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Facies variability in the Cambrian deposits from the Kościerzyna and Gdańsk sections (Pomeranian Caledonides foreland, northern Poland): a comparative study

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The origin of Cambrian clastics occurring in the marginal part of the East European Craton, in the foreland of the Pomeranian Caledonides is discussed. They were deposited in an epicontinental sea influenced by tides and storms. The first Lower Palaeozoic transgressive-regressive (T-R) cycle spans the Lower and most of the Middle Cambrian. The maximum transgression in the craton-margin part (Kościerzyna section) is marked by submarine erosion and a very low deposition rate around the Lower/Middle Cambrian boundary. The condensed deposit is a limestone — shell hash packstone with phosphatized mudstone clasts. In the inner part of the craton (Gdańsk section), the condensed deposit is represented by mudstones and heterolithic deposits with iron ooids. Transgressive phase deposits of the first T-R cycle from the Kościerzyna section are 323.5 m thick, while regressive phase deposits — 273.7 m thick. In the Gdańsk section the thicknesses are of 113.0 and 218.8 m, respectively. Deposits of the first T-R cycle of northern Poland and the Polish part of the Baltic Sea are overlain by those of the second T-R cycle, which, when complete, comprise the uppermost Middle Cambrian, Upper Cambrian and Lower Tremadoc. In both the sections discussed, deposits of the second T-R cycle were almost completely removed by pre-Arenig erosion. Facies analysis of deposits of the first T-R cycle from the Kościerzyna and Gdańsk sections shows that the source areas of terrigenous material, during both transgressive and regressive phases of this cycle, were elevated zones of the East European Craton.

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Key words: northern Poland, Cambrian, transgressive-regressive cycle, condensed deposits, sources of clastics.

INTRODUCTION

The Cambrian deposits discussed in this study comprise the first and second of four Lower Palaeozoic depositional sequences distinguished in northern Poland and the Polish part of the Baltic Sea. These sequences correspond to the first and second Lower Palaeozoic transgressive-regressive (T-R) cycles (Jaworowski, 1986), and are a cratonic record of Caledonian-stage tectonic events (Jaworowski, 1999). These events commenced with a break-up of the Precambrian supercontinent (Poprawa *et al.*, 1997, in press) that gave rise to the Teisseyre-Tornquist Zone (TTZ) which is at present the NE boundary of the Trans-European Suture Zone (TESZ; Dadlez, 1993). The suture separates the East European Craton from a mosaic of Phanerozoic terranes (*cf.* Pharaoh *et al.*, 1996).

An important problem in this context is the origin of Cambrian clastics occurring in the marginal part of the East European Craton, in the foreland of the Pomeranian Caledonides. Cambrian deposits are only known from the East European Craton, almost entirely from cored deep boreholes drilled by the Polish Geological Institute. Cambrian deposits in the Caledonian deformation area have not yet been drilled in Pomerania.

Cambrian clastic material in northern Poland is thought to have been derived from cratonic sources (Jaworowski, 1979, 1997), as evidenced by recent petrological studies (Sikorska, 2000). The mineralogical maturity of the Cambrian deposits renders petrological investigations indecisive. The Lower Cambrian deposits from northern Poland though, show a facies distribution suggesting the transport direction of E → W and SW → NE (Jaworowski, 1979, 1997). This suggests derivation from both cratonic and extracratonic sources.

This study is aimed at the character and provenance of the first Lower Palaeozoic T-R cycle in the foreland of the Pomeranian Caledonides. This cycle comprises Lower and Middle (ex-

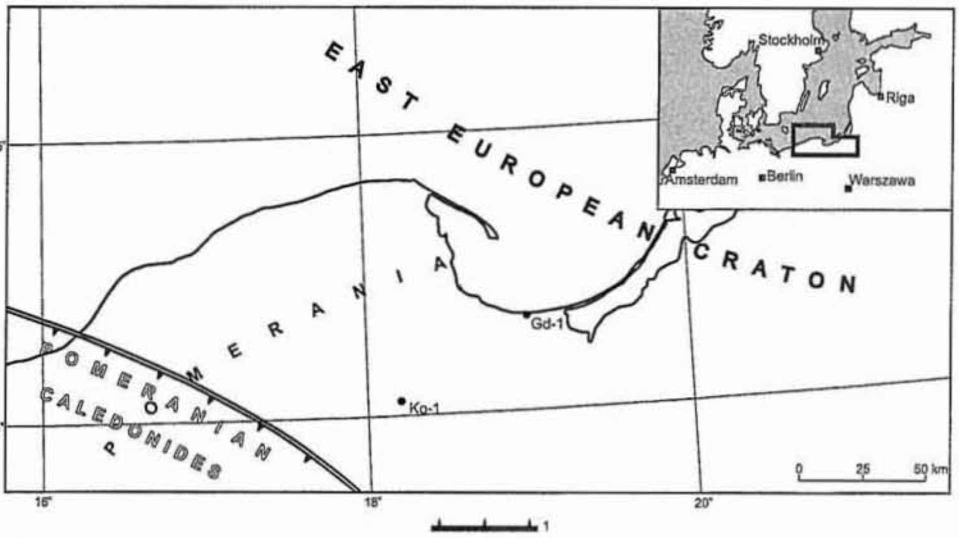


Fig. 1. Location map of the borehole sections studied

1 — Caledonian Deformation Front; Ko-1 — Kościerzyna IG 1 borehole; Gd-1 — Gdańsk IG 1 borehole

cluding the uppermost part) Cambrian marine deposits (Jaworowski, 1986, 1999). Comparative facies studies of the Cambrian sections from the boreholes Kościerzyna IG 1 and Gdańsk IG 1 (Fig. 1) were carried out. The line connecting these boreholes runs approximately perpendicular to the Caledonian Deformation Front, and the greatest facies and thickness changes in the Cambrian deposits of northern Poland are seen along this line. This paper also discusses deposits of the second Lower Palaeozoic T-R cycle which, in northern Poland and the Polish part of the Baltic Sea, comprises the uppermost Middle Cambrian, Upper Cambrian and Lower Tremadoc, were almost completely removed by pre-Arenig erosion in these borehole sections.

