 1963; Bukowy and Ślosarz, 1968; Konior, 1970; Heflik and Konior, 1972; Buła, 2000; Buła *et al.*, 2015). The conglomerates of the Łapczyca Formation near Zawiercie exhibit a qualitative composition of detrital components, similar to that of the greywacke conglomerates of the Niewachlów Beds. However, they show a distinct quantitative diversity of individual lithologic varieties and mineral groups (Malec *et al.*, 2004, 2005, 2008). In contrast to the conglomerates of the Holy Cross Mountains, the Zawiercie conglomerates are characterized by a lesser contribution of acidic volcanic rock grains and the presence of sandstones, corresponding to arkosic greywackes, which are almost absent in the Holy Cross Mountains. These studies have also shown that the greywacke material of the Kielce region of the Holy Cross Mountains came from an acidic volcanic zone, whereas its equivalent in the Zawiercie area came from a more intermediate volcanic zone. In the Zawiercie area, the bottom of the Łapczyca Conglomerate Formation consists of coarse clastic sandstone and conglomerate sediments, whereas the top of this formation is composed of mudstones with greywacke sandstone interbeds. In relation to the Niestachów Silurian profile, the Łapczyca Conglomerate Formation corresponds to the rock series that encompasses sediments of the upper part of the Niewachlów Beds within complexes E–L. The lower part of the greywacke series of the Niewachlów Beds from the Niestachów profile correlates with the upper part of sediments assigned to the Mrzygłód Formation (Malec *et al.*, 2004). The conglomerates of the Łapczyca Formation in the stratotype profile of the Łapczyca 2 borehole consist of greywacke sandstones and conglomerates with subordinate mudstones (Malec and Kuleta, 2009b). These conglomerates are dark brown and their volcanic rock pebbles are composed of volcanic, sedimentary and metamorphic rocks, averaging 5–8 mm up to 2–6 cm in diameter. In contrast to the Holy Cross Mountains and Zawiercie conglomerates, those from Łapczyca are characterized by a larger amount of mafic volcanoclasts. On the basis of the data from different studies, but especially on petrographic composition, the contribution of individual constituents and the colour of the sediments, the Silurian greywackes of the Kielce region of the Holy Cross Mountains are particularly similar to those occurring in the Batowice-Łapczyca zone (Malec and Kuleta, 2009b). In the area of the Małopolska Block, Late Silurian greywacke sedimentation was diachronous. In its western part (the Zawiercie area), the mudstones and sandstones of the Mrzygłód Formation seem to have deposited in the Wenlockian (Buła *et. al.*, 2015), whereas in the Kielce region the beginning of greywacke sedimentation of the Niewachlów Beds took place in the late Ludlovian (Tomczyk, 1956; Malec *et al.*, 2005).

