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# COMPOSITION AND PROVENANCE OF CLASTIC MATERIAL IN THE VENDIAN–LOWERMOST CAMBRIAN FROM NORTHERN POLAND: GEOTECTONIC IMPLICATIONS

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*Abstract*. The Vendian–lowermost Cambrian deposits from northern Poland belong to the Żarnowiec Formation. Data concerning the formation have been gained from deep boreholes. The Żarnowiec Fm. rests directly on the crystalline basement of the East European Craton and is developed almost exclusively as continental sandstones and conglomerates. They are grey-pink and red-brownish in colour. No fossils have been found in the Żarnowiec Fm. At the top it gradually passes into marine sandstones and sand-mud heteroliths which are early Cambrian in age. The Żarnowiec Fm. is believed to represent the Vendian and earliest Cambrian.

Mineral composition of the Żarnowiec Fm. shows close relationships with the crystalline basement of the East European Craton. When plotted on the Dickinson's diagrams (1985), mineral composition of the Żarnowiec Fm. indicates internal cratonic areas as the sources of clastic material. In the western part of the study area the clastic material was supplied from an elevated block of the basement. Chemical analyses point to a passive continental margin as the main source of clastic material.

Three depositional systems have been identified within the Żarnowiec Fm.: proximal part of alluvial fans; distal part of alluvial fans and braid-and-sheetflood plain. Clastic material of the Żarnowiec Fm. was transported in two opposite directions: W→E and E→W. Some of the clastics were transported in the N→S direction. The sources of clastic material were located: (1) west of the Teisseyre–Tornquist Zone, i.e. outside the present-day East European Craton; (2) in the marginal part of the East European Craton; (3) in the East European Craton in the area of the present-day Baltic Shield.

On the basis of the present paper, the breaking up of the Precambrian supercontinent of Rodinia and formation of the southwestern edge of Baltica (East European Craton) may be interpreted in terms of the model of asymmetric lithosphere stretching.

*Key words*: clastic material, geotectonic interpretation, petrology, geochemistry, sedimentology, Żarnowiec Formation, Vendian, earliest Cambrian, northern Poland.

*Abstrakt*. Wendyjsko-dolnokambryjskie osady północnej Polski należą do formacji żarnowieckiej. Dane dotyczące tej formacji uzyskano z głębokich otworów wiertniczych. Formacja żarnowiecka leży bezpośrednio na podłożu krystalicznym kratonu wschodnioeuropejskiego i jest wykształcona niemal wyłącznie jako kontynentalne piaskowce i zlepieńce. Są one barwy szaroróżowej i wiśniowej. W formacji żarnowieckiej nie znaleziono skamieniałości. W stropie przechodzi ona stopniowo w morskie piaskowce i heterolity piaszczysto-mułowcowe wieku dolnokambryjskiego. Uważa się, że formacja żarnowiecka reprezentuje wend i najniższy kambr.

Skład mineralny formacji żarnowieckiej wykazuje bliskie podobieństwo do składu podłoża krystalicznego kratonu wschodnioeuropejskiego. Na diagramach Dickinsona (1985) skład mineralny formacji wskazuje wewnętrzne obszary kratonu jako źródła materiału okruchowego. W zachodniej części badanego obszaru materiał okruchowy był dostarczany z wyniesionego bloku podłoża. Analizy chemiczne świadczą, że głównym źródłem materiału okruchowego był pasywny brzeg kontynentu.

W obrębie formacji żarnowieckiej wyróżniono trzy systemy depozycyjne: proksymalną część stożków napływowych, dystalną część stożków napływowych oraz równię roztokową i zalewowo-warstwową. Materiał okruchowy formacji żarnowieckiej był transportowany głównie w dwóch przeciwnych kierunkach: W→E i E→W. Część klastyków była transportowana w kierunku N→S. Źródła materiału okruchowego były położone: (1) na zachód od strefy Teisseyre'a–Tornquista, tj. poza

dzisiejszym kratonem wschodnioeuropejskim; (2) w brzeżnej części kratonu wschodnioeuropejskiego; (3) na kratonie wschodnioeuropejskim w miejscu dzisiejszej tarczy bałtyckiej.

Na podstawie niniejszej pracy, rozpad prekambryjskiego superkontynentu Rodinii i formowanie południowo-zachodniej krawędzi Baltiki (kratonu wschodnioeuropejskiego) mogą być interpretowane w kategoriach asymetrycznego modelu rozciągania litosfery.

*Słowa kluczowe*: materiał okruchowy, interpretacja geotektoniczna, petrologia, geochemia, sedymentologia, formacja żarnowiecka, wend, najniższy kambr, północna Polska.

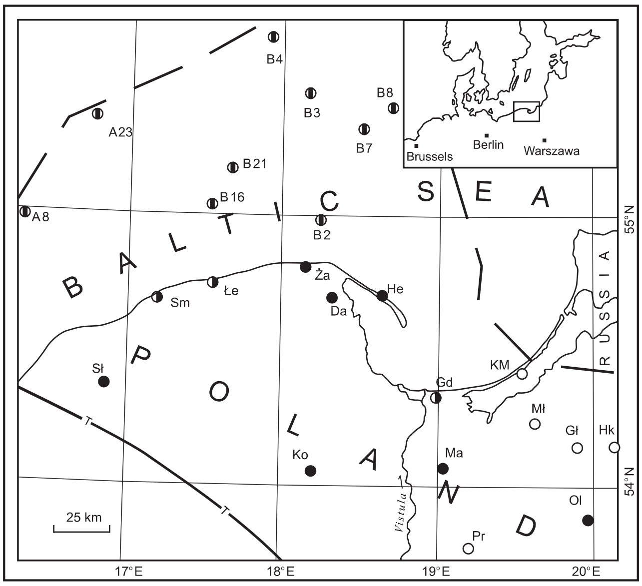
# INTRODUCTION

The evolution of the Trans-European Suture Zone (TESZ) represents important challenge of the present-day European Geology (Pharaoh *et al*., 1996). This zone was formed as a result of the Phanerozoic accretion, welding the western, Palaeozoic part of Europe and the much older East European Craton. The Teisseyre–Tornquist Zone (TTZ) is the north-eastern boundary of TESZ (Dadlez, 1993; Znosko, 1998), being simultaneously the south-western boundary of the craton, i.e. of the Baltica palaeocontinent. Weakly deformed sediments of the cratonic cover were deposited during the period spanning the Riphean through Cenozoic. A recently completed research project, concerning the area of northern Poland (Jaworowski, 2000a), provided much information on the Caledonian accretion of the Baltica palaeocontinent (East European Craton). The accretion proceeded through docking of the East Avalonia peri-Gondwanan terrane. The much earlier process of formation of the south-western margin of Baltica, along which the accretion occurred, had remained undefined. It is generally known that Baltica itself was created as a result of the breaking-up of the Precambrian Rodinia supercontinent (cf. Żelaźniewicz, 1998). An extentional event occurred at that time in northern Poland (Poprawa *et al*., 1999), as confirmed by the subsidence analysis of the Baltic Basin.

The studies of the sedimentary record of the evolution of Baltica and its southwestern margin required precise investigations of the Żarnowiec Formation which is the Vendian–lowermost Cambrian in age (Lendzion, 1970, 1976a, 1982, 1983a, b; Areń, Lendzion, 1978; Mens *et al*., 1990).

The studies required, in particular, investigations of the provenance and depositional conditions of clastic material of this formation. Investigations of this kind could only be performed on rock material, i.e. on drillcores. Therefore, a number of deep boreholes drilled in northern Poland by the Polish Geological Institute were selected for detailed analysis. In these boreholes the Żarnowiec Fm. was cored relatively well, permitting a wide range of petrographical-geochemical and facies studies. It refers to those boreholes in which deposits of the Żarnowiec Fm. were cored over 80% (Fig. 1, Tab. 1). More poorly cored boreholes, drilled by the Polish Geological Institute (Gdańsk IG 1 borehole) and the Polish Oil and Gas (Smołdzino 1 and Łeba 8 boreholes), were also taken into consideration. These boreholes were used for supplementary investigations and — tied to wireline logs — to determine the thickness of the Żarnowiec Fm.

The Żarnowiec Fm. continues far to the north offshore the Polish Baltic coast. It is evidenced by the results of boreholes sunk by the Polish Geological Institute in northernmost Poland (Żarnowiec IG 1 and Hel IG 1 boreholes, Fig. 1). Therefore, drilling data from boreholes drilled offshore northern Poland by the Petrobaltic Oil & Gas Co. were also analysed. As only small amount of drillcore has been obtained from the Żarnowiec Fm. in these boreholes, mainly wireline logs were examined for bed thickness variations.




Boreholes in which the Żarnowiec Fm. was cored:
0% 10–40% over 80%

boreholes without the Żarnowiec Fm.

Teisseyre–Tornquist Line

**Fig. 1. Location of the study area**

**Abbreviations of borehole names**: Da — Darżlubie IG 1, Gd — Gdańsk IG1, Gł — Gładysze 1, He — Hel IG 1, Hk — Henrykowo 5, Ko — Kościerzyna IG 1, KM — Krynica Morska 2, Łe — Łeba 8, Ma — Malbork IG 1, Mł — Młynary 3, Ol — Olsztyn IG 2, Pr — Prabuty IG 1, Sł — Słupsk IG 1, Sm — Smołdzino 1, Ża — Żarnowiec IG 1

# THE ŻARNOWIEC FORMATION IN THE LIGHT OF PREVIOUS STUDIES

The Żarnowiec Formation was established in the Żarnowiec IG 1 borehole by Lendzion (1970). This borehole revealed red and brownish vari-grained sandstones and conglomerates which overlie the crystalline basement and underlie light and dark grey sand and sand-mud deposits containing bioturbation structures and Lower Cambrian fauna. The red and brownish sandstones and conglomerates were originally defined by Lendzion (1970) as the informal Żarnowiec Series and assigned to the Eocambrian. The equivalent of the Żarnowiec Formation is the Smołdzino Formation, established later as a formal unit. The Smołdzino Fm. was defined (Bednarczyk, Turnau-Morawska, 1975) in the Smołdzino 1 borehole at a depth of 3330.0–3417.6 m. Unfortunately, this borehole was poorly cored and the drillcores are not longer available. Therefore, in the present paper the original and traditional name of this formation has been maintained in accordance with the standard scheme of the Cambrian in the East European Craton (Mens *et al*., 1990).

The total lack of fossils in the Żarnowiec Fm. gave rise to different opinions about the age of this formation. Many of them based on results of petrographical investigations, performed in order to search for analogies in Eocambrian deposits from other areas of the East European Craton. Analysing the possibility that the Żarnowiec Fm. is an equivalent of the Jotnian (Riphean) rocks, Juskowiakowa (1976) rejected such suggestions. On the basis of petrographical investigations and K–Ar datings, Łydka (1980) and Łydka *et al*. (1984) correlated the Żarnowiec Fm. deposits from the stratotype section of the Żarnowiec IG 1 borehole with the Vendian Sławatycze (Volhyn) and Lublin Series from southwestern Poland (cf. Areń, Lendzion, 1978). According to those authors the lower parts of the Żarnowiec Fm. from the Darżlubie IG 1, Kościerzyna IG 1 and Słupsk IG 1 boreholes are equivalent to the Jotnian rocks, whereas the upper parts are Vendian in age. This striking conclusion of Łydka (1980) and Łydka *et al.* (1984) will be discussed below. Łydka and co-authors (Łydka, 1975, 1976; Łydka *et al*., 1980) also performed detailed studies devoted to epigenetic alterations of clay minerals. The studies showed that illites from the basal strata of the Żarnowiec Fm. from the western part of the Peribaltic Syneclise are characterized by a markedly increased crystallinity ratio caused by processes which proceeded under anchimetamorphic conditions. The same author (Łydka, 1980), described thin beds of fine-grained rocks, containing pyroclastic material, from Vendian deposits of the Słupsk IG 1, Kościerzyna IG 1 and Darżlubie IG 1 boreholes. A brief information on petrography of the Żarnowiec Fm. from the Olsztyn IG 2 borehole is given in the geological documentation of this borehole (Rydzewska, 1977).

Many authors have emphasized a distinct lithological similarity of the Żarnowiec Fm. to the Lower Cambrian Nexo sandstones of Bornholm. This fact disposed Lendzion (1976b) to a suggestion that the entire formation should be included into the Cambrian. However, the Lendzion's final statements were that the Żarnowiec Fm. and its equivalents are Vendian–Lower Cambrian in age (Lendzion, 1976a, 1982, 1983a, b; Areń, Lendzion, 1978; Mens *et al*., 1990).

Sedimentary conditions of the Żarnowiec Fm. were discussed in some other papers (Jaworowski, 1979, 1982, 1997). According to the opinions expressed therein, the formation occurs beneath Lower Cambrian transgressive marine deposits and it represents a continental series deposited in the environment of alluvial fans under a hot and semi-arid climate.

Determination of the base of the formation is obviously no problem. More problems appear when defining the top of the formation because it passes upwards very gradually into Lower Cambrian marine deposits. The particular significance for determination of the top of the Żarnowiec Fm. had the discovery of transitional deposits between this formation and the Lower Cambrian marine deposits (Jaworowski, 1982, 1986). The transitional deposits were considered to represent a continental-marine environment of alluvial fans prograding into a transgressing sea.

In the present paper the top boundary of the Żarnowiec Fm., according to the formerly proposed approach (Jaworowski, 1979) and first of all for practical reasons, is assumed to be coincident with the basal boundary of deposits with the first appearance of bioturbation structures in each of the cored intervals (Figs. 1, 34–41). Bioturbation structures undoubtedly indicate the influence of Cambrian marine environment.

It means that in this paper the Żarnowiec Fm. is considered to be represented exclusively by continental deposits. The overlying transitional continental-marine deposits are hereafter called the transitional complex. Deposits of this complex at first glance are almost identical with those of the Żarnowiec Fm., however they differ primarily in the presence of bioturbation structures, distinct contribution of finer-grained sandstones and more frequent grey and grey-greenish colours. It should be reminded that Areń (1988) defined a distinct bipartition within the deposits underlying undoubtedly marine Lower Cambrian sediments in northern Poland. The informal Pomeranian beds, distinguished by that author, can be approximately considered an equivalent of the continental deposits, i.e. of the Żarnowiec Fm. while the Kaszuby beds can be an equivalent of the transitional continental-marine complex.

Furthermore, the transitional complex can be correlated with the lower part of the Kluki Fm. distinguished by Bednarczyk and Turnau-Morawska (1975, cf. Mens *et al*., 1990). The Kluki Fm. contains fauna of *Mobergella* and fragments of hyolites and acritarchs. On the basis of these fossils the Żarnowiec Fm. deposits were considered to be older than the *Mobergella* Zone, and correlated with the uppermost Vendian and Lower Cambrian *Sabellidites* and *Platysolenites* Zones (Lendzion, 1983a, b; Mens *et al*., 1990). In the stratotype section of the Żarnowiec Fm. the top boundary of the formation, which, according to the criterion adopted in this paper, is drawn in the Żarnowiec IG 1 borehole just beneath the first appearance of bioturbation structures at a depth of approximately 3200 m (Tab. 1, Fig. 36), coincides with the basal

Table 1

**Depth and thickness (in metres) of the Żarnowiec Fm. and transitional complex deposits in studied boreholes**

| Borehole | Bottom of the Żarnowiec Fm. | Top of the Żarnowiec Fm. | Thickness of the Żarnowiec Fm. (percentage of cored intervals) | Top of transitional complex deposits | Thickness of transitional complex deposits (percentage of cored intervals) |
|---|---|---|---|---|---|
| Darżlubie IG 1 | 3509.8 | 3491.0 | 18.8 (84.2%) | 3474.5 | 16.5 (45.5%) |
| Gdańsk IG 1 | 3486.9 | 3470.0 | 16.9 (11.8%) | 3465.0 | 5.0 (0%) |
| Hel IG 1 | 3484.5 | 3480.5 | 4.0 (100%) | 3468.3 | 12.2 (100%) |
| Kościerzyna IG 1 | 5143.8 | 5030.5 | 113.3 (88.4%) | 5018.4 | 12.1 (100%) |
| Łeba 8 | 3332.5 | 3212.5 | 120.0 (35.1%) | 3186.5 | 26.0 (54.0%) |
| Malbork IG 1 | 3662.7 | 3640.5 | 22.2 (100%) | 3617.7 | 22.8 (100%) |
| Olsztyn IG 2 | 2748.2 | 2719.0 | 29.2 (100%) | 2694.0 | 25.0 (100%) |
| Smołdzino 1 | 3418.5 | 3292.5 | 126.0 (19.3%) | 3260.5 | 32.0 (1.0%) |
| Słupsk IG 1 | 5078.0 | 4891.5 | 186.5 (94.1%) | 4852.5 | 39.0 (100%) |
| Żarnowiec IG 1 | 3236.5 | 3200.0 | 36.5 (94.5%) | 3186.5 | 13.5 (82.2%) |
| A 8 | 2272.0 | 2183.0 | 99.0 (0%) | 2173.0 | 10.0 (0%) |
| A 23 | 1777.0 | 1680.0 | 97.0 (0%) | 1670.0 | 10.0 (0%) |
| B 2 | 2907.0 | 2875.5 | 31.5 (0%) | 2870.0 | 5.5 (0%) |
| B 3 | 1733.6 | 1705.5 | 28.1 (0%) | 1692.0 | 13.5 (0%) |
| B 4 | 1453.5 | 1413.0 | 40.5 (0%) | 1393.0 | 20.0 (0%) |
| B 7 | 2681.5 | 2654.5 | 27.0 (0%) | 2646.5 | 8.0 (0%) |
| B 8 | 2501.0 | 2475.0 | 26.0 (0%) | 2468.0 | 7.0 (0%) |
| B 16 | 2408.5 | 2311.5 | 97.0 (0%) | 2291.5 | 20.0 (0%) |
| B 21 | 2241.0 | 2194.0 | 47.0 (0%) | 2173.5 | 20.5 (0%) |

boundary of deposits containing, upper in the section, fragments of *Mobergella* sp. and *Mobergella* cf. *holsti* (Mob.) (Lendzion, 1976a).

However, there are no reasons to preclude the suggestion that the Żarnowiec Fm. can reach in places at least up into the lower part of the *Mobergella* Zone, and that locally it is exclusively Lower Cambrian in age.

According to the previous opinions (Jaworowski, 1979, 1982), not confirmed by detailed studies, the whole of clastic material of the Żarnowiec Fm. was transported from NE towards SW. According to this interpretation during deposition of the Żarnowiec Fm., a number of vast alluvial fans stretched along the margin of the East European Craton. They formed a long clastic wedge stretching approximately from NW towards SE. The Pomeranian alluvial fan was recognized in northern Poland, and suggestions arose that to the north there is also the Baltic fan, and to the southeast — the Ciechanów fan (Jaworowski, 1979). In such a case, clastics could have been transported in a general direction NE→SW. However, a suggestion has recently been advanced that part of deposits from the Upper Vendian–Lower Cambrian transition of northern Poland was derived from the opposite direction, i.e. SW→NE (Jaworowski, 1997). This suggestion has been accompanied with a presumption that these deposits originated from erosion of horsts uplifted within the supposed rift that existed during the Vendian and earliest Cambrian in the area located southwestern of TTZ.

The results of computer modelling of subsidence, based on thicknesses of the entire Lower Palaeozoic of northern Poland (Poprawa *et al.*, 1999), suggest that the Żarnowiec Fm., as the oldest element of the cratonic sedimentary cover, is an echo of the first phases of the breaking up of the Precambrian supercontinent.

# PETROGRAPHICAL AND GEOCHEMICAL ANALYSIS

## RESEARCH METHODS

Petrographical and mineralogical studies were performed at the Petrology Department of the Polish Geological Institute. Geochemical analyses were made at the Activation Laboratories Ltd. — Actlabs (Canada) through the office of "Geoanaliza".

Staining technique was used on uncovered thin sections in order to identify various carbonate phases. Alizarin Red-S and Evamy's Solution were used as stains (Migaszewski, Narkiewicz, 1983).

### STUDIES IN THE POLARIZING MICROSCOPE AND CATHODOLUMINESCENCE (CL)

140 thin sections were analysed, and quantitative studies of mineral composition of rocks were performed using the Swift Model F automated point-counting device. 300–400 point-counting determinations were made for each thin section using the Gazzi–Dickinson method. This method allows to reduce the effect of grain size and diagenetic alterations on results of modal point counts, and thus to make more accurate interpretations of the provenance of clastic material on the discrimination diagram given by Dickinson (1985). This diagram is a triangle with corners defined as follows: $Q_t$ — mono- and polycrystalline quartz, F — feldspars, L — fragments of unstable aphanitic rocks. Inside the diagram are areas, corresponding to different geotectonic regions, on which projected points of the studied rocks are being marked.

Microscopic studies of quartz types were performed on thin sections, taking into account criteria such as the mono- and polycrystallinity of grains and type of extinction — undulose or non-undulose extinction. In each thin section, 100 grains were analysed to identify these features, qualifying the grains into the appropriate quartz type. Interpretation of results of these analyses was made using the diamond diagrams of Basu *et al.* (1975).

Heavy minerals were separated from sand-grade fraction using bromoform. Part of the heavy fraction was used to prepare powder preparations for microscopic studies. From the other part, zircon grains were selected for CL investigations.

Cathodoluminescence investigations were performed on thin sections and powder preparations (uncovered and polished surfaces) using the CCL 8200 mk3 device linked with the Optiphot 2 polarizing microscope. For these studies the voltage was 11–12 kV and the electron beam intensity was 800–900 uA. Microphotographs were taken on 1600 ISO Fuji films.

The CL analysis was used for determination of the original textural features of rocks and the provenance of quartz, as well as to identify diagenetic processes and diversity within zircon grains, based on the observed luminescence.

### STUDIES IN THE SCANNING ELECTRON MICROSCOPE (SEM) WITH THE ENERGY DISPERSIVE SPECTROMETER (EDS) AND CATHODOLUMINESCENCE (sCL)

Electron microscopy was employed to study morphology of grains and diagenetic minerals. The investigations were performed on rock fragments coated with gold and on uncovered carbon-coated thin sections. Chemical composition analyses were made using the energy dispersive spectrometer in order to identify mineral phases. All these investigations were performed on the JSM-35 JEOL microscope and the Oxford Instruments energy dispersive spectrometer (Link system — ISIS).

For studies of quartz cement and zircon, scanning cathodoluminescence was used, revealing the presence of very subtle structures, invisible on CL images. Photomicrographs were taken using the LEO electron microscope (type 1430) with a digital image record.

### MICROTHERMOMETRIC ANALYSIS

In order to determine the temperature of crystallization of quartz cement, studies of fluid inclusions were performed on thin sections (polished on both sides) using the Fluid Inc. System device linked with the Leitz–Orthoplan optical microscope.

### CHEMICAL ANALYSES

18 sandstone samples from the Żarnowiec IG 1, Słupsk IG 1 and Olsztyn IG 2 boreholes were selected for chemical analyses, performed with the use of the ICP method in order to identify the content of main chemical elements and Co, Th, Sc, La, Zr, Y, Sr, Ba. The results were used for interpretation of geotectonic environments on diagrams given by Bhatia (1983) and Bhatia and Crook (1986).

## PETROGRAPHIC CHARACTERISTICS

The investigations concerned with the entire Żarnowiec Fm. (continental deposits) and partly transitional complex (continental-marine deposits). When the project started it was impossible to distinguish between these two complexes which are almost identical petrographically. It is therefore the results of the detailed sedimentological analysis, presented in this paper, that allow precise identification of the top of the Żarnowiec Fm. and the boundaries of the transitional complex.

The Żarnowiec Fm. deposits are represented mainly by sandstones characterized by both: various colours (from grey through creamy to red-brownish) and variable grain size. Drill-core samples revealed the presence of numerous psephitic grains which locally form conglomerates. Sandstones contain thin grey and grey-green mud-clay interbeds.

Detailed petrographical analyses were focused mainly on sandstones since interpretational methods used in this project refer exactly to this rock type.

The sandstones are represented by dominant quartz and arkosic wackes, with subordinate arkoses and quartz arenites.

### TEXTURAL FEATURES

Microscopic observations reveal that the rocks are mostly medium- and coarse-grained with admixture of gravel-sized material, and subordinate fine-grained material. The coarsest deposits are dominant at bottom portions of the investigated sections. Sandstones are largely massive and compact (Kościerzyna IG 1, Słupsk IG 1, Malbork IG 1 and Hel IG 1 boreholes), more rarely porous and less compact (Olsztyn IG 2, partly Żarnowiec IG 1 and Darżlubie IG 1 boreholes). Sorting and roundness of clastic material is most often poor, decreasing at basal parts of the sections. Grain packing is highly variable due to variations in the clay cement content. If the clay cement content is high (>20%) grains are loosely packed and point intergranular contacts predominate (Fig. 2a). In the case where quartz cement is dominant (some of samples from the Żarnowiec IG 1 and Malbork IG 1 boreholes) cathodoluminescence observations also reveal fairly loose grain packing as well as point and long intergranular contacts (Fig. 2b). Concavo-convex and sutured intergranular contacts which, in some cases (Żarnowiec IG 1 and Darżlubie IG 1 boreholes), can be a dominant type of contacts, are observed in many samples (Fig. 2c).

All these observations indicate a moderate effect of mechanical compaction. It resulted probably from a large amount of primary clay matrix of the rocks, which, in spite of the increasing overburden pressure, has not allowed for close contacts between the grains. In places where clay cement was scarce, concavo-convex and sutured contacts were formed.

Point counting of thin sections showed the occurrence of empty pores. For samples impregnated with blue epoxy resin, the examinations were repeated (Tab. 2). These investigations indicate that empty pore spaces occur only in some of the sections: they are most frequent in the Olsztyn IG 2 borehole (0.6–4.0%). No empty pores have been observed in the Kościerzyna IG 1 and Słupsk IG 1 boreholes. In the remaining boreholes only some of samples reveal their presence. In most cases the rocks display intragranular (Fig. 2d) and moldic (Fig. 2e) secondary porosity. Blue epoxy resin-impregnated thin sections additionally reveal common and very distinct microporosity in clay cement between flakes minerals (Fig. 2f). Primary microporosity also occurs in places where authigenic quartz has not completely filled the intergranular space, that is visible in electron microscope images (Fig. 4a).

### MINERAL COMPOSITION

#### Grain framework

The grain framework of the studied rocks is composed mostly of quartz grains (Tab. 2). Monocrystalline quartz is dominant (with high percentage of grains showing undulose extinction). The amount of polycrystalline quartz varies accounting for from 12.2% (Hel IG 1 borehole) to 39.4% (Olsztyn IG 2 borehole) of all quartz grains on the average. Strongly tectonically deformed quartz grains (Fig. 3a) with non-typical nonuniform plumose extinction (Słupsk IG 1 and Kościerzyna IG 1 boreholes), and cataclased grains (Olsztyn IG 2 and Malbork IG 1 boreholes) are also observed. Feldspars occur in minor proportions (Tab. 2), with the average percentage considerably varying in different boreholes from trace amounts (Darżlubie IG 1 and Żarnowiec IG 1 boreholes) to 17.8% (Olsztyn IG 2 borehole). The maximum content of feldspars was recorded in the Olsztyn IG 2 (34.0%) and Słupsk IG 1 (31.6%) boreholes. Feldspars are represented by potassium feldspars, although the original occurrence of plagioclases cannot be precluded. The most common is microcline, with characteristic cross-hatched twinnings, and single micropertite grains. Most of the feldspar grains show dense cleavage. Feldspars grains are variably altered, ranging from fresh grains to completely altered ones. Many grains bear traces of dissolution that is particularly well visible in scanning microscope images (Fig. 4b–d). It is noteworthy that no authigenic feldspar overgrowths have been observed on detrital grains, though this phenomenon is fairly common in Cambrian sandstones (Sikorska, 1998).

The total amount of feldspars includes pseudomorphs identified either in CL images or on the basis of the grain shape which indicates their post-feldspar origin. As a result the original percentage of feldspars in the rock may be slightly underestimated.

Rock fragments are a subordinate component of the grain framework (Tab. 2).

It should be born in mind that the point counting, performed with the use of the Gazzi–Dickinson technique, results in an underestimation of the content of rock fragments since some of the fragments have been numbered among mineral compo-

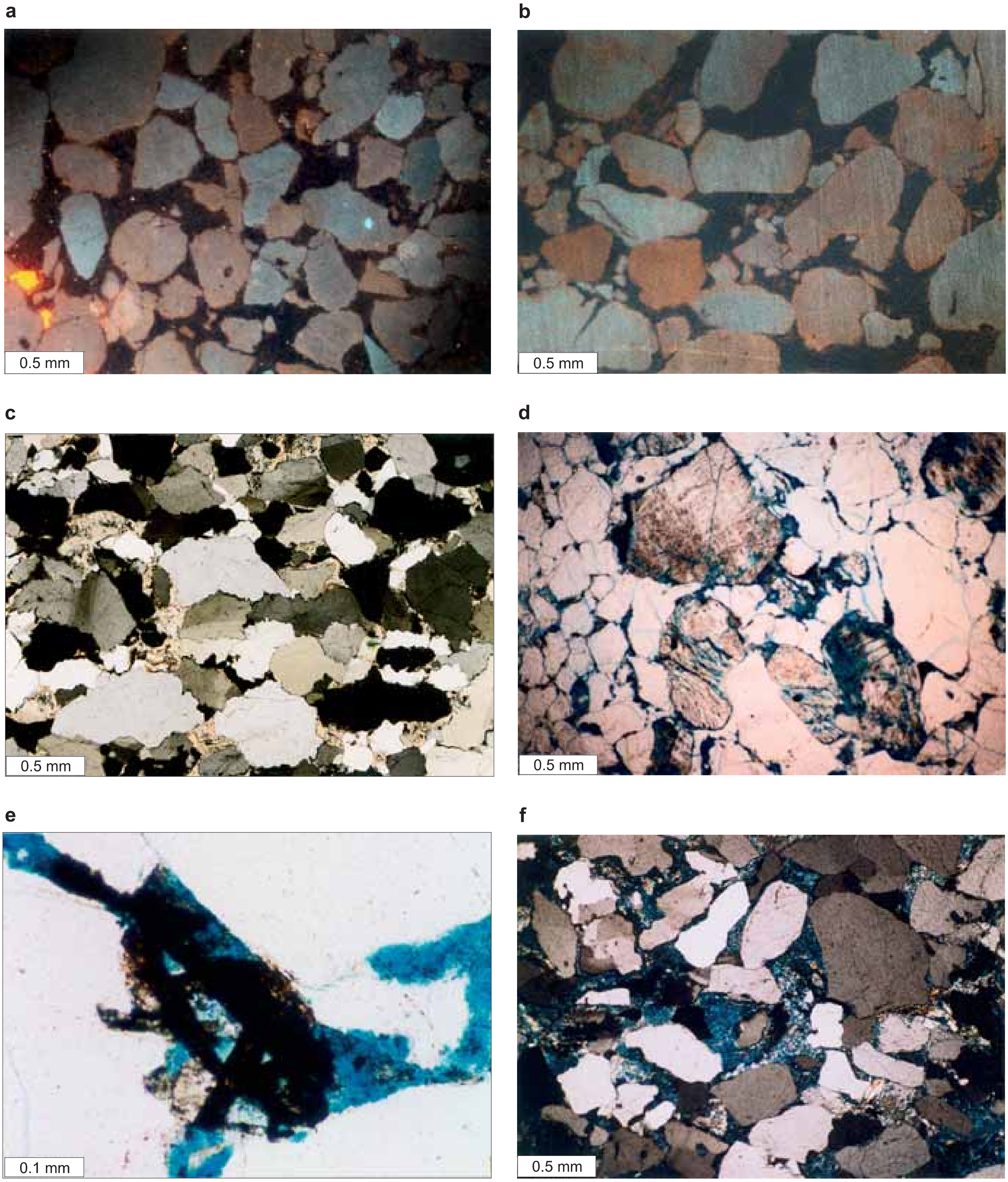



**Fig. 2. a** — loosely packed grains in a sandstone with clay matrix; point intergranular contacts are dominant; CL; Darżlubie IG 1 borehole, depth 3509.5 m; **b** — loosely packed grains in a sandstone cemented with quartz; point and long intergranular contacts; CL; Malbork IG 1 borehole, depth 3636.3 m; **c** — sutured intergranular contacts resulting from chemical compaction; TrL, crossed polars; Żarnowiec IG 1 borehole, depth 3219.1 m; **d** — partly dissolved feldspar grains in a sandstone — intragranular secondary porosity; TrL, plane-polarized light; thin section impregnated with blue epoxy resin; Hel IG 1 borehole, depth 3484.1 m; **e** — concentration of anatase formed through alteration of an ilmenite grain — moldic porosity; TrL, plane-polarized light; thin section impregnated with blue epoxy resin; Darżlubie IG 1 borehole, depth 3500.4 m; **f** — intercrystalline microporosity between small flakes of clay minerals; TrL, crossed polars; thin section impregnated with blue epoxy resin; Kościerzyna IG 1 borehole, depth 5056.2 m