PREVIOUS STUDIES

The stratigraphy of the Cambrian marine deposits in these borehole sections is given by Lendzion (1982*a*, 1989). Petrographic studies were performed by Rydzewska (1982) and Sikorska (1989). The regional stratigraphy of Precambrian and Cambrian deposits from Pomerania was discussed by Lendzion (1970, 1982*b*, 1983*a*, *b*, 1988), Bednarczyk (1972) and Bednarczyk and Turnau-Morawska (1975). Ichnocoenoses recorded in these deposits were studied in detail by Pacześna (1989, 1996) while the sedimentology of the Cambrian deposits of northern Poland was discussed by Jaworowski (1979, 1982, 1993, 1997, 1999) and Sikorska (1988). They have shown that the Lower and Middle Cambrian sediments were deposited in an epicontinental sea subjected to tides and storms. Tidal coastal sand tongues (shoals) and tidal channel-fills, as well as shelf muds with storm-surge channel fills and tidal sand ridges have been recognized (Jaworowski, 1997). Kiełt (1990), followed by Schleicher (1994), considered the Lower Cambrian sand bodies to be a result of shallow-marine deposition in a sand barrier environment. Schleicher (1994) interpreted the Middle Cambrian sediments as shelf and tidal flat deposits and noted the occurrence of condensed sediments. The two depositional cycles distinguished by Schleicher (1994) correspond to the first and second T-R cycles that had been described from the Cambrian of northern Poland (Jaworowski, 1986). The Middle Cambrian sandstones probably do not represent barrier sands as they are widespread and do not pass into deposits that could be associated with lagoons or barred tidal flats (Jaworowski, 1997); they seem to have been deposited on open, unbarred sandy tidal flats.

FACIES

Figure 2 shows simplified lithological logs of Cambrian deposits from the Kościerzyna IG 1 and Gdańsk IG 1 boreholes. These boreholes penetrated all the Cambrian facies types recognized from the Polish part of the East European Craton. The facies comprise (see Jaworowski, 1997 for more detail):

FACIES A

Lithology: grey and dark grey mudstones, nearly black claystones.

Sedimentary structures: rare lenticular bedding or isolated sandy laminae.

Interpretation: shelf muds.

FACIES B

Lithology: mud-sand heteroliths (mud laminae predominate).

Sedimentary structures: lenticular and wavy bedding, horizontal lamination in sandstones, small-scale cross bedding, occasional graded bedding, bioturbation, synaeresis mud cracks, deformational sedimentary structures.

Interpretation: transition zone from shelf muds to tidal coastal sands — shelf muds with distal storm sand layers.

FACIES C

Lithology: sandstones of various grain-size, containing muddy streaks and intraclasts; alternate with mud-sand heteroliths to form sand complexes within them, up to 25 m thick.

Sedimentary structures: large- and small-scale cross bedding, horizontal lamination, flaser bedding, bioturbation, thin accumulations of mudstone intraclasts.

Interpretation: transition zone from shelf muds to tidal coastal sands — fills of storm-surge channels (frequently amalgamated).

FACIES D

Lithology: sand-mud heteroliths (sand laminae predominate).

Sedimentary structures: wavy and lenticular bedding, small-scale cross bedding in sandstones, horizontal lamination, bioturbation, mud cracks.

Interpretation: transition zone from shelf muds to tidal coastal sands — shelf muds with proximal storm sand layers.

FACIES E

Lithology: fine-grained sandstones with mudstone streaks and intraclasts.

Sedimentary structures: small-scale cross bedding, horizontal lamination, flaser bedding, large-scale cross bedding, bioturbation, thin accumulations of mudstone intraclasts.

Interpretation: tidal coastal sands — sand tongues (shoals), subtidal zone below the wave base (or tidal channel fills).

FACIES F

Lithology: medium- and coarse-grained sandstones with mudstone streaks and intraclasts.

Sedimentary structures: large-scale cross bedding, horizontal lamination, flaser bedding, small-scale cross bedding, bioturbation, thin accumulations of mudstone intraclasts.

Interpretation: tidal coastal sands — sand tongues (shoals), subtidal zone above wave base (or tidal channel fills).

FACIES G

Lithology: very coarse-grained sandstones with mudstone streaks and intraclasts.

Sedimentary structures: large-scale cross bedding, horizontal lamination, flaser bedding, small-scale cross bedding, sparse bioturbation, thin accumulations of mudstone intraclasts.

Interpretation: tidal coastal sands — sand tongues (shoals), intertidal zone (or tidal channel fills).

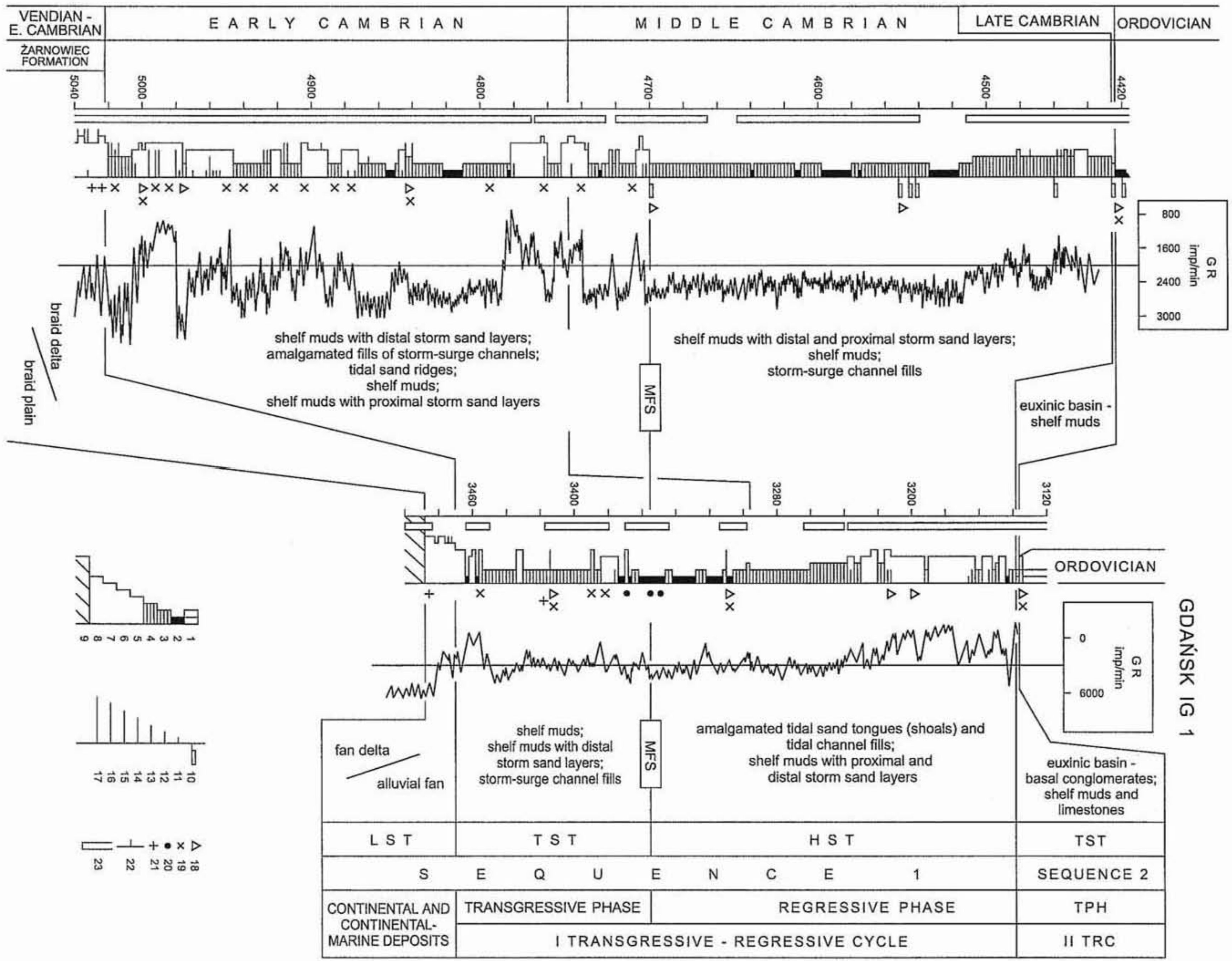
Facies E, F and G may represent tidal shelf not coastal sands (*cf.* Jaworowski, 1997, figs. 42, 43). In that case these facies would represent tidal sand ridges (facies E — below wave base, facies F and G — above wave base) and — possibly — fills of storm-surge channels dissecting them.