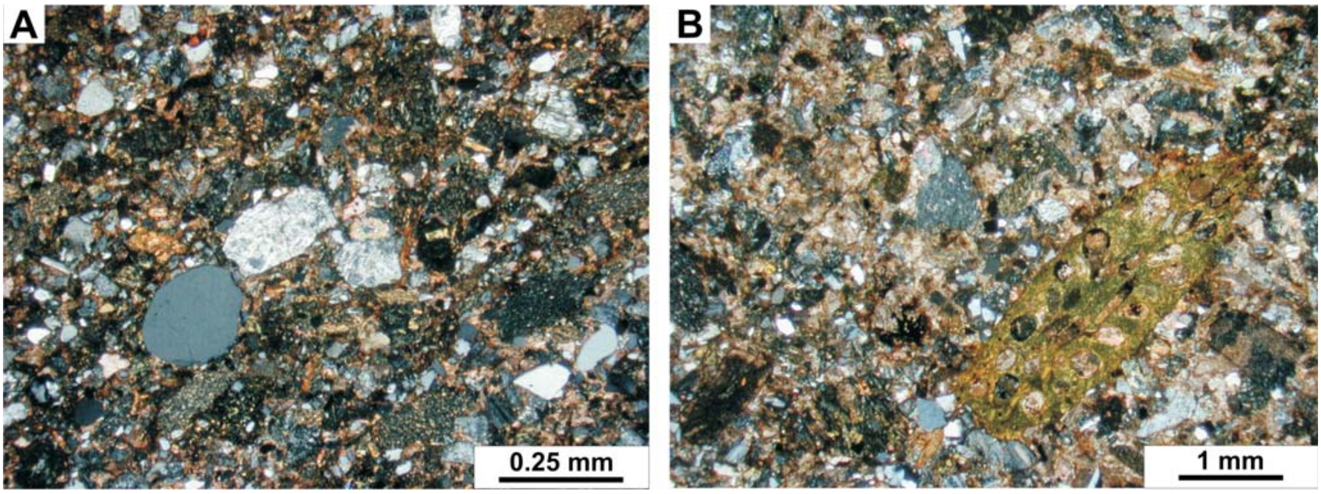

Fig. 16. Varigrained lithic wackes with clayey-chloritic and calcitic binder. Niewachlów Beds. Niestachów, trench I. Crossed nicols. **A.** Diverse roundness of quartz, feldspar and lithoclast grains is visible, sample 81. **B.** Partly chloritized bioclast in calcareous lithic wacke, sample 76.

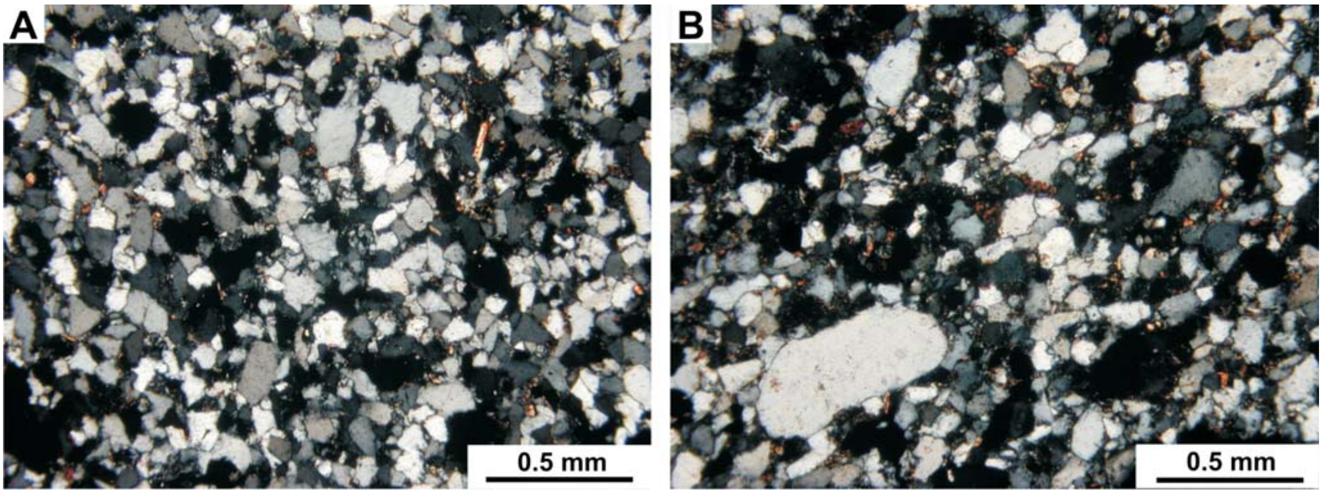

Fig. 17. Fine-grained quartz sandstones. Niewachlów Beds. Niestachów, outcrop 1. Crossed nicols. **A.** Fine-grained sublithic arenite, sample 2. **B.** Fine-grained sublithic wacke; sample 15.

The siliciclastic sediments, which are coeval with the Sillurian greywackes of the Holy Cross Mountains and the southwestern part of the Małopolska Terrane, occur in the northern part of Poland in the Koszalin-Chojnice zone and the marginal part of the East-European Platform (Jaworowski, 1971). In this area, the sediments are developed as a shaly-silty complex, deposited from suspension currents and cohesive flows in a deep-water basin (Jaworowski, 2000a, b), in the proximal part of a Caledonian foredeep (Poprawa *et al.*, 1999; Poprawa, 2006). In the Koszalin–Chojnice zone, the detrital material originated from the erosion of the Caledonian accretion prism that extended along a collision zone of the Baltica continent with the Eastern Avalonia Terrane, a subductive island arc and peri-Gondwana terranes (Jaworowski, 2000a,b; Poprawa *et al.*, 2006). The results of radiometric dating, performed on micas from the Silurian sediments, are indicative of the Middle Ordovician and Early Silurian. This fact points to the presence of the Caledonian orogen in an area located west of the Koszalin–Chojnice zone (Poprawa *et al.*, 2006). The geochemical studies of the Silurian clastic rocks from the Koszalin–Chojnice zone and the upper Ludlovian greywackes of the Łysogóry and Kielce regions of the Holy Cross Mountains have shown distinct consanguinity, pointing to the origin of the sediments derived from the orogen, which formed as a result of the collision of a continental magmatic arc with Baltica (Krzemiński and Poprawa, 2006).