**Table 2**

**Composition of rocks determined from point counting in thin sections (vol. %)**

| Sample number | Depth (m) | Qm | Qp | L | K | P | Pseudo-morphs after fds. | Mica | Accesso-ry mine-rals | Opaque minerals | Clay matrix | Chlorite | Barite | Carbonates | Pores |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Darżlubie IG 1 | | | | | | | | | | | | | | | |
| 1 | 3495.0 | 84.7 | 0 | 0 | 6.0 | 0 | 0 | 0.4 | 0 | 1.0 | 2.0 | 0 | 0.3 | 0 | 5.6 |
| 2 | 3498.0 | 66.6 | 0 | 0 | 3.3 | + | 1.0 | 8.6 | 0.3 | 0.6 | 18.0 | 1.6 | 0 | 0 | 0 |
| 3 | 3499.0 | 72.0 | 0 | 0 | 0 | 0 | 3.2 | 2.0 | 0.6 | 4.3 | 16.3 | 0.6 | 0 | 0 | 1.0 |
| 4 | 3500.4 | 80.3 | 0 | + | 0 | 0 | 0 | 0.6 | 0.5 | + | 16.9 | + | 0 | 0 | 2.7 |
| 5 | 3502.9 | 49.5 | 0 | 0 | 0 | 0 | 0 | 12.6 | 1.0 | 1.0 | 35.6 | 0.3 | 0 | 0 | 0 |
| 6 | 3504.0 | 83.8 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.3 | 0.3 | 11.7 | 0 | 0 | 0 | 3.6 |
| 7 | 3506.5 | 80.0 | 0 | 0.3 | 0 | 0 | 0 | 0.6 | + | 0.3 | 14.8 | 0 | 0 | 0 | 4.0 |
| 8 | 3507.9 | 71.7 | 0 | 0.3 | 0 | 0 | + | 0.9 | + | 0.6 | 24.9 | 0 | 0 | 0 | 1.6 |
| 9 | 3509.5 | 71.3 | 0 | + | 0 | 0 | 0.3 | 2.3 | + | 0.3 | 23.8 | 0 | 0 | 1.0 | 1.0 |
| Gdańsk IG 1 | | | | | | | | | | | | | | | |
| 1 | 3485 | 64.9 | 0 | 1.9 | 0 | 0 | 2.7 | 0.7 | 0 | 5.4 | 23.6** | 0 | 0 | 0 | 0.8 |
| 2 | 3486 | 56.6+23.5* | 0 | 0.6 | 0 | 0 | 3.3 | 0 | 0 | 0.3 | 13.6 | 0 | 0.9 | 0 | 1.2 |
| Hel IG 1 | | | | | | | | | | | | | | | |
| 1 | 3470.3 | 85.9 | 0 | 0 | 8.6 | 0 | + | 0.3 | 0.3 | + | 3.0 | 0 | 0 | 0.3 | 1.6 |
| 2 | 3475.0 | 89.6 | 0 | 0 | 3.3 | 0 | 0.3 | 0.3 | 0.3 | + | 3.3 | 0 | 0 | 1.3 | 2 |
| 3 | 3480.1 | 88.1 | 0 | + | 4.3 | 0 | + | 0 | 0.3 | + | 5.0 | 0 | 0 | + | 2.3 |
| 4 | 3481.1 | 73.0 | 0 | 0.3 | 7.3 | 0 | 1.3 | + | 0.3 | + | 17.2 | + | 0 | 0.3 | 0.3 |
| 5 | 3482.2 | 78.2 | 0 | 0 | 10.0 | 0 | 0.3 | 0.6 | 0.3 | 0 | 10.3 | 0 | 0 | + | 0 |
| 6 | 3484.1 | 76.9 | 0 | 0 | 13.0 | 0 | 0.6 | 0.3 | + | 0.3 | 3.6 | 0 | 0 | 4.0 | 1.3 |
| Kościerzyna IG 1 | | | | | | | | | | | | | | | |
| 1/14 | 5024.9 | 60.6+6.8* | 0.6 | 0 | 9.8 | 0 | 6.8 | 0.0 | 1.9 | 0 | 12.7 | + | 0 | 0.8 | 0 |
| 2/2 | 5026.5 | 68.6 | 0 | 0 | 9.1 | 0 | 6.3 | 1.0 | 0.3 | 1.1 | 13.6 | + | 0 | 0 | 0 |
| 3/3 | 5029.0 | 77.8 | 0 | 0 | 0 | 0 | 2.9 | 0.3 | 0 | 0.3 | 18.1 | 0.3 | 0 | 0.3 | 0 |
| 4/4 | 5031.3 | 54.3 | 0 | 0 | 3.1 | 0 | 8.3 | 6.3 | 0.6 | 2.1 | 24.3 | 1.0 | 0 | 0 | 0 |
| 5/5 | 5034.4 | 62.3 | 0 | 0 | 1.1 | 0 | 18.3 | 1.1 | 0.9 | 5.9 | 8.3** | 2.1 | 0 | 0 | 0 |
| 6/6 | 5037.4 | 58.2 | 0 | 0.3 | 0.6 | 0 | 19.9 | 3.9 | 0.3 | 1.9 | 13.3** | 1.6 | 0 | 0 | 0 |
| 7/7 | 5040.7 | 55.7 | 0 | 0.6 | 0 | 0 | 21.6 | 8.8 | + | 0.6 | 11.8** | 0.9 | 0 | 0 | 0 |
| 8/8 | 5043.8 | 62.4 | + | 0.3 | 0 | 0 | 19.5 | 0.6 | 0.3 | 4.9 | 11.6** | 0.4 | 0 | 0 | 0 |
| 9/15 | 5045.2 | 54.1+5.4* | 0.4 | 0.4 | 1.4 | 0 | 13.8 | 0.4 | 1.4 | 7.9 | 14.3** | 0.5 | 0 | 0 | 0 |
| 10/10 | 5049.6 | 43.3 | 0 | 0.3 | 0.0 | 0 | 16.3 | 22.3 | + | 3.3 | 12.2 | 2.3 | 0 | 0 | 0 |
| 11/11 | 5053.3 | 48.6 | + | 0.3 | 0.3 | 0 | 0.6 | 22.1 | 0.6 | 2.1 | 24.1 | 1.3 | 0 | 0 | 0 |
| 12/12 | 5056.2 | 66.6 | 0 | 0 | 0 | 0 | 3.1 | 3.1 | + | 3.1 | 23.5** | 0 | 0 | 0 | 0.6 |
| 13/13 | 5058.4 | 76.1 | + | 0 | 0 | 0 | 0 | 3.1 | + | 6.6 | 14.2 | 0.3 | 0 | 0 | 0 |
| 14/14 | 5061.4 | 53.8 | 0 | 0 | 0 | 0 | 0 | 8.9 | 0.8 | 1.7 | 35.6 | 0.5 | 0 | 0 | 0 |
| 15/16 | 5064.0 | 76.7 | 0.8 | 0 | 0 | 0 | 4.3 | 1.4 | + | 0 | 16.0 | + | 0 | 0 | 0 |
| 16/23 | 5067.8 | 70.2 | 0.3 | 0 | 0 | 0 | 6.3 | 1.3 | 0.3 | 1.6 | 20.3** | + | 0 | 0 | 0 |
| 17/24 | 5070.7 | 79.8 | 0 | 0 | 0 | 0 | 1.2 | 0.8 | + | 1.6 | 16.6** | 0 | 0 | 0 | 0 |
| 19/27a | 5076.6 | 69.4 | 0 | + | 0 | 0 | 4.3 | 2.3 | 0.3 | 4.1 | 19.6** | 0 | 0 | 0 | 0 |
| 20/28a | 5080.9 | 71.2 | 0.3 | 0 | 0 | 0 | 2.3 | 5.6 | 0 | 0.3 | 20.3** | 0 | 0 | 0 | 0 |
| 21/29a | 5084.7 | 78.2 | 0 | 0 | 0 | 0 | 3.3 | 3.6 | + | 1.6 | 13.3** | 0 | 0 | 0 | 0 |
| 22/17 | 5088.0 | 67.3 | 0.4 | 0.4 | 0 | 0 | 3.3 | 4.3 | + | 0.9 | 22.5 | 0.9 | 0 | 0 | 0 |
| 23/32c | 5092.4 | 81.1 | 0 | 0 | 0 | 0 | 1.3 | 1.3 | 0 | 1.1 | 14.6 | 0.6 | 0 | 0 | 0 |
| 24/19 | 5097.6 | 36.6 | 0 | 0 | 0 | 0 | 0.3 | 35.3 | 0.6 | 1.3 | 25.9 | 0 | 0 | 0 | 0 |
| 25/35a | 5101.0 | 67.2 | 0 | 0.3 | 0 | 0 | 4.3 | 1.3 | 0.3 | 9.3 | 17.3** | 0 | 0 | 0 | 0 |
| 26/37 | 5105.8 | 65.3 | 0 | 0.3 | 0 | 0 | 0 | 13.6 | 0.3 | 1.3 | 19.2** | 0 | 0 | 0 | 0 |

| Sample number | Depth (m) | Qm | Qp | L | K | P | Pseudo-morphs after fds. | Mica | Accesso-ry mine-rals | Opaque minerals | Clay matrix | Chlorite | Barite | Carbonates | Pores |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27/18 | 5111.9 | 59.9 | 0 | 0 | 0 | 0 | 0 | 14.6 | 0.6 | 7.6 | 16.2 | 0 | 1.1 | 0 | 0 |
| 28/39b | 5112.8 | 68.7 | 0.4 | 0.4 | 0.9 | 0 | 0.4 | 2.9 | + | 7.4 | 18.9 | + | 0 | 0 | 0 |
| 29/40 | 5121.9 | 49.6 | 0 | 0.6 | 0.3 | 0 | 6.6 | 11.1 | 0.3 | 5.1 | 24.3** | 2.1 | 0 | 0 | 0 |
| 30/21 | 5125.7 | 50.3 | 0 | 0.6 | 0 | 0 | 1.6 | 22.3 | + | 2.3 | 22.6** | 0 | 0.3 | 0 | 0 |
| 31/42b | 5131.9 | 42.2 | 0.3 | 0.3 | 0 | 0 | 1.3 | 4.6 | 1.1 | 23.3 | 26.6 | 0.3 | 0 | 0 | 0 |
| 32/44 | 5135.5 | 65.2 | 0 | 0 | 0 | 0 | 0 | 4.7 | 1.0 | 0.7 | 28.4 | 0 | 0 | 0 | 0 |
| 33/22 | 5138.0 | 63.1 | 0 | 0.3 | 0 | 0 | 0 | 5.3 | 1.0 | 2.3 | 28.0 | 0 | 0 | 0 | 0 |
| 34/49a | 5140.8 | 66.6 | 0 | 2.1 | 0 | 0 | 0 | 8.3 | 0.6 | 3.6 | 14.6 | 4.2 | 0 | 0 | 0 |
| 35/53 | 5143.8 | 53.8 | 0.4 | 1.9 | 0 | 0 | 1.5 | 6.4 | 0.9 | 9.0 | 23.7 | 2.4 | 0 | 0 | 0 |
| Malbork IG 1 | | | | | | | | | | | | | | | |
| 1 | 3628.6 | 92.3 | 0 | 0 | 0 | 0 | 0.3 | 0.3 | 0.3 | + | 3.6 | 0 | 0 | 0.2 | 3.0 |
| 2 | 3630.8 | 80.6 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0.2 | 0 | 12.6 | 0 | 0 | 0 | 6.3 |
| 3 | 3633.0 | 78.6 | 0 | 0 | 0 | 0 | 0 | 0 | 4.6 | 0.2 | 15.0 | 0 | 0 | 0 | 1.6 |
| 4 | 3634.2 | 73.9 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.3 | 14.6 | 10.2 | 0 | 0 | 0 | 1.0 |
| 5 | 3636.3 | 88.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | + | 10.2 | 0 | 0 | 0 | 1.4 |
| 6 | 3638.8 | 77.6 | 0 | 0 | 0 | 0 | 0.3 | 0 | 1.3 | 2.0 | 18.3*** | 0 | 0 | 0.3 | 0.5 |
| 7 | 3641.2 | 76.0 | 0.3 | + | 0 | 0 | 0 | 0 | 0.2 | 3.3 | 18.6 | 0 | 0 | 0 | 1.6 |
| 8 | 3643.4 | 46.4 | + | 0 | 0 | 0 | 0 | 4.0 | 0.6 | 3.0 | 46.0 | 0 | 0 | 0 | 0 |
| 9 | 3646.3 | 62.6 | 0.3 | 0 | 0 | 0 | 7.6 | + | 0.3 | 0.3 | 27.3 | 0.6 | 0 | 0 | 1.0 |
| 10 | 3648.1 | 68.9 | 0.3 | 0 | 0 | 0 | 3.9 | 0.3 | 0.6 | 1.6 | 23.5*** | 0 | 0 | 0 | 0.9 |
| 11 | 3650.1 | 69.6 | 0.6 | 0 | 0 | 0 | 6.6 | 0.3 | 0.3 | 0.6 | 21.6 | 0 | 0 | 0 | 0 |
| 12 | 3653.9 | 43.3 | 0 | 0 | 0 | 0 | 14.2 | 3.3 | 0.9 | 0.9 | 37.4 | 0 | 0 | 0 | 0 |
| 13 | 3655.2 | 34.3 | 0 | 0 | 0 | 0 | 1.0 | 6.0+8.3* | 0.6 | 9.7 | 39.0 | 1.0 | 0 | 0 | 0 |
| 14 | 3656.4 | 45.6 | 0 | 1.0 | 0 | 0 | 0 | 4.3 | 0.3 | 7.6 | 40.6 | 0.6 | 0 | 0 | 0 |
| 15 | 3658.1 | 54.0 | 0 | 0.3 | 0 | 0 | 3.0 | 3.0+3.6* | + | 16.6 | 19.3 | 0 | 0 | 0 | 0 |
| 16 | 3660.2 | 67.6 | 0 | 0.6 | 0 | 0 | 5.3 | 1.0 | 0.3 | 8.3 | 15.0 | 0.3 | 0 | 0 | 1.3 |
| 18 | 3662.5 | 30.4 | 0 | 10.9 | 0 | 0 | 14.9 | 20.8 | 0.2 | 5.8 | 17.0 | 0 | 0 | 0 | 0 |
| Olsztyn IG 2 | | | | | | | | | | | | | | | |
| 1/99 | 2700.4 | 87.3 | 0 | 0 | 0 | 0 | 0.3 | 0.2 | 0.3 | 0.3 | 11.0 | 0 | 0 | 0 | 0.6 |
| 2/2 | 2702.0 | clay siltstone | | | | | | | | | | | | | |
| 3/3 | 2704.9 | 67.3 | 0 | 1.6 | 0 | 0 | 0 | 2.0 | 0.4 | 2.0 | 24.3** | 0 | 0 | 0 | 1.6 |
| 4/104 | 2707.1 | 59.1 | 0 | 1.5 | 0 | 0 | 7.4 | 2.3 | 0.3 | 2.3 | 26.3 | + | + | 0 | 0.8 |
| 5/108 | 2708.3 | 59.6 | 1.0 | 2.0 | 6.3 | 0 | 3.3 | 1.3 | 0.3 | 2.6 | 22.8 | 0 | + | + | 0.8 |
| 6/109 | 2709.3 | 56.0 | 0 | 2.0 | 7.6 | 0 | 3.2 | 1.3 | 0.3 | 5.0 | 23.6 | + | + | + | 1.0 |
| 7/110 | 2712.8 | 40.0 | 0 | 0.3 | 5.6 | 0 | 7.2 | 3.0 | 0.6 | 1.3 | 42.0 | + | + | 0 | + |
| 8/114 | 2715.2 | 48.0 | 0 | 2.9 | 12.9 | 0 | 3.8 | 1.2 | + | 3.4 | 26.8 | + | + | + | 1.0 |
| 9/7 | 2716.1 | 49.6 | 0 | 0.3 | 12.0 | 0 | 4.9 | 2.3 | + | 9.6 | 17.8 | 0 | + | 0 | 2 |
| 10/117 | 2719.5 | 57.6 | 0.3 | 1.3 | 12.6 | 0 | 6.0 | 0.3 | 0.3 | 1.6 | 17.2 | + | + | + | 3 |
| 11/119 | 2721.1 | 49.6 | 0 | 0.6 | 17.6 | 0 | 4.2 | 1.6 | 0.3 | 0.6 | 22.4 | + | + | + | 2.6 |
| 12/122 | 2723.2 | 51.6 | 0 | 0 | 12.0 | 0 | 5.2 | 5.0 | 0.6 | 2.3 | 19.5 | + | + | 0 | 3.8 |
| 13/124 | 2725.4 | 47.4 | 0 | 0 | 15.4 | 0 | 1.1 | 0.3 | + | 9.8 | 24.2 | + | + | 0 | 1.8 |
| 14/11 | 2727.8 | 42.4 | 0 | 1.4 | 31.6 | 0 | 3.9 | 1.8 | 2.0 | 4.1 | 9.7 | + | + | 0 | 3.1 |
| 15/127 | 2730.3 | 39.0 | 0 | + | 26.6 | 0 | 2.6 | 2.6 | 0.2 | 6.0 | 23.0 | + | 0 | 0 | + |
| 16/13 | 2733.5 | 43.3 | 0 | 0.6 | 18.0 | 0 | 6.3 | 4.3 | 0.6 | 0.3 | 22.6 | 0 | + | 0 | 4 |
| 17/129 | 2736.3 | 42.7 | 0 | 0.9 | 21.9 | 0 | 1.8 | 4.9 | 0.3 | 1.3 | 22.4 | 0 | + | 0 | 3.8 |
| 18/15 | 2739.1 | 44.1 | 0 | 0 | 25.5 | 0 | 0.9 | 4.6 | 0.3 | 0.4 | 21.0 | 0 | 0 | 0 | 3.2 |
| 19/135 | 2741.4 | 32.0 | 0 | 0 | 18.0 | 0 | 3.1 | 10.6 | + | 0.3 | 35.6 | + | + | 0 | 0.4 |
| 20/137 | 2743.1 | 41.6 | 0 | 0 | 17.6 | 0 | 2.0 | 3.0 | 0.2 | 6.6 | 28.0 | + | 0 | 0 | 1.0 |
| 21/138 | 2746.2 | 49.8 | 0 | 0 | 24.6 | 0 | 3.3 | 1.0 | 0.3 | 6.0 | 14.4 | + | + | 0 | 0.6 |
| 22/18 | 2747.5 | disintegrated granitoid | | | | | | | | | | | | | |

| Sample number | Depth (m) | Qm | Qp | L | K | P | Pseudo-morphs after fds. | Mica | Accesso-ry mine-rals | Opaque minerals | Clay matrix | Chlorite | Barite | Carbonates | Pores |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Słupsk IG 1 | | | | | | | | | | | | | | | |
| 1a | 4898.1 | sandy claystone | | | | | | | | | | | | | |
| 2a | 4913.7 | 46.3 | 0 | 0 | 17.0 | 0 | 0 | 13.2 | 0.5 | + | 22.8 | 0.2 | 0 | 0 | 0 |
| 3a | 4924.7 | 56.2 | 0 | 0 | 16.6 | 0 | + | 3.0 | 2.0 | + | 22.0 | 0.2 | 0 | 0 | 0 |
| 4a | 4932.1 | 78.0 | + | 0 | 4.5 | 0 | 0.3 | 1.5 | 1.3 | + | 13.5 | 0.2 | 0 | 0.7 | 0 |
| 5a | 4946.9 | 79.0 | 0.0 | 0 | 6.1 | 0 | 0.5 | 6.3 | 0.3 | + | 1.0 | 6.8 | 0 | 0 | 0 |
| 6a | 4965.6 | 76.7 | 0 | 0 | 8.3 | 0 | 0.5 | 0.5 | 0.3 | + | 13.2 | + | 0 | 0.5 | 0 |
| 1/1 | 4975.4 | 82.3 | 0 | 0 | 6.3 | 0 | 1.6 | 1.0 | 0.3 | 0.3 | 6.6 | 2.0 | 0 | 0 | 0 |
| 2/8 | 4978.1 | 72.5 | 0.8 | 0 | 7.5 | 0 | 4.2 | 1.6 | 0.3 | 0.4 | 10.2 | 2.5 | 0 | 0 | 0 |
| 3/10 | 4981.1 | 74.6 | 0 | 0 | 4.9 | 0 | 4.9 | 2.1 | 0.2 | 0 | 11.9 | 1.4 | 0 | 0 | 0 |
| 4/12 | 4983.7 | claystone | | | | | | | | | | | | | |
| 5/5 | 4987.9 | ferruginous silty claystone | | | | | | | | | | | | | |
| 6/15 | 4989.6 | 57.3 | 0.3 | 0 | 20.6 | 0 | 1.3 | 5.3 | + | 0.3 | 14.6 | 0.3 | 0 | 0 | 0 |
| 7/17 | 4993.3 | 64.0 | 0.3 | 0 | 20.3 | 0 | 2.6 | 1.6 | + | 0.3 | 10.3 | 0.6 | 0 | 0 | 0 |
| 8/19 | 4996.6 | 58.3 | 0 | 0 | 22.2 | 0 | 3.3 | + | 0.5 | + | 13.8 | 1.6 | 0 | 0 | 0 |
| 9/9 | 4999.3 | 61.0 | 0.3 | 0.3 | 15.0 | 0 | 2.0 | 1.0 | + | 0.3 | 16.1 | 3.0 | 0 | 1 | 0 |
| 10/21 | 5002.7 | 68.3 | 0.3 | 0 | 17.0 | 0 | 1.3 | 0.6 | + | 0.6 | 8.3 | 2.3 | 0 | 1.3 | 0 |
| 11/11 | 5005.3 | 52.6 | 0 | 0.3 | 26.3 | 0 | 5.3 | 1.6 | + | 0.6 | 10.3 | 2.6 | 0 | 0 | 0 |
| 12/24 | 5007.4 | 42.0 | 0 | 0 | 18.7 | 0 | 0.7 | 12.2 | + | 1.7 | 24.1 | 0.3 | 0 | 0 | 0 |
| 13/27 | 5012.7 | 52.9 | 0.6 | 0 | 20.0 | 0 | 1.3 | 2.0 | 1.3 | 0.3 | 21.3 | 0.3 | 0 | 0 | 0 |
| 14/30 | 5015.8 | 59.0 | 0 | 0.0 | 19.5 | 0 | 2.0 | 3.5 | 0.5 | 0.5 | 14.2 | 0.5 | 0 | 0.3 | 0 |
| 15/15 | 5019.0 | 67.3 | 0 | 0 | 16.4 | 0 | 2.3 | 2.6 | + | 0.3 | 9.5 | 1.6 | 0 | 0 | 0 |
| 16/16 | 5022.7 | 18.3 | 0 | 0.3 | 21.6 | 0 | 4.0 | 44.6 | 0.3 | 2.3 | 8.6 | + | 0 | 0 | 0 |
| 17/17 | 5026.0 | 58.4 | 0.3 | + | 23.3 | 0 | 1.9 | 5.1 | + | 0.3 | 9.4 | 1.0 | 0 | 0.3 | 0 |
| 18/33 | 5027.9 | 62.1 | 0.3 | 0 | 16.8 | 0 | 3.9 | 2.3 | 0.2 | 0.6 | 8.9 | 3.6 | 0 | 1.3 | 0 |
| 19/35 | 5033.4 | 52.1 | 0 | 0 | 17.6 | 0 | 0.6 | 6.4 | 0.6 | 5.8 | 16.6 | 0.3 | 0 | 0 | 0 |
| 20/20 | 5036.4 | 74.6 | + | 0 | 0.3 | 0 | 0 | 2.3 | 0 | 1.3 | 20.2 | 0 | 0.3 | 0 | 1.0 |
| 21/37 | 5040.5 | 68.3 | 0 | 0.6 | 0 | 0 | 0 | 2.4 | + | 2.2 | 26.5 | 0 | 0 | 0 | 0 |
| 22/39 | 5044.4 | 49.0 | 0 | 0 | 0 | 0 | 0 | 17.4 | 0.4 | 2.2 | 31.0 | 0 | 0 | 0 | 0 |
| 23/42 | 5048.3 | 48.6 | 0 | 0 | 11.0 | 0 | 3.4 | 7.9 | 0.2 | 1 | 27.9 | 0 | 0 | 0 | 0 |
| 24/43 | 5052.2 | 57.1 | 0 | 0 | 8.5 | + | 2.0 | 4.8 | 0.4 | 2.8 | 24.4 | 0 | 0 | 0 | 0 |
| 25/26 | 5055.0 | 24.0 | 0 | 0 | 19.5 | 0 | 4.6 | 29.0 | 0.3 | 4.6 | 18.0 | 0 | 0 | 0 | 0 |
| 26/47 | 5060.4 | 58.8 | 0.3 | 0.3 | 8.6 | 0 | 2.9 | 3.7 | 0.5 | 1.1 | 23.5 | 0.3 | 0 | 0 | 0 |
| 27/49 | 5062.7 | 52.3 | 0 | 0 | 15.4 | 0 | 12.3 | 1.5 | 0.4 | 0.3 | 17.8 | 0 | 0 | 0 | 0 |
| 28/30 | 5066.0 | 55.3 | 0 | 0 | 15.9 | 0 | 6.3 | 5.6 | + | 1.3 | 15.3 | 0.3 | 0 | 0 | 0 |
| Żarnowiec IG 1 | | | | | | | | | | | | | | | |
| 1/1 | 3201.6 | 77.5 | 0 | 0 | 0 | 0 | 2.3 | 1.3 | 0.3 | + | 17.7 | 0.9 | 0 | 0 | + |
| 2/4 | 3204.0 | 75.0 | 0 | 0.2 | 0 | 0 | 8.6 | 2.9 | + | 0 | 10.4 | 2.9 | 0 | 0 | + |
| 3/8 | 3206.8 | 89.1 | 0 | 0 | 0 | 0 | 0 | 0 | 1.3 | 2.3 | 3.3 | 0 | 0 | 0 | 4.0 |
| 4/4 | 3210.0 | 74.3 | 0 | 0 | 0 | 0 | 0.6 | 1.6 | 0.2 | + | 22.5 | 0 | 0 | 0 | 0.8 |
| 5/12 | 3212.6 | 76.3 | 0 | 0.3 | 0 | 0 | 0 | 2.6 | + | 0.2 | 19.6 | 0 | 0 | 0 | 1.0 |
| 6/15 | 3214.7 | 87.6 | 0 | 0 | 0 | 0 | 0 | 0.3 | + | 0.5 | 10.0 | 0 | 0 | 0 | 1.6 |
| 7/17 | 3216.5 | 81.0 | 0 | 0 | 0 | 0 | 0 | 1 | 0.5 | 5.6 | 9.3 | 0 | 0 | 0 | 2.6 |
| 8/8 | 3219.7 | 57.6 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.2 | + | 41.9** | 0 | 0 | 0 | + |
| 9/23 | 3222.1 | 71.4+17.6* | 0 | 0 | 0 | 0 | 0 | 0 | + | 4.7 | 0.6 | 0 | 3.7 | 0 | 2.0 |
| 10/26 | 3225.2 | 62.0+9.1* | 0 | 0 | 0 | 0 | 0 | 5 | 0.3 | 2.0 | 16.9 | 0 | 4.7 | 0 | 0 |
| 11/12 | 3228.8 | 65.3 | 0 | 0 | 12.6 | 0 | 2.3 | 2.3 | 0.3 | 0.6 | 12.0 | 4.3 | 0 | 0 | 0 |
| 12/31 | 3231.2 | 56.3 | 0 | 0 | 0 | 0 | 0 | 9.9 | 0.2 | 0.6 | + | 0.0 | 33.0 | 0 | 0 |
| 13/33 | 3232.8 | 70.9 | 0 | 0 | 0 | 0 | 0 | 3.6 | 0.3 | 2.6 | 21.6** | 0 | 1.0 | 0 | 0 |
| 14/15 | 3234.5 | 65.3 | 0 | 0.0 | 0 | 0 | 0 | 5.8 | + | 0 | 28.6 | 0 | 0.3 | 0 | 0 |

* quartz overgrowths; ** ferruginous clay matrix; *** clay pseudomorphs after mica

Qm — monocrystalline quartz; Qp — polycrystalline quartz; L — unstable aphanitic rock fragments; K — K-feldspars; P — plagioclases

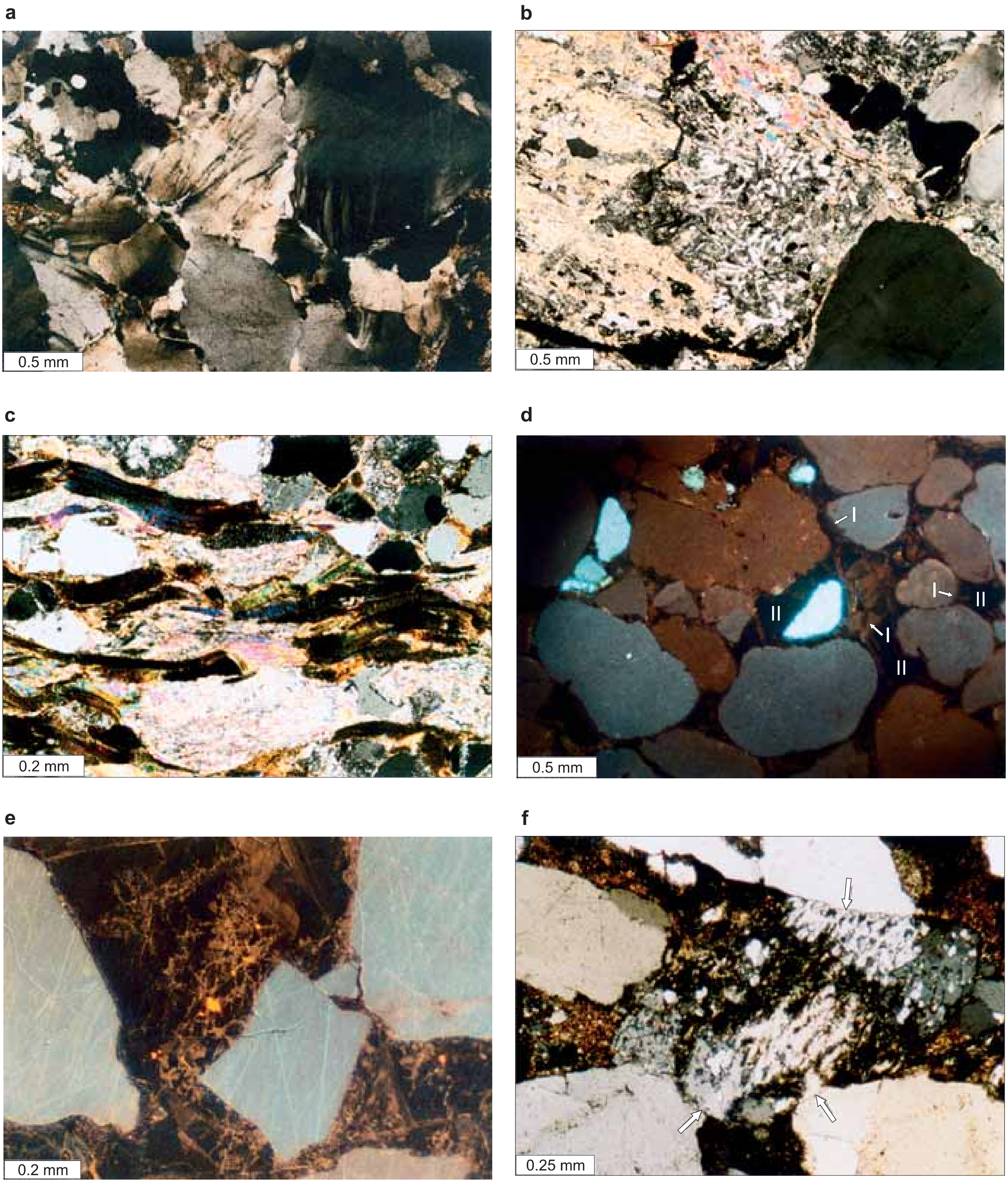



**Fig. 3. a** — strongly deformed quartz grains with nonuniform plumose extinction; TrL, crossed polars; Słupsk IG 1 borehole, depth 5019.0 m; **b** — strongly altered rock fragment with myrmeckite intergrowths in which feldspar was replaced by clay minerals; TrL, crossed polars; Malbork IG 1 borehole, depth 3662.5 m; **c** — micalith – a rock containing large amounts of mica and sericite; TrL, crossed polars; Słupsk IG 1 borehole, depth 5022.7 m; **d** — quartz-cemented sandstone; two generations of cement are visible: I — brown luminescing cement (arrows), II — non-luminescent cement; CL; Hel IG 1 borehole, depth 3480.1 m; **e** — quartz-cemented sandstone; cement with a complex inner structure is visible; CL; Gdańsk IG 1 borehole, depth 3486.0 m; **f** — feldspar grain, being replaced by authigenic quartz forming overgrowths on adjoining grains (arrows); TrL, crossed polars; Kościerzyna IG 1 borehole, depth 5034.4 m

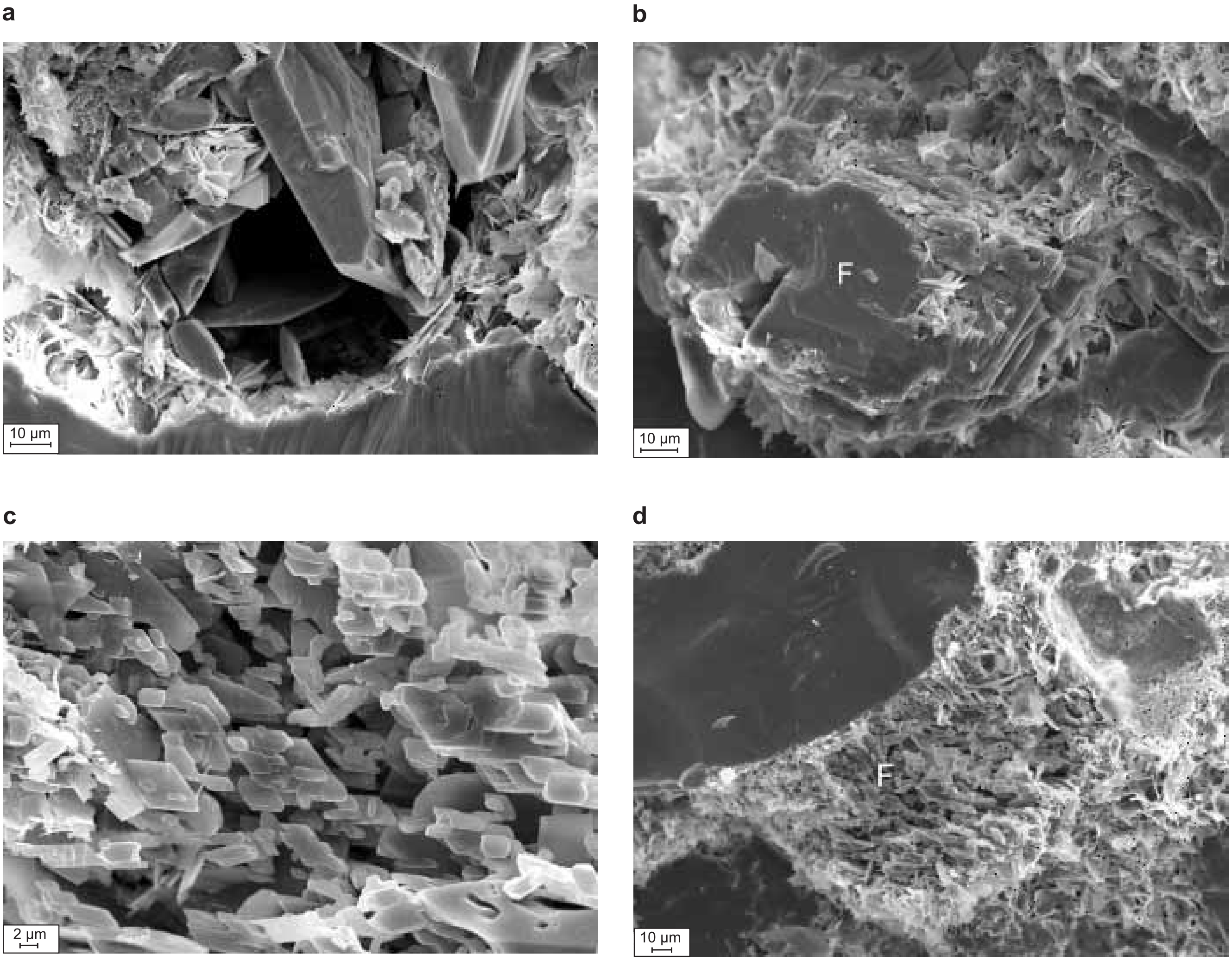



**Fig. 4. Secondary electron images (SEI)**

Darżlubie IG 1 borehole, depth 3495.0 m; **a** — authigenic quartz incompletely filling the pore space; **b** — potassium feldspar grain (F) with etched edges; **c** — fragment of partly dissolved potassium feldspar; **d** — relicts of partly dissolved potassium feldspar grain (F) — general view of photomicrograph **c**

nents, i.e. categorized as quartz or feldspar. The analysed thin sections also contain single fragments of quartz-feldspar rocks. Only in samples from the Olsztyn IG 2 borehole these fragments account for several percent. Identification of individual rock fragments, apart from quartzites and quartz schists, is difficult due to high degree of alteration. These fragments are represented most often by quartz-feldspar rocks, occasionally containing dominant microcline, with a small percentage of biotite. Strongly altered rock fragments with signs of myrmekite intergrowths are also observed (Fig. 3b). These fragments originally contained plagioclases which became altered, mostly argilitized, as the first ones of all grains. Of minerals composing the grain framework of sandstones, heavy minerals and micas should also be mentioned. The latter are represented by muscovite and biotite. Much concentrations of micas lead to the formation of a specific type of rock which is termed the micalith after Kopeliovich (1965) who identified such rocks in Vendian/Cambrian deposits of the Russian Platform. In the investigated sections micaliths occur as thin grey interbeds in sandstones of the Słupsk IG 1 and Kościerzyna IG 1 boreholes. These rocks contain clay matrix (partly originating from crumbled micas), psammite quartz grains and large amounts of muscovite and biotite (20–45%) in the form of packages deformed and squashed due to compaction (Fig. 3c).