LOWER BOUNDARY OF THE CAMBRIAN MARINE DEPOSITS

The Cambrian marine deposits of the Kościerzyna and Gdańsk sections rest on the Żarnowiec Formation assigned to the Vendian-lowermost Cambrian (Lendzion, 1970; Areń and Lendzion, 1978; Areń, 1988; Mens *et al.,* 1990). The Żarnowiec Formation of the two borehole sections was described by Areń (1982, 1989). It is composed of very coarse-, coarse- and also medium-grained sandstones with interbeds of conglomerates, and subordinate mudstones. The rocks are cherry-brown in colour and contain abundant feldspar grains. The Żarnowiec Formation was considered to reflect deposition on vast alluvial fans which — in the upper part of the formation — interfinger with the transgressive marine deposits (Jaworowski, 1979, 1982). Later investigations (Jaworowski, 1997) indicated a braid plain environment for part of the Żarnowiec Formation deposits in the marginal part of the East European Craton, distant from clastic sources in the inner part of the craton. During the Early Cambrian marine transgression, braid plain deposits entering into the sea formed braid deltas. As a result, a continuous transition is observed between the Żarnowiec Formation deposits and overlying Lower Cambrian marine ones.

This continuous Vendian/Cambrian transition in the Kościerzyna section makes the formational boundary difficult to place. Areń (1982) and Lendzion (1982*a*) suggested it at a depth of 5026.7 m. Jaworowski (1997) took the upper boundary of the Żarnowiec Formation as equivalent to the base of deposits in which bioturbation first appears. Bioturbation first appears in the Kościerzyna section at a depth of 5022.3 m. At this depth, braid delta deposits of the Żarnowiec Formation are overlain by transgressive marine deposits of the first Lower Palaeozoic T-R cycle in northern Poland.

Unfortunately, the boundary between the Żarnowiec Formation and Lower Cambrian marine deposits in the Gdańsk section was not cored. Areń (1982) and Lendzion (1989), using on well logs, placed the boundary at a depth of 3470.0 m, a value accepted here. The Żarnowiec Formation lithology is interpreted from a drillcore section cut at 3485.0–3487.0 m, well log data and correlations with other borehole sections from northern Poland. It is represented largely by conglomerates and


VENDIAN - E. CAMBRIAN
EARLY CAMBRIAN
MIDDLE CAMBRIAN
LATE CAMBRIAN
ORDOVICIAN
ŻARNOWIEC FORMATION
5040
5000
4900
4800
4700
4600
4500
4420
KOŚCIERZYNA IG 1
GR imp/min
800
1600
2400
3000
braid delta
braid plain
shelf muds with distal storm sand layers;
amalgamated fills of storm-surge channels;
tidal sand ridges;
shelf muds;
shelf muds with proximal storm sand layers
MFS
shelf muds with distal and proximal storm sand layers;
shelf muds;
storm-surge channel fills
euxinic basin -
shelf muds
3460
3400
3280
3200
3120
ORDOVICIAN
GDAŃSK IG 1
GR imp/min
0
6000
fan delta
alluvial fan
shelf muds;
shelf muds with distal
storm sand layers;
storm-surge channel fills
MFS
amalgamated tidal sand tongues (shoals) and
tidal channel fills;
shelf muds with proximal and
distal storm sand layers
euxinic basin -
basal conglomerates;
shelf muds and
limestones
LST
TST
HST
TST
SEQUENCE 1
SEQUENCE 2
CONTINENTAL AND CONTINENTAL-MARINE DEPOSITS
TRANSGRESSIVE PHASE
REGRESSIVE PHASE
TPH
I TRANSGRESSIVE - REGRESSIVE CYCLE
II TRC
9 8 7 6 5 4 3 2 1
17 16 15 14 13 12 11 10
23 22 21 20 19 18

very coarse-grained and conglomeratic feldspatic sandstones, interpreted as an alluvial fan derived from a cratonic high (Jaworowski, 1979). The upper (uncored) part of the Żarnowiec Formation in the Gdańsk section presumably comprises fan delta deposits.

In terms of the sequence stratigraphy, the Żarnowiec Formation continental and continental-marine deposits represent a lowstand systems tract (LST, Fig. 2).

GENERAL DESCRIPTION OF CAMBRIAN MARINE DEPOSITS

KOŚCIERZYNA SECTION

FIRST T-R CYCLE. TRANSGRESSIVE PHASE DEPOSITS

5022.3–5019.5 m. Coarse-grained pebbly and muddy sandstone. Intense bioturbation suggests a low sedimentation rate. This is interpreted as condensed and reworked braid delta deposit, an onlap deposit related to the initial phase of transgression of the first T-R cycle.

5019.5–5007.0 m. Grey and grey-greenish sand-mud heteroliths (facies C) with scattered glauconitic sandstones (facies D). These are shelf muds with proximal storm layers and storm-surge channel-fills, and indicate a high sedimentation rate during the Early Cambrian transgression.

5007.0–4872.0 m. Medium- and coarse-grained sandstones (especially in the lower part) and fine-grained sandstones, alternating with mud-sand heteroliths containing thin intercalations of coarse- and fine-grained sandstones. The sandstones are commonly glauconitic and form packets, up to 25 m thick; concentrations of phosphorites and mudstone intraclasts as well as thin claystone intercalations are quite frequently observed. Facies C sandstones are locally amalgamated, and may represent fills of storm-surge channels. Coarsening upwards sandstone units are referred to facies E and F, and were probably deposited within tidal sand ridges. Heterolithic packets are up to 20 m thick, and belong to facies B, while thin sandstone intercalations contained within them belong to facies C. They represent shelf muds with distal storm layers.

4872.0–4782.0 m. Mud-sand heteroliths with mostly thin interbeds of fine- and medium-grained glauconitic sandstones and rare mudstones. They belong to facies B, C and A, and represent shelf muds with distal storm layers, storm-surge channel-fills and shelf muds.

