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Provenance petrological study of the Upper Vendian and Cambrian clastic material; foreland of the Pomeranian Caledonides (northern Poland)

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The provenance of clastic material in the oldest part of the sedimentary cover of the East European Craton, in northern Poland, is analysed. Analysis of the Żarnowiec Formation sandstones (Upper Vendian-lowest Cambrian) confirm earlier views of a local origin. The crystalline basement in the Kościerzyna IG 1 region mainly yielded enderbitic detritus while that in the Gdańsk IG 1 region provided migmatitic detritus. Triangle diagrams of the overlying, mature, sandy marine Cambrian show unequivocally that the detritus was transported from the craton interior. Analysis of mono- and polycrystalline quartz and cathodoluminescence (CL) analysis indicates erosion of metamorphic, magmatic and sedimentary rocks, and this is confirmed by CL observations of zircons. These results are consistent with the view that the Upper Vendian and Cambrian strata on the Pomeranian Caledonides foreland were formed on the passive margin of Baltica.

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Key words: northern Poland, Lower Cambrian, Upper Vendian, clastic material, zircon.

INTRODUCTION

The study deals with some petrological results of a research programme on the Trans-European Suture Zone (TESZ) in northern Poland. Two boreholes: Kościerzyna IG 1 and Gdańsk IG 1, in the foreland of Pomeranian Caledonides, were chosen. Location points of the boreholes mark a line oriented approximately perpendicular to the Caledonian deformation front (Fig. 1).

The Żarnowiec Formation comprises the oldest deposits (Upper Vendian and the lowest part of Lower Cambrian), lying directly on crystalline basement in the Peribaltic Syneclise. According to Jaworowski (1979, 1982, 1997), these sediments represent alluvial fans, braided plains, fan deltas and braided deltas, with a gradual change from continental to marine conditions. Cambrian sedimentation occurred in a shallow marine environment exposed to tidal and storm action (Jaworowski, 1979, 1982, 1997). These deposits occur at 5143.8–4424.3 and 3487.0–3137.4 m depth (Fig. 2), in the Kościerzyna IG 1 and Gdańsk IG 1 boreholes respectively.

54 thin sections (partially from Juskowiakowa's collection) were analysed, while cathodoluminescence analysis was carried out on 29 polished thin sections and on 25 powder preparations of the heavy fraction.

RESEARCH OBJECTIVE

A study of the TESZ is one of the main tasks of the international EUROPROBE Programme which encompasses the whole European continent. In this context, the provenance of detrital material in the oldest part of the sedimentary cover of the East European Craton in the Pomeranian Caledonides foreland area (northern Poland) may provide important palaeogeographic constraints. Petrographic research of Cambrian sediments in this area pointed to the crystalline basement of the East European Craton as a source of detrital material (Juskowiakowa, 1976; Sikorska, 1988). In this study, additional petrographic techniques were used to characterise the original composition of Cambrian detrital minerals more precisely. In case of the marine Cambrian deposits, which are mineralogically and texturally mature, provenance studies are difficult. The Żarnowiec Formation deposits (Upper Vendian/lowest Lower Cambrian) are easier to interpret, due to their immature, continental-marine character.

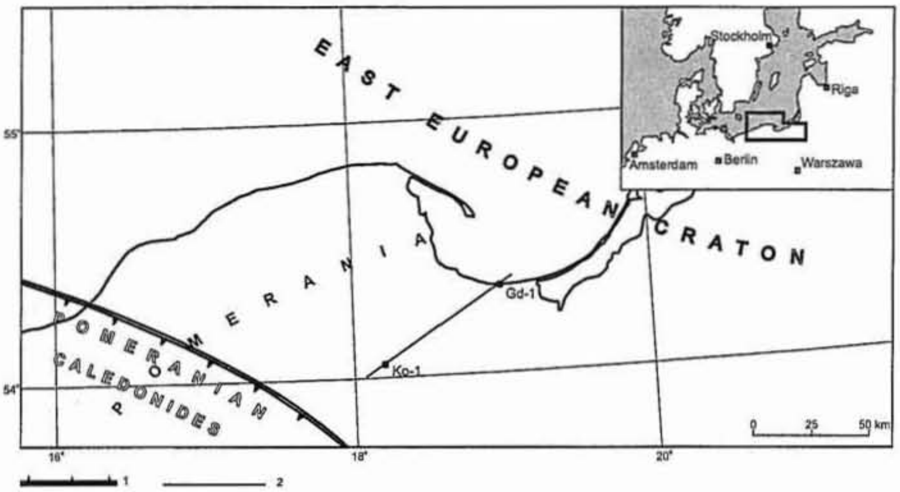


Fig. 1. Location of boreholes investigated

Ko-1 — Kościerzyna IG 1, Gd-1 — Gdańsk IG 1; 1 — Caledonian deformation front; 2 — line connecting location points of the boreholes

RESEARCH METHODS

The petrographic database was assembled by point-counting mineral grains on thin sections using *Swift Model F* apparatus (*Prio Scientific Instruments* Ltd.). Planimetry was done using Gazzi-Dickinson's method, so as to interpret results using triangular diagrams with geotectonically separated patterns of source areas (Dickinson and Suczek, 1979; Dickinson, 1985). These authors attempted to reduce the effect of grain-size on mineral composition, as this effect may significantly influence the interpretation of source areas. In practice, this method treats rock grains accordingly to their subgrain-size. The diagrams proposed by Dickinson and Suczek (1979) are based on three main categories: (1) stable quartz grains (mono- and polycrystalline and quartz lithoclasts); (2) feldspars (potash feldspars and plagioclases, pseudomorphs after feldspars); (3) unstable rock fragments (volcanic, metavolcanic, sedimentary and metasedimentary).

The next task was to determine the source rock type. Quartz grain types were used to provide an indication of igneous or metamorphic provenance. Diamond diagrams (after Basu *et al.*, 1975) were used. These are based on the inter-relation of four components: monocrystalline quartz (comprising up to 3 subgrains), polycrystalline quartz (comprising more than 3 subgrains), parallel-extinction quartz (extinction angle $< 5°$) and undulose extinction quartz (angle $> 5°$). This method is particularly useful for mineralogically mature sandstones, where quartz is the dominant component.