## Clay matrix

The term "clay matrix" refers to clay material that fills the intergranular space. Unfortunately, it is very difficult to identify the genetic variety of the matrix. Most of the matrix, according to the terminology given by Dickinson (1970), is represented by protomatrix, i.e. pelite of detrital origin. However, epimatrix (pseudomorphs after feldspars) and pseudomatrix (crushed rock fragments) also occasionally occur. These are contained within the clay cement and therefore difficult for identification. In many cases, particularly in samples collected from large depths (Słupsk IG 1 and Kościerzyna IG 1 boreholes), clay material is recrystallized (sericitized) and occurs as orthomatrix. It cannot be excluded that it indicates transitional conditions between deep diagenesis and anchimetamorphism.

The content of clay cement in the investigated sandstones is reasonably high (Tab. 2). On average, in individual boreholes it ranges from approximately 7% (Hel IG 1 borehole) to 23% (Malbork IG 1 and Olsztyn IG 2 boreholes). In many samples the percentage of clay cement is in excess of 25%. The cement is composed of illite with frequent admixture of brown-cherry iron pigment (mainly in Olsztyn IG 2, Kościerzyna IG 1, as well as in Żarnowiec IG 1, Malbork IG 1 and Gdańsk IG 1 boreholes), and fine-flaked chlorites.

### Cements

**Authigenic quartz** cement occurs as overgrowths on detrital quartz grains. Sporadically it forms individual automorphic crystals (Fig. 5a). Quartz cement is observed mainly in those samples where the clay matrix content is low (Hel IG 1, Darżlubie IG 1, Żarnowiec IG 1 and Gdańsk IG 1 boreholes). Authigenic quartz overgrowths are fragmentary and irregular, and account for approximately 2–3% of rock volume. Such an estimate could be done analysing CL images since in the standard microscope image quartz overgrowths used to be joined with detrital grains and therefore they are nonidentifiable. Only in several thin sections which contain much quartz cement, its precise percentage contribution could be determined (Tab. 2). It accounts for as follows: 23.5% (Gdańsk IG 1 borehole), 17.6 and 9.1% (Żarnowiec IG 1 borehole), 6.8 and 5.4% (Kościerzyna IG 1 borehole).

The mechanism of formation of quartz overgrowths relies on the growth of fine, parallel-oriented quartz crystals which coalesce to form thick rims giving to the grains an automorphic shape (Fig. 6c, d). This process can be traced in scanning microscope images (SEI). Some of the images reveal a “stepwise” morphology of authigenic quartz overgrowths (Figs. 5b, 6d),

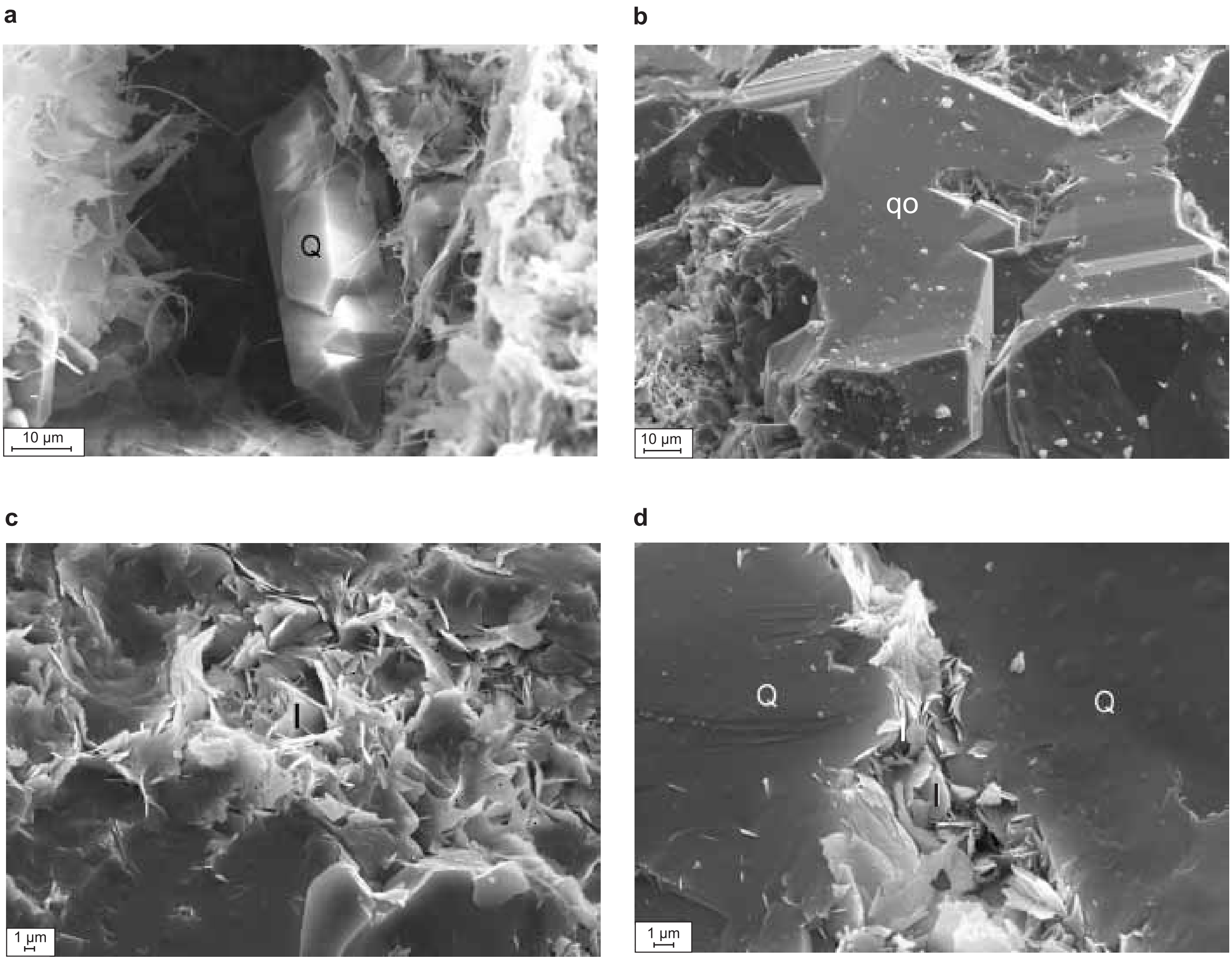



**Fig. 5. Secondary electron images (SEI)**

**a** — automorphic grain of authigenic quartz (Q) in association with illite in the pore space; Gdańsk IG 1 borehole, depth 3486 m; **b** — regeneration quartz cement (qo) with visible stair surfaces; **c** — illite concentration (I) in association with quartz cement; **d** — llite (I) between quartz grains (Q) with overgrowths; note illite flakes within the overgrowths; Malbork IG 1 borehole, depth 3636.3 m (**b**–**d**)

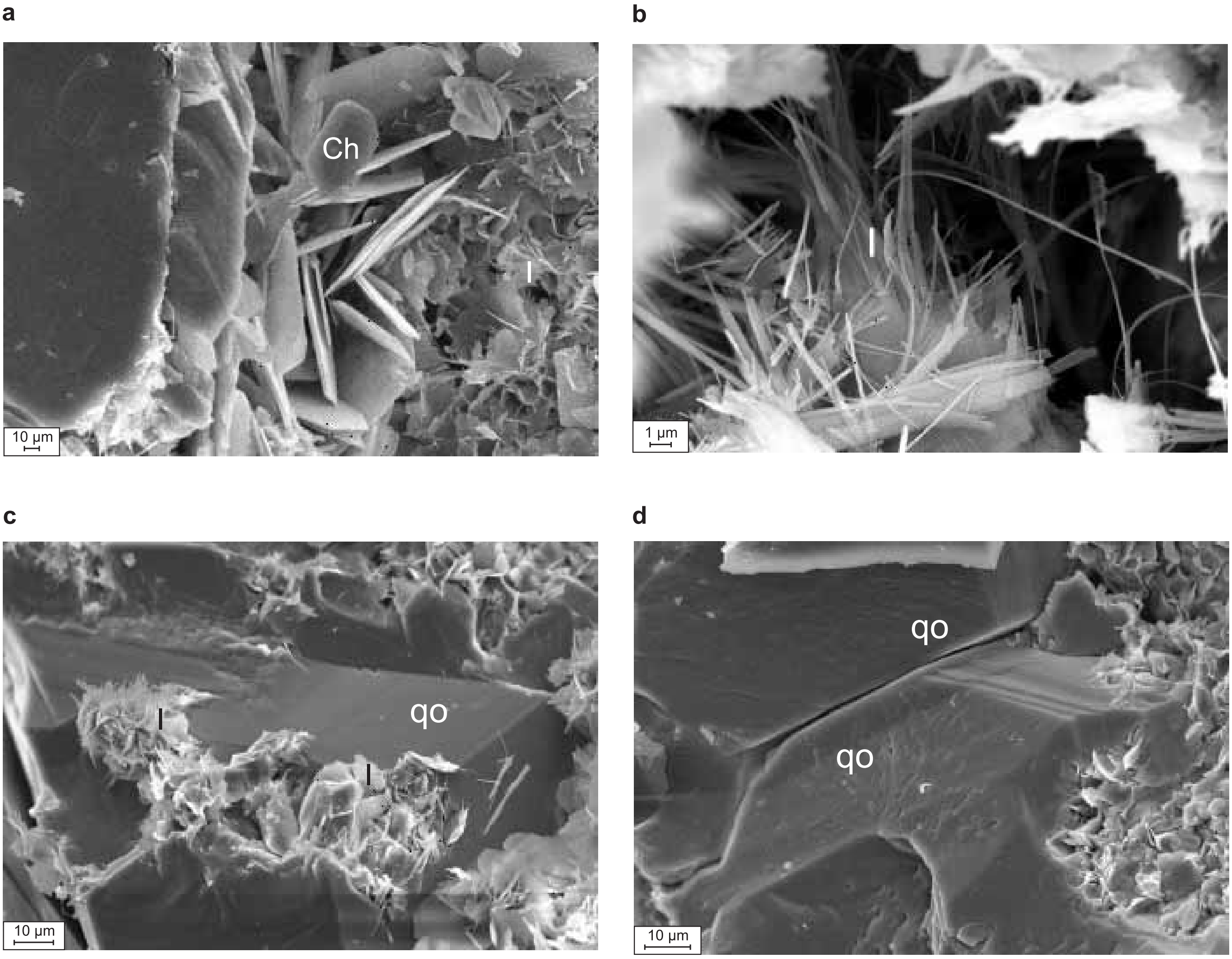



**Fig. 6. Secondary electron images (SEI)**

**a** — pseudohexagonal chlorite flakes (Ch) and illite concentration (I); Darżlubie IG 1 borehole, depth 3498 m; **b** — filaments of authigenic illite (I) in the pore space; **c** — authigenic illite flakes (I) within quartz cement (overgrowths)(qo); **d** —quartz overgrowths (qo) giving an automorphic shape of quartz grains; Gdańsk IG1 borehole, depth 3486 m (**b**–**d**)

suggesting their gradual growth. An additional information on the process of quartz cementation is provided by cathodoluminescence observations (CL and sCL). In most of samples which contain quartz cement, CL images reveal a distinct dominance of almost black (non-luminescent) authigenic quartz. Locally, concentrations of cement showing light brown luminescence colour can be observed (Fig. 3d). An exceptional case is a sandstone sample from the Gdańsk IG 1 borehole, in which a heterogenous and very complicated inner structure of quartz cement is visible (Fig. 3e). Light brown and almost black colours intermingle, creating a poorly legible image. Locally, non-luminescent, homogenously black cement is observed. In this case the sCL image is also very complicated (Fig. 7a–d) and suggests a complex process of quartz cement crystallization. Previous cathodoluminescence analyses of the Lower Cambrian sandstones from this section (Sikorska, 1998) pointed to the occurrence of a complicated sector structure of quartz cement, observed in scanning microscope images (sCL). Two (or more?) interfingering cement generations, showing different tones of grey, are visible in the sCL image. This observation is of the essential significance for interpretations of microthermometric studies of fluid inclusions.

Quartz cement not only fills the pore space but also replaces other minerals. Partial or complete silicification of feldspars (Fig. 3f) is observed extremely frequently (in samples from all the investigated boreholes). In the case of total silicification, a contour of the original grain and traces of cleavage can only be visible. The inside of the pseudomorph is filled with irregular neogenic quartz units, which form a mosaic making the entire grain alike a fragment of a quartzitic rock. The formation of these neogenic units is associated with formation of authigenic quartz overgrowths on the neighbouring detrital quartz grains. An additional evidence for feldspatic origin of the pseudomorph are feldspar relicts often observed in CL images.

The same mechanism of silicification is observed in rock fragments where feldspars are being replaced by quartz overgrowths of quartz grains adjoining to the rock fragment (Fig. 9a). Authigenic quartz fills small fractures in some of quartz grains (Fig. 8). No quartz cement-healed fractures, typical of Cambrian orthoquartzites, have been found.

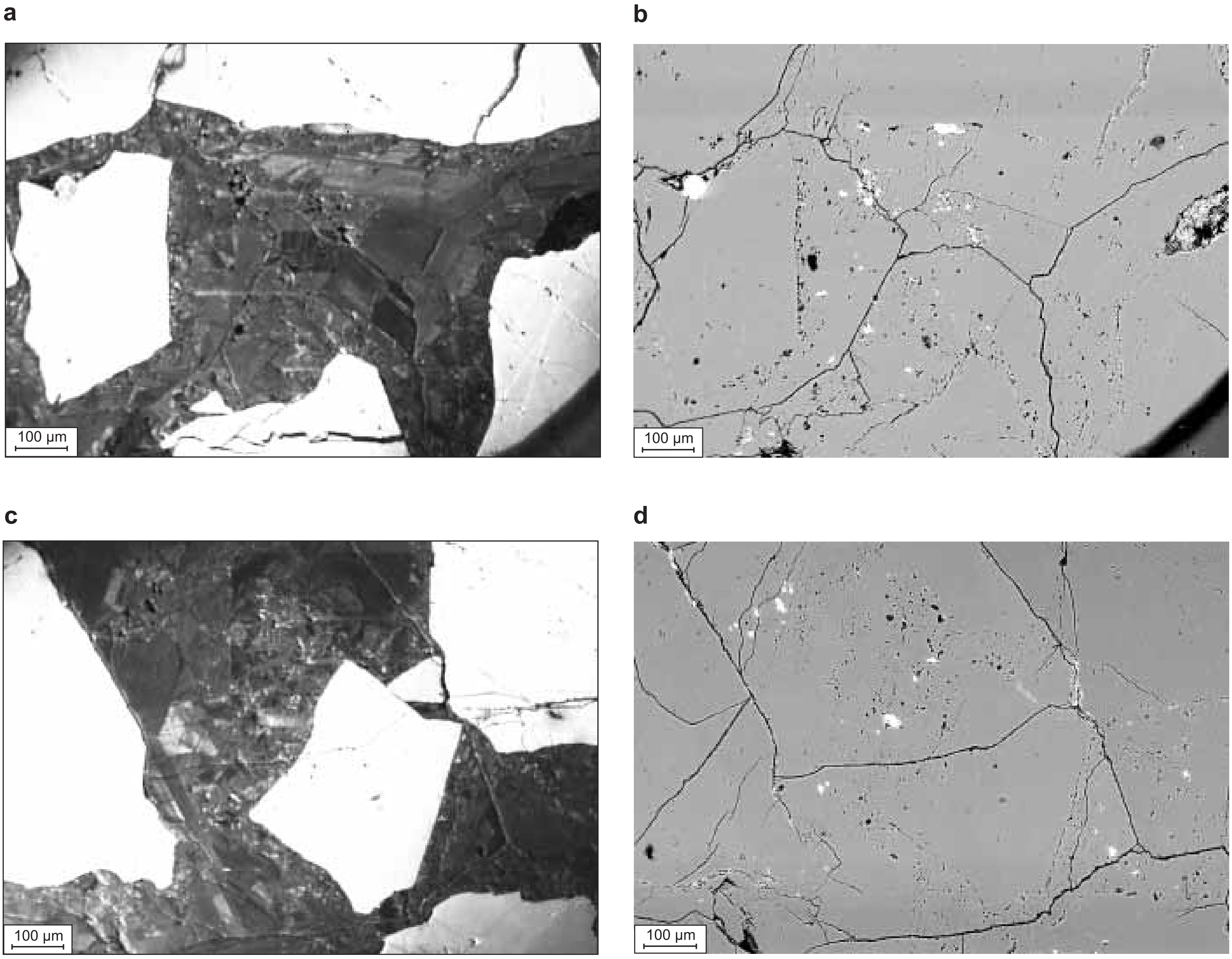



**Fig. 7. Quartz cement**

Gdańsk IG 1 borehole, depth 3486 m; **a**, **c** — complex structure of quartz cement formed due partly to recrystallization of primary siliceous cement, and partly to crystallization in the free pore space; zonal and sector structures are visible (sCL images); **b**, **d** — quartz grains densely cemented with authigenic quartz cement (photomicrographs **a** and **c** correspond to **b** and **d** respectively) (BSE images)

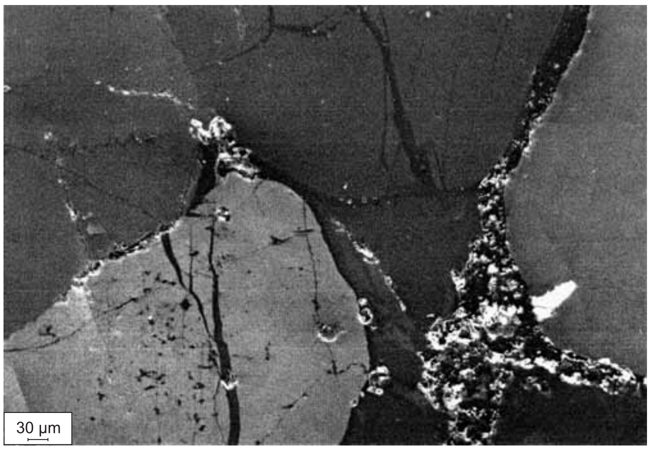



**Fig. 8. Quartz grains, fractured due to mechanical compaction**

Fractures healed with authigenic quartz; sCL image; Hel IG 1 borehole, depth 3484.1 m

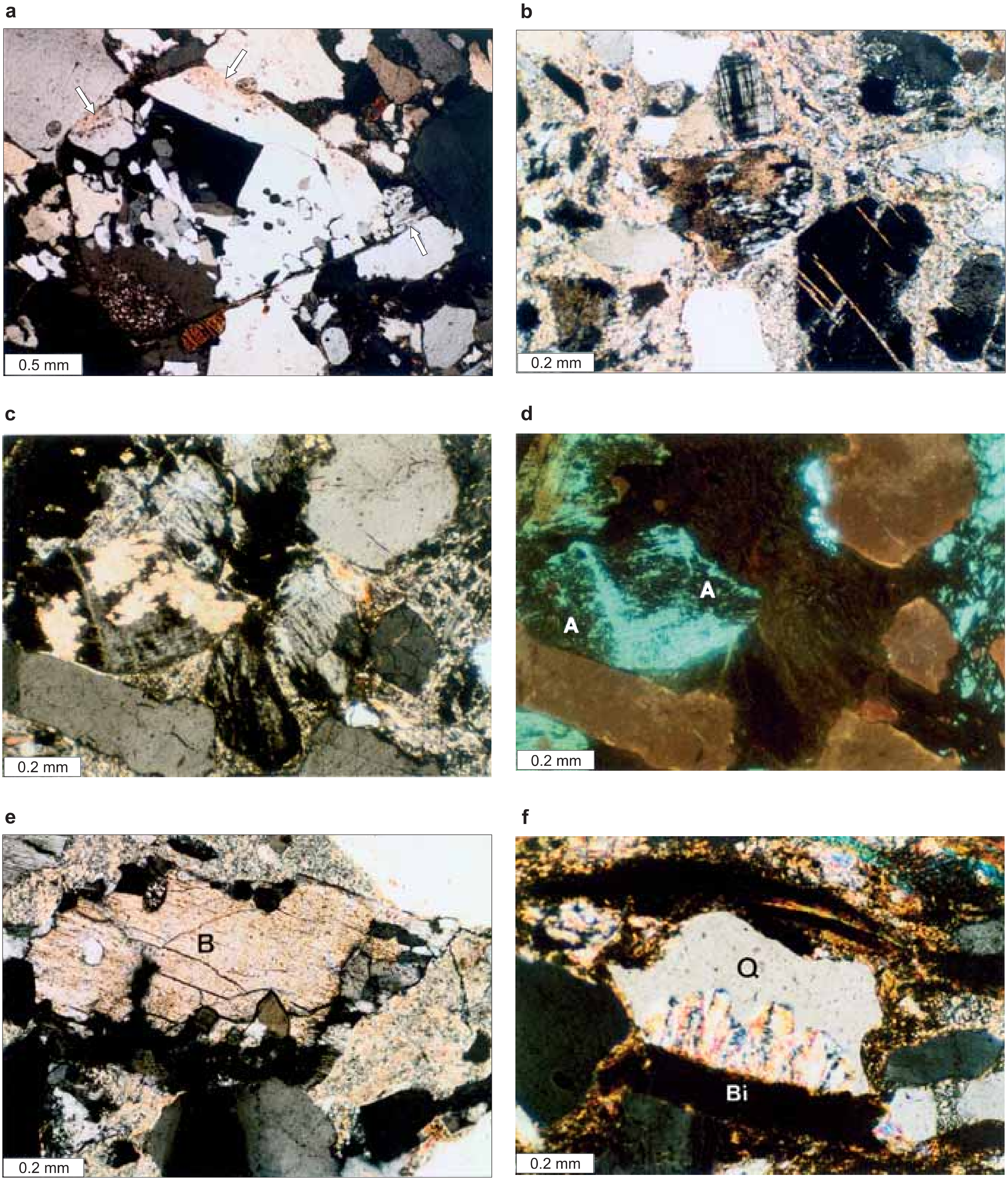



**Fig. 9. a** — quartz pseudomorph after a rock fragment; forming of authigenic quartz overgrowths on detrital grains inwards the rock fragment in sites of the originally occurring feldspars (arrows); TrL, crossed polars; Żarnowiec IG 1 borehole, depth 3201.6 m; **b** — ankerite-kaolinite pseudomorph after feldspar (centre); TrL, crossed polars; Olsztyn IG 2 borehole, depth 2741.4 m; **c** — pseudomorphs after potassium feldspars; TrL, crossed polars; Olsztyn IG 2 borehole, depth 2733.5 m; **d** — the same object as in **c**, CL image; feldspar grains completely silicified — brownish luminescence (centre), and partly replaced by non-luminescent ankerite (A); feldspar relicts — blue luminescence; **e** — barite (B) pseudomorph after feldspar grain; authigenic quartz is visible at its margins; TrL, crossed polars; Olsztyn IG 2 borehole, depth 2721.1 m; **f** — dissolution of quartz (Q) at the contact with biotite (Bi), and growth of authigenic mica; TrL, crossed polars; Słupsk IG 1 borehole, depth 5022.7 m

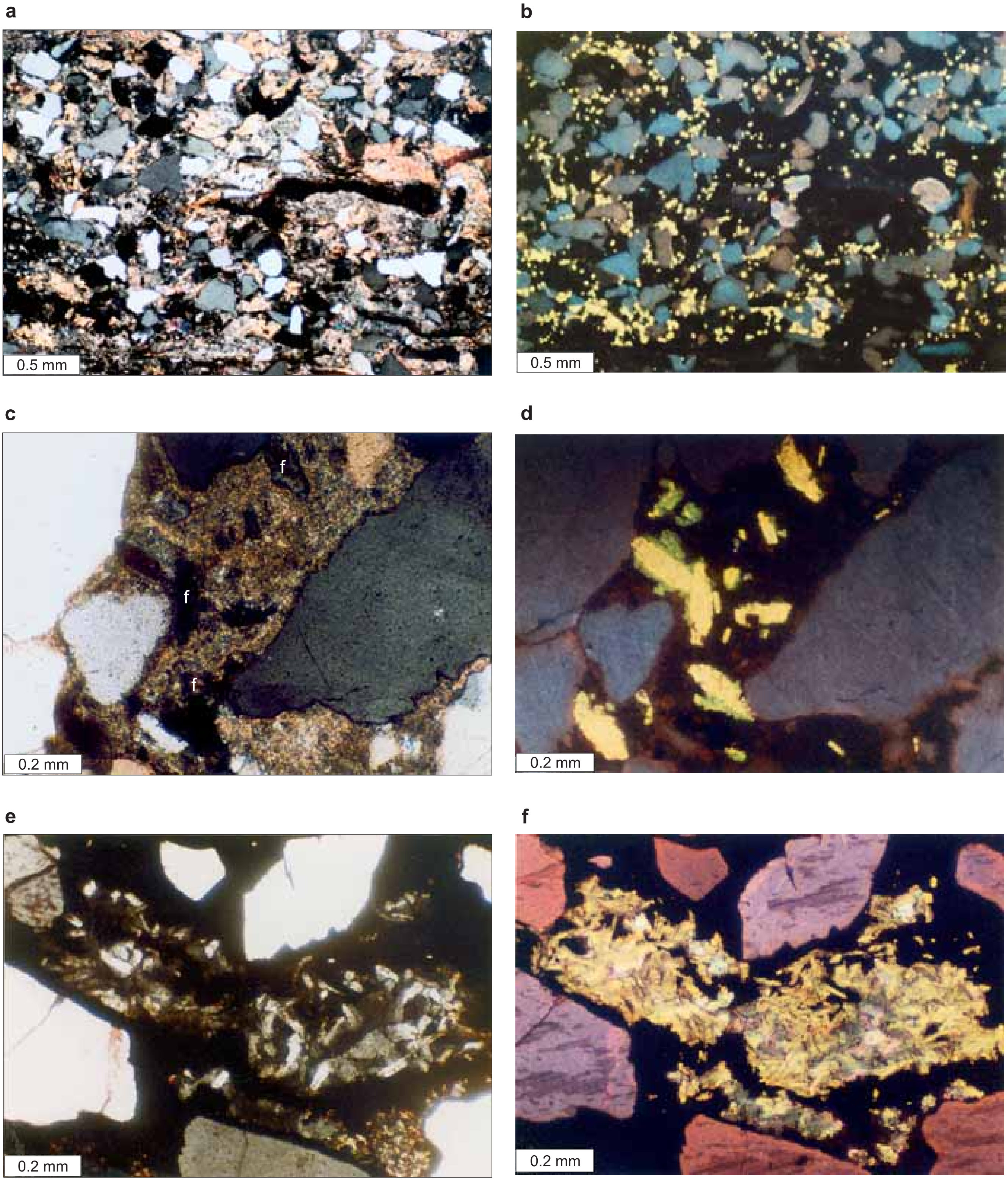



**Fig. 10.** **a** — fine-grained sandstone containing clay matrix; TrL, crossed polars; Malbork IG 1 borehole, depth 3655.2 m; **b** — the same object as in **a**, CL image; large number of dispersed fluorapatite crystals (yellow luminescence) is visible; **c** — fluorapatite crystals (f) in sericite matrix; TrL, crossed polars; Kościerzyna IG 1 borehole, depth 5138.0 m; **d** — the same object as in **c**, CL image; clearly visible fluorapatite crystals (yellow luminescence) with authigenic rims (green luminescence); **e** — hematite-fluorapatite cement in sandstone; TrL, crossed polars; Żarnowiec IG 1 borehole, depth 3219.7 m; **f** — the same object as in **e**, CL image; clearly visible fluorapatite cement showing yellow-green luminescence

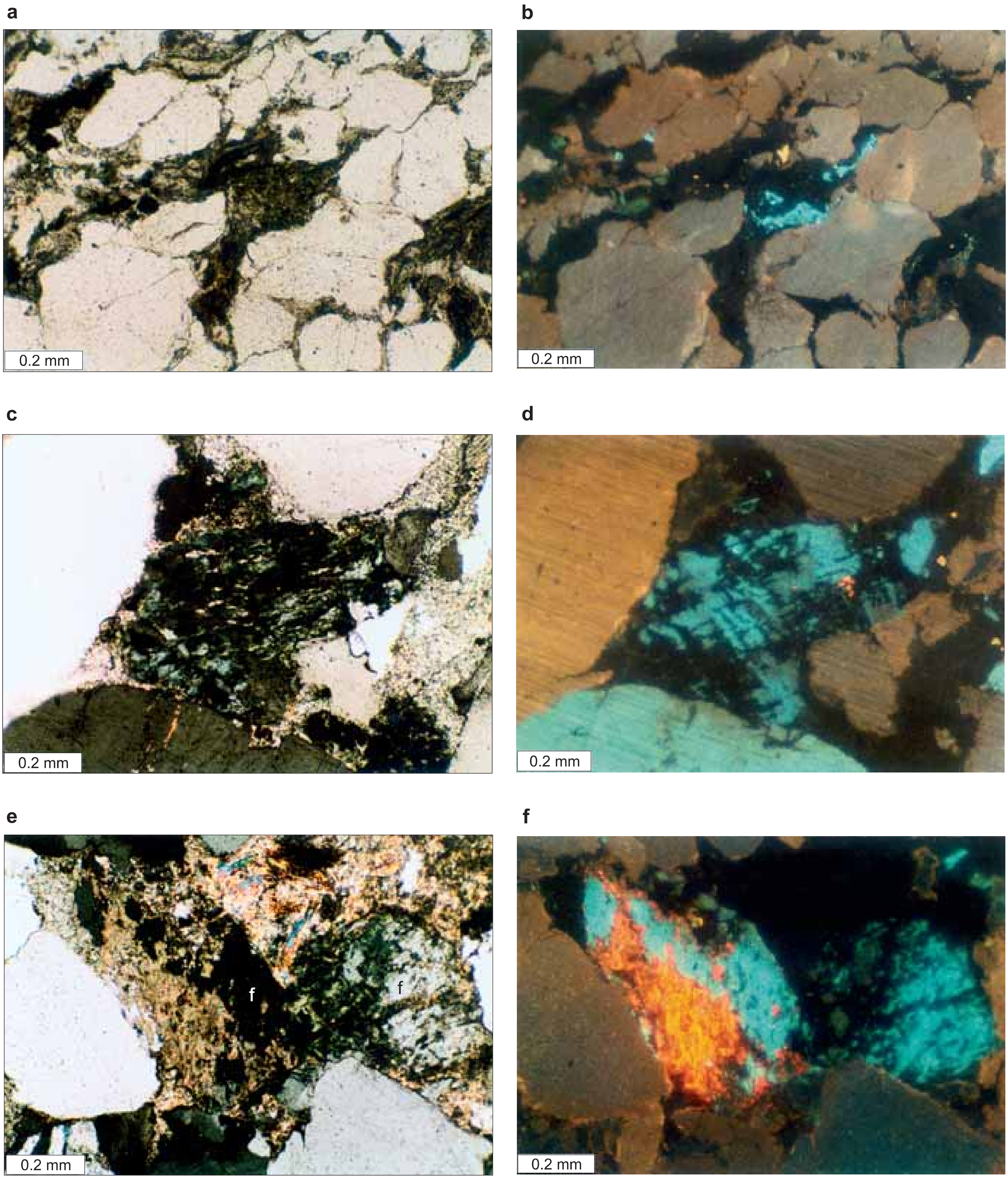



**Fig. 11. a** — chlorite-illite matrix in sandstone; TrL, plane-polarized light; Darżlubie IG 1 borehole, depth 3498.8 m; **b** — the same object as in **a**, CL image; potassium feldspar relicts (blue luminescence) are visible in the matrix; **c** — strongly chloritized potassium feldspar; TrL, crossed polars; Słupsk IG 1 borehole, depth 5005.3 m; **d** — the same object as in **c**, CL image; well visible potassium feldspar relicts (blue luminescence); **e** — partly carbonatized and chloritized feldspar grains (f); TrL, crossed polars; Żarnowiec IG 1 borehole, depth 3228.8 m; **f** — the same object as in **e**, CL image; potassium feldspar relicts (blue luminescence) and calcite (orange luminescence)

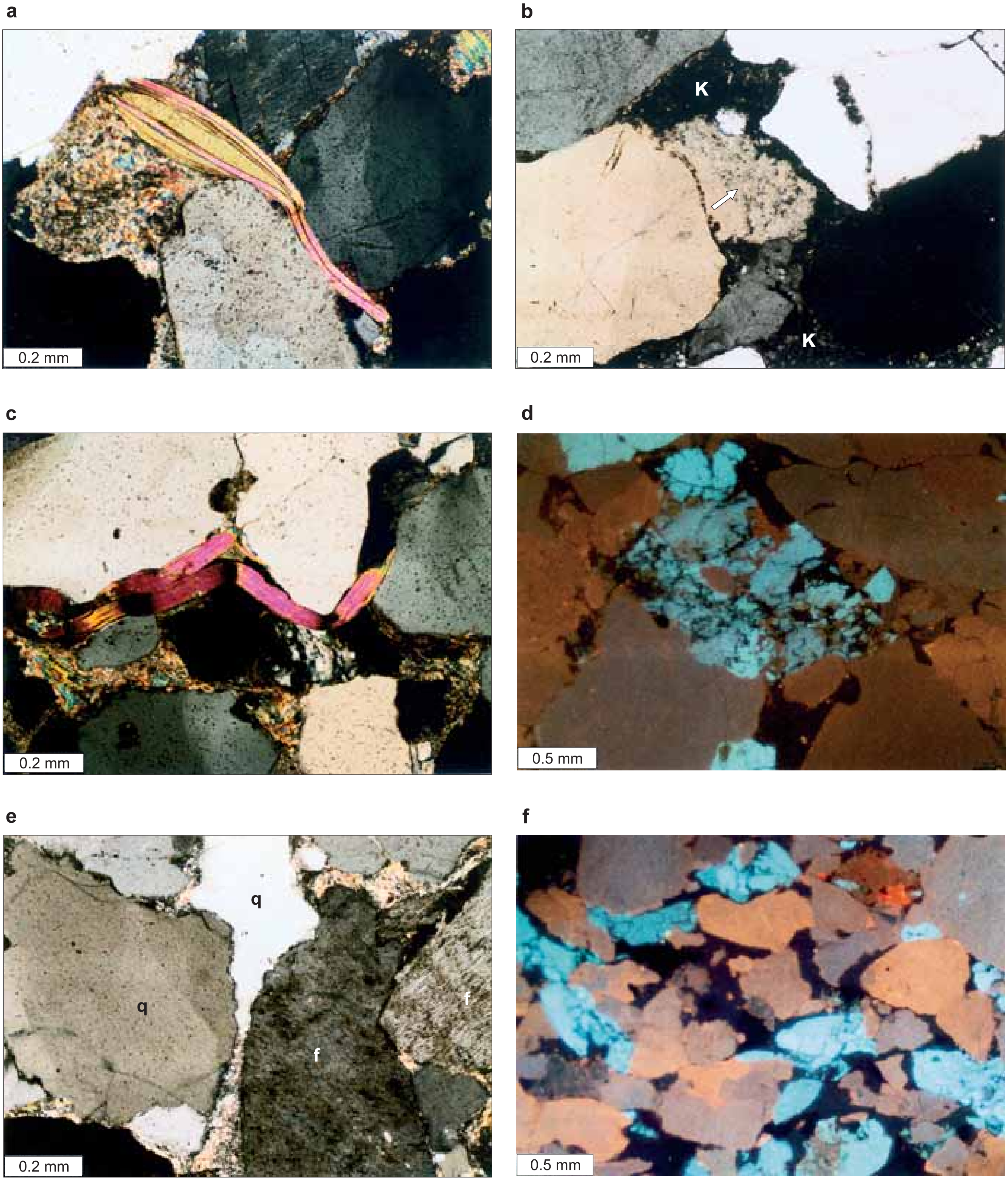



**Fig. 12. a** — authigenic chlorite between muscovite flakes; TrL, crossed polars; Żarnowiec IG 1 borehole, depth 3228.8 m; **b** — kaolinite (K) filling pore space in sandstone and kaolinite engulfed by authigenic quartz overgrowths (arrow); TrL, crossed polars; Żarnowiec IG 1 borehole, depth 3222.1 m; **c** — muscovite deformed as a result of mechanical compaction; TrL, crossed polars; Słupsk IG 1 borehole, depth 5026.0 m; **d** — potassium feldspar (blue luminescence) crumbled due to mechanical compaction; CL; Słupsk IG 1 borehole, depth 5005.3 m; **e** — pressure solution at quartz/quartz, quartz/feldspar and feldspar/feldspar contacts (q — quartz, f — feldspar); TrL, crossed polars; Hel IG 1 borehole, depth 3482.2 m; **f** — dominant brown and brownish luminescing quartz, indicates the provenance from metamorphic rocks; CL; Słupsk IG 1 borehole, depth 5026.0 m

**Carbonate minerals** occur sporadically and in small amounts (Tab. 2). They commonly form a replacive cement, rarely intergranular pore-filling cement. Carbonates are most common in the Olsztyn IG 2 borehole, occurring in most of the samples. The carbonate content ranges from trace amounts up to 2.3%. Ankerite forms partial pseudomorphs after feldspars, occasionally together with kaolinite (Fig. 9b) (Olsztyn IG 2 borehole).