4782.0–4698.8 m. This interval includes the Lower/Middle Cambrian boundary at a depth of 4748.0 m (Fig. 2) according to Lendzion (1982*a*). It comprises alternating sandstones and mud-sand heteroliths. Medium- and coarse-grained sandstones occur in its lower part, and fine-grained sandstones in its upper part. Coarser-grained sandstones compose two sand packets, approximately 20 and 15 m thick. All the sandstones belong to facies C and represent amalgamated and individual storm-surge channel-fills. Heterolithic deposits of facies B represent shelf muds with distal storm sand layers. A layer of dark grey phosphatized mudstone a few centimetres thick overlies the C facies sandstone. Its upper surface shows very uneven relief (Pl. I, Fig. 1), a result of strong mechanical erosion.

FIRST T-R CYCLE. REGRESSIVE PHASE DEPOSITS

4698.8–4516.0 m. Light grey limestone (shell hash packstone) occurs at depths of 4698.8–4698.6 m above an erosional surface (see above). Erosion of the partly lithified (phosphatized) muddy deposit produced intraclasts up to several centimetres in size, which "float" in the packstone matrix. The limestone bed indicates a break in deposition and sediment starvation, being an erosion-soled condensed deposit *sensu* Kidwell (1991), a product of long and slow deposition, with internal discontinuity surfaces evident (Pl. I, Fig. 1). The underlying phosphatized mudstone also indicates slow sedimentation. The intervening erosional surface is the maximum flooding surface of the first T-R cycle, with regressive phase deposits above. These are mud-sand heteroliths and mudstones of facies B and A corresponding to shelf muds with distal storm layers. In the upper part, at depths of 4554.3–4554.0 m, the heterolithic deposits contain a sandy-marly limestone with phosphatized mudstone clasts. This limestone, indicating a lower sedimentation rate and less clastic supply, is evidence of a lower-order transgressive event within the main regressive phase. Very thin (1–2 cm), dark grey marly limestones occur at depths of approximately 4547.0 and 4543.5 m.

4516.0–4440.0 m. Sand-mud heteroliths deposits, muddy in the lower part (facies D), with sandstone interbeds (facies C). A fine-grained sandstone bed, 7 m thick, occurs in the upper part. These are shelf muds with proximal storm sand layers and single and amalgamated storm-surge channel-fills.

4440.0–4425.1 m. Sand-mud heteroliths of the facies C, i.e. shelf muds with proximal storm sand layers.

SECOND T-R CYCLE. TRANSGRESSIVE PHASE DEPOSITS

4425.1–4424.3 m. The Middle/Upper Cambrian boundary is at a depth of 4425.1 m according to Lendzion (1982*a*) (Fig. 2).

Fig. 2. General lithological logs of Cambrian deposits from boreholes Kościerzyna IG 1 and Gdańsk IG 1

Lithology: 1 — limestones, 2 — mudstones, claystones, 3 — mud-sand heteroliths, 4 — sand-mud heteroliths, 5 — fine-grained sandstones, 6 — medium- and coarse-grained sandstones, 7 — very coarse-grained sandstones, 8 — conglomerates, 9 — crystalline basement; **thin intercalations of**: 10 — limestones, 11 — mudstones and claystones, 12 — mud-sand heteroliths, 13 — sand-mud heteroliths, 14 — fine-grained sandstones, 15 — medium- and coarse-grained sandstones, 16 — very coarse-grained sandstones, 17 — conglomerates; **specific rock components**: 18 — phosphorites, 19 — glauconite, 20 — iron ooids, 21 — feldspars, 22 — depth in metres, 23 — cored intervals; LST — lowland systems tract; TST — transgressive system tract; HST — highstand system tract; TPH — transgressive phase; TRC— transgressive-regressive cycle

On the left — stratigraphy after Lendzion (1982*a*, 1989), on the right — sequence correlation based on the position of the maximum flooding surface (MFS)

This interval commences with a black sandy mudstone (10 cm) followed by a dark grey shelly limestone (35 cm) and then a clayey mudstone with rare sandy laminae (35 cm). These are shelf muds with limestone interbeds deposited in an euxinic and periodically dysaerobic basin, as shown by trace fossils observed by Lendzion (1982*a*) in the upper mudstone bed. The limestone may be a storm coquina. These rocks are relics of the transgressive deposits of the second Lower Palaeozoic T-R cycle in northern Poland and the Polish part of the Baltic Sea (*cf.* Jaworowski, 1986). They are overlain by Arenig deposits composed of basal conglomerate, glauconitic sandstone and black claystones (Modliński, 1982).

GDAŃSK SECTION

FIRST T-R CYCLE. TRANSGRESSIVE PHASE DEPOSITS

3470.0–3384.0 m. Mud-sand heteroliths interbedded with mostly medium-grained glauconitic sandstones locally with phosphatic pebbles and rare feldspar grains (Fig. 2). Dark grey mudstones occur in the lower part. Heterolithic deposits belong to facies B, sandstones to the facies C and mudstones to facies A. These deposits represent shelf muds with distal storm layers and storm-surge channel-fills, deposited during a rapid transgression. This interval was not entirely cored (Fig. 2). Lower part of the drillcore (3465.0–3459.0 m) is very intensively bioturbated and presumably represent condensed onlap deposits related to the initial phase of transgression.

3384.0–3370.0 m. Fine-grained glauconitic sandstones and mud-sand heteroliths of facies C, B and A represent amalgamated storm-surge channel-fills, shelf muds with distal storm layers and shelf muds.

FIRST T-R CYCLE. TRANSITIONAL DEPOSITS BETWEEN THE TRANSGRESIVE AND REGRESSIVE PHASES

3370.0–3310.0 m. Grey-green mudstones (facies A) with heterolithic interbeds (facies B). Some layers are reddened (oxidised) and some contain iron ooids. A medium-grained sandstone bed (facies C) with abundant thin muddy intercalations occurs at depths of 3370.0–3367.4 m. These represent shelf muds, locally with distal storm layers, and storm-surge channel-fill.

Ooids occur at depths of approximately 3367.0 (Pl. I, Figs. 2, 3), 3357.0 and 3350.0 m, of both hematite and chamosite (Sikorska, 1989), suggesting redeposition which accords with the storm origin of these deposits. According to Young (1989), iron ooids form in a shelf environment during periods of low clastic supply, particularly in shallow and high-energy waters. According to Einsele (1992), land areas subjected to laterite weathering provided the source of iron. T-R cycles resulted in repeated mixing of ooids and, during the maximum water-depth of a transgressing sea, their ultimate deposition in the form of oolitic sand bodies. In the tidal environment, iron ooids accumulated in the subtidal zone or in the lower intertidal zone.

Thus, following Young (1989) and Einsele (1992), these iron ooids may reveal the occurrence of condensed deposits. In the case of the Gdańsk section, iron was sourced from a lateritic weathering of the East European Craton crystalline basement. Iron ooids deposited coastally were later transported by storm currents to the Gdańsk section site. The occurrence of iron ooids (3370.0–3350.0 m) corresponds here to the maximum transgression in the Early Cambrian, the condensed deposits straddling the boundary between transgressive and regressive deposits of the first T-R cycle, the boundary being arbitrarily placed at a depth of 3357.0 m, in the middle occurrence of the storm-redeposited iron ooids (Fig. 2).