Cathodoluminescence (CL) observations also provide information regarding detrital quartz origin (Zinkernagel, 1978; Matter and Ramseyer, 1985; Marshall, 1988). This method allows the distinction of grains derived from plutonic, volcanic rocks and highly metamorphosed rocks (blue luminescence), from grains from low to medium regionally metamorphosed rocks (brown luminescence). Marshall (1988) also distinguished a category of plastically deformed plutonic grains (blue-black luminescence).

N.b. luminescence colour determinations were made directly during the CL examination, and not on the images illustrated in the paper. To obtain a good quality photograph of quartz, it is necessary to extend the exposure time to 8 minutes; this causes a significant brightening of colours compared to the original picture in the luminescope, and so causes an apparent discrepancy between the CL colour description and the colours seen on the accompanying photos. The luminescence colours which complement the colours observed during analysis are shown on Plate II, Figure 2a (exposure time 5 minutes).

Cathodoluminescence analysis was conducted on *CCL 8200 mk3* apparatus (made by *Cambridge Image Technology* Ltd.) using a polarising microscope. The range voltage applied was 16 to 17 kV and the current of the electron beam was from 700 to 750 μA. To better differentiate the source rocks of the Cambrian deposits, CL zircon analysis was conducted on the heavy fraction. Heavy minerals were separated in bromoform and set in heat-resistant resin on a base glass. The surface of each preparation was polished to prepare for the CL study. The variety of zircon luminescence colours suggest an origin from different source rocks (Marshall, 1988).

COMPOSITION OF CLASTIC MATERIAL

The determination of grain composition under the microscope was not difficult because the examined Cambrian rocks are mainly oligomictic sandstones or, more precisely, quartz arenites. Difficulties arise only when we consider the original (diagenetically unchanged) composition of detrital material, directly after sedimentation.

The Żarnowiec Formation deposits include, apart from quartz, feldspars and rock fragments, which have undergone strong diagenetic alteration. These are altered to such a degree that it is difficult to distinguish them from the rock matrix, having undergone intensive silicification, sericitization, chloritization and locally carbonatization. It was also difficult to identify the quartzite grains under the microscope, as these resemble the polycrystalline quartz grains and *vice versa*. In this situation, cathodoluminescence observations help recognition of original grain character.

The Lower Cambrian sandstones of the Gdańsk IG 1 borehole (depth 3367.4 m) include silicified chamoisite ooids as well as rounded grains of chert, siltstone, mudstone and very fine-grained quartzite. Using normal microscopy (Pl. I, Fig. 1) these two grain types are difficult to distinguish. Using CL, though (Pl. I, Fig. 1a), the silicified ooids show very weak, uniform luminescence (black colour), while the siliceous lithic grains (cherts and siltstones) show varied luminescence (brown and blue colours) which reflect their granular structure. The CL analysis helped to settle, in many cases, the identification of the altered feldspars and crystalline rock fragments hidden within the matrix. These were revealed due to visible potash feldspar relics in the CL light (which have a distinct light blue luminescence colour — Pl. I, Figs. 2 and 2a). Diagenetic quartz pseudomorphs after feldspars were distinguished from polycrystalline quartz or quartzite fragments using CL (Pl. II).

Identification of feldspars and evaluation of their percentage in very fine sandstones, normally problematic, are aided by CL analysis (Pl. III, Figs. 1 and 1a), as is the distinction between polycrystalline quartz and quartzite fragments, visible in CL light only. The polycrystalline quartz grains have a uniform luminescence colour and invisible subgrains, in contrast to the quartzite fragments. It is easy, too, to mistake finely crystalline authigenic quartz for siltstone fragments (Pl. III, Figs. 2 and 2a).

Cathodoluminescence analysis thus determines differences between the current detrital composition and the original composition, the latter reflecting provenance, i.e. the petrological and geotectonic character of the source area. The results show that the Żarnowiec Formation sandstones originally were sublithic and arkosic wackes, whereas now they are mainly quartz wackes, and this is consistent with the interpretation of Juskowiakowa (1982) regarding these deposits in the Kościerzyna IG 1 borehole. Originally, quartz arenites were dominant in the Lower and Middle Cambrian rocks of this region, but now they are represented mainly by orthoquartzites.