Samples collected from the Hel IG 1 borehole contain irregular concentrations of calcite which locally form cement. In several thin sections from the Słupsk IG 1 and Żarnowiec IG 1 boreholes calcite occurs together with chlorite in pseudomorphs after feldspar. In CL images calcite shows an intense orange luminescence (Fig. 11f), whereas ankerite remains black (non-luminescent) due to the high iron content (Fig. 9d).

**Sulphates** are extremely rare in the studied rocks (Tab. 2), and their contents do not exceed 0.6% (Malbork IG 1, Olsztyn IG 2, Gdańsk IG 1 and Darżlubie IG 1 boreholes). Of these minerals only barite is present. Its occurrence is associated with pseudomorphs after feldspars, in which it is accompanied by authigenic quartz (Fig. 9e).

**Phosphates** occur as very fine fluorapatite crystals dispersed in clay matrix (Kościerzyna IG 1 and Malbork IG 1 boreholes). They are difficult to be identified in the standard microscope but CL images reveal even small grains (0.01 mm) owing to their strong light-yellow luminescence. It has appeared that the matrix in some of sandstones contains numerous small apatite crystals (Fig. 10a, b). Some of them show a complex structure in CL images: a green irregular rim is growing on a yellow grain (Fig. 10d). Exceptionally frequent occurrences of phosphates, not noted before in Cambrian rocks, are observed in the samples from a strongly ferruginous sandstone of the Żarnowiec IG 1 borehole. The chemical analysis (EDS) shows that the phosphates have a chemical composition of fluorapatite. These crystals (approximately 0.1 mm in length) form cement that fills the intergranular space of the sandstone. CL images (Fig. 10f) show luminescence ranging from various tones of yellow to green and violet. The rock was originally dominated by phosphate cement and subsequently strongly impregnated with hematite.

**Hematite** occurs in many samples as a pigment giving sandstones a red-brownish appearance. It is dispersed in clay matrix, forms irregular concentrations, fills cleavage fractures in feldspars or forms rims on detrital magnetite grains. There are also so large hematite concentrations (Fig. 10e) that it becomes a binder cementing the rock (Malbork IG 1, Olsztyn IG 2 and Żarnowiec IG 1 boreholes).

**Authigenic chlorites** form coarse-crystalline concentrations within pseudomorphs after feldspars (and lithoclasts?) or, rarely, they are a component of clay cement (Fig. 11a, b; Fig. 6a). Authigenic chlorites are most frequently of a fan-like shape and they are green in colour with distinct pleochroism, locally displaying abnormal interference colours. In pseudomorphs they occur singly (Fig. 11c, d) or together with authigenic quartz, rarely with carbonates (Fig. 11e, f). Chloritization of micas is also observed (Fig. 12a). One sample from the Słupsk IG 1 borehole contains chlorites and aggregates of monacite (Fig. 13).

**Kaolinite** occurs as irregular coarse-crystalline concentrations filling the intergranular space, and in pseudomorphs after feldspars (Żarnowiec IG 1 and Olsztyn IG 2 boreholes). Its total content in individual thin sections does not exceed 5%. In one sample from the Żarnowiec IG 1 borehole (Fig. 12b) kaolinite flakes stick in quartz cement, indicating that kaolinite was formed either prior to or simultaneously with authigenic quartz. Kaolinitization of micas, which suffer decolourisation and have low interference colours, is occasionally observed.

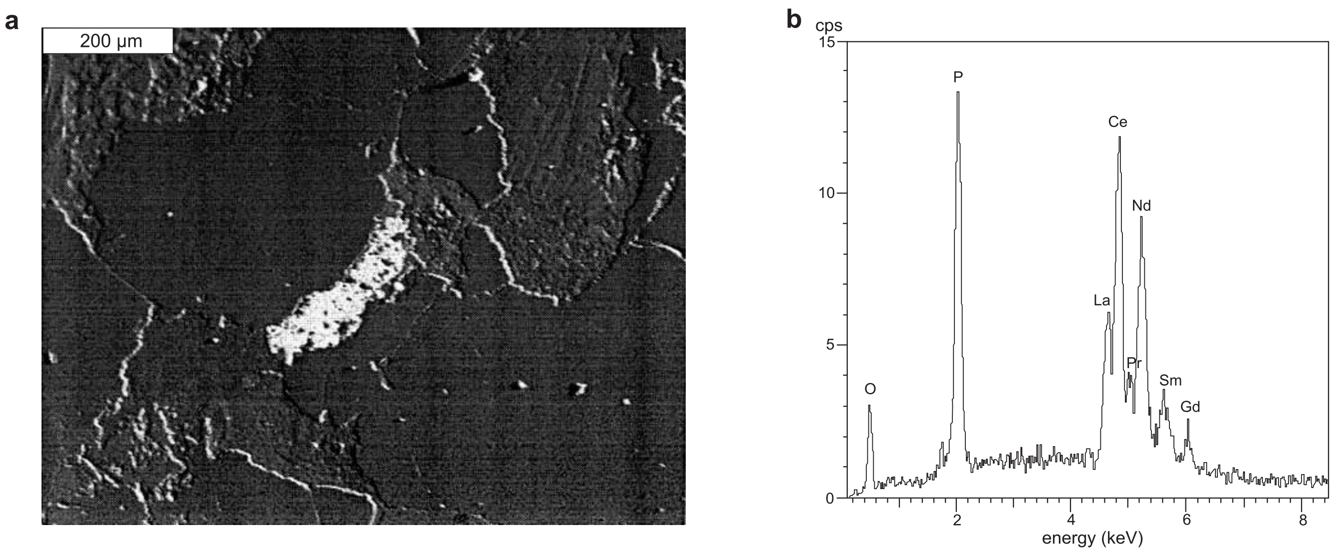



**Fig. 13. Monacite**

Słupsk IG 1 borehole, depth 4975.4 m; **a** — monacite aggregates (centre) (BSE image); **b** — X-ray spectrum (EDS) of chemical composition of monacite

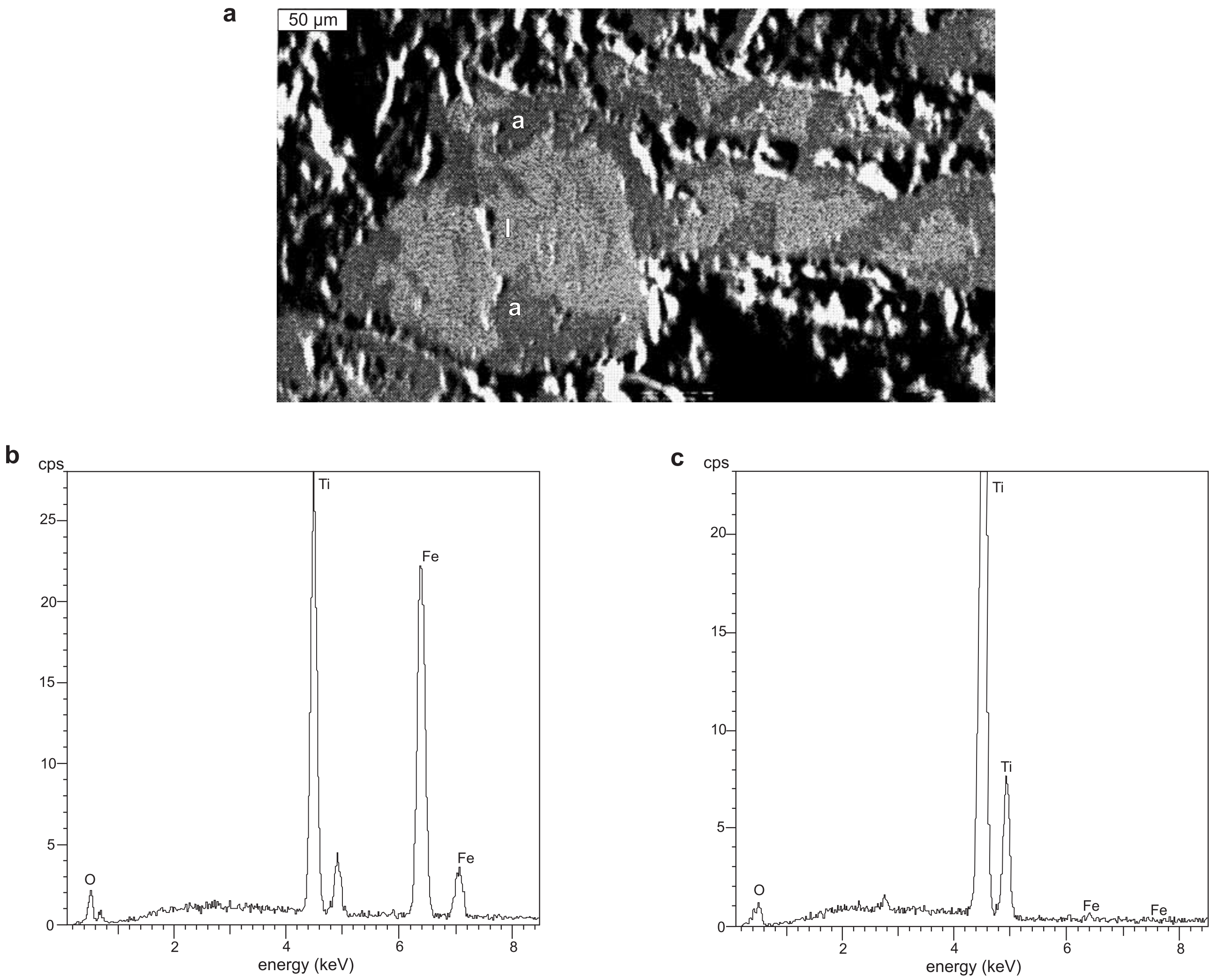



**Fig. 14. Titanium minerals**

Kościerzyna IG 1 borehole, depth 5043.8 m; **a** — ilmenite grains (I) being replaced from margins by anatase (a) (BSE image); **b** — X-ray spectrum (EDS) of chemical composition of ilmenite; **c** — X-ray spectrum (EDS) of chemical composition of anatase

**Authigenic illite** is observed in the scanning electron microscope studies of bulk samples. It occurs as concentrations and subtle filaments in empty pore spaces (Fig. 6b). Illite flakes either stick in quartz cement or fill the space between regeneration rims (Figs. 5c, d, 6c).

**Authigenic titanium minerals** are a frequent (although quantitatively subordinate) component of the studied rocks. They commonly form yellow-brown long rods, rarely plates, whose optical properties indicate the presence of **anatase**. Their secondary origin is evidenced by the presence of idiomorphic crystals and immediate neighbourhood of primary titanium minerals. These observations are confirmed by both BEI images and dispersive spectometer analyses of ilmenite grains which were only partly altered into anatase (Fig. 14a–c). In the case of complete alteration of a primary grain, the newly grown anatase crystals only partly fill the empty space that has formed. This process results in the formation of moldic porosity (Fig. 2e).

## DIAGENETIC PROCESSES AND RESERVOIR PROPERTIES

The following principle diagenetic processes affected the porosity and permeability of the Żarnowiec Fm.: mechanical compaction (Fig. 12c, d; Fig. 8), cementation and dissolution. These processes were primarily influenced by the original mineral composition of deposits and sorting of clastic material, that is in turn related to depositional conditions. It is very clearly accentuated as compared the Żarnowiec Fm. sandstones with the overlying Lower and Middle Cambrian sandstones. All of these were deposited under high-energy conditions but in completely different sedimentary environments. Sedimentological investigations presented in this paper show that sandstones of the Żarnowiec Fm. are represented mainly by alluvial fan and alluvial plain (braid-and-sheetflood) deposits. Lower and Middle Cambrian sandstones were deposited in a tide-dominated marine basin, periodically influenced by storms. High energy of waters and, moreover, prolonged reworking of clastic material within a nearshore zone of the basin resulted in the high textural maturity of the sandstones (Sikorska, 1998) represented mainly by quartz arenites. They are characterized by the high primary porosity that enabled intense development of cementation processes.

The Żarnowiec Fm. deposits, subjected to short-lived episodes of mechanical reworking, are characterized by the exceptionally low textural maturity. These rocks contain considerable amounts of primary clay matrix and are conspicuous by poor sorting of clastic material. It made them possess the very low primary porosity and permeability. In these deposits compaction exerted a greater effect on porosity reduction than cementation did.

Due to overburden pressure the grains became more closely packed, and some of feldspars (Fig. 12d), as well as unstable rock fragments, were crumbled and, becoming a component of the cement, additionally sealed the rock. Furthermore, the process of crystallization of early cement, which could stabilize the grain framework and reduce the effect of mechanical compaction, was very limited in that case.

The significant role in the lithification of these sediments was played only by quartz cementation. However, it had a limited effect. Sandstones which contain small amounts of primary clay cement became silicified, and are a minority among the studied deposits. Quartz cement occurs as thin overgrowths, and only in sandstones from the Gdańsk IG 1 borehole it fills the vast intergranular space.

Referring to the two-stage silicification model proposed for Cambrian rocks (Sikorska, 1998) we must limit our considerations to pure sandstones. In other rocks, quartz cement could not freely form since the intergranular space was most often filled with clay material. That is why quartz cement is observed in trace amounts. In quartz arenites occur two generations of cement that is visible in CL images (Fig. 3d). Non-luminescent cement is dominant (II). It contains relicts (?) of earlier cement (I). That allows to suppose that the stable grain framework was buried, and late quartz cement (II) filled empty spaces during mesodiagenesis. In this case silica could have originated from the process of alteration of clay minerals (alteration of smectite into illite), dissolution of quartz (at grain contacts) under overburden pressure, or from alteration of feldspars.

Abundant quartz cement in sandstones from the Gdańsk IG 1 borehole is very atypical in CL and sCL images (Fig. 3e; Fig. 7a, c). It was probably formed as a result of re crystallization of primary siliceous cement (Marechal *et al.*, 1996; Sikorska, 1998). Quartz cement could freely crystallize only in the remaining pore space, forming cement with a distinct inner structure (zonal and sector structure).

Silicification of feldspars, very common in the studied rocks, was also a cementing factor since it significantly reduced the amount of earlier pores after dissolved feldspars.

Carbonate cementation is of very little importance for estimates of reservoir properties of the rocks due to its small extent and only single occurrences of calcite and ankerite.

Authigenic clay minerals locally play a cementation role, reducing the free pore space. Kaolinite, observed in pseudomorphs after feldspars and in the intergranular space, reduced porosity of the rocks. The occurrence of fibrous illite negatively influenced the permeability of the sandstones.

Chemical compaction should also be mentioned among factors that worsen reservoir properties of the studied rocks. It is manifested as dissolution at intergranular contacts (quartz/quartz, quartz/feldspar, feldspar/feldspar, quartz/mica), observed in some of the samples (Fig. 12e; Fig. 9f).

Replacing of one mineral by another is also a process which reduces porosity. Feldspars can not only undergo silicification, but they can also be altered by carbonates, barite, kaolinite, chlorite, sericite.

Of the diagenetic processes discussed above, only dissolution of feldspars and ilmenite contributed to the formation of empty pores. However, only insignificant part of them was not subsequently filled with secondary minerals. Besides, isolated pores, formed as a result of this process, have no essential effect on permeability.

To sum up, it can be stated that the original composition of the Żarnowiec Fm. (associated with energy of the sedimentary environment) exerted a significant effect resulting in poor reservoir properties of the rocks. Diagenetic processes (compaction, cementation) additionally reduced the porosity and permeability.

## PROVENANCE OF CLASTIC MATERIAL

In order to identify rocks that supplied clastic material for the Żarnowiec Fm. deposits, various investigations and microscopic observations were made. Not all of them have provided the expected results but their mutual confrontation allows for some statements. One of the more significant indicators of the type of rock being a source of clastic material is the content of unstable components of the grain framework: feldspars and lithoclasts. The essential information has also been provided by studies of quartz grains: quantitative determination of contribution of different quartz types and cathodoluminescence analysis of individual grains. Additional information comes from studies of the mineral composition of heavy fraction in powder specimens, as well as CL observations of zircon grains.

## FELDSPARS AND LITHOCLASTS

Feldspars are represented in the Żarnowiec Fm. almost exclusively by potassium feldspar. The grains are auto- or hipautomorphic with faint signs of mechanical reworking. They are often crumbled or altered (see chapter "Diagenetic processes and porosity of rocks").

Rock fragments are yet strongly altered, that sometimes makes them difficult to be identified. Feldspar grains in these fragments are occasionally partly argilitized, chloritized or silicified, with entire fragments deformed by compaction.

The most common are fragments of quartzites and magmatic or metamorphic rocks composed of several quartz grains, occasionally with admixture of opaque minerals or biotite. Quartz-feldspar fragments are observed in minor proportions.

K-feldspar dominated rock fragments, in which quartz is a subordinate component (Słupsk IG 1 and Olsztyn IG 2 boreholes) or one large feldspar grain (2 cm in diameter) constitutes most of the rock fragment (Malbork IG 1 borehole), are sporadic.

The lack of plagioclases in the studied material results from their low resistance to weathering processes and from secondary alterations. It seems that potassium feldspars and the above-described rock fragments originate primarily from granitoids and microcline syenites. Fragments of quartzites were probably sourced from Jotnian rocks, rich in quartzites and quartzitic sandstones (Ryka, 1973). It explains the Jotnian age of deposits (regoliths) from the lower part of the Żarnowiec Fm., postulated by Łydka *et al*. (1980, 1984). This conclusion is confirmed by K–Ar datings (approximately 1240 Ma). Earlier, Juskowiakowa (1976) excluded the possibility of correlation of the Żarnowiec Fm. with the Jotnian sediments. Petrographical investigations presented in the present paper indicate that the unquestionable and striking observation of Łydka *et al*. (1980, 1984) refers to the age of parent deposits for the lower part of the Żarnowiec Fm. These deposits are partly Jotnian in age. They were subsequently eroded and incorporated into coarse-grained deposits accumulated much later, i.e. during the Vendian.

## QUARTZ

Quartz belongs to the most common components of the rocks. It is also highly resistant to weathering and transport, that makes it difficult for provenance interpretations.

Positive results of provenance studies of quartz in Cambrian rocks (Sikorska, 2000) were obtained using the diamond diagrams given by Basu *et al*. (1975). This method is based on a precise microscopic analysis of quartz grain types. The principle criteria are as follows: monocrystallinity (<3 subgrains in specimen) and polycrystallinity (>3 subgrains), as well as undulose extinction (extinction angle >5°) and non-undulose extinction (extinction angle <5°). The percentage of individual quartz types in each thin section has been plotted on the diamond diagram with three rock types representing sources of quartz (Basu *et al*., 1975). The projection of points on the diagram allows to identify the provenance of quartz as originated either from plutonic rocks or middle and upper rank metamorphic rocks or low rank metamorphic ones.

The results of quartz grains investigations are shown in diamond diagrams (Fig. 15), in which projection points are concentrated in different areas. Basing on their distribution it can be suggested that quartz grains from the Malbork IG 1 and Olsztyn IG 2 boreholes originate from low rank metamorphic rocks, whereas in the remaining boreholes clastic material of different provenance is mixed. In the Hel IG 1, Gdańsk IG 1, Żarnowiec IG 1 and Darżlubie IG 1 boreholes quartz grains were derived from low rank metamorphic and plutonic rocks, whereas the dominant sources of quartz in the sandstones from the Słupsk IG 1 and Kościerzyna IG 1 boreholes were not only low rank metamorphic rocks but also plutonic and middle and upper rank metamorphic ones. The distinctly dominant source of quartz were low rank metamorphic rocks, with smaller percentage of plutonic rocks and insignificant role of middle and upper rank metamorphic rocks.

Microscopic investigations of quartz grains were supplemented with cathodoluminescence studies, that enables a general determination of the provenance of quartz. It has been assumed (Zinkernagel, 1978; Matter, Ramseyer, 1985) that blue-violet luminescing quartz grains were derived from magmatic or high-temperature metamorphic rocks (contact metamorphism), whereas brown luminescing grains were sourced from low-temperature metamorphic rocks (regional metamorphism). These are obviously only suggestions that require investigations of many thin sections because single observations can lead to erroneous conclusions. The latest studies of Walderhaug and Rykkje (2000), concerning the dependence of orientation of quartz grains on their luminescence, show that CL observations should be interpreted with much caution.

The cathodoluminescence analysis of quartz from sandstones of the Żarnowiec Fm. enables unambiguous determination of the provenance of quartz as originated from low--temperature metamorphic rocks only for the Słupsk IG 1 borehole (Fig. 12f). In the remaining boreholes, rock material is strongly mixed and difficult to be interpreted.

## HEAVY MINERALS

The mineral composition of heavy fraction is very monotonous and dominated by opaque minerals (ilmenite, hematite, magnetite). Among non-opaque minerals, zircon is markedly dominant, being accompanied by tourmaline, occasionally rutile and individual pyroxene (Darżlubie IG 1, Żarnowiec IG 1 and Słupsk IG 1 boreholes) and garnet grains (Hel IG 1 borehole). These observations confirm the earlier suggestions about the poor and monotonous mineral composition of heavy fraction in sandstones of the Żarnowiec Fm. (Juskowiakowa, 1976; Rydzewska, 1977).

Zircons, separated out of heavy fraction, were examined in the cathodoluminescence (Tab. 3). Dark blue luminescing zircons are markedly dominant (43.8–92.4%; Fig. 16a), many grains are non-luminescent or show very faint luminescence

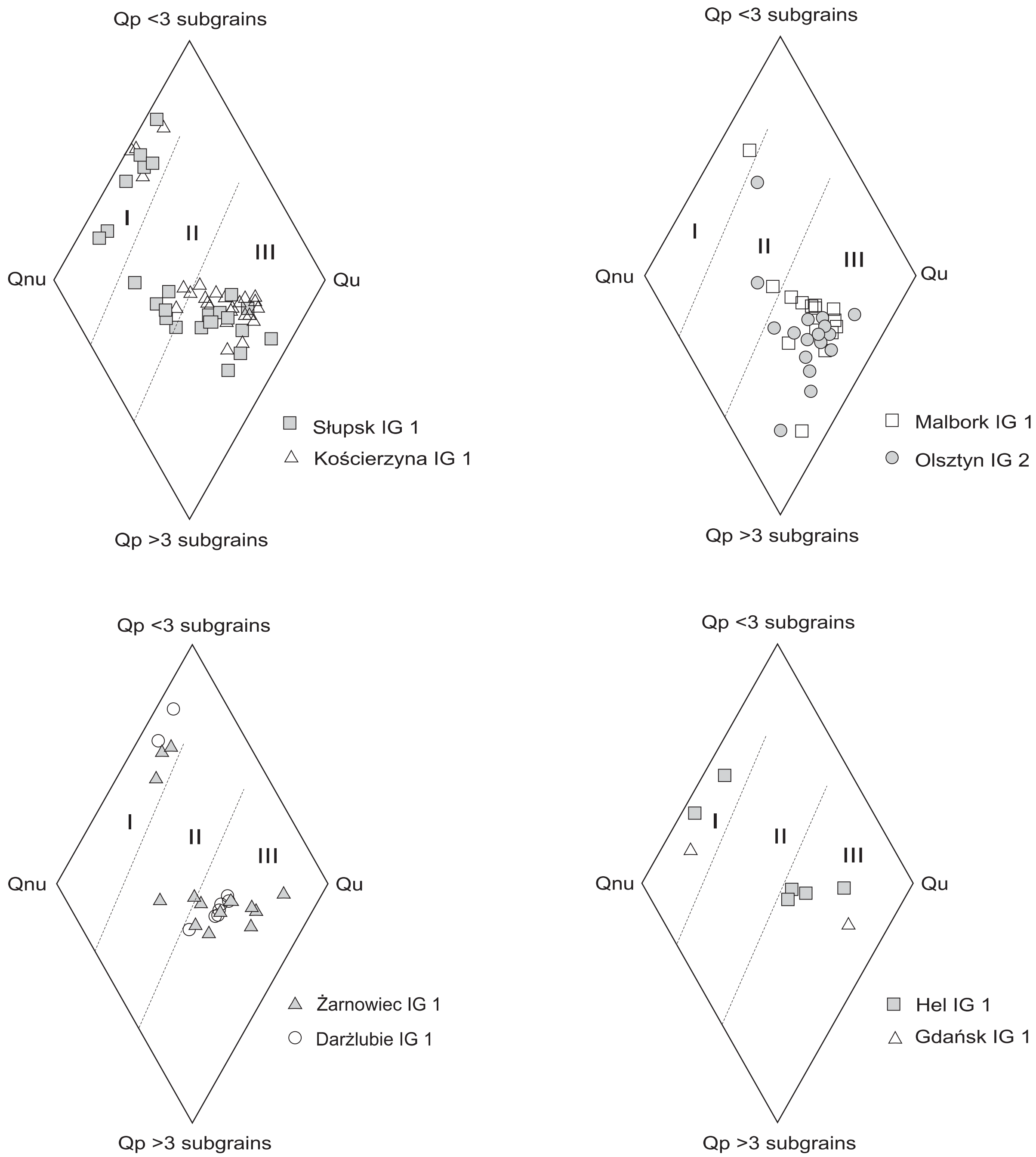



**Fig. 15. Diamond diagrams (after Basu *et al*., 1975) demonstrating the provenance of quartz in sandstones of the Żarnowiec Fm.**

Qp — polycrystalline quartz, Qnu — monocrystalline quartz with non-undulose extinction, Qu — monocrystalline quartz showing undulose extinction; **parent rocks**: I — plutonic, II — middle and upper rank metamorphic, III — low rank metamorphic

(4.4–54.4%; Fig. 16b), the remaining grains are characterized by blue-white (0–4.8%; Fig. 16c), white (0–3.6%; Fig. 16d) or yellow luminescence (0.5%; Fig. 16e).

The major luminescence activator in blue-luminescent zircons is $Dy^{+3}$ and, to a minor extent, other rare earth elements ($Sm^{+3}$, $Tb^{+3}$, $Nd^{+3}$, $Er^{+3}$). The significant role is also played by electron defects in crystal lattice, not identified unambiguously as yet. In yellow-luminescent zircons, the activator is $Yb^{+2}$, formed as a result of “radioactive reduction” of $Yb^{+3}$ due to U (and Th) radiation (Kempe *et al*., 2000).

The factor that limits the luminescence intensity is uranium and partly ytrium (Rubatto, Gebauer, 2000). Within one zircon grain, light-luminescent domains contain considerably smaller amounts of uranium than dark-luminescent domains. Therefore, electron microscope cathodoluminescence images are negatives of backscattred electron images (BEI) (Fig. 17b, c).