FIRST T-R CYCLE. REGRESSIVE PHASE DEPOSITS

3310.0–3238.0 m. The Lower/Middle Cambrian boundary is at a depth of 3296.5 m according to Lendzion (1989) (Fig. 2).

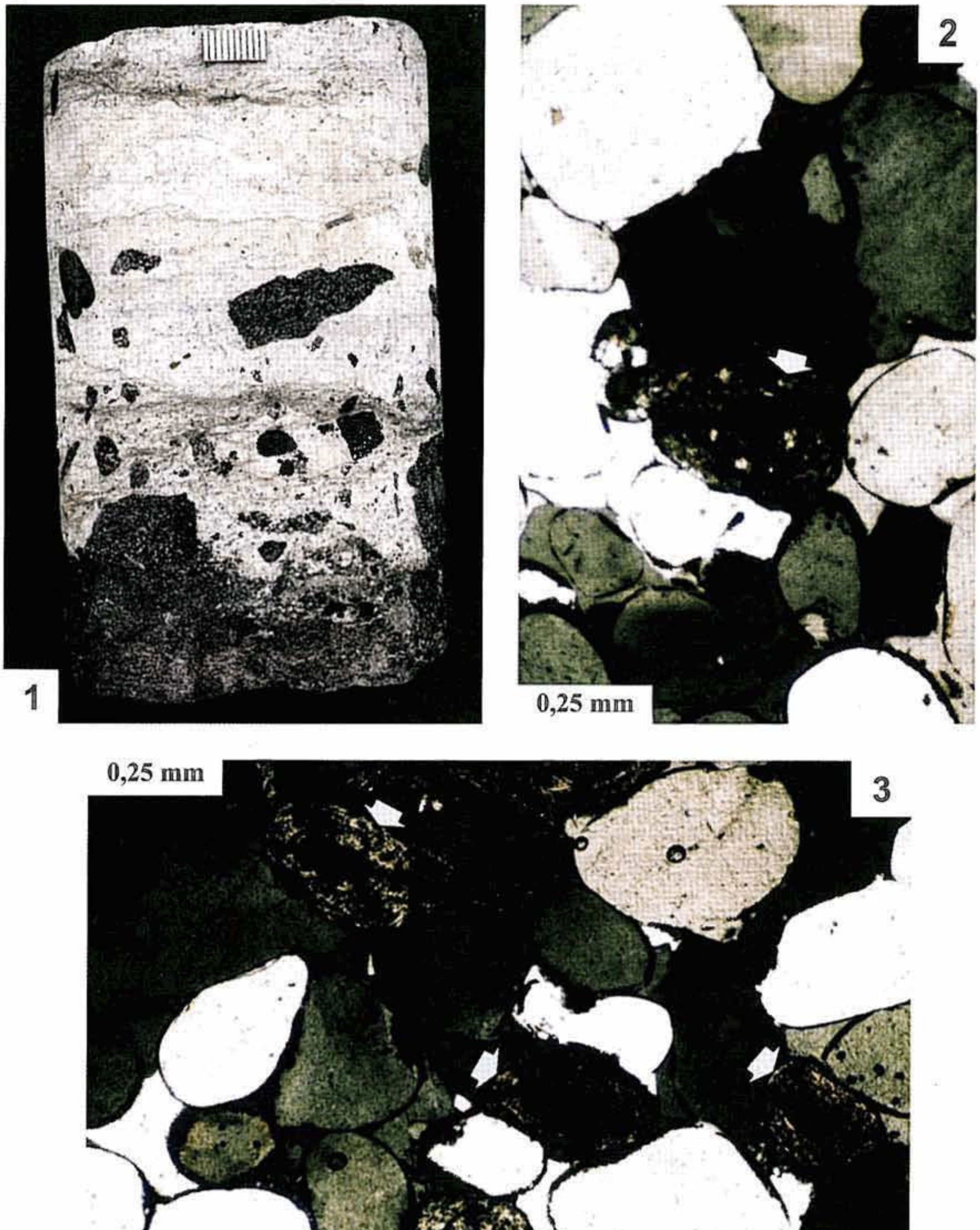
This interval commences with a medium-grained muddy, glauconitic sandstone (3310.0–3309.8 m) containing phosphatic pebbles. Above, a dark grey mudstone is followed by mud-sand heteroliths passing up into sand-mud heteroliths (facies A, B and D). These are shelf muds with distal and proximal storm layers. The sandstone observed in the lower part (facies C) is a storm-surge channel-fill. It is underlain and overlain by intensively bioturbated shelf muds, indicating lower sedimentation rates. These condensed rocks (3311.0–3306.0 m) do not represent the maximum Cambrian transgression because the bioturbation is of the Monocraterion-Teichichnus ichnofacies (Pacześna, 1989), suggesting the upper sublittoral zone above wave base. This indicates shallowing and so the discussed deposits are assigned to the regressive phase of the first T-R cycle.

3238.0–3138.2 m. Fine-grained, locally medium- and coarse-grained sandstones (facies E and F) with phosphatic pebbles and muddy and heterolithic intercalations. These represent subtidal coastal sands and include the Bergaueria ichnofacies (Pacześna, 1989). Coarser sandstone packets up to 25 m thick form coarsening-upward successions interpreted here as sand tongue (shoal) deposits amalgamated with fining-upward successions interpreted as tidal channel fills. These mark the maximum regression in the Gdańsk section. The heterolithic deposits and mudstones of facies D, B and A represent a transition zone between tidal coastal sands and shelf muds.

SECOND T-R CYCLE. TRANSGRESSIVE PHASE DEPOSITS

3138.2–3137.4 m. According to Lendzion (1989) the Middle/Upper Cambrian boundary is at 3137.8 m, and the Upper Cambrian/Tremadoc boundary is at 3137.4 m (*cf.* Modliński, 1989) (Fig. 2).