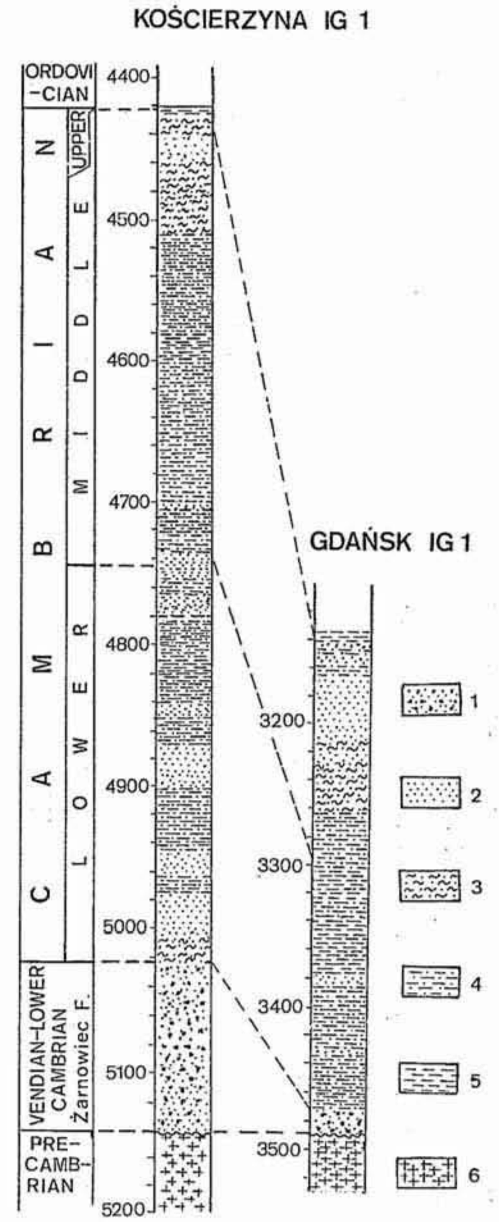


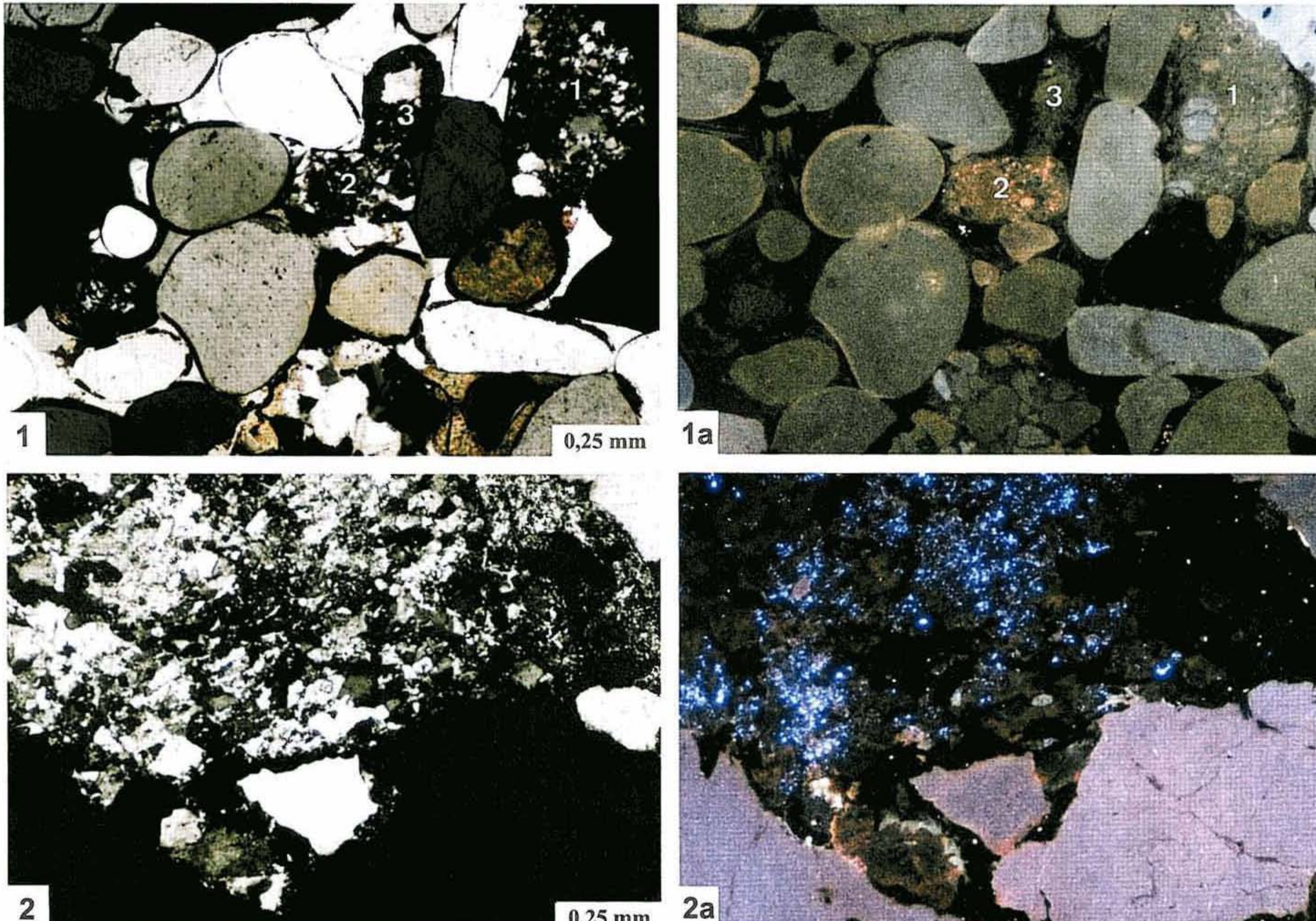
Fig. 2. Simplified lithostratigraphical profiles of Cambrian sediments

1 — coarse-grained sandstones and conglomerates; 2 — fine- and medium-grained sandstones; 3 — sandy heteroliths; 4 — muddy heteroliths; 5 — siltstones; 6 — crystalline rocks