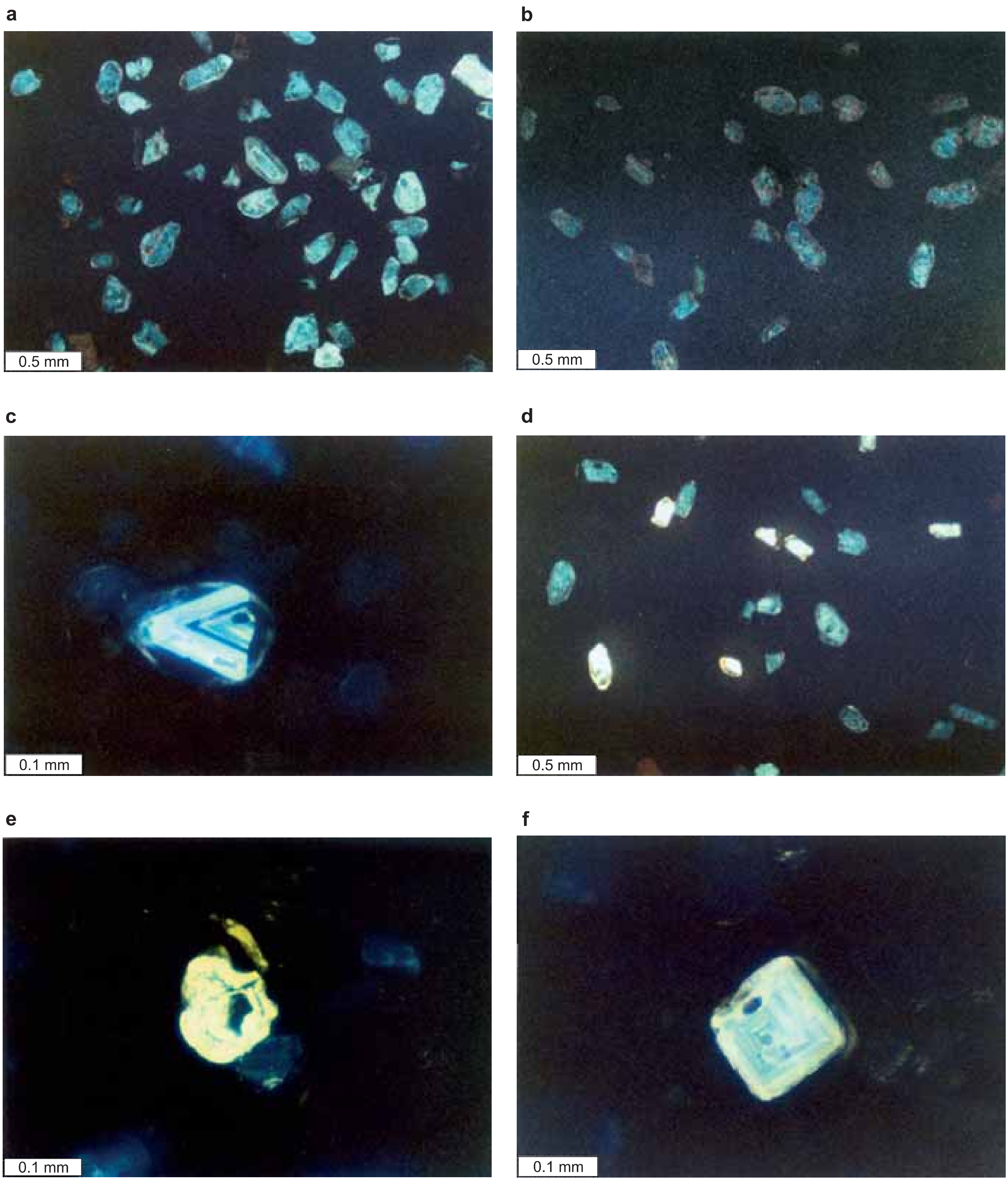



**Fig. 16.** **a** — zircon grains showing mainly dark blue luminescence; CL; Kościerzyna IG 1 borehole, depth 5053.3 m; **b** — zircon grains showing very faint luminescence; CL; Olsztyn IG 2 borehole, depth 2710.3 m; **c** — dark blue and white luminescing zircon grain; zonal structure and homogenous navy blue luminescing rim are visible; CL; Darżlubie IG 1 borehole, depth 3495.0 m; **d** — zircon grains showing dark blue and white luminescence; CL; Żarnowiec IG 1 borehole, depth 3213.0 m; **e** — yellow luminescing zircon grain; CL; Darżlubie IG 1 borehole, depth 3495.0 m; **f** — zircon grain showing oscillatory zonal structure that indicates its magmatic origin; CL; Malbork IG 1 borehole, depth 3638.8 m

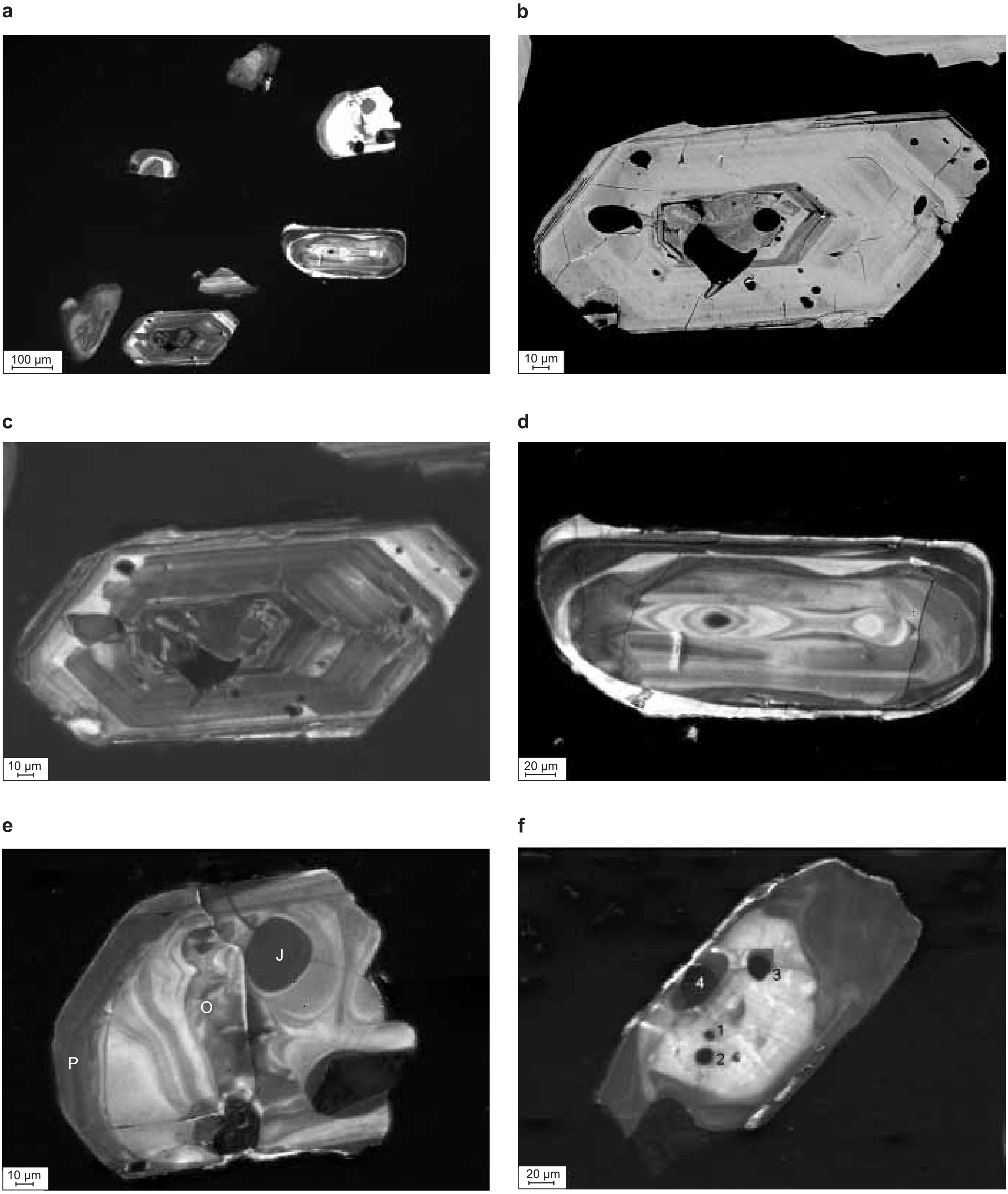



**Fig. 17. Zircon grains**

**a** — zircon grains with a complex inner structure and variable intensity of luminescence (sCL image); **b** — zircon with visible zonal structure reflecting variations in the U content (BSE image); **c** — zircon as in photomicrograph **b**, signs of resorbtion are visible (arrow) – broken regularity in the zonal structure (sCL image); **d** — light-colour metamorphic rim around a zircon grain with zonal structure (arrow) (sCL image); **e** — fragment of zircon grain with a nucleus (J), inherited component (O) and outer part with poorly marked zonal structure (P) (sCL image); Kościerzyna IG 1 borehole, depth 5053.3 m (**a**–**e**); **f** — zircon with inclusions of: *1* — potassium feldspar and plagioclase, *2* — potassium feldspar and quartz, *3* — potassium feldspar, *4* — iron oxides (sCL image); Żarnowiec IG 1 borehole, depth 3213.0 m

Table 3

**Percentage of zircons displaying different CL colours**

| Borehole | Sample number | Depth (m) | CL colours | | | | |
|---|---|---|---|---|---|---|---|
| | | | no CL/very weak | dark blue | blue-white | white | yellow |
| Kościerzyna IG 1 | 6/6 | 5037.4 | 7.3 | 91.8 | 0.9 | 0 | 0 |
| | 11/11 | 5053.3 | 7.2 | 91.5 | 1.3 | 0 | 0 |
| | 15 | 5063.8 | 10.1 | 88.4 | 0.6 | 0.9 | 0 |
| Żarnowiec IG 1 | 5 | 3213.0 | 4.4 | 87.2 | 4.8 | 3.6 | 0 |
| Malbork IG 1 | 6 | 3638.8 | 6.4 | 92.4 | 1.0 | 0.2 | 0 |
| | 14 | 3656.4 | 8.4 | 90.4 | 0.9 | 0.3 | 0 |
| Olsztyn IG 2 | 5 | 2710.3 | 16.3 | 81.0 | 2.5 | 0.2 | 0 |
| | 16/13 | 2733.5 | 36.8 | 62.6 | 0.4 | 0.2 | 0 |
| Darżlubie IG 1 | 1 | 3495.0 | 12.2 | 86.5 | 0.4 | 0.4 | 0.5 |
| Gdańsk IG 1 | 2 | 3486.0 | 25.7 | 73.8 | 0.5 | 0 | 0 |
| Słupsk IG 1 | 28 | 5060.1 | 54.4 | 43.8 | 0 | 1.8 | 0 |

Most of zircons from the studied samples show a homogenous inner structure and do not exhibit in CL images much variations in luminescence colour (Fig. 16a, b). There are also zircons with a distinct oscillatory concentric zonal structure (Fig. 16f; Fig. 17a) typical of grains which are magmatic in origin. If any nucleus is not visible inside, the grain was formed during one crystallization stage (Poller *et al*., 2000). Rarely, the entire zircon grain is characterized by a zonal structure, more frequently the structure is observed in its fragment, and the remaining part of the grain shows a homogenous nature (Fig. 16c). It is considered that such a CL image indicates a complex origin of the grain which, after crystallization from the magma, underwent a stage of metamorphic alterations (Hanchar, Miller, 1993; Kempe *et al*., 2000). This magmatic grain interior often shows a very irregular shape resulting from resorbtion during metamorphic processes (Carter, Bristow, 2000; Rubatto, Gebauer, 2000). Some of zircon grains have carbonate inclusions identifiable owing to their red luminescence, and inclusions of plagioclases, potassium feldspars, quartz, and iron oxides (Fig. 17f) detected with the use of the energy dispersive spectrometer (EDS).

The cathodoluminescence analysis of zircon grains in the scanning electron microscope (sCL) confirms their complex inner structure (Fig. 17a). Even at places where a fairly regular oscillatory zonal structure occurs, signs of resorbtion (at high magnification) (Fig. 17c) or a light colour metamorphic rim (Fig. 17d) are visible. Many grains show a very complex structure composed of the nucleus (inherited component), resorbed portion and a portion of a zonal structure (Fig. 17e). The source of these zircons is associated with polymetamorphic terranes (Rubatto, Gebauer, 2000).

Several remarks concerning the provenance of zircons from sandstones of the Żarnowiec Formation can be given from CL observations. Most of the zircon grains were derived from metamorphic rocks, and only small percentage of them from magmatic rocks. The latter seem to be poorer in uranium. Zircons from the Olsztyn IG 2 borehole are conspicuous in the microscopic investigations by brown colouration. In the cathodoluminescence images they show faint luminescence (Fig. 16b). Grains with a zonal structure are almost absent, indicating that all of the zircons originate from metamorphic rocks. This conclusion fully corresponds with the previously postulated opinion (see chapter “Quartz”) that metamorphic rocks were the source of quartz in sandstones from the Olsztyn IG 2 borehole.

## GEOTECTONIC SETTING OF SOURCE AREAS

### INTERPRETATION OF THE MINERAL COMPOSITION OF ROCKS

The problem of determination of geotectonic setting of source areas on the basis of the mineral composition of grain framework in terrigenous sedimentary rocks has long been broadly discussed (Crook, 1974; Schwab, 1975; Dickinson, Suczek, 1979; Dickinson, Valloni, 1980; Dickinson, 1985). Basing on a wide range of ancient and recent sediments for which source areas of clastics are well known, diagrams that enable geotectonic interpretations have been constructed.

In order to identify the geotectonic setting of source areas, the $Q_t$FL discrimination diagram given by Dickinson (1985) was used. That author divided the diagram into three basic sectors representing source areas of clastic material: CB — continental block, RO — recycled orogen, MA — magmatic arc, and subdivided them into subsectors. Since the composition of the Żarnowiec Formation sandstones falls within the area CB, thus the subsectors are portrayed only in this portion of the diagrams, as follows: CI — craton interior, TC — transitional continental area and BU — basement uplift.

Projection points in the Dickinson diagrams (Fig. 18) reflect the percentage of the three components ($Q_t$, F, L). The distribution of these points indicates that the grain framework of the analysed sandstones is composed largely of quartz and feldspars with small contribution of rock fragments. The occurrence of rock fragments, described above (see chapter "Grain framework"), is not distinctly accentuated here since, due to sand-size of most of these lithoclasts, they were included within the appropriate types of mineral grains. It results from using the Gazzi–Dickinson technique of point counting.

Projection points of the sandstone composition for individual boreholes most frequently group within subsector CI (all of the studied boreholes), some of the samples concentrate in subsectors TC (Olsztyn IG 2, Słupsk IG 1 and Kościerzyna IG 1 boreholes) and BU (Słupsk IG 1 borehole).

The investigations show that the East European Craton, in particular its inner areas and, in one case (Słupsk IG 1 borehole) the uplifted basement blocks, was the source area for the Żarnowiec Fm.

### INTERPRETATION OF THE CHEMICAL COMPOSITION OF ROCKS

The chemical composition of terrigenous sedimentary rocks is a function of several factors, first of all the provenance of clastic material, weathering processes, transportation and diagenesis. The geotectonic setting of source area is an original element affecting the mineral composition and thus geochemistry of the sedimentary rock. This dependence is essential for interpretations of results of chemical analyses. Not only the percentage content of individual main chemical elements, but also relationships between the elements are taken into considerations (Bhatia, 1983; Roser, Korsch, 1986, 1988).

Basing on investigations of the chemical composition of sandstones of different ages, whose tectonic setting of source areas was unambiguously identified, Bhatia (1983) constructed diagrams for geotectonic interpretations. The most useful are those diagrams which represent the relationship between $Fe_2O_3$ + MgO and: $TiO_2$, $Al_2O_3/SiO_2$, $K_2O/Na_2O$ and $Al_2O_3$/CaO + $Na_2O$. Areas, corresponding to different geotectonic environments: oceanic island arch (OIA), continental island arch (CIA), active continental margin (ACM) and passive continental margin (PM), have been defined within these diagrams.

Provenance studies of clastic material and geotectonic setting of source areas also involve geochemistry of trace and rare earth elements (Bhatia, Taylor, 1981; Peterman *et al.*, 1981; Bhatia, Crook, 1986). Triangular plots constructed by Bhatia and Crook (1986) are used in similar interpretation as in the case with the main chemical elements. Diagrams with corners defined as: La–Th–Sc, Th–Co–Zr, Th–Sc–Zr were adopted for the interpretation proposed in the present report. These diagrams were considered by their creators to be the most useful for the discrimination analysis. The triangles include analogous areas (OIA, CIA, ACM, PM) as in the plots constructed for the main chemical elements.

Interpretation of geotectonic environments in the studied rocks is based on the content of La, Sc, Th, Co and Zr, since the proportion of these chemical elements remains unchanged during transportation from source areas to the depositional site, and they are characterized by immobility under conditions of weathering, as well as during the transport of clastics and diagenetic process. Owing to these features the chemical elements can be used for determination of the geotectonic setting of source areas of clastic material.

### MAIN CHEMICAL ELEMENTS

Chemical analyses were performed on rock samples from boreholes drilled in various parts of the study area. The results show little order both in variability between individual sections and with depth (Tab. 4).

The $SiO_2$ content is variable and ranges from 56.33 to 90.71%, with an average of 82.67% (Żarnowiec IG 1 borehole), 80.70% (Słupsk IG 1 borehole) and 76.84% (Olsztyn IG 2). The average content of $Al_2O_3$ is inversely proportional to $SiO_2$ content. This tendency is clearly visible in the plot of mutual relationships between these components (Fig. 19). The least average content of $Al_2O_3$ is recorded in the samples from the Żarnowiec IG 1 borehole (5.64%), which are rich in quartz arenites, higher content in the Słupsk IG 1 borehole (8.92%) and the highest one in the Olsztyn IG 2 borehole (10.52%) due to extremely large amounts of feldspars. A comparable content (in some samples even greater) of feldspars is noted in

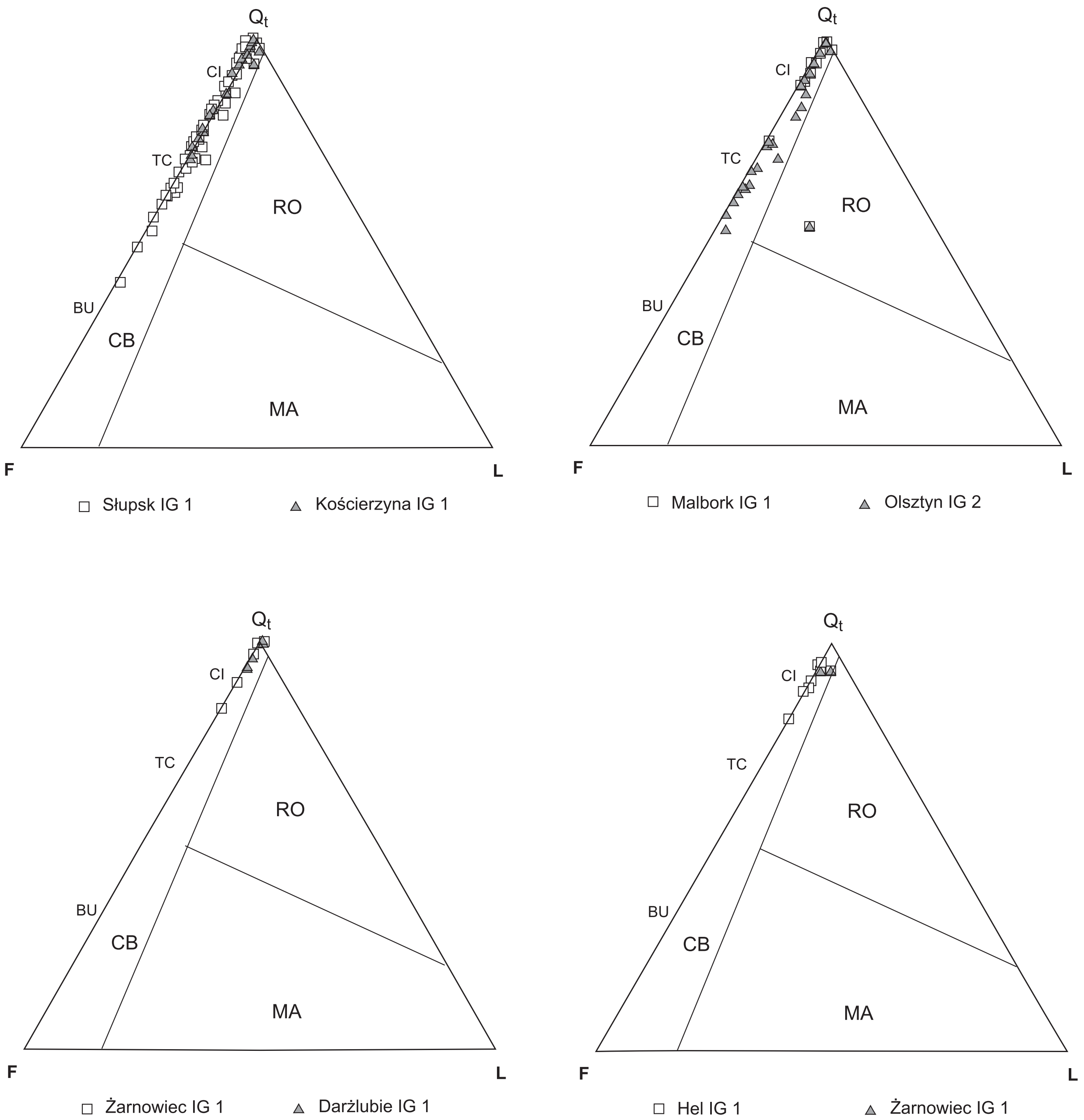



**Fig. 18. Discrimination diagrams $Q_t$FL (after Dickinson, 1985) demonstrating the provenance of clastic material in the Żarnowiec Fm. deposits**

$Q_t$ — mono- and polycrystalline quartz, F — feldspars, L — unstable aphanitic rock fragments; CB — continental block, RO — reworked orogen, MA — magmatic arc, CI — craton interior, TC — transitional continental area, BU — uplifted basement

the Słupsk IG 1 borehole, as evidenced in the $Q_t$FL triangle discrimination diagram (Fig. 18a). However, these samples contain smaller amounts of $Al_2O_3$ as compared with the Olsztyn IG 2 borehole. This fact can be somewhat strange, but the apparent discrepancy may be explained by the very intense silicification of feldspars in sandstones from the Słupsk IG 1 borehole, whereas feldspars from the Olsztyn IG 2 borehole were subjected mostly to kaolinitization and carbonatization, and to a lesser extent, to silicification.

The analysis of the results shows the considerable $K_2O$ content: 1.4% on average in the Żarnowiec IG 1 borehole, and 4.2% in the Olsztyn IG 2 and Słupsk IG 1 boreholes, with the very low average content of $Na_2O$: 0.18% (Żarnowiec IG 1 borehole), 0.29 (Olsztyn IG 2 borehole) and 0.09% (Słupsk IG 1 borehole). It makes that the $K_2O/Na_2O$ ratio is extremely high ranging from 2.9 to 16.9 in the Żarnowiec IG 1 borehole, from 10.1 to 18.8 in the Olsztyn IG 2 borehole, and from 38.4 to 57.0 in the Słupsk IG 1 borehole. So small amount of $Na_2O$ re-

**Table 4**

**Major and trace elements in sandstones of the Żarnowiec Fm.**
**(oxides in weight %; trace elements in ppm)**

| Borehole | Olsztyn IG 2 | | | | | | Żarnowiec IG 1 | | | | | | Słupsk IG 1 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | 2 | 5 | 7 | 11 | 13 | 15 | 1 | 4 | 8 | 11 | 12 | 15 | 1 | 9 | 15 | 17 | 20 | 26 |
| Depth | 2702.0 | 2710.3 | 2716.1 | 2727.8 | 2733.5 | 2739.1 | 3201.6 | 3210.0 | 3219.7 | 3225.9 | 3228.8 | 3234.5 | 4975.4 | 4999.3 | 5019.0 | 5026.0 | 5036.4 | 5055.0 |
| $SiO_2$ | 83.20 | 74.60 | 74.83 | 74.71 | 78.37 | 75.33 | 90.71 | 86.41 | 56.33 | 88.46 | 88.68 | 85.41 | 90.20 | 83.40 | 82.32 | 81.20 | 85.21 | 61.87 |
| $Al_2O_3$ | 8.76 | 11.48 | 10.74 | 8.92 | 10.65 | 12.58 | 3.72 | 6.74 | 2.55 | 6.46 | 5.19 | 9.17 | 4.34 | 7.84 | 6.36 | 9.35 | 6.85 | 18.76 |
| $Fe_2O_3$ | 1.10 | 1.70 | 4.89 | 1.76 | 0.98 | 1.34 | 1.93 | 1.10 | 36.57 | 0.99 | 2.42 | 0.51 | 1.72 | 2.09 | 4.65 | 2.34 | 2.49 | 5.36 |
| MnO | 0.004 | 0.038 | 0.010 | 0.015 | 0.011 | 0.004 | 0.013 | 0.002 | – | 0.002 | – | – | 0.006 | 0.011 | 0.019 | 0.011 | 0.010 | 0.015 |
| MgO | 0.38 | 0.77 | 0.49 | 0.39 | 0.47 | 0.42 | 0.37 | 0.17 | 0.02 | 0.04 | 0.03 | 0.05 | 0.31 | 0.26 | 0.17 | 0.26 | 0.21 | 0.55 |
| CaO | 0.14 | 0.99 | 0.34 | 0.38 | 0.45 | 0.22 | 0.14 | 0.25 | 0.84 | 0.10 | 0.11 | 0.08 | 0.08 | 0.34 | 0.53 | 0.29 | 0.15 | 0.07 |
| $Na_2O$ | 0.14 | 0.26 | 0.27 | 0.41 | 0.36 | 0.32 | 0.20 | 0.24 | 0.22 | 0.13 | 0.16 | 0.11 | 0.04 | 0.09 | 0.09 | 0.10 | 0.07 | 0.13 |
| $K_2O$ | 2.61 | 3.25 | 4.31 | 4.14 | 4.86 | 6.02 | 0.99 | 2.22 | 0.63 | 1.54 | 1.28 | 1.86 | 2.24 | 4.29 | 3.46 | 4.53 | 3.36 | 7.41 |
| $TiO_2$ | 0.888 | 1.982 | 0.396 | 6.018 | 0.304 | 0.381 | 0.250 | 0.308 | 0.160 | 0.360 | 0.464 | 0.166 | 0.221 | 0.144 | 1.089 | 0.213 | 0.232 | 1.110 |
| $P_2O_5$ | 0.04 | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.06 | 0.09 | 0.67 | 0.08 | 0.09 | 0.06 | 0.05 | 0.09 | 0.08 | 0.06 | 0.08 | 0.04 |
| LOI | 2.72 | 5.13 | 3.90 | 3.46 | 3.72 | 3.45 | 1.64 | 2.54 | 1.28 | 2.01 | 1.83 | 2.76 | 1.29 | 1.65 | 1.56 | 1.96 | 1.45 | 3.42 |
| Co | 3.7 | 2.8 | 3.3 | 3.3 | 3.8 | 3.4 | 7.8 | 2.9 | 1.5 | 0.8 | 1.3 | 1.5 | 2.3 | 1.9 | 2.2 | 4.2 | 2.7 | 7.8 |
| Sc | 7.4 | 9.6 | 5.3 | 18.2 | 5.6 | 7 | 2.5 | 3.7 | 6.6 | 3.8 | 2.5 | 3.7 | 1.4 | 2.4 | 5.9 | 5.5 | 4 | 19.2 |
| Th | 11.6 | 23.9 | 10.4 | 140.0 | 14.2 | 18.8 | 14 | 8.6 | 8.7 | 20.8 | 24.1 | 12.2 | 7.7 | 6.6 | 23.7 | 5.6 | 10.9 | 23.1 |
| La | 25.8 | 44.4 | 20.8 | 47.2 | 37.7 | 48.3 | 73.8 | 50.4 | 59.7 | 59.6 | 41.2 | 47.4 | 21.9 | 19.3 | 54.6 | 21 | 7.1 | 53.5 |
| Zr | 629 | 1336 | 245 | 3105 | 226 | 297 | 254 | 194 | 255 | 580 | 476 | 216 | 213 | 115 | 361 | 124 | 158 | 812 |
| Y | 47 | 29 | 16 | 97 | 18 | 22 | 11 | 41 | 391 | 10 | 13 | 20 | 7 | 10 | 19 | 12 | 9 | 42 |
| Sr | 71 | 182 | 86 | 144 | 118 | 141 | 58 | 80 | 142 | 127 | 120 | 110 | 31 | 75 | 62 | 71 | 45 | 82 |
| Ba | 135 | 166 | 323 | 609 | 375 | 484 | 383 | 42 | 55 | 32 | 33 | 41 | 369 | 870 | 689 | 737 | 536 | 1004 |

"–" below detection limit

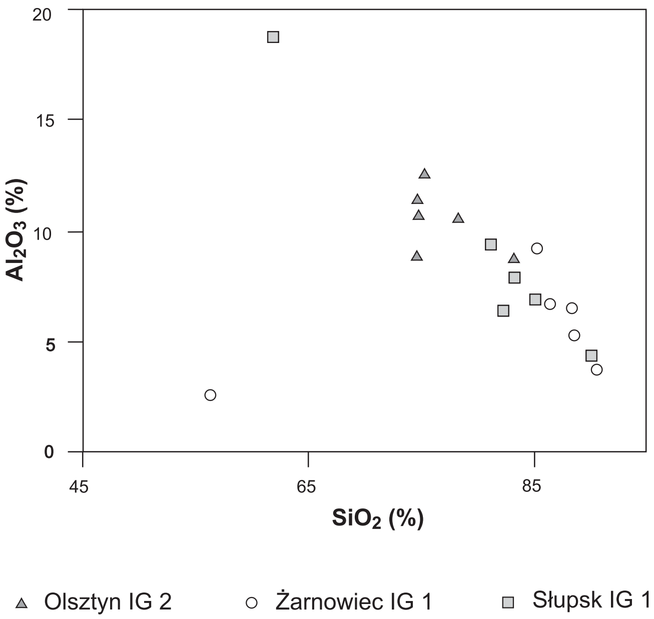



**Fig. 19. Relationship between the contents of $Al_2O_3$ and $SiO_2$ in sandstones of the Żarnowiec Fm.**

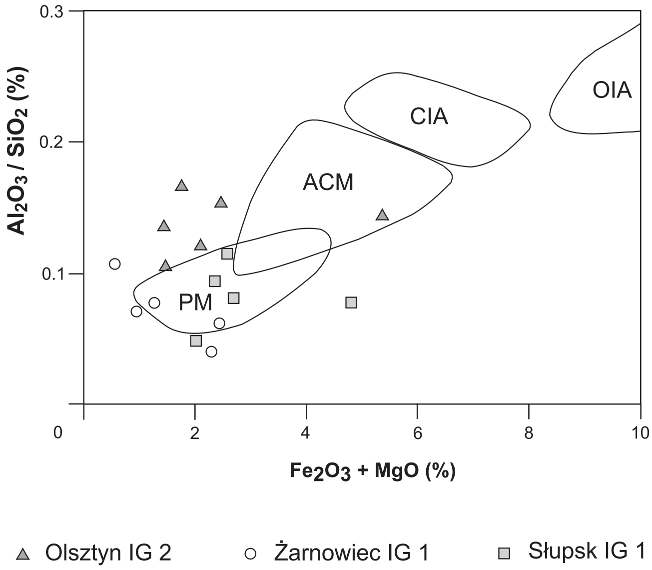



**Fig. 20. $Al_2O_3/SiO_2$ – $Fe_2O_3$* + MgO diagram of geotectonic environments (after Bhatia, 1983) with projection of mineral composition of the Żarnowiec Fm. sandstones**

PM — passive continental margin, ACM — active continental margin, CIA — continental island arc, OIA — oceanic island arc; * — total iron

sults from both almost complete lack of plagioclases in the sediment and diagenetic alterations of potassium feldspars, that proceed mainly towards silicification, not albitization. The high $K_2O$ content is believed to be associated with abundance of potassium feldspars and phyllosilicates. In the samples from the Słupsk IG 1 borehole an essential role in the enhancement of K content is played by sericitized clay matrix. The highest $K_2O$ content was recorded in the sample representing the micalith (see chapter "Grain framework"), which contained sericite matrix, feldspars and 29.0% of mica crystals (muscovite and biotite). Hence, the contents of $Al_2O_3$ (18.76%) and $Fe_2O_3$ (5.36%) are also increased. The latter component originates from biotite ($Fe_2O_3$ represents the total Fe amount). In the remaining cases the increased $Fe_2O_3$ content is associated with the occurrence of iron oxides and hydroxides. This is the case with one sample from the Żarnowiec IG 1 borehole, where the sandstone is cemented by hematite (36.57% $Fe_2O_3$). Moreover, it contains apatite cements (Fig. 10e, f), that is manifested by the extremely high $P_2O_5$ content in the rock (0.67%). The anomalously high $TiO_2$ contents (6.02%) are caused by the occurrence of titanium accessory minerals (ilmenite, anatase).

Contents of some of the main chemical elements gave Bhatia (1983) a base for the construction of discrimination diagrams of geotectonic environments. One of such diagrams is based on the relationship between $Al_2O_3/SiO_2$ and $Fe_2O_3$ + MgO contents. The projection points of the Żarnowiec Fm. sandstones do not concentrate exactly within the defined sectors of this diagram (Fig. 20). They are distributed within the PM area (passive continental margin) and concentrate around it. It refers in particular to the Olsztyn IG 2 section, where the concentration of $Al_2O_3$, associated with the considerable amount of feldspars, is the highest.

Fe and Ti are also very useful for interpretations due to their low mobility and short residence time in sea water. In the $TiO_2$ – $Fe_2O_3$ + MgO discrimination diagram (Fig. 21) the projection points are also distributed within and around the PM area. Several samples with the high Ti content (accessory minerals — ilmenite, anatase) are located outside the defined sectors or even beyond the limits of the diagram. The $K_2O/Na_2O$ – $Fe_2O_3$ + MgO discrimination diagram cannot be used for interpretations due to the extremely high values of $K_2O/Na_2O$ ratio.

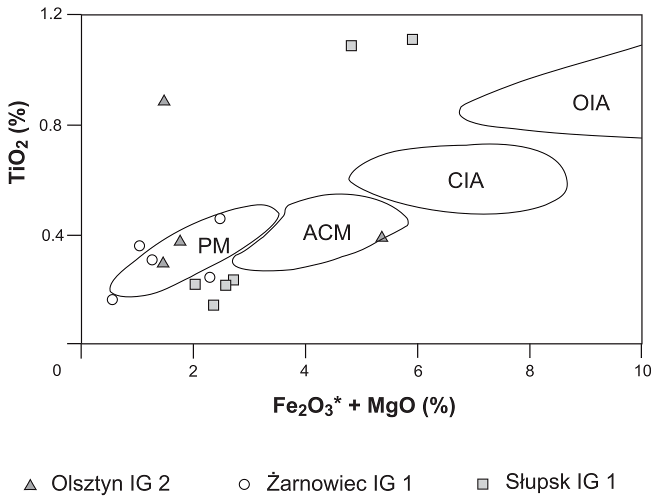



**Fig. 21. $TiO_2$ – $Fe_2O_3^*$ + MgO diagram of geotectonic environments (after Bhatia, 1983) with projection of mineral composition of the Żarnowiec Fm. sandstones**

Explanations as in Figure 20

They are highly variable (from 2.9 to 57.0) exceeding by several times (even up to 30 times) the maximum value of this parameter used for the diagram construction. According to Bhatia (1983) the high variability of $K_2O/Na_2O$ and $Al_2O_3/CaO + Na_2O$ ratios is characteristic of sandstones that originated from the passive continental margin. The $Al_2O/CaO + Na_2O$ ratio varies within very broad limits (from 24 to 93.8) and the average values for individual boreholes are as follows: 17.6 (Olsztyn IG 2), 20.4 (Żarnowiec IG 1) and 35.6 (Słupsk IG 1). These values are so high that they go beyond the scale of the diagram (for the $Al_2O/CaO + Na_2O/Fe_2O_3 + MgO$ ratio). This fact indicates that the studied rocks can be related to the passive continental margin. The contents of the main chemical components and their mutual quantitative relationships in sandstones of the Żarnowiec Fm. show that clastic material was derived from the passive continental margin.

## TRACE CHEMICAL ELEMENTS

The following trace chemical elements were analysed: Y, La (representing rare earth chemical elements) and Sr, Ba, Co, Sc, Th, Zr (Tab. 4).