According to Lendzion (1989), this interval commences with a 6 cm-thick conglomerate layer composed of sandstone pebbles in black claystone matrix overlain, at depths of 3138.14–3137.8 m, by mudstone with sandstone laminae, and, 3137.8–3137.4 m, by a dark limestone with a thin conglomerate and claystone interbed. Above, a conglomerate grades upwards into a dark sandstone at depths of 3137.4–3137.3 m, upon an uneven erosional surface (Modliński, 1989). These deposits, assigned to the Upper Cambrian (Lendzion, 1989) and Tremadoc (Modliński, 1989), are here interpreted as transgressive deposits of the second Lower Palaeozoic T-R cycle. Both the conglomerate layers are basal conglomerates, suggesting oscillations in the initial transgression. The black claystones and dark grey limestones are remains of euxinic shelf deposits. Other transgressive deposits of this cycle, as



1. Lower part — phosphatized mudstone with an uneven erosional top surface; this surface is the maximum flooding surface of the first Lower Palaeozoic T-R cycle in northern Poland; above — limestone (shell hash packstone) with phosphatized mudstone clasts; the limestone represents an erosion-soled condensed deposit; scale in mm; Kościerzyna IG 1 borehole, depth 4698.8 m; photo by B. Ruszkiewicz. *2.* Quartz arenite with an iron ooid (arrowed); thin section, crossed polars; condensed deposits associated with the maximum transgression of the first Lower Palaeozoic T-R cycle; Gdańsk IG 1 borehole, depth 3367.4 m; collection and photo by M. Sikorska. *3.* Another part of the thin section shown in Fig. 2; abundant iron ooids are visible (arrowed); collection and photo by M. Sikorska

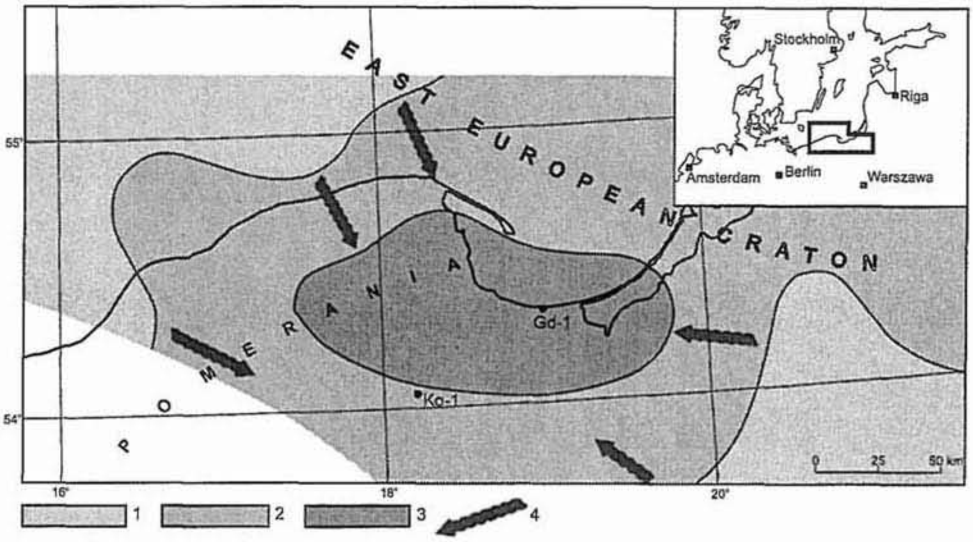


Fig. 3. Palaeogeographical sketch of the first Lower Palaeozoic T-R cycle — transgressive phase (~ Lower Cambrian)

1 — tidal coastal sands (sand tongues — shoals, tidal channels); 2 — transition zone deposits (shelf muds with proximal and distal storm sand layers, storm-surge channel-fills, tidal sand ridges); 3 — shelf muds (rare storm beds); 4 — major directions of storm-surge ebb currents transporting sand; other explanations as in Fig. 1

well as regressive deposits, were removed by pre-Arenig erosion. The Arenig deposits in the Gdańsk section begin with a glauconitite containing phosphatic pebbles (Modliński, 1989).

COMPARISON OF CAMBRIAN DEPOSITS FROM THE KOŚCIERZYNA AND GDAŃSK SECTIONS

CONDENSED DEPOSITS ASSOCIATED WITH THE MAXIMUM FLOODING SURFACE OF THE FIRST LOWER PALAEOZOIC T-R CYCLE

The recognition of condensed deposits associated with the maximum flooding surface is critical to this study. The maximum flooding surface occurs at a depth of 4698.8 m in the Kościerzyna section, and at 3357.0 m in the Gdańsk section (Fig. 2), the respective condensed deposits being dissimilar. In the Kościerzyna section, the erosion surface at the base of the condensed deposit, is considered to represent the maximum flooding surface. The condensed deposit is a limestone (shell hash packstone) with phosphatized mudstone clasts. In the Gdańsk section, condensed deposits comprise mudstones and sand-mud heteroliths containing hematite and chamosite ooids, the second of three ooid occurrences has been arbitrarily assigned as the maximum flooding surface.

Typically, iron ooids show a broad palaeogeographical extent. Beyond the Gdańsk section they reach west as far as the Hel Penninsula (Lendzion, 1982*b*, 1983*a*, 1986; Sikorska, 1986), and they also occur in the east Baltic countries (Brangulis, 1985; Brangulis *et al.*, 1986), normally being confirmed to the upper part of the *Holmia* Zone of the Lower Cambrian.

The dissimilarity of the condensed deposits between the Kościerzyna and Gdańsk sections stems from their different palaeogeographical positions (Jaworowski, 1997) the former being more distal (Figs. 3, 4).

Early biostratigraphical studies suggested that the maximum flooding surface in these two sections occurs in deposits of different ages. According to Lendzion (1982*a*, 1989), the boundary between the Lower and Middle Cambrian is at a depth of 4748.0 m in the Kościerzyna section, and 3296.5 m in the Gdańsk section. Thus, (*cf.* Fig. 2) in the Kościerzyna section the maximum flooding surface lies within the Middle Cambrian (*Eccaparadoxides oelandicus* Zone: Lendzion, 1982*a*), whereas in the Gdańsk section it occurs within the Lower Cambrian (*Holmia* Zone: Lendzion, 1989). This is an obvious discrepancy.

This discrepancy can be avoided by modifying the position of the Lower/Middle Cambrian boundary in the Kościerzyna section. Lendzion (1982*a*) noted a lack of palaeontological evidence for the *Protolenus* Subzone (Lower Cambrian) and *Eccaparadoxides insularis* Subzone (Middle Cambrian). Both the insightful biostratigraphical study of Lendzion (1982*a*) and facies variability analysis given in the present paper show that most probable is the following interpretation:

— erosional surface recognized in the Kościerzyna section at a depth of 4698.8 m, i.e. the maximum flooding surface of the first Lower Palaeozoic T-R cycle, runs within the *Holmia* Zone deposits;

— erosion leading to the formation of this surface, and deposition of the overlying condensed deposit (limestone, shell hash packstone with phosphatized mudstone clasts) took place during: upper part of the *Holmia* Zone + *Protolenus* Zone + *Eccaparadoxides insularis* Subzone.

The acceptance of this interpretation means that the Lower/Middle Cambrian boundary runs in the Kościerzyna section within the condensed deposit associated with the maximum transgression of the first Lower Palaeozoic T-R cycle. For practical reasons, this boundary should be placed at a depth of 4698.8 m, i.e. at the base of the condensed deposit (limestone). The condensed deposit is immediately overlain by the *Eccaparadoxides pinus* Subzone deposits, documented palaeontologically. This interpretation is in full conformity with biostratigraphical observations made by Lendzion (1982*a*). The only difference is that the Lower/Middle Cambrian boundary in the Kościerzyna section has been shifted upwards by 49.2 m, i.e. placed along the maximum flooding surface (*cf.* Fig. 2).