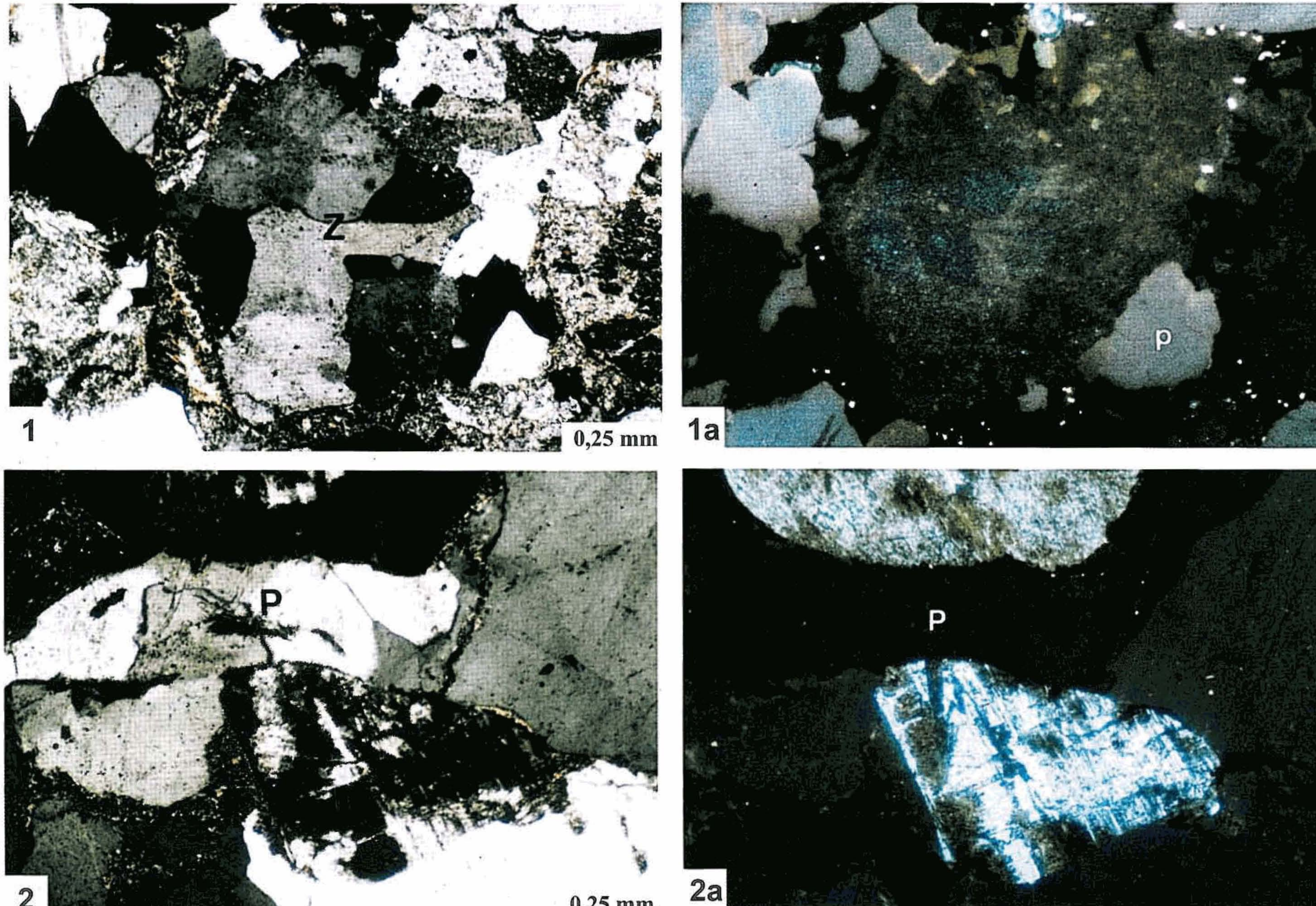
PROVENANCE

THE GEOTECTONIC CHARACTER OF THE SOURCE AREA

In the mineralogically mature Cambrian sandstones, triangular diagrams (Dickinson, 1985) were used to interpret the geotectonic character of the source area, to show proportions of quartz grains (Q_t), total feldspar (F), and aphanitic, unstable rock fragments (L) (Fig. 3). The majority of points, both for sandstones derived from the Kościerzyna IG 1 borehole and from the Gdańsk IG 1 borehole, are grouped along the Q_t corner, mostly in the field which indicates the craton interior as the source area, though one point lies in the field indicating an eroded orogenic area. This interpretation is supported by the CL photo (Pl. I, Figs. 1 and 1a) showing very good grain round-