The Sr content does not considerably varies in individual sections, and the smallest amounts of Sr occur in samples collected from the Słupsk IG 1 borehole. The amount of Ba is much more variable and a relative enrichment in this chemical element is observed in the samples from the Słupsk IG 1 borehole, in particular in the micalith (1004 ppm) where Ba occurs in micas and partly in potassium feldspars. In the Olsztyn IG 2

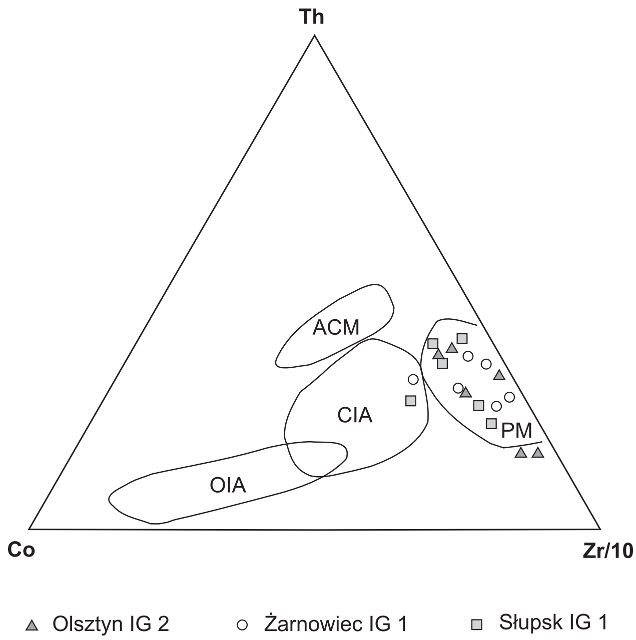



**Fig. 23. Th–Co–Zr diagram of geotectonic environments (after Bhatia and Crook, 1986) with projection of mineral composition of the Żarnowiec Fm. sandstones**

Explanations as in Figure 20

section the average Ba content is 349 ppm, where Ba is a component of potassium feldspars and pseudomorphs after them, filled among others with barite (Fig. 9e). Sandstones from the Żarnowiec IG 1 borehole are very poor in micas and feld-

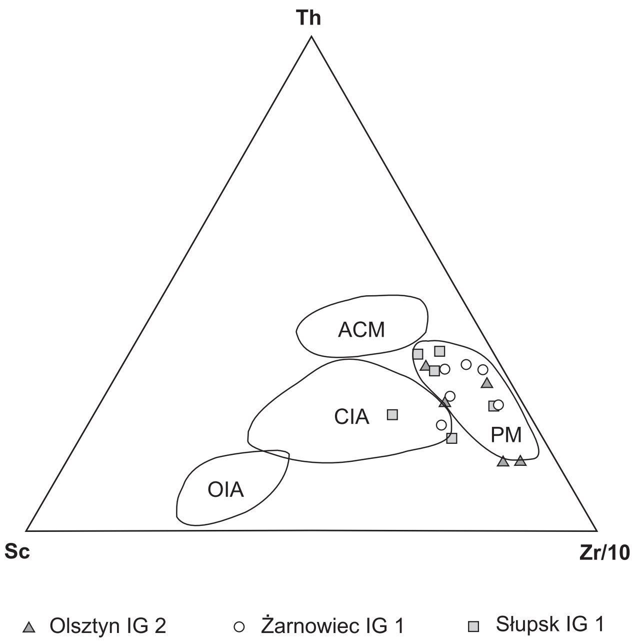



**Fig. 22. Th–Sc–Zr diagram of geotectonic environments (after Bhatia and Crook, 1986) with projection of mineral composition of the Żarnowiec Fm. sandstones**

Explanations as in Figure 20

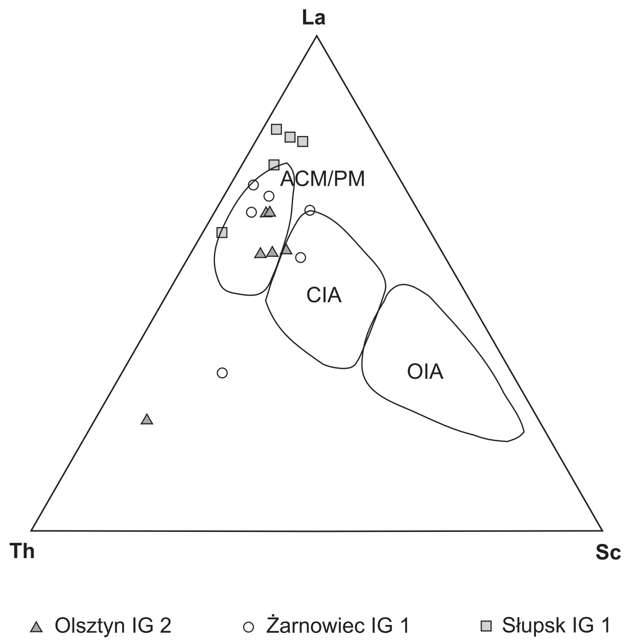



**Fig. 24. La–Th–Sc diagram of geotectonic environments (after Bhatia and Crook, 1986) with projection of composition of the Żarnowiec Fm. sandstones**

Explanations as in Figure 20

spars, and therefore they contain small amounts of Ba (98 ppm on the average). Among magmatic rocks, syenites, foyaites and charnockites are especially highly enriched in Ba (Polański, Smulikowski, 1969).

The Y content is uniform, except in one sample (391 ppm), and varies from 7 to 97 ppm. Only in a sandstone with apatite cement (Żarnowiec IG 1 borehole), the Y content is drastically increased to 391 ppm.

Among chemical elements used for interpretations on diagrams given by Bhatia and Crook (1986) the Co content shows the smallest variations in the studied rocks. The Sc content is highly increased in two samples probably due to the much amount of biotite in the micalith (Słupsk IG 1 borehole) and high concentration of ilmenite in the arkose (Olsztyn IG 2 borehole). The Th content is below 20 ppm in most of the samples investigated, and only in a sandstone from the Olsztyn IG 2 borehole it reaches 140 ppm with the considerably increased Zr content (3105 ppm). This is the case with the above-mentioned ilmenite-rich sample. Large amounts of Zr in two samples from the Olsztyn IG 2 borehole (over 1000 ppm) can be explained by an increased content of zircon grains.

Almost all the projection points in the Th–Sc–Zr discrimination diagram (Fig. 22) are distributed within the PM area (passive continental margin), and only three of them (two from the Słupsk IG 1 borehole and one from the Żarnowiec IG 1 borehole) within the CIA area (continental island arch).

The distribution of projection points in the Th–Co–Zr discrimination diagram (Fig. 23) indicates that the Żarnowiec Formation sandstones were derived from the craton (PM). Also in this diagram, single points are included within the CIA sector (one from the Słupsk IG 1 borehole and one from the Żarnowiec IG 1 borehole).

The greatest scatter of projection points is observed in the La–Th–Sc diagram (Fig. 24), where most of the points are distributed within the ACM/PM area (active continental margin/passive continental margin), two points are within the CIA area (Słupsk IG 1 borehole) and several points are located beyond the defined sectors.

The content of trace chemical elements and their mutual quantitative relationships in the Żarnowiec Formation sandstones are the other arguments in favour of the conclusion that clastics were derived from the passive continental margin. The distribution of some of the projection points in the discrimination diagram can also suggest a minimum influence of another geotectonic environment — continental island arch, but this environment should be considered little probable. It is not supported by the analysis of diagrams based on the contents of the main chemical components.

# FACIES ANALYSIS

## INTRODUCTORY REMARKS

In drillcore studies, facies is a drillcore interval of a given borehole, being conspicuous by characteristic lithological features and a definite set of sedimentary structures. This definition is the basis for the coding system of facies (see below). Each facies can occur many times in the investigated sections. The facies analysis demonstrated in the present paper consists of the following successive tasks:

— general characteristics of sedimentary conditions;

— facies identification;

— interpretation of conditions under which facies were formed;

— identification of facies associations, grouping facies of individual depositional systems;

— construction of the depositional model;

— determination of transport directions and location of source areas of clastic material;

— interpretation of geotectonic setting.

Facies identification was performed using sedimentological logs (Figs. 30–36). The logs were originally drawn at the scale of 1:250. Grain size is illustrated by the width of the lithology column. Special symbols denote the maximum pebble size and colour of deposits. Also is marked the occurrence of thin interbeds. “Thin interbeds” means that beds are too small in thickness (below 25 cm) to be illustrated to the original vertical scale. The presence of thin interbeds is marked with horizontal lines whose length is proportional to the grain size. Sedimentary structures are indicated with graphic symbols. The criteria used for identification of the upper boundary of the Żarnowiec Fm. made that much attention is devoted to bioturbation structures. They are the characteristic feature of the transitional complex which overlies the Żarnowiec Fm. Bioturbation structures are commonly represented by vertically oriented dwelling burrows. Individual facies were identified in each section by distinguishing intervals characterized by specific lithologies (e.g. medium- and coarse-grained gravelly sandstones), and within them — intervals with the occurrence of characteristic sedimentary structures (e.g. horizontal bedding).

Individual facies are denoted with a letter symbols as their shortest description. The coding system includes the two major features of each facies: grain size and sedimentary structures (cf. Miall, 1977; Hwang, Chough, 2000). Considering the grain size, the following facies have been identified: C — conglomerates, S — sandstones, M — mudstones.

The occurrence and type of sedimentary structures is denoted by the following symbols: m — massive structureless deposits, g — grain-size grading, h — horizontal bedding, c — large-scale cross bedding, r — small-scale cross bedding (ripplemarks).

According to the adopted coding system, the symbol of each facies includes a combination of elements that characterize the grain size and sedimentary structures. For instance, symbol Chc denotes horizontally bedded and large-scale cross-bedded conglomerate facies, and symbol Sg — graded sandstones.

The identified facies and facies associations (FA) enabled detailed interpretation of sedimentary conditions of the Żarnowiec Fm. Each facies association was interpreted in terms of depositional systems assuming after Allen and Allen (1990) that depositional systems are sets of depositional environments linked by the process of sediment dispersal.

## GENERAL CHARACTERISTICS OF SEDIMENTARY CONDITIONS

The most significant features of the Żarnowiec Fm. are as follows (cf. Jaworowski, 1979, 1982, 1997):

— red-brownish colour of deposits, indicating their considerable oxidation and the most probable continental depositional environment;

— almost exclusive occurrence of conglomerates and sandstones (most frequently pebbly and vari-grained);

— low proportions of fine-grained sediments (mudstones);

— lack of any organic remains;

— sedimentary structures, indicating transport and deposition of clastic material during episodes of high water discharge;

— occurrence of deposits characteristic for sediment gravity flows.

All these features when considered together lead to the conclusion that the Żarnowiec Fm. was deposited in the coarse-grained alluvial environment under continental conditions and a semi-arid climate with intermittent rainfloods. According to the earlier opinions (Jaworowski, 1979, 1982, 1997), these deposits were accumulated in the environment of very vast alluvial fans. Both the above-presented general characteristics of the Żarnowiec Fm. and the research results discussed in this report suggest that this view should be revised. The studied deposits might have been deposited not only on alluvial fans but also in the environment of sandy and gravelly alluvial plain. The thickness proportions of individual facies in the Żarnowiec Fm. sections (see below) seem to suggest that the amount of alluvial fan deposits is smaller than it was believed before.

The concept of alluvial fans has been a subject of many controversies in the literature (see discussion given by Miall, 2000). In the present paper the Blair and McPherson's (1994) concept has been adopted. It assumes that the alluvial fan is represented by an alluvial depositional body with a relatively high slope inclination (up to 25°) that leads to the formation of characteristic facies associations. The last mentioned aspect is particularly important in the facies analysis of the ancient alluvial fan environment. The Blair and McPherson's (1994) concept of the alluvial fan assumes that it consists of debris flow deposits, and, moreover, hyperconcentrated flow and sheetflood deposits.

## DESCRIPTION AND INTERPRETATION OF FACIES

The available geological material (drillcores) rendered it impossible to make observations leading to a direct use of code symbols of alluvial facies, introduced in the classical papers of Miall (1977, 1985, 1996). It was necessary to make some modifications that relies on simplifications adjusted to the quality of the studied material. The employed coding system has been discussed above. Occurrences of individual facies in the studied sections range in thickness from several centimetres to 5–6 metres. Each facies description includes the most frequent thickness of its occurrences.

The description of facies occurrences also includes the names of boreholes in which the facies were identified, and the percentage of the facies in relation to the total thickness of cored intervals (in brackets).

### FACIES Cm

**Description**. Grain- or matrix-supported massive conglomerates composed mostly of variably rounded quartz and feldspar clasts, from several millimetres to several centimetres in size (Fig. 25a–f; Fig. 26a, b; Fig. 29b). Common mud-sand matrix, rare sand matrix. Occurrences of this facies reach 1 m in thickness.

**Interpretation**. Matrix-supported conglomerates of facies Cm were deposited as a result of debris flows. Grain-supported massive conglomerates can also represent debris flow deposits. However, in this case they are probably associated with very high water discharge. These deposits may have been accumulated in braided gravelly streams or rivers as channel bars or channel lags. Some of the grain-supported conglomerates with a sand matrix can be interpreted as sieve deposits. Conglomerates of facies Cm very often are both grain- and matrix-supported. Conglomerates of this type probably represent debris flow deposits partly reworked by running waters. In some thin beds of a matrix-supported conglomerates subhorizontal orientation of clasts is observed (Fig. 26c). These beds represent relatively diluted debris flow deposits.

**Occurrence**. Żarnowiec Fm.: Darżlubie IG 1 (3.1%), Gdańsk IG 1 (75.0%), Kościerzyna IG 1 (3.5%), Malbork IG 1 (4.5%), Olsztyn IG 2 (1.7%), Słupsk IG 1 (8.4%), Żarnowiec IG 1 (2.9%).

Transitional complex: Kościerzyna IG 1 (4.1%), Olsztyn IG 2 (2.0%).

## FACIES Cg

**Description**. Graded conglomerates with normal grading being the most common (Fig. 27a). Fining-upward grading from gravel (10–20 mm) to fine sand, and even to mud (Fig. 27d) is observed. Inversely graded conglomerates are rare. Occurrences of facies Cg most commonly reach 0.5 m in thickness.

**Interpretation**. Both normal and inversely graded conglomerates of facies Cg may have been deposited as a result of debris flows (cf. Shanmugam, 1997).

**Occurrence**. Żarnowiec Fm.: Kościerzyna IG 1 (0.7%), Słupsk IG 1 (1.6%).

Transitional complex: no occurrence of facies Cg.

## FACIES Chc

**Description**. Grain-supported conglomerates with very indistinct horizontal or large-scale cross bedding. On the basis on the available drillcores it is impossible to find whether the cross bedding is represented by flat or trough cross bedding. The most common thickness of occurrences of facies Chc is 0.5 m.

**Interpretation**. Conglomerates of facies Chc represent channel bars and fills of braided gravelly streams or rivers.

**Occurrence**. Żarnowiec Fm.: Darżlubie IG 1 (6.2%), Hel IG 1 (12.6%), Kościerzyna IG 1 (14.8%), Słupsk IG 1 (3.9%), Żarnowiec IG 1 (1.4%).

Transitional complex: Kościerzyna IG 1 (12.4%).

## FACIES Sm

**Description**. Massive vari-grained sandstones (Fig. 27e; Fig. 29c, e). Facies Sm is subdivided into subfacies: SmS — massive sandstones, and subfacies SmP — massive pebbly sandstones. The most common thickness of subfacies SmS and SmP is 0.5 m and 1.0 m, respectively.

**Interpretation**. Sandstones of facies Sm were deposited as a result of decelerating high-energy flows. Some of sandstones of this facies show very indistinct incipient horizontal bedding (Fig. 27e). Facies Sm represents sheetfloods related to intermittent heavy rainfalls.

**Occurrence**. S u b f a c i e s SmS. Żarnowiec Formation: Kościerzyna IG 1 (0.5%), Malbork IG 1 (25.0%), Olsztyn IG 2 (3.4%), Żarnowiec IG 1 (2.9%).

Transitional complex: Darżlubie IG 1 (73.3%), Malbork IG 1 (53.3%), Olsztyn IG 2 (12.0%), Słupsk IG 1 (15.5%), Żarnowiec IG 1 (30.4%).

S u b f a c i e s SmP. Żarnowiec Fm.: Kościerzyna IG 1 (4.3%), Malbork IG 1 (36.4%), Olsztyn IG 2 (71.6%), Słupsk IG 1 (10.3%), Żarnowiec IG 1 (13.0%).

Transitional complex: Kościerzyna IG 1 (8.3%), Olsztyn IG 2 (35.0%), Słupsk IG 1 (4.5%).

## FACIES Sg

**Description**. Graded vari-grained, commonly pebbly, sandstones. Both normal and inverse grading is observed. The latter is less common. Transitions from normal to inverse grading is occasionally visible (Fig. 28e). Occurrences of facies Sg, locally composed of several graded beds, most commonly reach from ten to several tens of cm in thickness.

**Interpretation**. Sandstones of facies Sg show normal grading which indicates gradually decelerating flows with considerably high initial energy. This facies was formed presumably as a result of deposition from sheetfloods caused by intermittent heavy rainfalls. Sandstones, in which transition from normal to inverse grading is observed, seem to indicate a slow growth-and-fall in energy of flood events. Deposits of facies Sg, represented in the continental-marine transitional complex by normal-graded sandstones, may be of a different origin. These are probably marine sand storm beds.

**Occurrence**. Żarnowiec Fm.: Kościerzyna IG 1 (1.5%), Malbork IG 1 (9.1%), Słupsk IG 1 (1.0%).

Transitional complex: Malbork IG 1 (8.7%).

## FACIES Sh

**Description**. Horizontally bedded vari-grained sandstones (Fig. 26c–f; Fig. 27a, d, f; Fig. 28a, c; Fig. 29c, d, f). The bedding is commonly poorly visible in particular in coarse-grained sandstones (Fig. 26d). In fine-grained sandstones it is better developed and locally occurs as fine lamination (Fig. 29f). Facies Sh includes: subfacies ShS — horizontally bedded sandstones, and subfacies: ShP — horizontally bedded pebbly sandstones. The most common thickness of subfacies ShS and ShP is 0.5 and 1.0 m, respectively.

**Interpretation**. Sandstones of facies Sh were deposited as a result of deposition from high-energy flows in a plane-bed phase of the upper flow regime. These deposits are associated with sheetfloods on fans and sand alluvial plains, as well as with braided sandy streams and rivers. A fine horizontal lamination might have been formed under slower flow conditions in a plane-bed phase of the lower flow regime.

**Occurrence**. S u b f a c i e s ShS. Żarnowiec Fm.: Darżlubie IG 1 (37.5%), Kościerzyna IG 1 (23.5%), Słupsk IG 1 (39.6%), Żarnowiec IG 1 (8.7%).

Transitional complex: Darżlubie IG 1 (13.3%), Hel IG 1 (39.6 %), Kościerzyna IG 1 (31.2%), Malbork IG 1 (33.7%), Olsztyn IG 2 (20.0%), Słupsk IG 1 (41.3%), Żarnowiec IG 1 (30.4%).

S u b f a c i e s ShP. Żarnowiec Fm.: Darżlubie IG 1 (31.2%), Gdańsk IG 1 (25.0%), Hel IG 1 (43.7%), Kościerzyna IG 1 (42.4%), Olsztyn IG 2 (23.3%), Słupsk IG 1 (23.1%), Żarnowiec IG 1 (34.8%).

Transitional complex: Hel IG 1 (8.3%), Kościerzyna IG 1 (12.5%), Olsztyn IG 2 (21.0%), Słupsk IG 1 (8.4%).

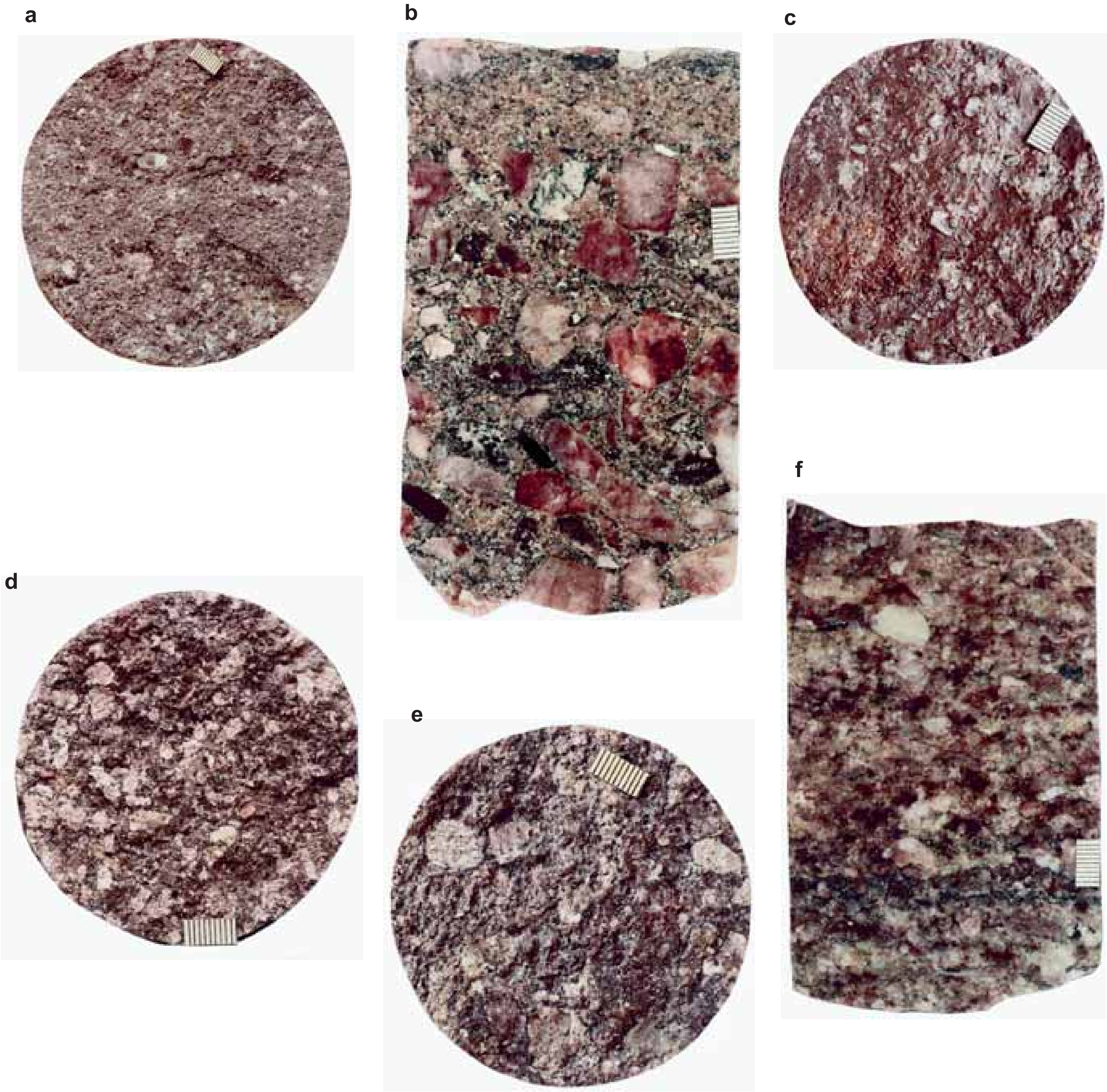



**Fig. 25.** Scale marked in millimeters; **a** — facies Cm — matrix-supported massive conglomerate; Żarnowiec IG 1 borehole, depth 3229.0 m; **b** — facies Cm — grain- and matrix-supported massive conglomerate; Słupsk IG 1 borehole, depth 5018.2 m; **c** — facies Cm — matrix-supported massive conglomerate; Kościerzyna IG 1 borehole, depth 5138.0 m; **d** — facies Cm — grain-supported massive conglomerate; numerous feldspar grains poorly rounded; Malbork IG 1 borehole, depth 3659.5 m; **e** — facies Cm — grain- and matrix-supported massive conglomerate; numerous variably rounded feldspar grains; Kościerzyna IG 1 borehole, depth 5104.5 m; **f** — facies Cm — grain-supported massive conglomerate; Słupsk IG 1 borehole, depth 5064.3 m

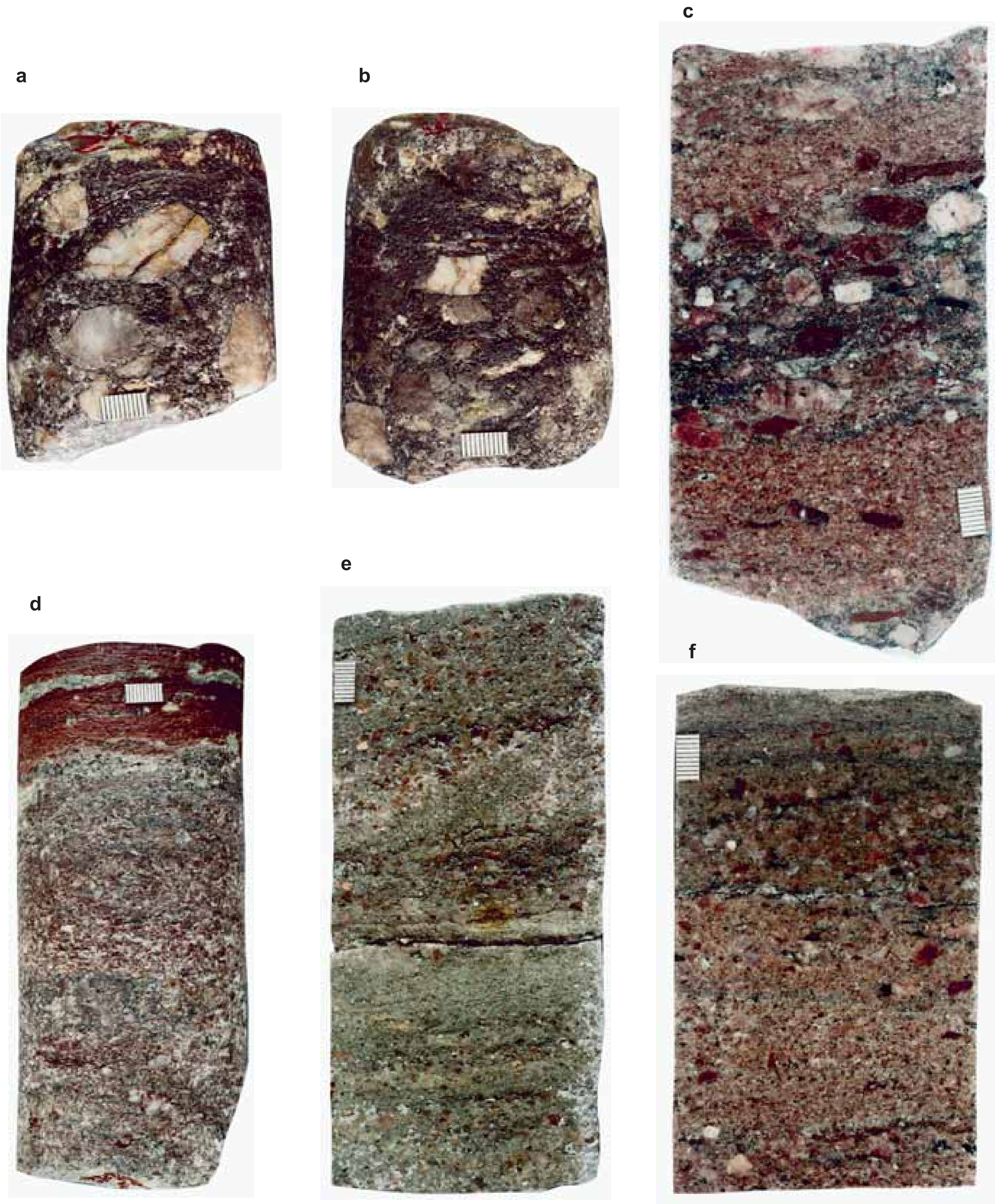



**Fig. 26.** Scale marked in millimeters; **a** — facies Cm — matrix-supported massive conglomerate; Darżlubie IG 1 borehole, depth 3509.3 m; **b** — the same drillcore fragment as in **a**, rotated by 180°; **c** — facies Sh (subfacies ShP) — horizontally bedded pebbly sandstone; in the centre: facies Cm — massive grain- and matrix-supported conglomerate; note subhorizontal orientation of some of clasts; Słupsk IG 1 borehole, depth 5030.7 m; **d** — facies Sh (subfacies ShP) — indistinct horizontal bedding in medium- and coarse-grained pebbly sandstone; at the top: facies Mm — massive mudstone; Kościerzyna IG 1 borehole, depth 5135.5 m; **e** — from bottom to top: facies Sh (subfacies ShP) — indistinct horizontal bedding in medium- and coarse-grained pebbly sandstone; facies Sr — small-scale cross-bedded fine-grained sandstone; facies Sc (subfacies ScP) — large-scale cross-bedded medium- and coarse-grained pebbly sandstone; Hel IG 1 borehole, depth 3481.5 m; **f** — Facies Sh (subfacies ShP) — indistinct horizontal bedding in very coarse-grained pebbly sandstone; normal grading visible at the top; Słupsk IG 1 borehole, depth 5001.2 m

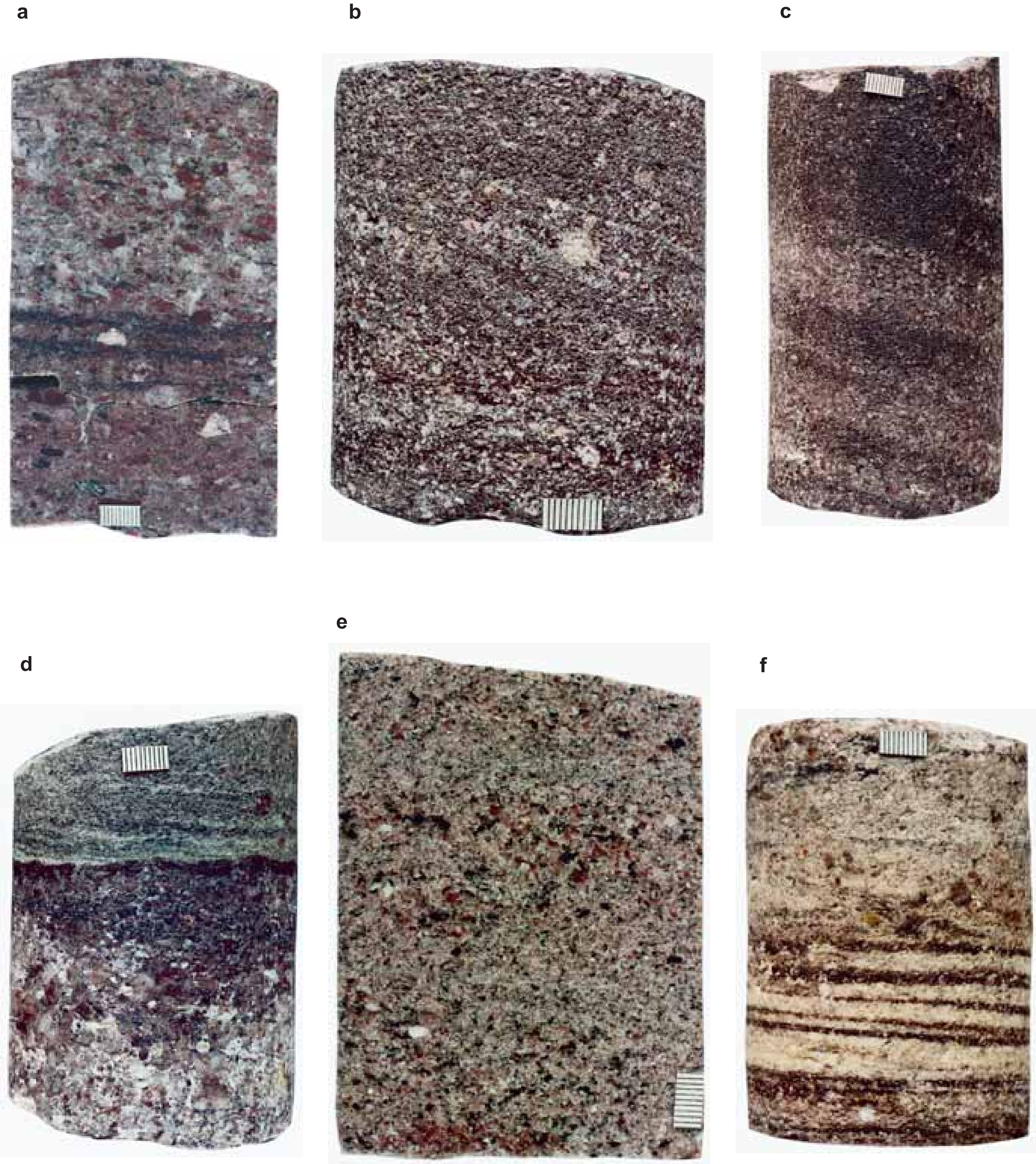



**Fig. 27.** Scale marked in millimeters; **a** — from bottom to top: facies Sh (subfacies ShP) — horizontally bedded medium- and coarse-grained pebbly sandstone and facies Cg — normally graded conglomerate; Słupsk IG 1 borehole, depth 5021.4 m; **b** — facies Sc (subfacies ScP) — large-scale cross-bedded very coarse-grained pebbly sandstone; Malbork IG 1 borehole, depth 3660.5 m; **c** — facies Sc (subfacies ScP) — large-scale cross-bedded very coarse-grained pebbly sandstone; Kościerzyna IG 1 borehole, depth 5041.2 m; **d** — at the bottom: facies Cg — normally graded conglomerate passing into mudstone with desiccation cracks; above: facies Sh (subfacies ShS) horizontally laminated fine-grained sandstone; Kościerzyna IG 1 borehole, depth 5056.8 m; **e** — facies Sm (subfacies SmS) — massive medium- and coarse-grained sandstone, with incipient horizontal lamination (?); Słupsk IG 1 borehole, depth 4978.8 m; **f** — at the bottom: facies Sh (subfacies ShS) horizontally bedded medium- and coarse-grained sandstone; above: facies Sm (subfacies SmP) — massive medium- and coarse-grained pebbly sandstone; Darżlubie IG 1 borehole, depth 3505.6 m