According to the above-presented interpretation, the maximum transgression of the first T-R cycle is recorded by submarine erosion and a period of the very slow sedimentation rate at the border zone between the Lower and Middle Cambrian (upper part of the *Holmia* Zone + *Protolenus* Zone + *Eccaparadoxides insularis* Subzone) in the marginal part of the East European Craton (Kościerzyna section). It is worth noting that the condensed deposit that begins the regressive phase of the first T-R cycle occurs in a similar position to the Hawke Bay Event, i.e. the widespread circum-Iapetus regression (*cf.* Mens *et al.*, 1990).

TRANSGRESSIVE PHASE DEPOSITS OF THE FIRST T-R CYCLE

The Cambrian marine deposits beneath the maximum flooding surface represent in terms of depositional sequence stratigraphy, the transgressive system tract (TST, Fig. 2). The deposits are 323.5 m thick in the Kościerzyna section. The percentage contribution of rock types in this section is as follows:

— coarse-grained sandstones — 2.5%,
— medium- and coarse-grained sandstones — 18.6%,
— fine-grained sandstones — 24.2%,
— sand-mud heteroliths — 5.6%,
— mud-sand heteroliths — 42.2%,
— mudstones, claystones — 6.8%.

The mud-sand ratio of these Cambrian deposits can be expressed by the formula MSR = (mc + mh)/(s + sh) (*cf.* Jaworowski, 1997) where: mc — mudstone and claystone thickness; mh — mud-sand heteroliths thickness; s — sandstone thickness; sh — sand-mud heteroliths thickness.

The transgressive phase deposits of the first T-R cycle in the Kościerzyna section have an MSR of 0.96.

In the Gdańsk section, the transgressive phase deposits of the first T-R cycle are 113.0 m thick. The percentage contribution of rock types in this section is as follows:

— coarse-grained sandstones — absent,
— medium- and coarse-grained sandstones — 15.8%,
— fine-grained sandstones — 10.5%,
— sand-mud heteroliths — absent,
— mud-sand heteroliths — 59.7%,
— claystones, mudstones — 14.0%.

The transgressive phase deposits of the first T-R cycle in the Gdańsk section have an MSR of 2.66.

The accomodation space of the transgressive deposits at Kościerzyna was thus much greater than at Gdańsk. This can be related to submergence of the crystalline basement in the marginal part of the East European Craton (Baltica) due to the formation of an extensional sedimentary basin in the Vendian-Middle Cambrian, following break-up of the Precambrian supercontinent (Poprawa *et al.*, 1997, in press; Jaworowski, 1999).

These transgressive phase deposits of the first T-R cycle also show differences in lithology and facies resulting from contrasting depositional conditions. The MSR from Kościerzyna indicates considerable supply of sand into storm-surge channel-fills (facies C), tidal sand ridges (facies E and F) and the distal storm layers of heterolithic deposits (facies B). The MSR from Gdańsk points to a smaller sand material supply and a dominance of mudstones and claystones, deposited as shelf muds, locally with distal sand layers (facies A and B). Rare iron ooids and reddening indicate deposition in well-oxygenated bottom waters.

The Lower Cambrian deposits from Gdańsk lie in the central part of the "Gdańsk clay anomaly" (Jaworowski, 1979) recorded also in other deep boreholes drilled by the Polish Geological Institute. This "anomaly" is an area of MSR > 1.0, where claystones, mudstones and mud-sand heteroliths predominate. It forms an oval area within the transgressive deposits of the first T-R cycle in northern Poland (Fig. 3), and is an area of shelf mud (Jaworowski, 1979, 1997). The sand deposited in the Cambrian sea of northern Poland was generally sourced from elevated areas of the East European Craton. However, as the "Gdańsk clay anomaly" area is bordered to SW by deposits of 0.25 < MSR < 1.0, as at Kościerzyna there is a suspicion that part of the sand supply may have been transported from the SW, i.e. from outside the craton. An extracratonic, perhaps tectonically generated, origin is possible, perhaps as island arcs of the Caledonian geosyncline. This cannot be proved on the basis of petrological studies (Sikorska, 2000) due to the high mineralogical maturity of the Cambrian sandstones, but may be approached via comparative facies analysis.

The Kościerzyna section, located between the SW boundary of the East European Craton (Fig. 1) and the Gdańsk section, is of significance here. The Cambrian deposits of this section (MSR = 0.98) are sandier than those of Gdańsk. But, this does not require an assumption of sand transported from the SW, from extracratonic sources. Rather, the higher contribution of sand material in the marginal part of the East European Craton (Baltica continent), i.e. in the Kościerzyna section, than in the inner part of the craton, i.e. in the Gdańsk section, may be explained by the distribution of storm-surge ebb currents.

Aigner and Reineck (1982) described how such currents worked on the coast of the SE North Sea. These are macrotidal coasts with open, unbarred tidal flats. Storm-surge ebb currents transport sand material seawards along tidal channels, depositing it where tidal coastal sands grade into shelf muds. Between the mouths of major tidal channels sand supply is markedly smaller.

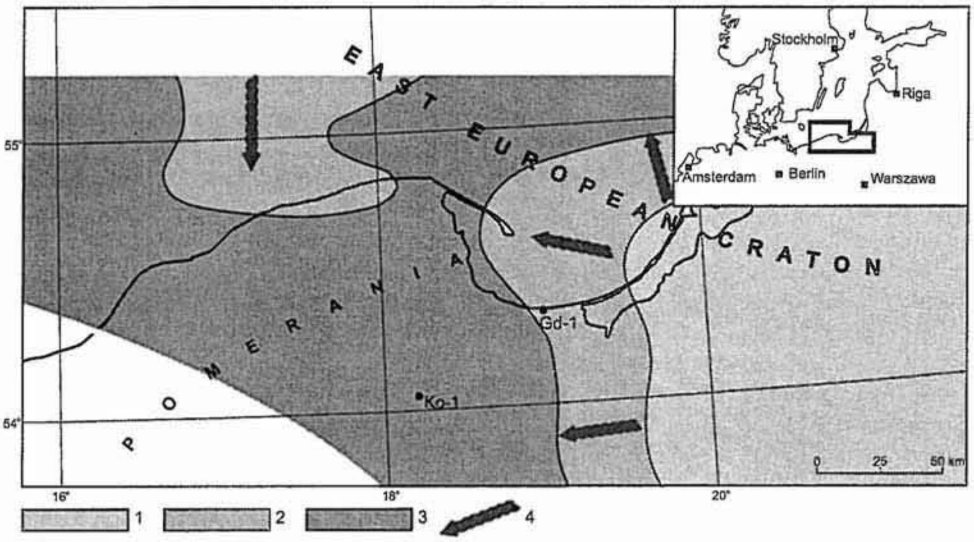


Fig. 4. Palaeogeographical sketch of the first Lower Palaeozoic T-R cycle — regressive phase (~ Middle Cambrian)

For explanations see Fig. 3

Major storm-surge ebb current directions during the transgressive phase of the first T-R cycle have been reconstructed referring to the Aigner and Reineck model (1982). Current directions are drawn perpendicular to the outer boundary of coastal sands, which was determined using data from the Kościerzyna IG 1, Gdańsk IG 1 and other boreholes drilled in northern Poland and the adjacent Baltic Sea by the Polish Geological Institute and the Petrobaltic Oil and Gas Company. The constructed palaeogeographical sketch is shown in Figure 3. It shows Cambrian clastic material sourced from the East European Craton being transported mainly from NW to SE and from SE to NW. The Gdańsk region was located on the shelf out of the reach of storm-surge ebb currents. There was increased sand supply in the area of transgressive deposition in the Kościerzyna section, with a transport direction of NW → SE along the craton margin (Figs. 1, 3).