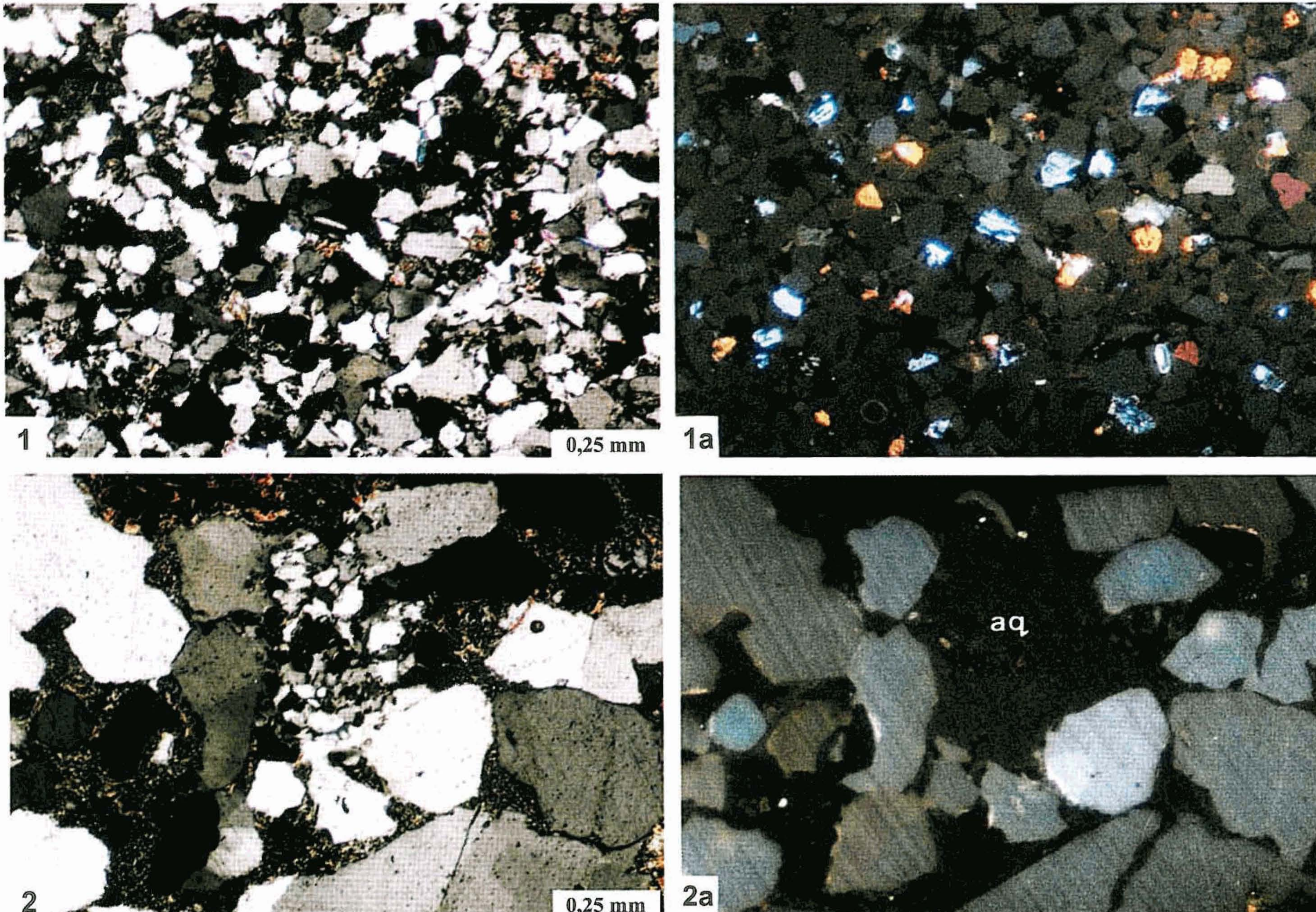


1. PL — seemingly identical (grains 1–3) silicified ooids and lithic grains; crossed polars; Gdańsk IG 1 borehole, depth 3367.4 m. *1a.* CL — grain 1 — lithic grain (visibly fine-grained texture), grains 2 and 3 — silicified ooids. *2.* PL — argillic-siliceous pseudomatrix in sandstone; crossed polars; Kościerzyna IG 1 borehole, depth 5045.2 m. *2a.* CL — altered potash feldspar relics (blue luminescence colour) occurring among clay minerals (black colour) and authigenic quartz (brown luminescence colour). PL — polarised light; CL — cathodoluminescence

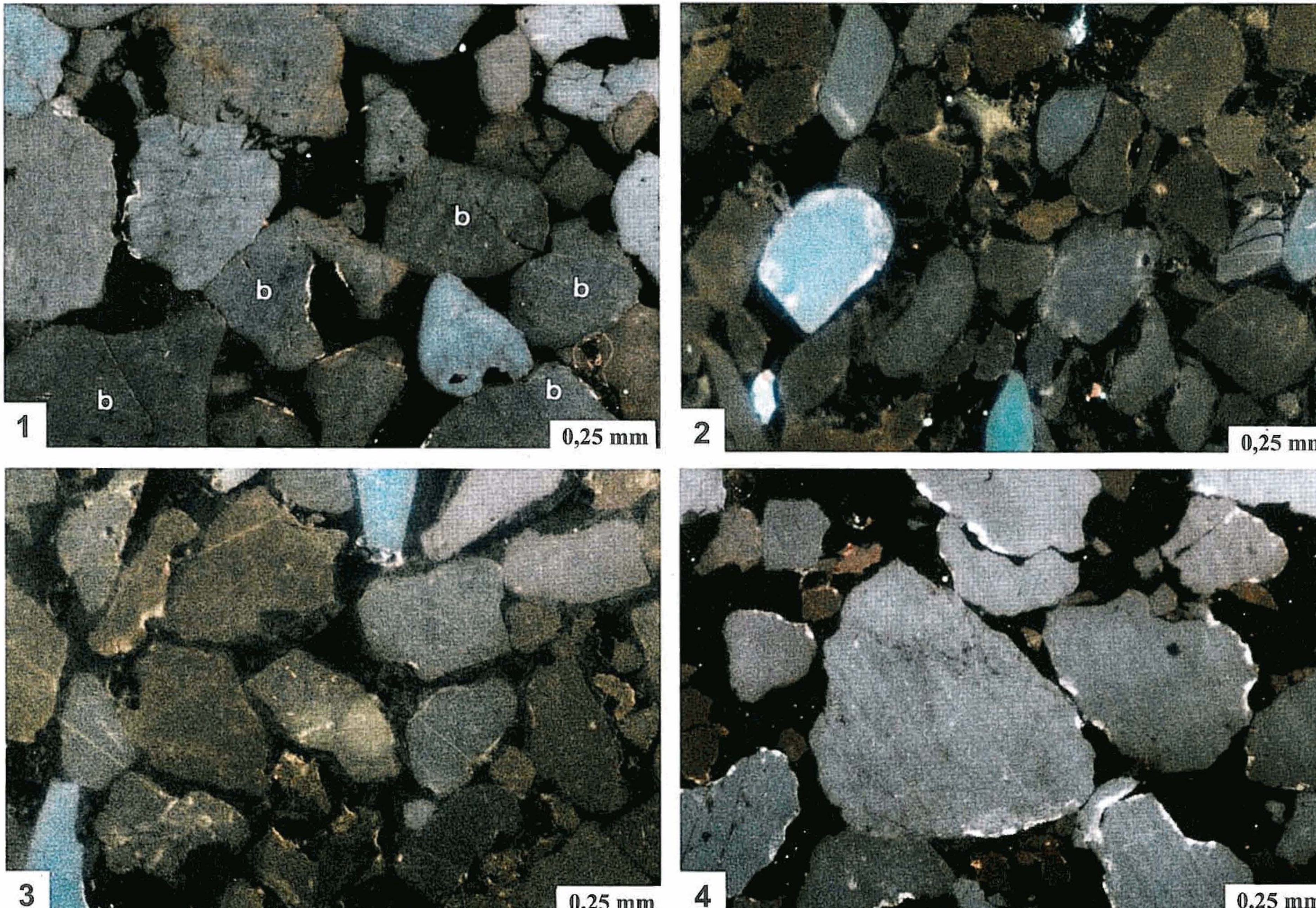


1. PL — grain (Z) resembling polycrystalline quartz or quartzite fragment; crossed polars; Kościerzyna IG 1 borehole, depth 5045.2 m. *1a.* CL — silicified feldspar relics (blue luminescence colour) in a cement of authigenic quartz (brown luminescence colour); adjacent, small polycrystalline quartz grain (p), difficult to identify optically. *2.* PL — polycrystalline quartz or quartzite fragment (P) occurring between two potash feldspars; crossed polars; Kościerzyna IG 1 borehole, depth 5024.9 m. *2a.* CL — quartz pseudomorph (P) (dark brown luminescence) occurring between potash feldspars (blue luminescence); the pseudomorph is probably after feldspar. For other explanations see Pl. I