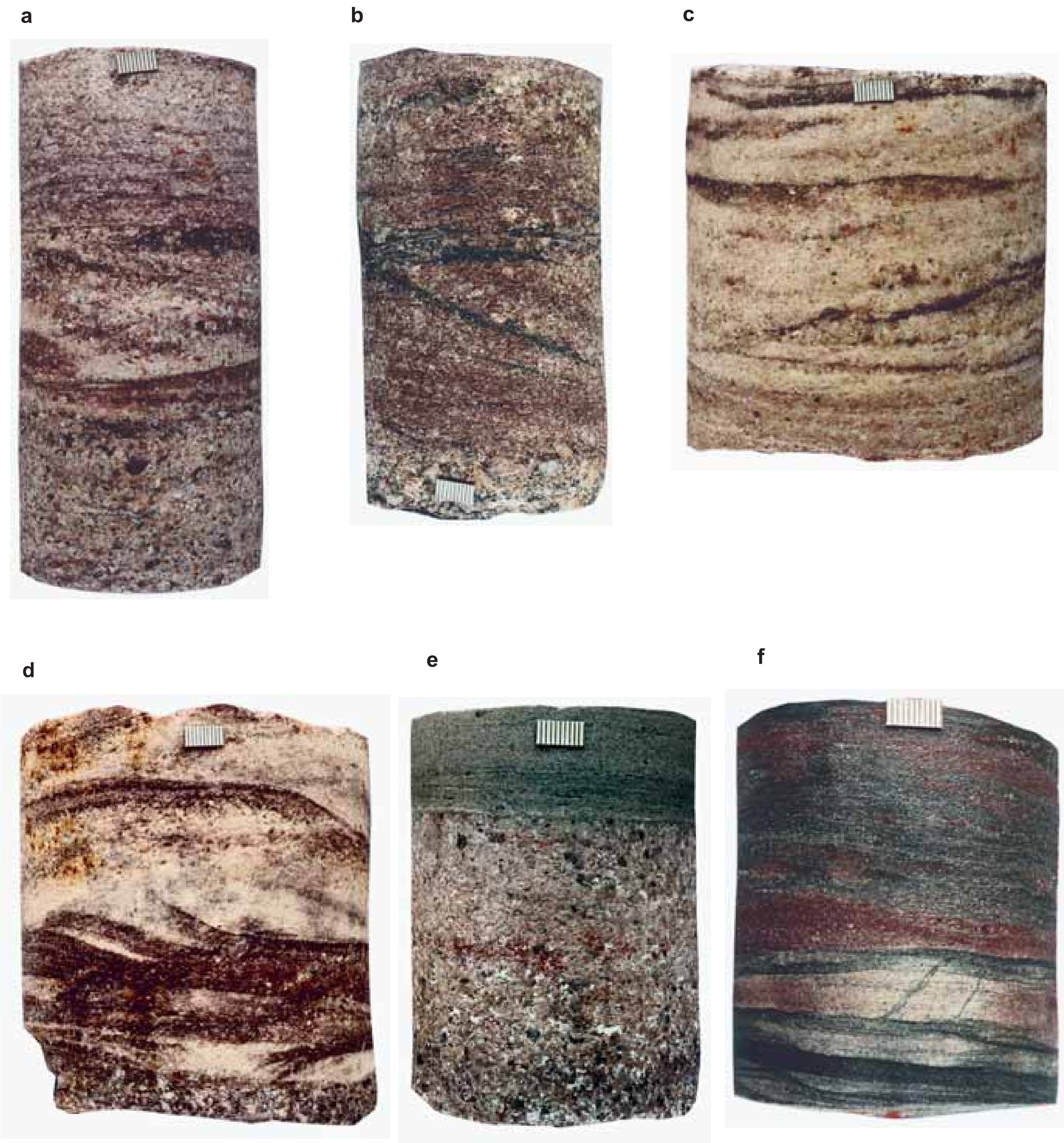


**Fig. 28.** Scale marked in millimeters; **a** — from bottom to top: facies Sh (subfacies ShS) — indistinct horizontal bedding in very coarse-grained pebbly sandstone; facies Sc (subfacies ScS) — large-scale cross-bedded medium- and coarse-grained sandstone; facies Sh (subfacies ShS) — indistinct horizontal bedding in medium- and coarse-grained sandstone; Kościerzyna IG 1 borehole, depth 5064.5 m; **b** — facies Sc (subfacies ScS) — large-scale cross-bedded very coarse-grained sandstone; Kościerzyna IG 1 borehole, depth 5073.0 m; **c** — at the bottom: facies Sh (subfacies ShS) — horizontally bedded medium- and coarse-grained sandstone; above: facies Sc (subfacies ScS) — large-scale cross-bedded medium- and coarse-grained sandstone; Żarnowiec IG 1 borehole, depth 3218.0 m; **d** — at the bottom: facies Sr — small-scale cross-bedded medium- and coarse-grained sandstone; above: medium- and coarse-grained sandstone — facies Sc (subfacies ScS); Żarnowiec IG 1 borehole, depth 3224.4 m; **e** — at the bottom: facies Sg — normally graded medium- and coarse-grained sandstone, passing into inversely graded sandstone; above: facies Sh (subfacies ShS) — horizontally laminated fine-grained sandstone; Kościerzyna IG 1 borehole, depth 5057.9 m; **f** — facies Mrh — mudstone and sand/mud heterolith with lenticular and wavy bedding; Słupsk IG 1 borehole, depth 4985.5 m

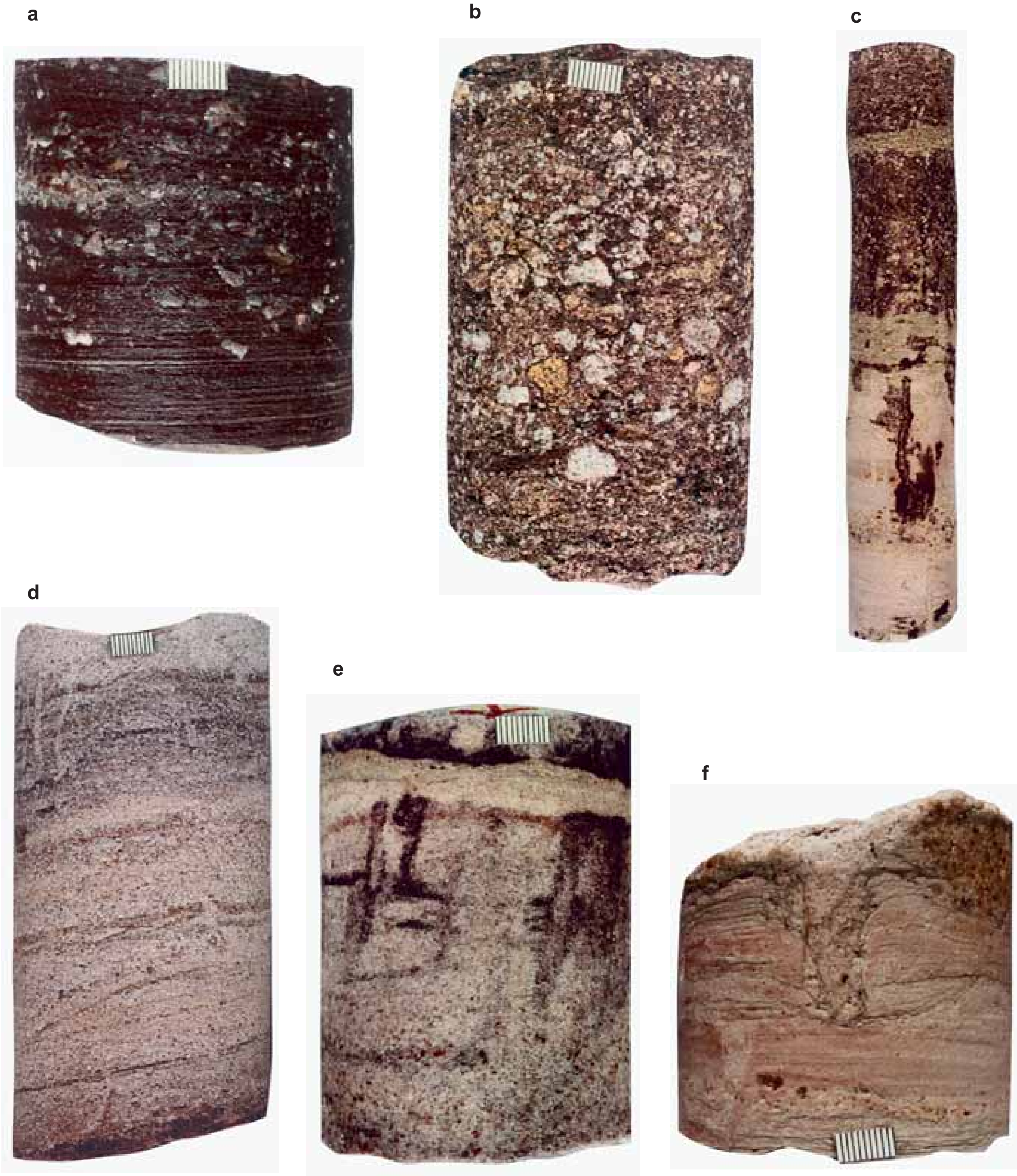



**Fig. 29.** Scale marked in millimeters; **a** — facies Mm — massive mudstone with scattered fine pebbles; Malbork IG 1 borehole, depth 3657.7 m; **b** — facies Cm — grain-supported massive conglomerate; transitional complex — continental-marine deposits; Olsztyn IG 2 borehole, depth 2709.1 m; **c** — at the bottom: facies Sh (subfacies ShS) — horizontally laminated fine-grained sandstone with admixture of finepabbles; note vertical burrows; above: facies Sm (subfacies SmP) – massive medium- and coarse-grained pebbly sandstone; transitional complex – continental-marine deposits; Olsztyn IG 2 borehole, depth 2706.3 m; **d** — facies Sc (subfacies ScS) and Sh (subfacies ShS): large-scale cross bedded medium- and coarse-grained sandstone, passing upwards into horizontally bedded sandstone with vertical bioturbation structures; transitional complex — continental-marine deposits; Malbork IG 1 borehole, depth 3637.7 m; **e** — facies Sm (subfacies SmS) — massive medium- and coarse-grained sandstone with vertical bioturbation structures; transitional complex — continental-marine deposits; Malbork IG 1 borehole, depth 3640.4 m; **f** — facies Sh (subfacies ShS) — horizontally laminated fine-grained sandstone; a vertical burrow filled with very coarse-grained sandstone (subfacies SmS); transitional complex — continental-marine deposits; Olsztyn IG 2 borehole, depth 2703.6 m

### FACIES Sc

**Description**. Large-scale cross-bedded vari-grained sandstones (Fig. 27b, c; Fig. 28b, c; Fig. 29d). It was impossible to distinguish between flat and trough cross bedding, on the basis of available drillcores. It seems that flat cross bedding is more common. Facies Sc is subdivided into subfacies ScS — large-scale cross-bedded sandstones, and subfacies ScP — large-scale cross-bedded pebbly sandstones. The most frequent thickness of subfacies ScS ranges from over 10 cm to 1.0 m, while subfacies ScP is usually 0.5 m thick.

**Interpretation**. Sandstones of facies Sc were deposited in the lower flow regime. They represent transverse and longitudinal channel bars of braided sandy streams and rivers.

**Occurrence**. Subfacies ScS. Żarnowiec Fm.: Darżlubie IG 1 (15.6%), Kościerzyna IG 1 (2.8%), Słupsk IG 1 (6.4%), Żarnowiec IG 1 (3.6%).

Transitional complex: Darżlubie IG 1 (13.3%), Hel IG 1 (39.6%), Kościerzyna IG 1 (2.1%), Malbork IG 1 (4.3%), Olsztyn IG 2 (2.0%), Słupsk IG 1 (15.5%), Żarnowiec IG 1 (30.4%).

Subfacies ScP. Żarnowiec Fm.: Darżlubie IG 1 (6.3%), Hel IG 1 (43.7%), Kościerzyna IG 1 (5.8%), Malbork IG 1 (9.1%), Słupsk IG 1 (2.6%), Żarnowiec IG 1 (23.9%).

Transitional complex: Hel IG 1 (8.3%), Kościerzyna IG 1 (12.5%), Olsztyn IG 2 (4.0%), Słupsk IG 1 (1.9%).

### FACIES Sr

**Description**. Small-scale cross-bedded vari-grained, mostly fine- and medium-grained rarely coarse-grained sandstones with admixture of fine pebbles (Fig. 26e; Fig. 28d). Thickness varies between 10 and 20 cm.

**Interpretation**. Sandstones of facies Sr were deposited in the lower flow regime within small channel bars of braided sandy streams and rivers.

**Occurrence**. Żarnowiec Fm.: Słupsk IG 1 (1.1%), Żarnowiec IG 1 (8.7%).

Transitional complex: Kościerzyna IG 1 (16.6%), Olsztyn IG 2 (4.0%), Słupsk IG 1 (10.3%).

### FACIES Mm

**Description**. Massive mudstones (Fig. 26d), locally with dispersed coarse-grained sands and gravels (Fig. 29a). Thickness of facies Mm ranges most frequently between several and 20 cm, reaching exceptionally 1.5 m in the Malbork IG 1 borehole.

**Interpretation**. Deposits of facies Mm with dispersed gravel material accumulated as a result of mud flows. Mudstones of this facies without sand and gravel admixtures presumably represent fills of abandoned stream and braided river channels or they were deposited in local small pools after flood events. Note: deposits of facies Mm in the continental-marine transitional complex probably represent shelf muds.

**Occurrence**. The Żarnowiec Fm.: Malbork IG 1 (15.9%). In the other boreholes, deposits of facies Mm occur as thin interbeds within other facies types and their percentage accounts for less than 0.1% of the total thickness of cored intervals. The same refers to the transitional complex.

### FACIES Mrh

**Description**. Mudstones and mud/sand heteroliths. Thin beds of fine-grained sandstones in mudstones show small-scale cross lamination (Fig. 28f). They are accompanied by horizontal sand laminae. Occurrences of facies Mrh most commonly range from several to 20 cm (rarely up to 0.5–1.0 m) in thickness.

**Interpretation**. Deposits of facies Mrh accumulated as a result of alternate deposition from suspension (mud) and weak currents (fine-grained sandy material). They were deposited as fills of abandoned braided stream and river channels. Note: deposits of facies Mrh in the continental-marine transitional complex probably represent shelf muds.

**Occurrence**. Żarnowiec Fm.: Słupsk IG 1 (2.0%). In the other boreholes facies Mrh occurs as thin interbeds within other facies types and its percentage accounts for less than 0.1% of the total thickness of cored intervals.

Transitional complex: Hel IG 1 (4.2%), Słupsk IG 1 (2.6%), Żarnowiec IG 1 (8.7%).

## FACIES ASSOCIATIONS — DEPOSITIONAL SYSTEMS

The pecularity of the studied rock material, which is represented exclusively by drillcores, as well as low density of distribution of boreholes (Fig. 1) render it impossible to make precise reconstructions of the spatial facies pattern. It also precludes a wide use of the facies architecture analysis. Nevertheless, the identification of facies associations (FA) is here an attempt to refer to the major elements of the alluvial facies architecture distinguished by Miall (1985, 2000). Three facies associations have been identified in the Żarnowiec Formation.

### FACIES ASSOCIATION I (FAI)

This association includes the facies (subfacies): Cm, Cg, Chc, ShP, ScP.

According to the interpretation of individual facies, FAI should be related to the depositional system of proximal alluvial fans. The features of FAI reflect depositional conditions characteristic of this system. Proximal parts of alluvial fans are dominated by conglomerates deposited as a result of sediment gravity flows. Some of the conglomerates were accumulated by waters running in channels of intermittent braided streams which commonly dissect and occasionally rework debris flow deposits. Proximal alluvial fans also contain sieve deposits as well as sand and gravel deposits associated with braided streams.

When referring — in simplification — to the facies architecture analysis, it is noteworthy that FAI deposits resemble those elements of the alluvial deposits architecture which were regarded by Miall (1985) as: SG — sediment gravity flows, GB — gravel bars and bedforms, and SB — sand bedforms. The set of these elements is typical of proximal alluvial fans. This is an additional argument for including FAI in this depositional system.

## FACIES ASSOCIATION II (FAII)

This association includes facies (subfacies): Chc, SmP, ShP, ScP, Mm.

According to the interpretation of facies Chc, Sm, Sh and Sc, FAII deposits are considered to belong to the depositional system of distal alluvial fans. This system is characterized by a low inclination of the fan surface and is composed of finer-grained deposits as compared with proximal alluvial fans. The major proportion of this system is represented by coarse-grained sandstones. Conglomerates are subordinate, and mudstones are rare. Conglomerate and pebbly sandstone facies of FAII indicate of high water and sediment discharge. These are interpreted as distal fan deposits accumulated largely in streams and braided rivers, and from sheetfloods. Massive mudstones, containing dispersed coarse-grained sandy and gravelly material, were deposited by mud flows.

FAII deposits resemble those elements of the facies architecture which were classified by Miall (1985) as SB and GB. The co-occurrence of these elements is being related, among others, to large alluvial fans and wide braided rivers. It confirms the interpretation that FAII belongs to the depositional system of distal alluvial fans which are particularly well developed on vast fans gradually passing into alluvial plains.

## FACIES ASSOCIATION III (FAIII)

This association includes facies (subfacies): ShS, ScS, SmS, Sg, Sr, Mm, Mrh.

Deposits of FAIII are assigned to the sandy braid-and-sheetflood plain. Sandy facies (subfacies) typical of FAIII were deposited mainly by braided rivers and — particularly frequently — by sheetfloods. The origin of these deposits is similar to that of FAII, which represents the depositional system of distal alluvial fans. This fact is obvious since deposition from braided streams, rivers and sheetfloods is the dominant process in both the distal alluvial fans and sandy plains, subjected to periodic and dramatic floods.

Massive mudstones and mud/sand heteroliths which are a component of FAIII were developed in abandoned braided river channels.

The affinities between FAII and FAIII entailed that the grain size, fining outwards from proximal alluvial fans, is the dominant parameter to discriminate between these two associations. According to this criterion, facies and subfacies of pebbly sandstones are included within FAII (i.e. belong to the depositional system of distal alluvial fans), whereas facies and subfacies of sandstones with low or no content of pebbly material are referred to FAIII (i.e. belong to the depositional system of sandy braid-and-sheetflood plain). This is an arbitrary division but the discrimination between depositional environments of the alluvial fan and braided river is usually arbitrary (cf. discussion in Miall, 1977).

Deposits of FAIII are similar to the facies architecture elements proposed and interpreted by Miall (1985) as: SB — sand bedforms and LS — laminated sand sheets. The exclusive presence of element SB is associated with distal braidplains, whereas the co-occurrence of elements SB and LS, very frequent in FAIII, indicates the sheetflood alluvial plain. In both these elements transport and deposition of sand material is associated largely with intermittent rainfalls. Thus, the inclusion of FAIII in the depositional system of sandy braid-and-sheetflood plain finds the additional justification.

## FACIES OF THE TRANSITIONAL COMPLEX

The transitional complex is represented by almost all the facies (except for facies Cg) and facies associations identified within the Żarnowiec Fm. As it was indicated before, the basic difference is that deposits of the transitional complex contain bioturbation structures (Fig. 29c–f). It proves that the complex was deposited, at least in part, in a shallow sea. Researches conducted by Pacześna (1996) show that the oldest ichnocoenoses of northern Poland commonly represent a high-energy marine environment associated with the intertidal zone. An ichnocoenose, typical of the low-energy subtidal zone (below the wave base), was identified only in the Kościerzyna IG 1 borehole.

The occurrence of facies known from the Żarnowiec Fm. in the transitional complex was originally interpreted as the evidence for the existence of fan deltas at the transition from the Vendian to Cambrian in onshore and offshore northern Poland (Jaworowski, 1982). Subsequently, it was assumed that these were braid deltas (Jaworowski, 1997). The identification of the depositional system of sandy braid-and-sheetflood plain (FAIII) in the Żarnowiec Fm. confirms the opinion of the existence of braid deltas. It should be assumed (see below) that during the deposition of the transitional complex, as the Lower Cambrian transgression proceeded, both types of coarse-grained deltas developed (fan deltas and braid deltas sensu McPherson *et al*., 1987).

Facies associations identified within the Żarnowiec Fm. also suggest that, in the continental-marine environment of the transitional complex, they formed shallow water deltas of type A and type B, according to the classification of deltas proposed by Postma (1990). In the case of the A type shallow water delta (fan delta), FAI developed on the delta plain, whereas the delta front and prodelta were composed of FAII. In the case of the B-type shallow water delta (braid delta), FAII developed on the delta plain and delta front, whereas the prodelta was the site of deposition of FAIII. The considerable proportions of subfacies ShP and ShS in FAII and FAIII suggest that, according to the classification scheme of Corner (fide Nemec, 1990), these were gentle-slope "mouth-bar" deltas, lacking cross-sets.

## REGIONAL TRANSPORT DIRECTIONS AND LOCATION OF SOURCE AREAS OF CLASTIC MATERIAL

The lack of oriented drillcores makes it impossible to use sedimentary structures (in particular large-scale cross bedding) for direct determination of transport directions. The only way out is to bring together the results of facies analysis and petrographical and geochemical studies. The thickness proportions of facies associations (Figs. 30–36) allow to classify the studied sections to the two main depositional systems: alluvial fans and alluvial plains. A more detailed classification of depositional systems in individual sections is impossible as some of the facies occur in associations related to both the proximal and distal alluvial fans. The same refers to the alluvial plains where there are facies observed in associations formed both within the braid plain and sheetflood plain. It has been assumed that every studied section should be included within depositional system which predominates in thickness in this very section. Accordingly, cored intervals of individual sections of the Żarnowiec Fm. have been interpreted as follows:

Darżlubie IG 1 borehole (Fig. 30). This section is dominated by FAIII that accounts for 53%. The percentage contribution of deposits representing the alluvial plain depositional system is almost equal as that of the alluvial fan depositional system. The Darżlubie IG 1 section should be related to the area located at the transition between these two depositional systems.

Hel IG 1 borehole (Fig. 31). The only facies associations observed here are FAI and FAII. The section is located within the area of the alluvial fan depositional system.

Kościerzyna IG 1 borehole (Fig. 32). FAI and FAII are dominant, comprising 73% of the total thickness. It means that this section should be related to the alluvial fan depositional system, and strictly speaking to the peripheral areas of this system since the percentage of deposits representing the alluvial plain depositional system (the remaining part of the section) is significant. The interfingering of deposits belonging to these two systems indicates the proximity to a transitional area between them.

Malbork IG 1 borehole (Fig. 33). FAI and FAII are dominant, accounting for 66% of all deposits. This section belongs to the alluvial fan depositional system interfingering with alluvial plain deposits. Noteworthy is that the Malbork IG 1 section contains the particularly high percentage of facies Mm representing mud flows.

Olsztyn IG 2 borehole (Fig. 34). FAI and FAII are represented almost exclusively, comprising 96% of the Żarnowiec Fm. This section is located within the alluvial fan depositional system.

Słupsk IG 1 borehole (Fig. 35). FAI and FAII deposits slightly dominate, comprising 52% of the total section. It means that this section is located within the area of the almost equal percentage of deposits representing the alluvial fan and the alluvial plain depositional systems. The section belongs to the area located at the transition between these two systems.

Żarnowiec IG 1 borehole (Fig. 36). In this section FAI and FAII are dominant, comprising 76% of all deposits. This section should be assigned to the peripheral part of the alluvial fan depositional system. The percentage of FAIII deposits (the remaining part of the section) is significant. This fact, as in the case of Kościerzyna IG 1 borehole, can be interpreted as the evidence for the proximity to the transitional area between the alluvial fan and alluvial plain depositional systems.

The classification of individual sections according to whether they belong to the alluvial fan or alluvial plain depositional system, or to the areas in which these two systems interfinger, leads to determination of transport directions of clastic material. The regional transport took place from the fans towards alluvial plain.

The sections representing the alluvial fan depositional system occur in the eastern part of the study area (Fig. 1). The only exception is the Słupsk IG 1 borehole located in the western part of the area, in which deposits of the alluvial fan depositional system are also dominant. This fact proves that clastic material of the Żarnowiec Fm., transported from source areas through alluvial fans to the alluvial plain, was derived from both the west and east. This is one of the most important conclusion of this paper.

Previous studies suggested the transport direction of clastic material from the east. It was postulated in papers on the lowermost Cambrian (Jaworowski, 1979, 1982, 1986). Deposits of the Żarnowiec Fm. were dealt with in less detail. The recent publication by Jaworowski (1997), concerning the possibility of westerly derivation of the lowermost Cambrian clastic material, suggests the existence of older fans and braid deltas sourced from areas located in the southwestern part of the study area. That was only a hypothesis based on preliminary sedimentological observations made on the Żarnowiec Fm. deposits. The facies analysis presented in the present paper has proved that these deposits were transported from both the west and east. As it was mentioned above, the eastern transport direction was postulated in sedimentological reports and also in earlier petrographical papers of Juskowiakowa (1976), Łydka (1980) and Łydka *et al.* (1984). All of them suggested that clastic material of the Żarnowiec Fm. originated from the crystalline basement of the East European Craton.

Petrographical-geochemical investigations, conducted within the framework of this study, considerably broaden and modify this opinion because they show that the mineral composition of the Żarnowiec Fm. indicates the provenance of

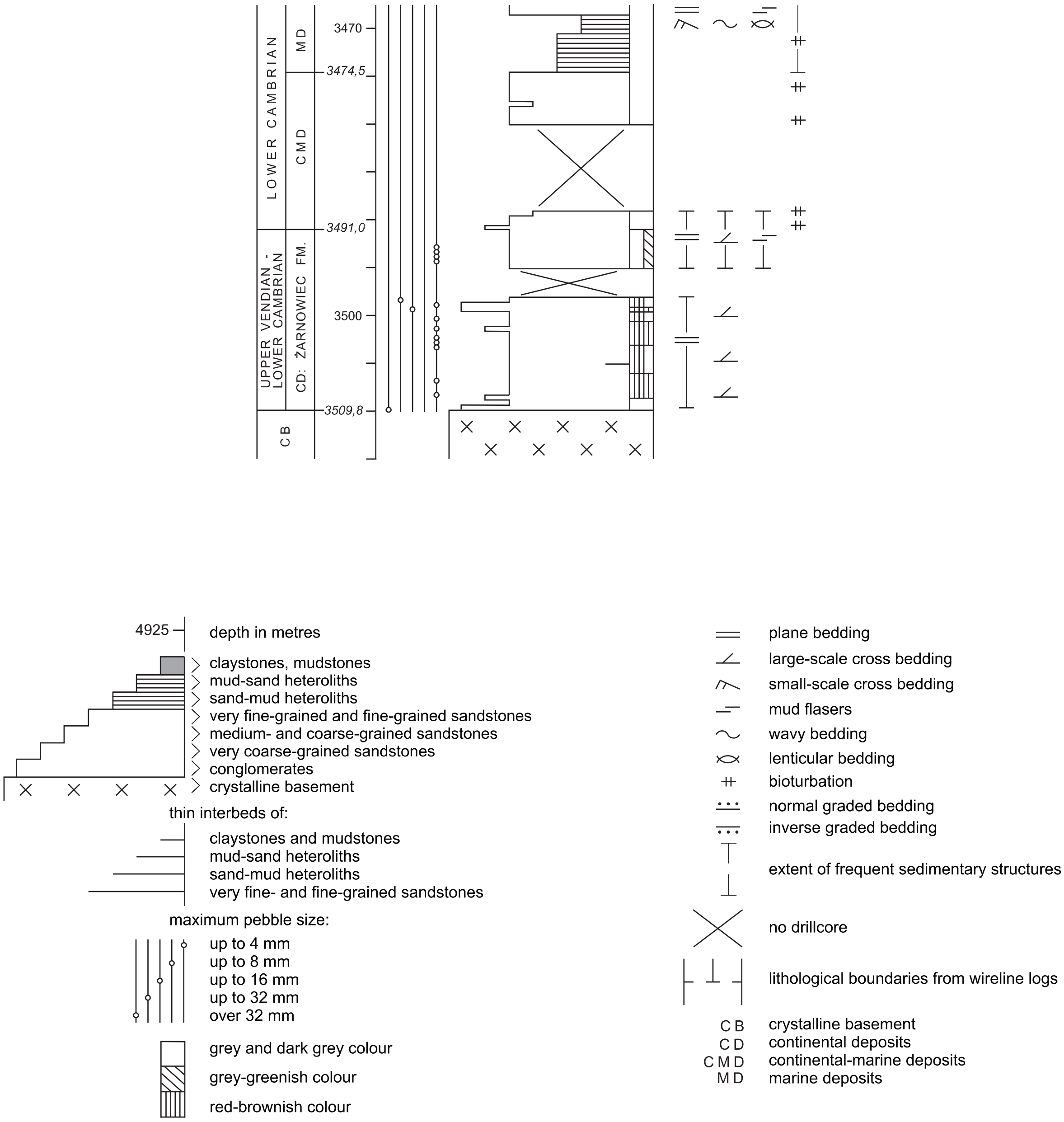



**Fig. 30. Sedimentological log of the Żarnowiec Fm. and transitional complex in the Darżlubie IG 1 borehole**

the material not only from the inner part of the craton but also both from its marginal parts which exhibit features of a transitional continental area, and from the uplifted area of the crystalline basement. The last area refers to the Słupsk IG 1 section and is of the utmost importance for considerations concerning the transport direction of the Żarnowiec Fm. It confirms the conclusion that the regional transport direction of clastics of the Żarnowiec Fm. was not only E→W, as previously suggested, but also W→E.

The depositional model of the Żarnowiec Fm. (Fig. 37), constructed on the basis of the available data assumes that these deposits accumulated in a tectonic trough developed within the Precambrian supercontinent. The western part of this trough is represented in the Słupsk IG 1 section, whereas the eastern part — in the remaining sections (see Fig. 1). The model shows that the transport of clastic material took place from two opposite directions. This material originated from erosion of fault scarps. Alluvial fans developed at the foot of the fault scarps. Towards the basin axis the alluvial fans were passing into the braid-and-sheetflood plain. The sediment, discharged through the fans, reached the alluvial plain and then it was transported southwards along its axis. This was the direction in which the accumulation surface of the sedimentary basin was inclined. The last observation results from the regional direction

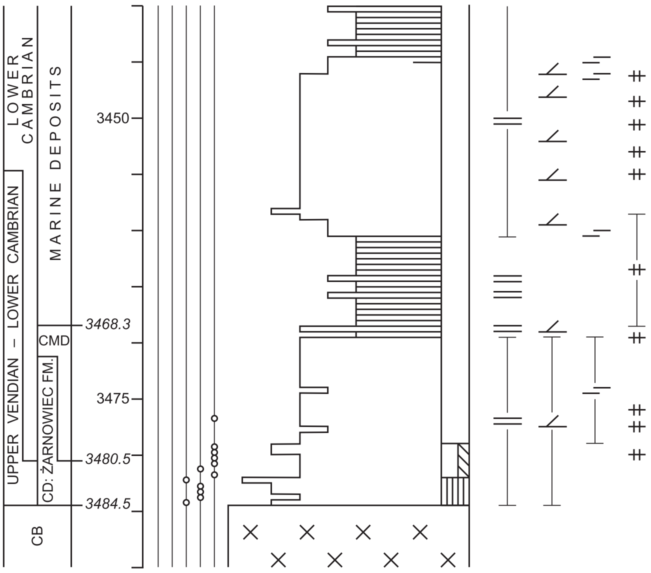



**Fig. 31. Sedimentological log of the Żarnowiec Fm. and transitional complex in the Hel IG 1 borehole**

For explanation see Figure 30

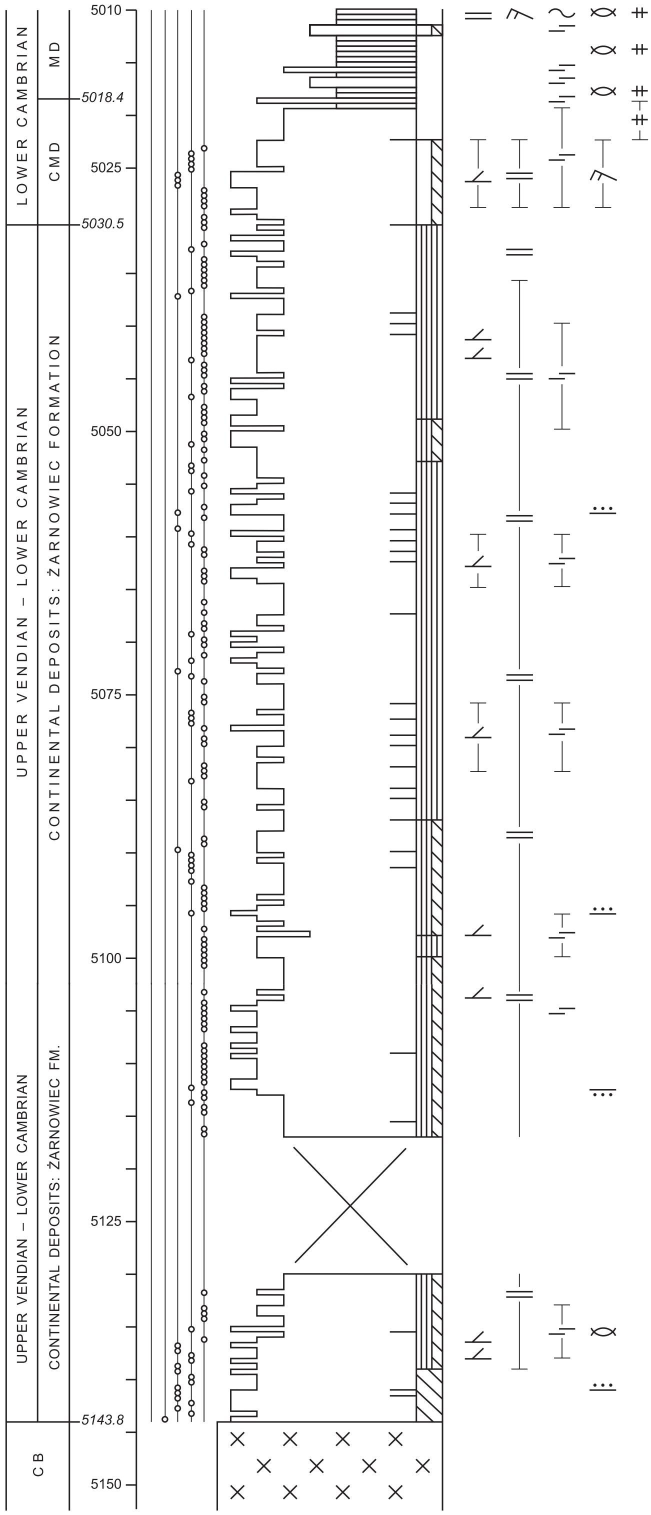



**Fig. 32. Sedimentological log of the Żarnowiec Fm. and transitional complex in the Kościerzyna IG 1 borehole**

For explanation see Figure 30

of expansion of the Lower Cambrian marine transgression in northern Poland. Coming from the south, the transgression reached first the area of the Kościerzyna IG 1 borehole (Jaworowski, 1979).

Petrographical-geochemical investigations show that the areas located on both sides of the tectonic trough where deposits of the Żarnowiec Fm. accumulated were petrologically similar and composed of rocks known from the crystalline basement of the present-day East European Craton. In other words, both these areas, located outside the rift and being source areas for deposits of the Żarnowiec Formation, belonged to the same Precambrian supercontinent.

While considering regional transport directions, the thickness pattern of the Żarnowiec Fm. deserves particular attention (Fig. 38). The greatest thickness is observed in the southwestern part of the study area, over 180 m in the Słupsk IG 1 borehole. The thickness pattern indicates that the Żarnowiec Fm. was deposited in an asymmetric sedimentary basin (Fig. 37). The greatest thickness is observed in the southwestern part of the basin. On a regional scale the thickness decreases north- and eastwards. The thickness pattern of the Żarnowiec Fm. can be interpreted as suggesting the following transport directions: W→E, E→W and N→S. The N→S direction of clastic material in northern Poland during the Valdaian (Vendian) and Lower Cambrian was postulated by Brodowicz (1977). Areń (1988) considered this direction as the major one for the Żarnowiec Fm.