Most of these sandstones are amalgamated storm-surge channel-fills incised into heteroliths and shelf muds (facies C). Such deep and long storm-cut cross-shelf channels are unknown from modern environments, although they were described from ancient (Silurian) storm- and tide-influenced deposits of a shallow epicontinental sea (Duke *et al.,* 1991).

This interpretation (Fig. 3) reconciles the seeming discrepancy of a higher proportion of transgressive sandstones at Kościerzyna compared to Gdańsk, with the generally acknowledged cratonic provenance of Cambrian clastic material deposited during the first T-R cycle in northern Poland (*cf.* Jaworowski, 1997, 1999; Sikorska, 2000).

REGRESSIVE PHASE DEPOSITS OF THE FIRST T-R CYCLE

These are the Cambrian marine deposits above the maximum flooding surface, representing the highstand system tract in terms of depositional sequence stratigraphy (HST, Fig. 2). Their upper boundary in the Kościerzyna section is at a depth of 4425.1 m, and in the Gdańsk section is at 3138.2 m.

At Kościerzyna these regressive deposits are 273.7 m thick. The percentage contribution of rock types in this section is as follows:

- — very coarse-grained sandstones — absent,
- — medium- and coarse-grained sandstones — absent,
- — fine-grained sandstones — 4.5%,
- — sand-mud heteroliths — 25.2%,
- — mud-sand heteroliths — 54.0%,
- — claystones, mudstones — 16.0%.

These regressive deposits in the Kościerzyna section have an MSR of 2.34.

The corresponding thickness of regressive phase deposits in the Gdańsk section is 218.8 m. The percentage contribution of rock types in this section is as follows:

- — very coarse-grained sandstones — absent,
- — medium- and coarse-grained sandstones — 3.6%,
- — fine-grained sandstones — 31.2%,
- — sand-mud heteroliths — 15.6%,
- — mud-sand heteroliths — 31.2%,
- — claystones, mudstones — 18.4%.

They have an MSR of 0.98.

The difference in thickness of regressive deposits between these sections is smaller than in the case of the transgressive deposits. The accomodation space during the regressive phase of the first T-R cycle was thus similar at both these sites. (It might also have been much the same case during the transgressive phase, the smaller thickness of transgressive deposits at Gdańsk perhaps being due to a smaller sand material supply).

The relative MSR values of the regressive phase of the first T-R cycle in these sections are opposed in sense to those of the transgressive phase. Here, the Gdańsk section has a higher sand supply. Regressive sands in the Gdańsk section are represented predominantly by amalgamated sand tongues (shoals) and tidal channel fills (facies E and F), the result of marine regression that caused the zone of tidal coastal sands to shift towards Gdańsk. The Kościerzyna section shows a dominance of shelf muds, locally with distal storm layers (facies B and A, respectively). Sand transport directions (E → W, SE → NW, N → S) from the inner areas of the East European Craton are shown in the palaeogeographical sketch of the regressive phase of the first T-R cycle (Fig. 4).

SECOND T-R CYCLE

The transgressive phase deposits of this cycle are fully developed in extreme northern Poland and in the Polish part of the Baltic Sea. They are included in the uppermost Middle Cambrian (*Paradoxides forchhammeri* Zone), Upper Cambrian and lowermost Tremadoc. The cycle begins with local basal conglomerates and sandstones overlain by black alum-type shales with interbeds and lenses of dark grey limestones (biosparites). The shales probably represent both the transgressive and regressive phase of this T-R cycle. The upper part of the regressive deposits in extreme northern Poland and in the Polish part of the Baltic Sea was removed by pre-Arenig erosion.

TRANSGRESSIVE PHASE DEPOSITS

In both the sections under discussion, the second T-R cycle deposits are almost completely destroyed by pre-Arenig erosion. In the Kościerzyna section only 0.8 m represents the transgressive phase and, in the Gdańsk section, the second T-R cycle deposits are only 0.9 m thick. In both the sections they are overlain by the Arenig deposits of the third T-R cycle.

Deposits of the second Lower Palaeozoic T-R cycle in northern Poland and the Polish part of the Baltic Sea are related to a stage of slow thermal collapse of the extensional basin that formed in the marginal part of the East European Craton, due to a break-up of the Precambrian supercontinent (Jaworowski, 1999; *cf.* Poprawa *et al.*, 1997, in press).

The second T-R cycle corresponds to the second, and the third cycle — to the third (Ordovician) depositional sequence distinguished within the Lower Palaeozoic of northern Poland and the Polish part of the Baltic Sea (Jaworowski, 1999).

CONCLUSIONS

1. In the marginal part of the East European Craton, the condensed deposit associated with the maximum flooding surface of the first T-R cycle is represented by limestones with phosphatized mudstone clasts (Kościerzyna section), and, in the inner part of the craton, by mudstones and heterolithic deposits containing iron ooids (Gdańsk section).

2. A comparison with biostratigraphical studies (Lendzion, 1982*a*) shows that the maximum transgression of the first T-R cycle on the craton margin (Kościerzyna section) was recorded by submarine erosion and a period of very slow deposition around the Lower/Middle Cambrian boundary (upper part of the *Holmia* Zone + *Protolenus* Zone + *Eccaparadoxides insularis* Subzone).

3. There was greater relative sand input to the transgressive phase deposits of the first Lower Palaeozoic T-R cycle in the marginal part (Kościerzyna section) than in the inner part of the craton (Gdańsk section). The Gdańsk region was located on the shelf out of the reach of sand-carrying storm-surge ebb currents. Sand supply to the Kościerzyna region had the transport direction of NW → SE along the East European Craton margin.

4. Facies analysis of the first Lower Palaeozoic T-R cycle in the Kościerzyna and Gdańsk sections shows that, during both the transgressive and regressive phases of this cycle, terrigenous material was transported to the sedimentary basin from elevated areas of the East European Craton. The Lower and Middle Cambrian deposits occurring in the foreland of the Pomeranian Caledonides were deposited on the shelf in the marginal part of this craton (Baltica continent).

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