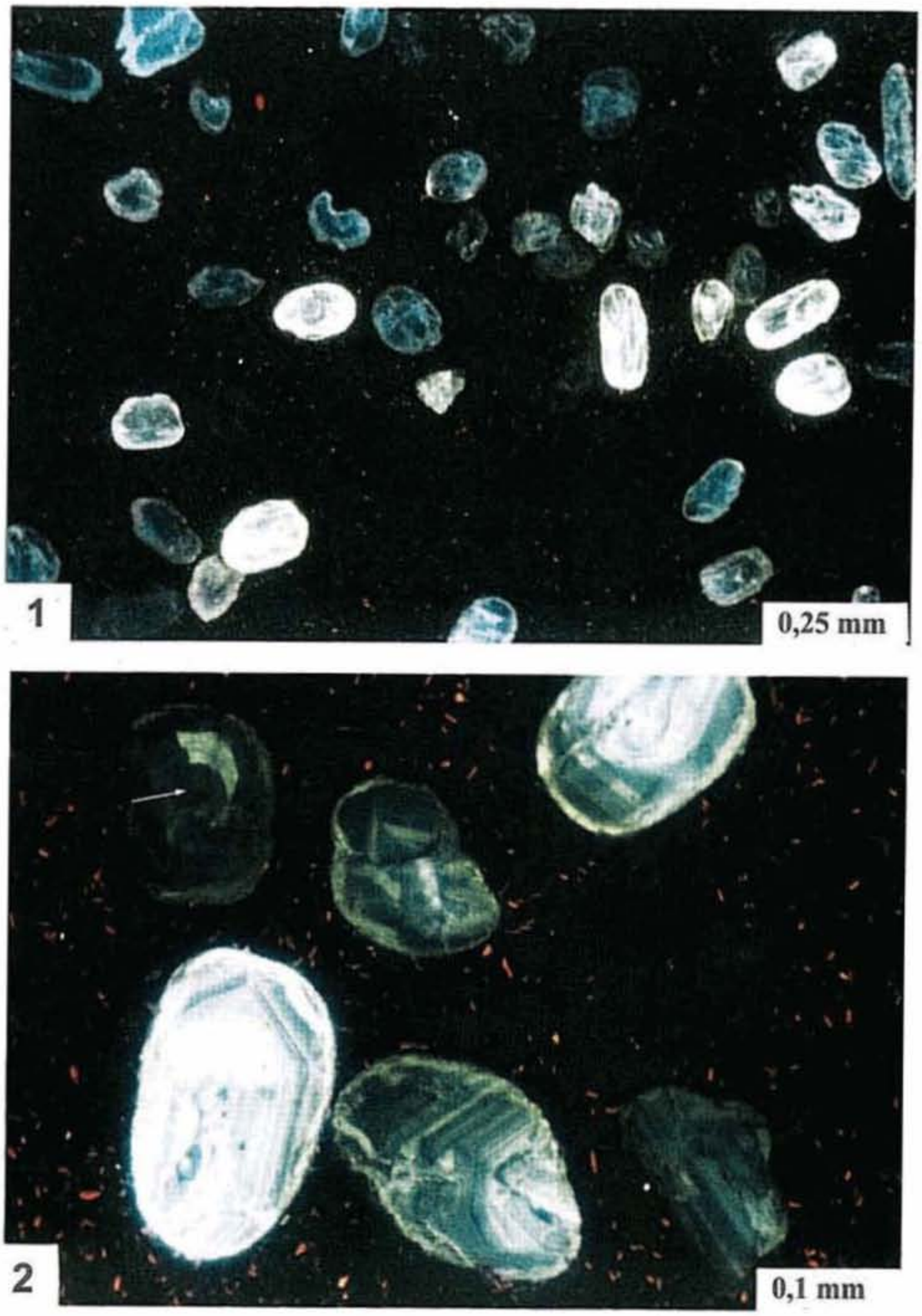
PLATE III



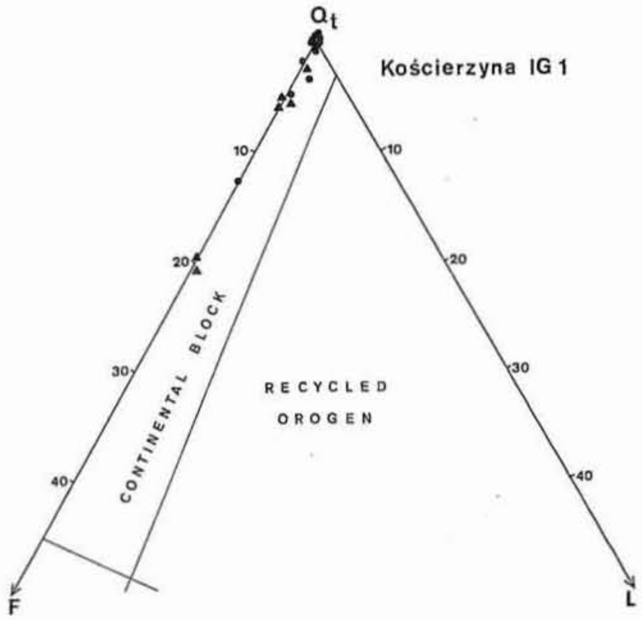
1. PL — very fine-grained quartz arenite; feldspar grains are difficult to distinguish; crossed polars; Kościerzyna IG 1 borehole, depth 4877.5 m. *1a*. CL — many scattered potash feldspar grains, distinguished by an intensive blue luminescence. *2*. PL — probable lithic clast (centre); crossed polars; Kościerzyna IG 1 borehole, depth 5064.0 m. *2a*. CL — "grain" in centre of photo is fine-grained authigenic quartz (aq). For other explanations see Pl. I



1. CL — quartz grains with dominant blue luminescence; blue-grey quartz (b) is blue-black in the luminoscope (see text); Kościerzyna IG 1 borehole, depth 5064.0 m. *2.* CL — quartz grains with dominant brown luminescence; Kościerzyna IG 1 borehole, depth 4706.5 m. *3.* CL — quartz grains with dominant brown luminescence; Gdańsk IG 1 borehole, depth 3389.9 m. *4.* CL — bimodal grain distribution — coarse quartz grains show blue luminescence and fine-grains show brown luminescence; Gdańsk IG 1 borehole, depth 3459.9 m. For other explanations see Pl. I



1. CL — two zircon populations, showing dark blue and white luminescence respectively; powder preparation; Gdańsk IG 1 borehole, depth 3144.8 m. *2*. CL — zonal structure in zircons of various luminescence colours; one grain shows a core (arrowed), inherited from the protolith of the source rock; powder preparation; Kościerzyna IG 1 borehole, depth 4781.8 m. For other explanations see Pl. I