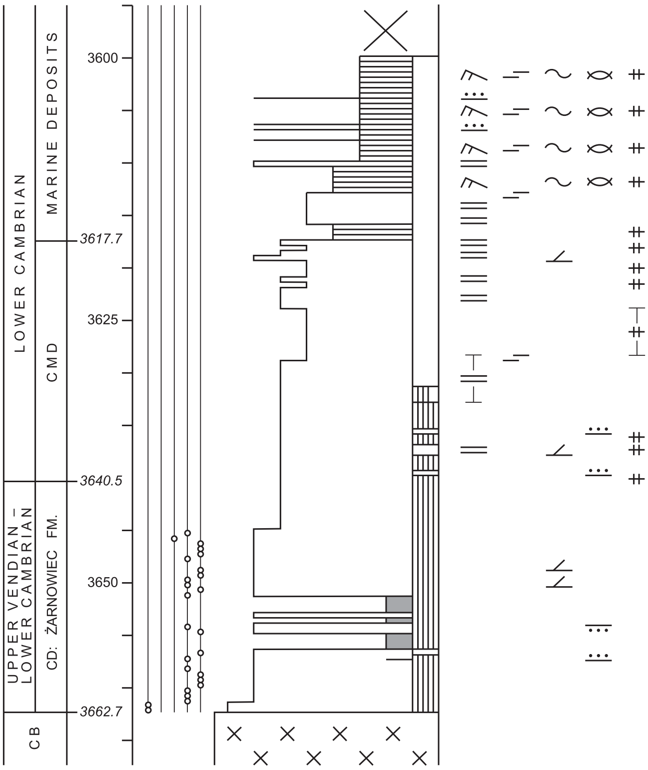



**Fig. 33. Sedimentological log of the Żarnowiec Fm. and transitional complex in the Malbork IG 1 borehole**

For explanation see Figure 30

The largest amounts of material were transported to the sedimentary basin in the W→E direction. The clastic material originated from erosion of an area located west of the tectonic trough in which the deposition of the Żarnowiec Fm. took place. A zone of increased thickness of this formation (Fig. 38) (area enclosed by the isopach 100) approximately corresponds to the axial part of the basin where the braid-and-sheetflood depositional system dominated. Along the western and eastern margins of the trough stretched alluvial fans (Fig. 37).

The above-presented observations enabled the construction of a palaeogeographical sketch map of northern Poland and the southern Baltic area during deposition of the Żarnowiec Fm. (Fig. 40). The sketch map is highly probable within the study area (cf. Fig. 1). Outside of the area it is only hypothetical.

The Baltic, Pomeranian and Ciechanów alluvial fans were distinguished during the studies on the Cambrian marine transgression in northern Poland (Jaworowski, 1979). The image presented in the present paper (Fig. 40) differs primarily in their areal extents. The facies analysis shows that these fans neither extended far to the west nor represented the only one depositional system of the Żarnowiec Fm. In particular it refers to the area of the Słupsk IG 1 borehole. According to the new concept, this borehole lies not in the distal part of the fan fed from the east, but in the marginal part of one of the fans consisting of the material derived from the west. Between the Baltic, Pomeranian and Ciechanów fans, and the remaining ones, viz. northern and western fans, a vast braid-and-sheetflood plain extended (Figs. 37, 39). The area of the Darżlubie IG 1 borehole, where the percentage of deposits representing the alluvial plain and alluvial fan depositional systems are almost equal, lies at the transition between the Baltic and Pomeranian fans, as indicated in the sketch. Braid and sheetflood plain deposits, interfingering with fan deposits, were accumulated over that area. Interpretation of the region located around the Prabuty IG 1 borehole (Fig. 1), where the Żarnowiec Fm. is lacking also differs from the previous image of the eastern part of the study area (Jaworowski, 1979). This region is at present interpreted as a local tectonic horst that was an additional source of clastic material of the Pomeranian and Ciechanów fans. Particularly noteworthy is the asymmetry of the sedimentary basin, as evidenced from the thickness pattern of the Żarnowiec Fm. In other words, the sedimentary basin was a half-graben (Fig. 37) whose edge, defined by a fault zone with larger fault throw, was located west of the Teisseyre–Tornquist Line (Fig. 1), i.e. outside of the present-day East European Craton. The opposite edge, defined by a fault zone with a smaller fault throw, was situated in the eastern part of the study area, i.e. within the East

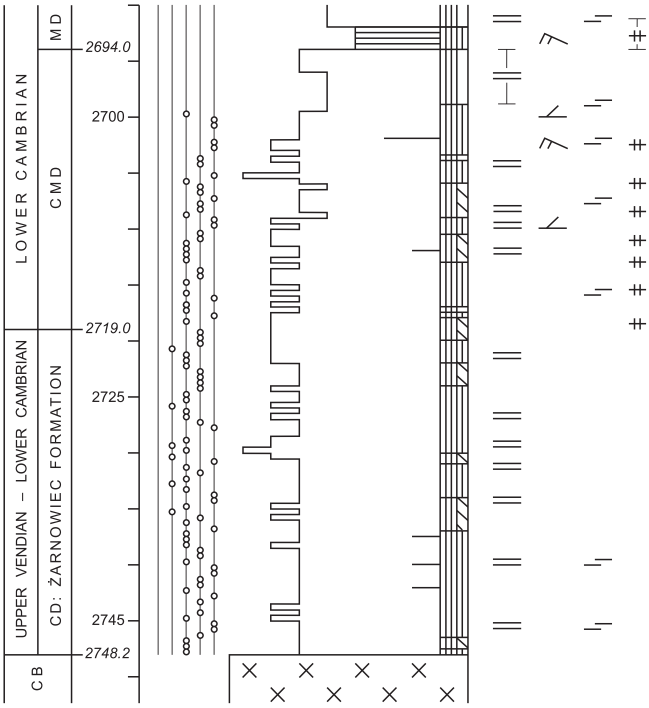



**Fig. 34. Sedimentological log of the Żarnowiec Fm. and transitional complex in the Olsztyn IG 2 borehole**

For explanation see Figure 30

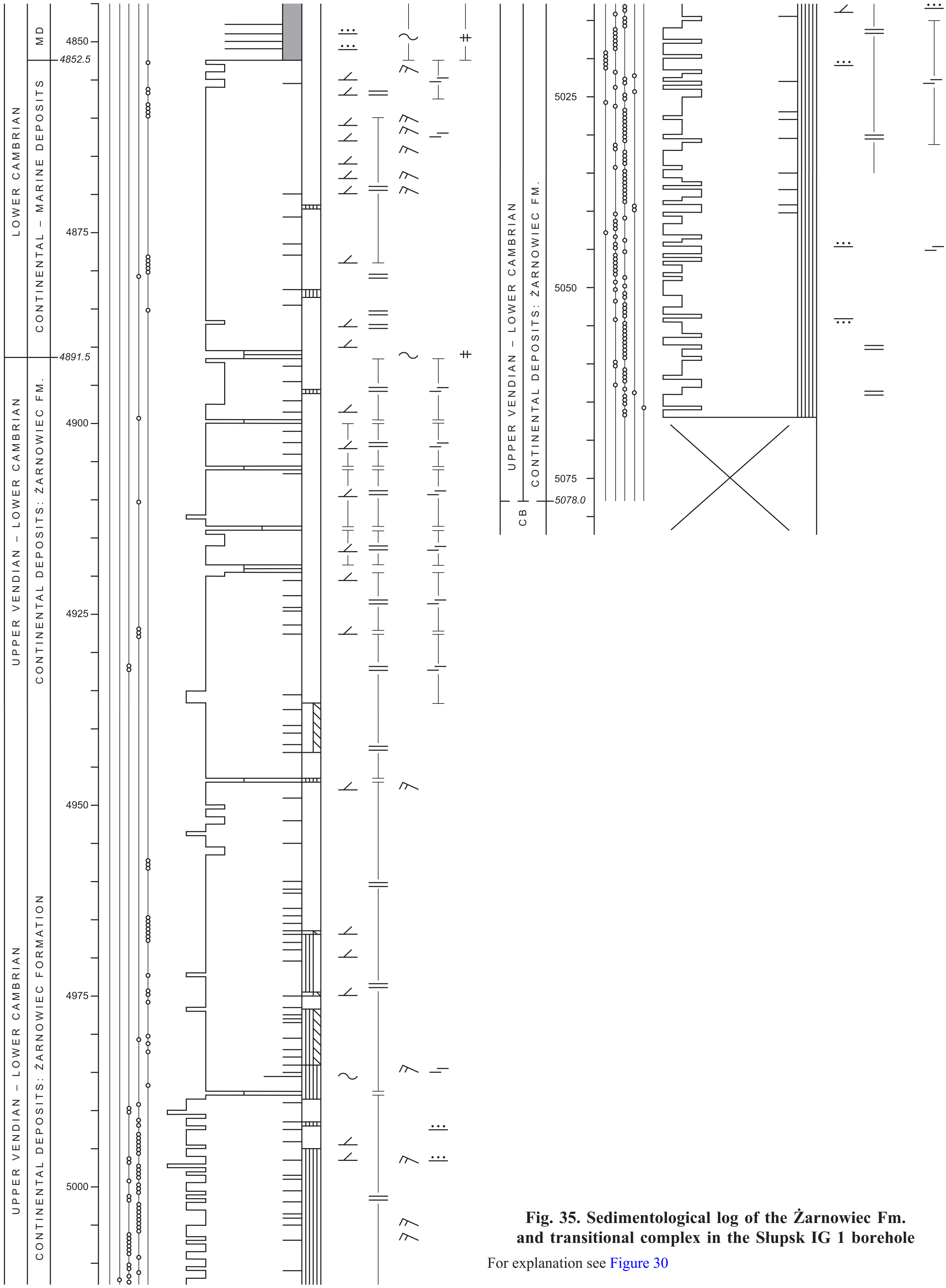



**Fig. 35. Sedimentological log of the Żarnowiec Fm. and transitional complex in the Słupsk IG 1 borehole**

For explanation see Figure 30

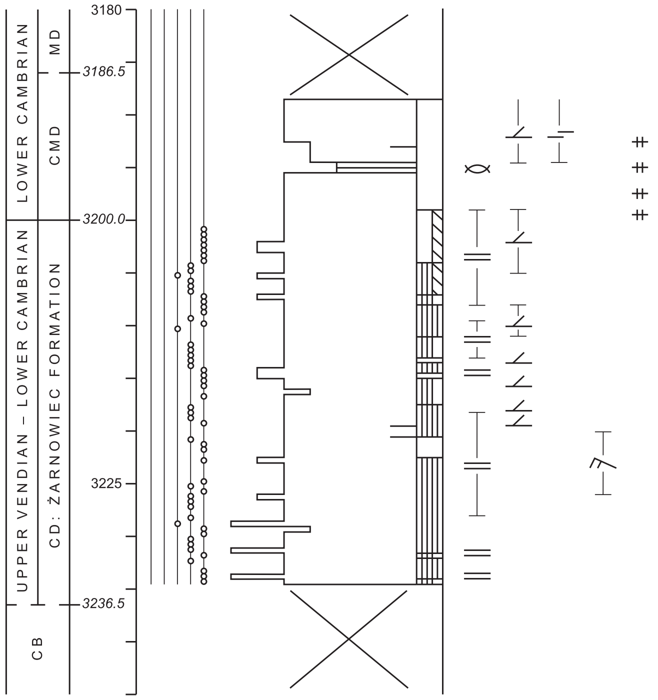



**Fig. 36. Sedimentological log of the Żarnowiec Fm. and transitional complex in the Żarnowiec IG 1 borehole**

For explanation see Figure 30

European Craton. The palaeogeographical sketch map also shows those presumed source areas of clastic material of the Żarnowiec Fm. which were located north of the study area within the present-day Baltic Shield.

The transport directions, reconstructed on the basis of the facies analysis, petrographical-geochemical investigations and thickness pattern of the Żarnowiec Fm., indicate that the source areas of clastic material, i.e. uplifts that occurred outside of the rift, were located in the following areas:

— west of the Teisseyre–Tornquist Zone, outside of the present-day East European Craton;

— in the eastern part of the study area, in the marginal part of the East European Craton;

— north of the study area, i.e. within the East European Craton, in the present-day Baltic Shield.

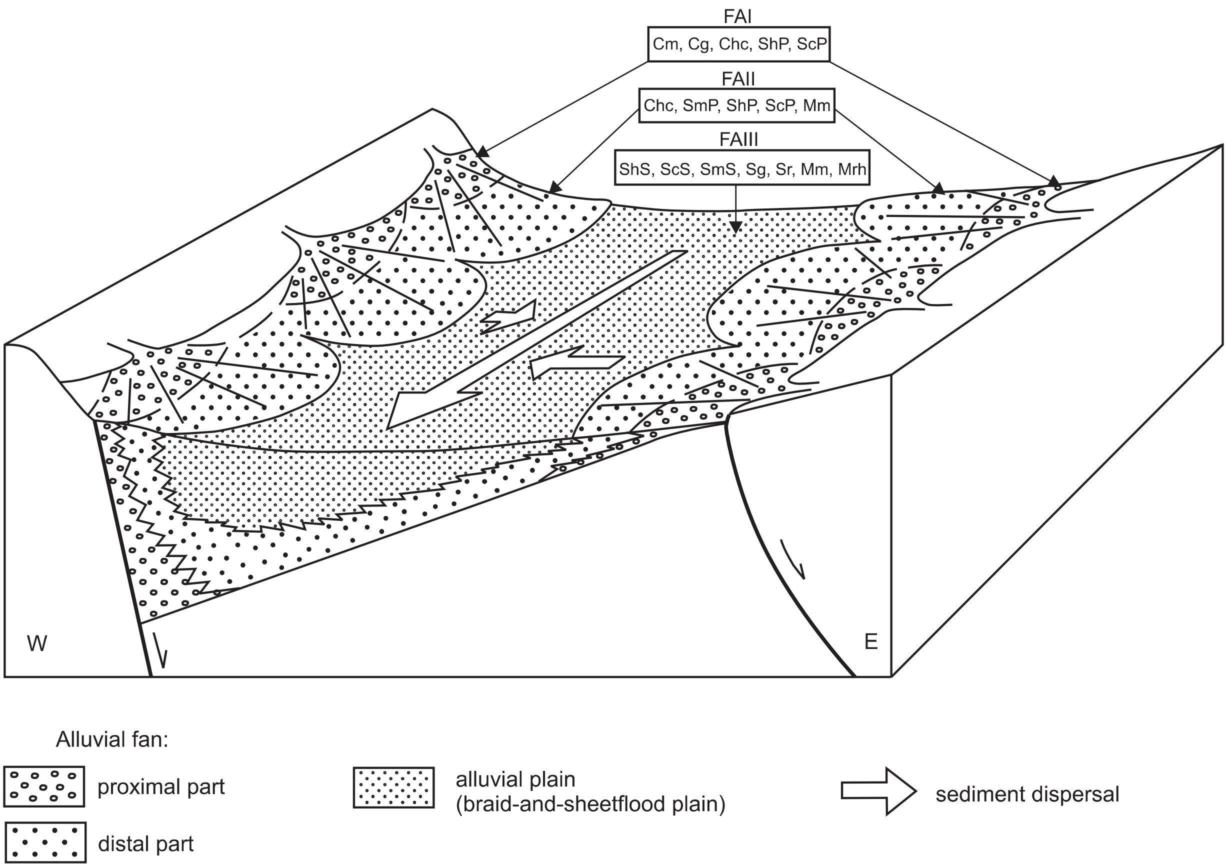



**Fig. 37. Depositional model of the Żarnowiec Fm. (not to scale)**

For facies symbols see chapter "Description and interpretation of facies" on the page 38

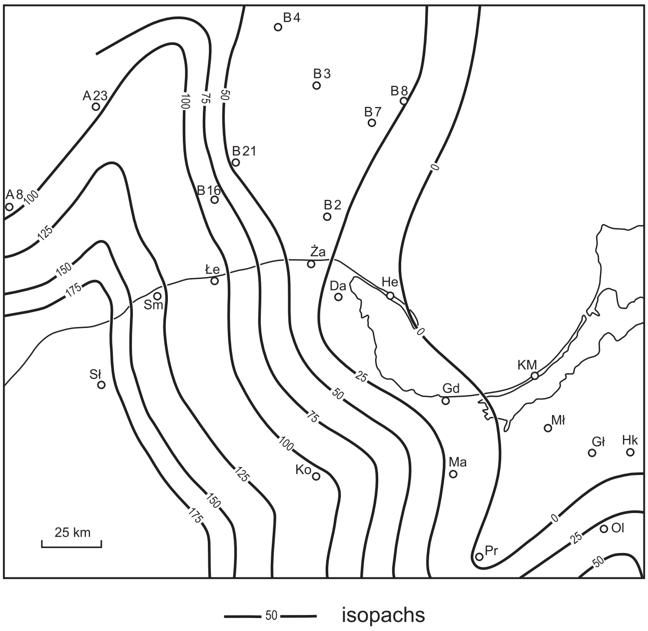



Fig. 38. Thickness (in metres) of the Żarnowiec Fm.

For explanation see Figure 1

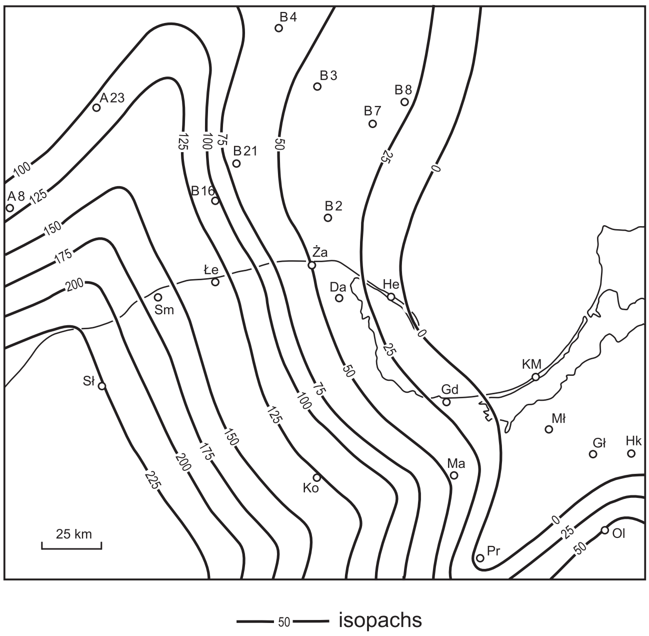



**Fig. 39. Thickness (in metres) of the Żarnowiec Fm. and transitional complex deposits**

For explanation see Figure 1

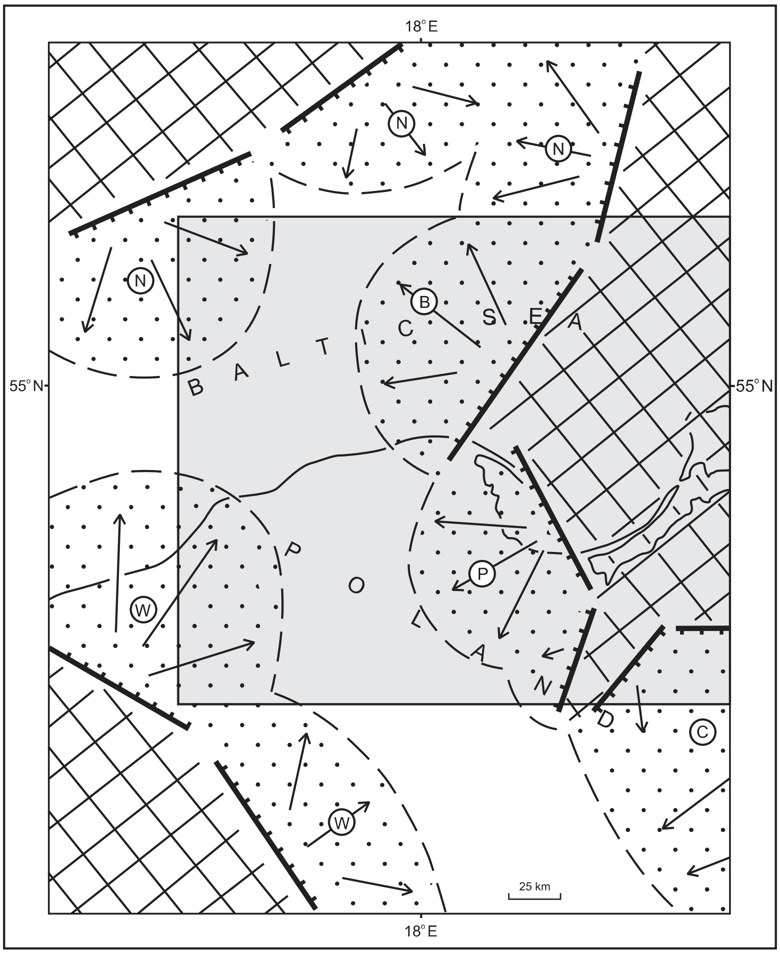




**Fig. 40. Palaeogeography of onshore and offshore northern Poland during deposition of the Żarnowiec Fm.**

## FORMATION OF THE TRANSITIONAL COMPLEX, THE PROBLEM OF BRAID DELTAS

During the deposition of the Żarnowiec Fm., the early Cambrian marine transgression took place in northern Poland and the southern Baltic area. It first reached the area of the Kościerzyna borehole (Jaworowski, 1979). The opinion that the area of the strongest Valdaian (Vendian) subsidence was located southwestern of Kościerzyna was already postulated by Kotański (1977). The early Cambrian sea expanded S→N and SW→NE, inundating the southern part of the tectonic half-graben in which the Żarnowiec Fm. was deposited. In this way the transitional continental-marine complex was formed. It shows gradual transitions into both the underlying continental Żarnowiec Fm. and the overlying marine Lower Cambrian sediments. The transgressive marine Cambrian deposits overstep the transitional complex, and occur also outside of the half-graben filled with the Żarnowiec Fm. Beyond the area of the Żarnowiec Fm. deposition, i.e. outside of the half-graben, the transitional complex has not been found.

The alluvial fan and braid-and-sheetflood depositional systems prograded into the transgressing sea. It resulted in the formation of coarse-grained deltas: fan-deltas and braid deltas. Facies associations, identified within the transitional complex allow to assign the cored intervals of the studied sections to the following types of deltas.

Darżlubie IG 1 borehole (Fig. 30). In this section the transitional complex is represented exclusively by FAIII deposits that means that the complex was deposited in the braid delta environment.

Hel IG 1 borehole (Fig. 31). FAIII deposits are distinctly dominant, comprising 83% of the entire transitional complex. This section lies in the area dominated by sedimentation in the braid delta environment, although initially a fan delta occurred here.

Kościerzyna IG 1 borehole (Fig. 32). FAIII deposits comprise 50% of the transitional complex. In this area the initial fan delta deposition was subsequently replaced by braid delta sedimentation.

Malbork IG 1 borehole (Fig. 33). The entire transitional complex is represented by FAIII deposits. A fan delta developed in this area.

Olsztyn IG 2 (Fig. 34). The transitional complex is dominated by FAI and FAII deposits, accounting for 62% of the entire section. A fan delta developed and existed during most of the deposition of the transitional complex in this area. Subsequently, braid delta deposits accumulated.

Słupsk IG 1 borehole (Fig. 35). In this section FAIII deposits comprise 85% of the transitional complex. According to the above-presented palaeogeographic interpretation of the Żarnowiec Fm. (Fig. 40), the Słupsk IG 1 borehole is situated in a peripheral part of an alluvial fan. A fan delta was initially formed in this area, and subsequently was replaced by a braid delta which was dominated the transitional complex.

Żarnowiec IG 1 borehole (Fig. 36). The transitional complex is represented exclusively by FAIII deposits. A fan delta developed in this area.

An approximate correlation of borehole sections, based on wireline logs, suggests that the transitional complex occurs also in borehole sections offshore the Baltic Sea coast (Fig. 1). It is difficult to estimate how far north the Cambrian sea reached during the deposition of the transitional complex. It seems that north of the study area continental deposits continued to be deposited at that time. Aeolian sandstones known from Bornholm, which gradually pass at the top into Lower Cambrian marine sandstones (Clemmensen, Dam, 1993), can be considered a continental equivalent of the transitional complex.

The analysis of borehole sections with the transitional complex cored, shows that the Żarnowiec–Darżlubie and Malbork areas are the most important from the point of view of the occurrence of reservoir rocks. Apart from Middle Cambrian marine sandstones, the potential reservoir rocks are here represented by braid delta sandstones recognized in the Vendian and lowermost Cambrian continental-marine deposits. Although petrological investigations indicate that reservoir properties of the complex are poor, it seems highly probable, that locally, within braid deltas, they may be much better.

# GEOTECTONIC IMPLICATIONS: THE FORMATION OF THE PASSIVE MARGIN OF THE BALTICA CONTINENT

In the previous papers, the Żarnowiec Fm. deposits were identified as a cratonic product of the Caledonian tectonic cycle (Jaworowski, 1979). The formation was included to the red continental sediments (cf. Chain, 1974) characteristic of early stages of platform development under an arid climate (Jaworowski, 1982). That view is generally up-to-date and will be extended in this report by further-reaching conclusions of the geotectonic nature. The essential role is played here by the depositional model of the Żarnowiec Fm., which indicates that the sedimentary basin was a half-graben (Fig. 37). The formation of this half-graben, should be related to the breaking up of the Precambrian Rodinia supercontinent.

The breaking up of Rodinia was initiated by the opening of the Teisseyre–Tornquist rift which came into being after the Svekonorwegian (Greenvillian) orogeny, i.e. not earlier than 0.9 Ga BP (Żelaźniewicz, 1998). The Teisseyre–Tornquist rift was probably formed in the place of the pre-existing Middle Riphean and Lower Vendian aulacogen, connected with the Volhyn–Orsha aulacogen. A similar opinion can be found in Pożaryski and Kotański (1979), and in the recent publication by Poprawa and Pacześna (2002). The tectonic half-graben was a fragment of the Teisseyre–Tornquist rift.

The palaeogeography of northern Poland and the southern Baltic area during the deposition of the Żarnowiec Fm., demonstrated in the present paper, suggests the occurrence of a triple junction in this area (Fig. 40). Two of the triple junction arms were oriented WNW–ESE and NW–SE, i.e. parallel to the present-day border of the East European Craton. The third arm, oriented SW–NE, stretched into the craton. As the Teisseyre–Tornquist rift expanded, after the Varangerian Glaciation (<650 Ma) and the formation of an ocean, the third arm remained an intracontinental rift (failed arm). The two remaining arms became transformed into mid-ocean rift. Such an evolutionary pattern (RRr triple junction) resulted in the formation of the Baltica passive margin stretching along the present-day southwestern border of the East European Craton.

Poprawa *et al*. (1999; Fig. 14) claim that the Teisseyre–Tornquist rift was formed according to the classical lithospheric stretching model, i.e. the symmetric model given by McKenzie (1978). The results of the present investigations suggest that the opinion should be revised. The thickness distribution of the Żarnowiec Fm. (Fig. 38), as well as of the Żarnowiec Fm. together with the transitional complex (Fig. 39), i.e. Upper Vendian and lowermost Cambrian deposits, indicate that the sedimentary basin was an asymmetric half-graben (see Fig. 37). Therefore, for the Upper Vendian and Lower Cambrian extension in onshore and offshore northern Poland, an asymmetrical extension model of Wernicke (1981) should be adopted. A closer interpretation of the extension model is possible if all the petrographical-geochemical and sedimentological investigations are considered together. The petrographical-geochemical studies suggest as follows:

— clastic material of the Żarnowiec Fm. was derived from the passive continental margin, and partly from the uplifted crystalline basement;

— source areas of clastic material of the Żarnowiec Fm. were composed of the same rocks as the crystalline basement of the present-day East European Craton, i.e. the material originated from the Precambrian Rodinia continent.

Sedimentological investigations indicate that:

— clastic material of the Żarnowiec Fm. was transported mainly from two opposite directions: W→E and E→W;

— western source areas were situated southwestern of the Teisseyre–Tornquist Line, outside of the present-day East European Craton;

— the subsidence axis of the asymmetric sedimentary basin of the Żarnowiec Fm. was shifted westwards.

All these observations lead to the following conclusion about the most probable model of the Upper Vendian–Lower Cambrian extension manifested by the development of the Żarnowiec Fm. (Fig. 41):

The main boundary fault, bounding the half-graben where the Żarnowiec Fm. was deposited, was located southwestern of the Teisseyre–Tornquist Line and stretched approximately parallel to that line. Southwestern of the main boundary fault extended the western source area of clastic material, which — as evidenced from petrographical-geochemical investigations — was composed of the same rocks as the eastern source areas

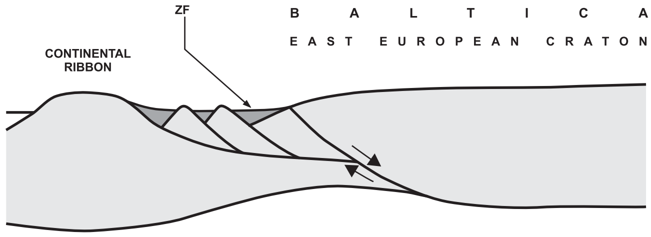



**Fig. 41. The model of breaking up of the Precambrian supercontinent in onshore and offshore northern Poland**

Asymmetric lithospheric stretching model; ZF — site of deposition of the Żarnowiec Fm.

located in the marginal part of the East European Craton. This fact can be easily explained by the existence of an uplift area composed of the continental crust of Rodinia, southwestern of the main boundary fault. This area was one of the most important sources of clastic material of the Żarnowiec Fm.

The composition of clastic material and sedimentary conditions (depositional systems, transport directions, thickness pattern) of the Żarnowiec Fm. indicate that the Upper Vendian–Lower Cambrian breaking up of Rodinia in onshore and offshore northern Poland took place according to the Wernicke model (1981), more precisely according to the model given by Lister *et al*. (1986). This model assumes that an inland rift system can exist between the main landmass and a fragment of the continental crust, i.e. continental ribbon. Tilted blocks, composing the rift system associated with asymmetrical lithospheric stretching, are underlain by a detachment fault inclined cratonward. The continental ribbon, bounding from the west the asymmetric rift system in which the sedimentary basin of the Żarnowiec Fm. existed, is at present located southwestern of the Teisseyre–Tornquist Zone, within the basement of the European Palaeozoic Platform.

While analysing geotectonic aspects of the development of the Żarnowiec Fm. one should consider these deposits in terms of the sequence stratigraphy. From this point of view the Żarnowiec Fm., and also partly transitional complex, represent the lowstand system tract (Jaworowski, 2000b).

Sedimentation of the Żarnowiec Fm. was under strong influence of tectonic activity that is characteristic of all rift basin fills. Therefore, considering this formation, tectonic system tracts should be distinguished. The term “tectonic system tract” was introduced by Prosser (1993) who distinguished four stages of the rift basin development. Each of these stages resulted in the formation of an individual tectonic system tract. These stages are represented by rift initiation, rift climax, immediate post-rift and late post-rift. Tectonic system tracts are associated with these stages and can be identified on the basis of either very good knowledge of rift fill (large exposures, very high drilling density) or very detailed seismic exploration. None of these conditions is fulfilled in the case of the Żarnowiec Fm. The petrographical-geochemical and facies analysis presented in this paper suggest the following interpretation of close relationships between tectonics and sedimentary processes that accompanied the development of the Żarnowiec Fm.

Coarse-grained conglomerates from the basal part of the Żarnowiec Fm., immediately overlying the crystalline basement and showing features of a regolith (as already indicated by Łydka, 1980) or a slightly displaced weathering mantle, probably represent pre-rift deposits. These are particularly well developed in the Malbork IG 1 (Fig. 33) and Słupsk IG 1 (Fig. 35) boreholes. Sharing the views of Blair (1987, 1988), the present authors assume that large amounts of coarse-grained deposits are supplied into rift basins after the cease of active rifting. According to this concept, the Żarnowiec Fm. deposits represent the immediate post-rift system tract. Continuing this interpretation, the transitional complex should be considered to represent the late post-rift system tract. Such an interpretation is confirmed by the fact that the thickness pattern of the Żarnowiec Fm. and the transitional complex (Fig. 39) reveals the same structural pattern of the sedimentary basin as that which results from the thickness pattern of the formation itself (Fig. 38).

# CONCLUSIONS

**1**. Clastic material of the Żarnowiec Fm. originally contained considerable amounts of potassium feldspars, along with dominant quartz and infrequent rock fragments. Only in deposits from the Żarnowiec IG 1 and Darżlubie IG 1 boreholes the grain framework is composed almost exclusively of quartz grains with trace amounts of feldspars.

**2**. The Żarnowiec Fm. deposits are strongly affected by diagenetic changes and almost completely devoid of primary porosity. Their poor reservoir quality results from textural immaturity associated with the alluvial sedimentary environment, as well as subsequent diagenetic processes: mostly mechanical and chemical compaction, and — to a lesser extent — cementation.

**3**. The mineral composition of clastic material of the Żarnowiec Fm. shows close relationships with the crystalline basement of the East European Craton.

**4**. When plotted on the Dickinson's diagrams, mineral composition of the Żarnowiec Fm. indicates internal cratonic areas as the sources of clastic material. In the western part of the study area the clastic material was supplied from an elevated block of the basement.

**5**. Chemical analyses point to a passive continental margin as the main source of clastic material.

**6**. Three depositional systems have been identified within the Żarnowiec Fm.: (1) proximal alluvial fan, (2) distal alluvial fan, (3) braid-and-sheetflood plain.

**7**. Clastic material of the Żarnowiec Fm. was transported in two opposite directions: W→E and E→W. Some of the clastics were transported in the N→S direction.

**8**. The sources of clastic material were located: (1) west of the Teisseyre–Tornquist Zone, i.e. outside the present-day East European Craton; (2) in the marginal part of the East European Craton; (3) in the East European Craton in the area of the present-day Baltic Shield.

**9**. The depositional model of the Żarnowiec Fm. indicates that the sedimentary basin shows features of a half-graben. The formation of this half-graben should be related to a rift system developed during the breaking up of the Precambrian Rodinia supercontinent.

**10**. The breaking up of Rodinia, and the formation of the southwestern edge of Baltica in northern Poland, took place according to the asymmetric lithospheric stretching model.

**11**. According to this model, an inland rift system existed between the main landmass and the elevated peripheral fragment (i.e. continental ribbon *sensu* Lister *et al*., 1986) of the Rodinia supercontinent. The sedimentary basin of the Żarnowiec Fm. developed within this rift system. The fragment of the Rodinia's continental crust (continental ribbon) is at present located southwestern of the Teisseyre–Tornquist Zone, being buried within the basement of the Palaeozoic European Platform.

**12**. To the potential hydrocarbon reservoirs of the present-day Baltic Basin one should include the continental-marine transitional complex occurring between the continental Żarnowiec Fm. (Vendian–Lower Cambrian) and the overlying Lower Cambrian marine deposits. Although petrological investigations suggest that reservoir qualities of the complex are poor, it seems highly probable that locally, especially within braid deltas, they may be much better.

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