The accumulation of greywacke sediments in the area of the Łysogóry and Małopolska terranes occurred in a foredeep (Narkiewicz, 2002; Kozłowski *et. al.*, 2004; Nawrocki and Poprawa, 2006). The amount of detrital material from the middle part of the greywackes of the Niewachlów Beds and Łapczyca Formation (up to fine- and medium-pebble fraction) indicates that sedimentation on the Małopolska Terrane took place in a zone relatively close to the active orogen, in an environment of submarine fans and a

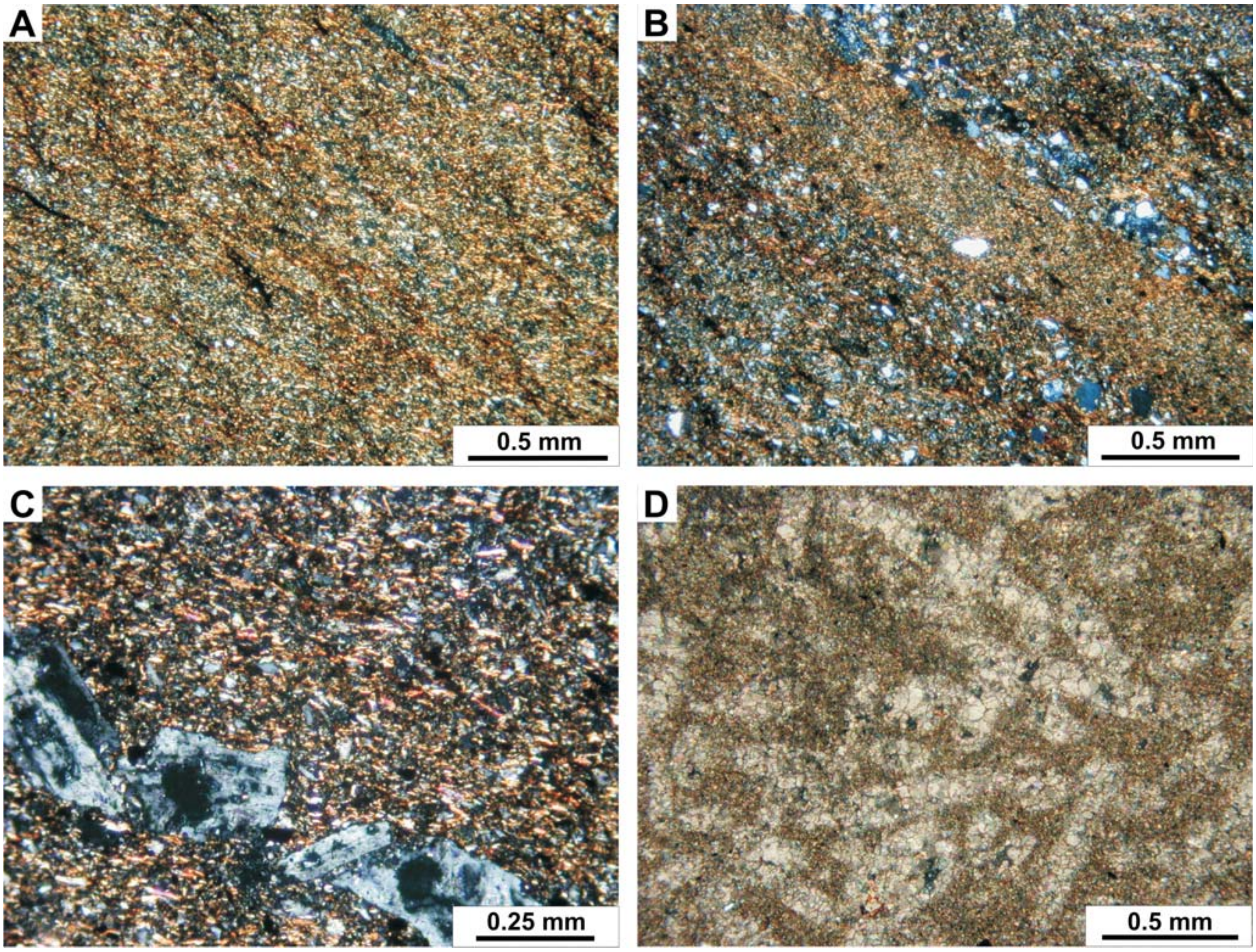

Fig. 18. Graptolitic claystones. Prągowiec Beds. Niestachów. Crossed nicols. **A.** Silty claystone with streaky laminae of bituminous-ferruginous substance, trench II, sample 1. **B.** Claystone with mudstone laminae of different thickness, trench III, sample 4. **C.** Pyroclastic albite grains (?) in silty claystone, trench II, sample 16. **D.** Algae in carbonate concretion, trench II, sample 8.