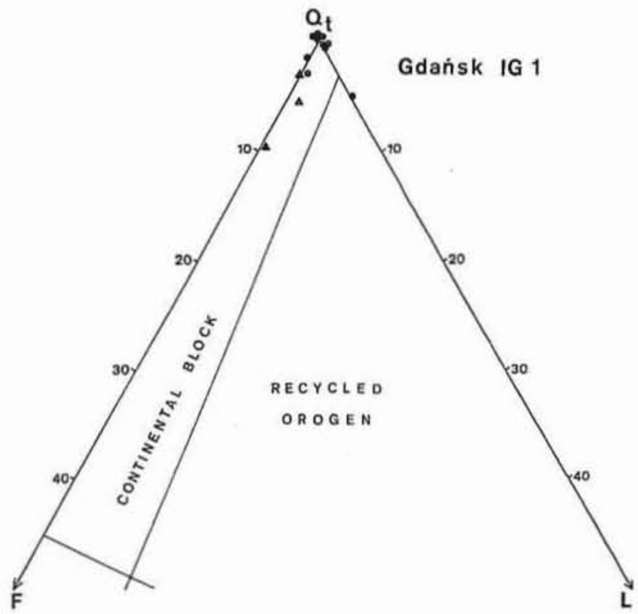


Fig. 3. Discriminant diagrams (after Dickinson, 1985) showing provenance of the clasic material

Q_t — quartz (mono- and polycrystalline); F — feldspars; L — aphanitic unstable rock fragments; triangles — Lower Cambrian sandstones; circles — Middle Cambrian sandstones

ness and sorting, characteristic of polycyclic deposits — though alternatively explained by prolonged reworking of sediment in a tidal environment (Jaworowski, 1979; Sikorska, 1988).

SOURCE ROCKS

The initial data on the nature of source rocks are provided by rock fragments found in the Żarnowiec Formation sandstones. As the fragments are highly altered one may only recognise primary occurrence of potash feldspar grains larger than associated quartz grains. Scarce myrmekite fragments, with the feldspar altered to clays, have been also identified (the Kościerzyna IG 1 borehole). These observations point to the erosion of local basement rocks, which in the Kościerzyna IG 1 region include enderbites, metasomatic granitoids and migmatites (Ryka and Krystkiewicz, 1982; Jackowicz, 1997). Ryka and Krystkiewicz (1982) note the size of the potash feldspars (up to 11 mm) in the enderbites, compared to the associated quartz grains which are on average 0.3 mm in diameter (max. 3.4 mm). Quartz-feldspathic intergrowths (myrmekites) also comprise up to 11.2% of these rocks. In the Żarnowiec Formation sandstones from Gdańsk IG 1 borehole, a local origin from eroded migmatites (Ryka and Krystkiewicz, 1989) is indicated by ferrous pigmentation, the low feldspar percentage and the equal sizes of quartz and feldspar grains.

An enderbite provenance is not, though, unambiguous as these are described both as igneous and as metamorphic rocks (Ryka and Maliszewska, 1991), causing difficulty with interpretations based on the Basu *et al.* (1975) method and with CL analysis.

In the diamond diagram (after Basu *et al.*, 1975) almost all Żarnowiec Formation (Kościerzyna IG 1) points plot in the low rank metamorphic field two points occurring along the boundary with or just inside the medium or high rank metamorphic field (Fig. 4a). This is consistent with the above presented conclusions about the local provenance of clastic material. However, these conclusions are not in agreement with the data coming from analysis of quartz CL colours. Such a discrepancy may reflect the complex genesis of the crystalline rock basement (enderbites). Dark blue and navy blue grains (blue-black) are dominant, suggesting an origin from plutonic rocks. The quartz grains with very dark luminescence colours (blue-black), according to Marshall (1988), might be grains of plutonic origin, plastically deformed, consistent with a genetic relation to the migmatites. The CL data thus relate part of the detrital material to metamorphosed rocks and part to plutonic rocks.

It is more difficult to infer the source rocks of the marine Lower and Middle Cambrian, because of the maturity of these rocks, and their essentially monomineral (quartz) composition. Interpretation was based solely on the diamond diagrams (after Basu *et al.*, 1975) and the CL analyses, i.e. those methods which differentiate between the various quartz characters. The sandstones from the Kościerzyna IG 1 borehole (Fig. 4A) yielded points occupying two fields: medium and high rank metamorphic rocks and plutonic rocks. CL observations also

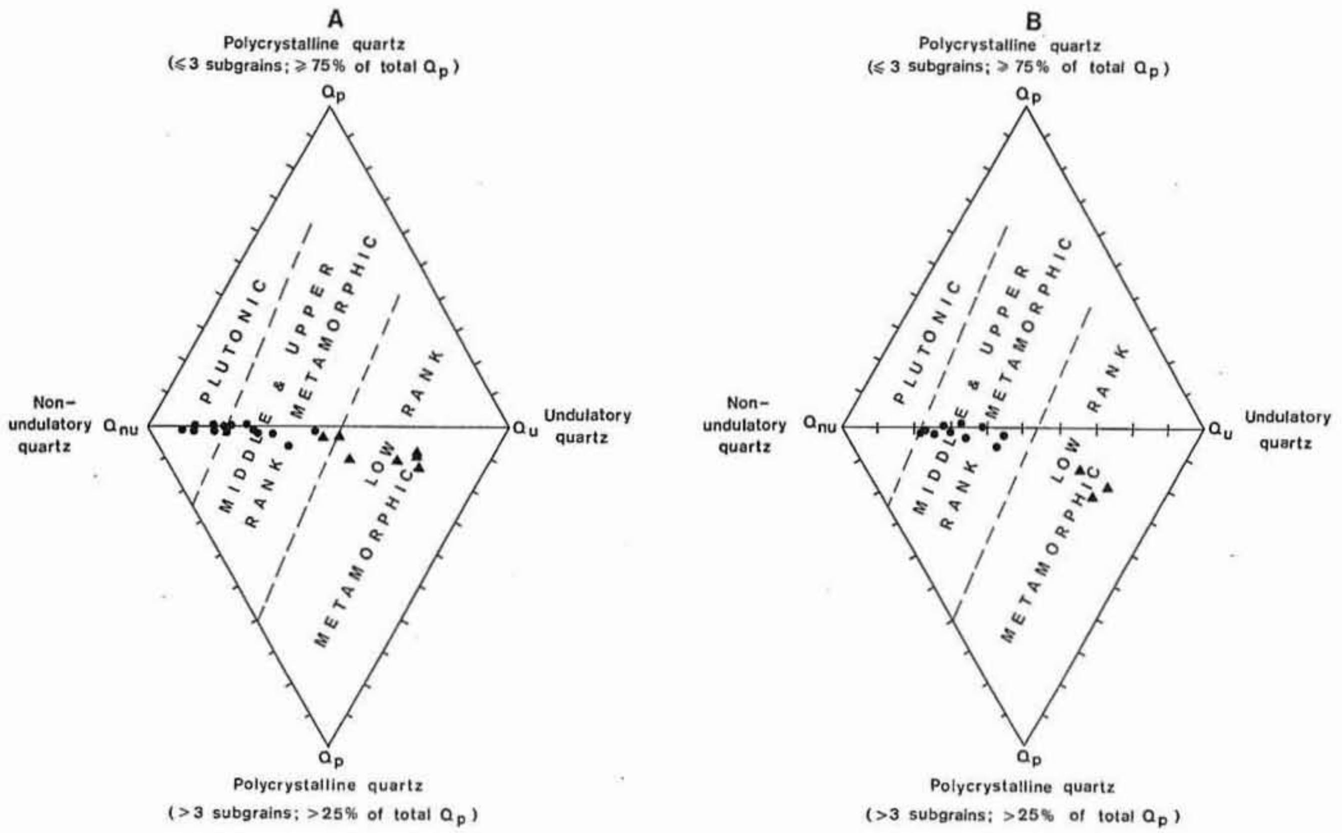


Fig. 4. Diamond diagrams (after Basu *et al.*, 1975) demonstrating quartz origin in the Cambrian sandstones from the Kościerzyna IG 1 (A) and Gdańsk IG 1 (B) boreholes

Triangles — Lower Cambrian sandstones; circles — Middle Cambrian sandstones

show that the quartz grains, showing blue and brown luminescence colours, can originate from both plutonic and metamorphic rocks. However, the dominance of blue and navy blue grains (Pl. IV, Fig. 1) with one exception (sample at 4706.5 m with brown luminescent quartz) (Pl. IV, Fig. 2) indicates a preponderance of metamorphic rocks in the source area.

Sandstones from the Gdańsk IG 1 borehole all plot in the medium and high rank metamorphic field of the diagram (Fig. 4B). Navy blue and brown quartz luminescence colours are consistent with this interpretation. As in Kościerzyna IG 1, individual samples (depth 3389.9 m) show dominant brown quartz luminescence colours (Pl. IV, Fig. 3), indicating a metamorphic source. The sample from 3459.9 m shows coarse-grained quartz with dark blue luminescence colours, while finer fractions have brown colours (Pl. IV, Fig. 4). This suggests derivation from plutonic rocks and metamorphic rocks respectively.

CL observations on zircons were consistent with these interpretations of provenance. Three basic white, dark blue and yellow and one intermediate (blue-white) luminescence types amongst the zircons were recognised (Pl. V). This CL colour differentiation indicates that the zircon originated from various source rocks. Zircons of a very similar dark blue luminescence colour (Marshall, 1988) were isolated from Precambrian gneisses in the Bighorn Mountains (Wyoming, USA).

Table 1 gives quantitative data on the zircon luminescence types. There is a gradual increase in dark blue luminescent zircons and a decrease in white luminescent zircons with depth in both boreholes.

INTERPRETATION

The continental-marine clastic material of the Żarnowiec Formation (Upper Vendian/lowest Lower Cambrian) was derived from crystalline basement (enderbites and migmatites). The Cambrian marine deposits (Lower and Middle Cambrian) are of cratonic origin (Fig. 3). Only one sample (Gdańsk IG 1 borehole) differs from this general trend and this detrital material might derive from a Precambrian orogen. Further work is needed to verify this assumption.

The source rocks for the Cambrian comprised mainly metamorphic rocks with subordinate magmatic rocks. CL analysis suggests possible presence of volcanic quartz with a blue luminescence colour, though the microscopic observations indicate otherwise.

In the Cambrian, when sea level was low (particularly in the Middle Cambrian), earlier Vendian and Cambrian deposits were eroded and supplied clastic material.

Table 1

Percentage of zircons displaying different CL colours

Borehole	No. of sample	Depth [m]	CL colours			
			dark blue	blue-white	white	yellow
Kościerzyna IG 1	5	4745.8	67.3	7.4	21.6	3.7
	6	4762.5	74.9	8.1	16.3	0.7
	9	4877.5	81.8	12.3	5.9	–
Gdańsk IG1	1	3144.8	74.1	8.7	16.2	1.0
	4	3219.9	78.3	8.1	12.6	1.0
	8	3456.7	85.0	11.1	5.5	0.4

Both the compositional patterns (Fig. 4) and the CL analyses indicate different source rock types during the sedimentation of the Żarnowiec Formation and during the sedimentation of the younger marine Cambrian sediments.

The results of this study support the opinions of Juskowiakowa (1976) and Jaworowski (1979, 1997) that both the continental-marine Żarnowiec Formation and the Cambrian marine deposits derive from the East European Craton. This petrological identification of source areas for the Upper Vendian-Cambrian deposits in the foreland of Pomeranian Caledonides is consistent with the latest tectonic subsidence models of this area (Poprawa *et al.*, 1997). The deposits were formed in an extensional sedimentary basin tied to the disintegration of the Precambrian supercontinent (Poprawa *et al.*, 1997; Jaworowski, 1999). The passive margin of Baltica was developing along the evolving south-west rim of the East European Craton. The Upper Vendian-Cambrian sedimentary basin stretching along the margin of Baltica was the site of deposition of craton-derived clastic material.

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