basin plain (Malec *et al*., 2005). At a farther distance from the orogenic zone, deposition of the Silurian greywackes in the area of the Łysogóry Terrane took place. This is evidenced by finer detrital material (to a psammitic fraction) of the Wydryszów Beds (Malec, 2000a,c, 2001; Kozłowski *et al.*, 2004, 2014; Malec and Kuleta, 2009a). The geochronological dating of detrital micas of the Silurian greywackes of the Łysogóry and Małopolska terranes points to the same Neoproterozoic age (about 730 Ma) of terrigenous material derived from the Wielkopolska Terrane, located west of the Holy Cross Mountains, and to an age of about 403 and 442 Ma linked to the Silurian activity of the volcanic arc that surrounded this terrane, distinguished as the Teisseyre Arc (Kozłowski *et al.*, 2004, 2014; Nawrocki and Poprawa, 2006; Nawrocki *et al.*, 2007).

The larger fraction of detrital material in the greywackes of the Niewachlów Beds in relation to those of the Wydryszów Beds can be explained by translocation of the Małopolska Terrane in the Silurian along the Holy Cross Fault to a distance of 200 km westward of the orogen (Kozłowski *et al.*, 2014). Here, the authors assume that in the Late Silurian, the orogenic area was located south or southwest of the Małopolska Terrane, which is evidenced by the growing size of detrital material of the greywacke sediments in this direction. The orogen and volcanic arc, from which the greywackes of the Łysogóry and Małopolska terranes were derived, are supposed to have been buried beneath Variscan structures and the Carpathian nappies. The difference in grain size of greywacke material in the Łysogóry and Małopolska terranes results from the palaeographic location of the latter in the Late Silurian. It was presumably situated about several hundred kilometers from the present location. According to Lewandowski (1993), this terrane was moved from Ordovician time along the southwestern margin of the East European Platform, to dock on the opposite side of the Łysogóry Terrane in the Variscan epoch.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. Twelve rock complexes, diversified in terms of lithofacies, were distinguished in the Silurian profile of the

Niestachów area. One of them encompasses graptolitic shales of the Prągowiec Beds, whereas the remaining eleven complexes occur in a greywacke series of the Niewachlów Beds.

2. The Niewachlów conglomerates are fine-grained and polymictic. Both the contacts and the binder content classify these rocks as ortho- or paraconglomerates. The predominant albitic composition of feldspars in all the volcanic lithoclasts allow these rocks to be assigned to albitic varieties, i.e. rhyolites, dacites, trachytes and diabases.

3. The sandstones of the Niewachlów Beds exhibit diversity in composition of the framework grains and binding material as well as in sorting, grain-size, composition and degree of roundness. In some parts of the profile, the sandstones are lithic wackes and poorly sorted, calcareous, lithic wackes of varying grain size, similar in composition to the conglomerates. Only in places, they occur as sublithic and lithic arenites with subordinate quartz arenites.

4. The source area of the sandstones and conglomerates was located in an eroded, reactivated orogen, composed of sandstones and mudstones as well as the magmatic rocks of a continental volcanic arc characterized by acidic-intermediate volcanism.

5. Lithoclasts of volcanic rocks and quartz grains of volcanic origin have been regarded as epiclastic material. The sediments accumulated in a deep marine environment. It was also recognized that the detrital material was deposited and later reworked in a marginal or a nearshore zone of the sea, before it was finally deposited in the deeper part of the basin by gravitational subaqueous flows.

6. The presence of carbonate lithoclasts and bioclasts in the conglomerates and sandstones indicates the erosion of intrabasinal carbonate platform sediments.

Acknowledgements

The authors are grateful to Elżbieta Porębska for determination of graptolithic fauna from the Niestachów profile and Ewa Starnawska for structural and microchemical analysis of conglomerate samples by means of the SEM-EDS method. The authors also want to express their thanks for the reviewers: Justyna Domańska-Siuda and Andreas Wetzel for their valuable remarks and corrections. We also want to thank Frank Simpson for linguistic corrections and Włodzimierz Mizerski for constructive comments that considerably improved the quality of our manuscript.

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