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Geotectonic significance of Carboniferous deposits NW of the Holy Cross Mts. (central Poland)

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Carboniferous sandstones and shales encountered in deep boreholes drilled in central Poland, NW of the Holy Cross Mts., represent a pseudoflysch i.e. they show facies features of flysch and, simultaneously, are of cratonic provenance. Clastic sediments were derived from a peripheral bulge formed within the East European Craton as a result of stresses exerted by the accretion/thrust wedge advancing up the marginal part of the craton. In central Poland, NW of the Holy Cross Mts., a Variscan foredeep existed. The foredeep was the depositional site of interfingering exo- and pseudoflysch which, from a geodynamic point of view, are equivalent to an outer molasse. Huge masses of Carboniferous deposits (generally corresponding to flysch) from southwestern and central Poland successively represent, moving from SW to NE, Variscan ortho-, exo- and pseudoflysch.

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INTRODUCTION

This study deals with Carboniferous deposits encountered in deep boreholes drilled by the Polish Geological Institute in an area located NW of the Holy Cross Mts. (central Poland). These are the Ostałów PIG 2, Opoczno PIG 2 and Studzianna IG 2 boreholes. The study area will be hereafter abbreviated as the “OOS area” (Fig. 1). Carboniferous deposits, occurring farther to the west of this area, have also been drilled, the most important boreholes being the Milianów IG 1, Radwanów IG 1 and Budziszewice IG 1. The area penetrated by those boreholes will hereafter be abbreviated as the “MRB area” (Fig. 1), though consideration of that area go beyond the scope of this study. The MRB area boreholes show poor core recovery. Nevertheless, the data obtained can be used for a sedimentological-geotectonic comparative analysis of the Carboniferous strata NW of the Holy Cross Mts.

The geotectonic character of Carboniferous deposits from western, central and southern Poland remains unclear. Carboniferous deposits from the Fore-Sudetic Monocline, from the Moravian-Silesian segment of the Variscan orogen and from the area located NW of the Holy Cross Mts. show, despite local differences, facies features of flysch (Pożaryski and Karnkowski eds., 1992; Pożaryski *et al.*, 1992). It should be stressed, however, that the deposits from the NW border of the Holy Cross Mts. (OOS area) are anorogenic (Krzemiński, 1999), i.e. they have a cratonic provenance, whereas those from the other areas (including the MRB area) are considered to represent the Variscan Externides.

Where in that case is the Variscan Deformation Front? Is there nowhere in Poland, except in Upper Silesia, any Variscan foredeep outside of this front? And if such a foredeep does exist, why have not any deposits of a molasse character been found at the site of its probable occurrence (e.g. NW of the Holy Cross Mts.)? This study is an attempt to answer these questions on the basis of sedimentological investigations.

PREVIOUS STUDIES

Because of the scarcity of fossils, the age of Carboniferous deposits from the OOS area has long been controversial. On the map compiled by Pożaryski and Karnkowski (1992) these deposits were assigned to the Namurian-lower Westphalian. Other authors (Żakowa and Migaszewski, 1995*a*, *b*) included them within the Westphalian A/B. Results of palynostratigraphical investigations conducted by Turnau

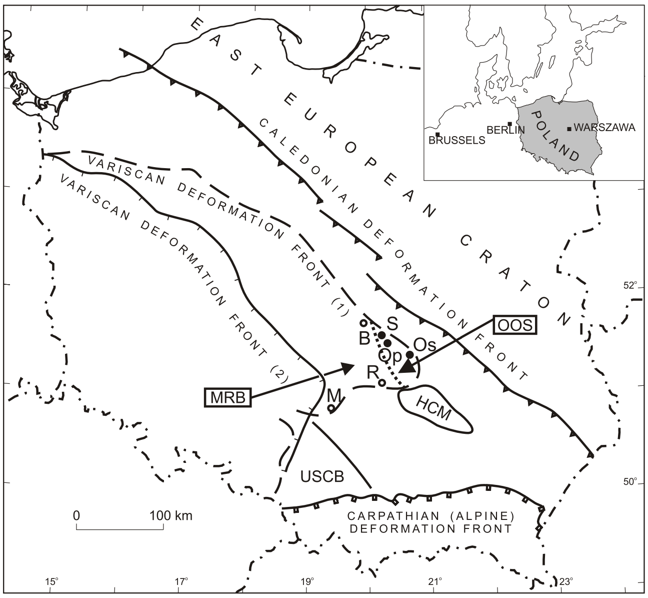


Fig. 1. Location of deep boreholes (discussed in the text) against the background of major tectonic units of Poland

Symbols used for boreholes with sedimentological investigations made (black-filled circles): Os — Ostałów PIG 2, Op — Opoczno PIG 2, S — Studzianna IG 2; symbols used for boreholes selected for comparative analysis (empty circles): M — Milianów IG 1, R — Radwanów IG 1, B — Budziszewice IG 1; Caledonian Deformation Front after Dadlez *et al.* (1994) (*cf.* Znosko, 1966; Znosko ed., 1998); Variscan Deformation Front (1) after Pożaryski and Karnkowski eds. (1992) and Pożaryski *et al.*(1992); Variscan Deformation Front (2) after Dadlez *et al.* (1994); HCM — Holy Cross Mts., USCB — Upper Silesian Coal Basin, OOS — OOS area (see text), MRB — MRB area (see text)

(1999) indicate that Carboniferous deposits from the Ostałów PIG 2 and Opoczno PIG 2 boreholes belong to the upper Tournaisian and, presumably, the lowermost Viséan. Strictly speaking, that author identified the occurrence of the *Prolycospora claytonii* Zone, not excluding the presence of the *Lycospora pusilla* Zone. Turnau (1999) also remarked that these deposits may, at least in part, correspond to the Chmielno Supracomplex (*sensu* Żelichowski, 1983) found in northern Poland. The deposits investigated show many lithological similarities to those from the lower part of that supracomplex. This part has lately been classified lithostratigraphically as the Gozd Arkosic Sandstone Formation (Fm) (Lipiec and Matyja, 1998).

According to Pożaryski and Karnkowski (1992) and Pożaryski *et al.* (1992), the Carboniferous deposits encountered north-west of the Holy Cross Mts. represent Variscan flysch. Dadlez *et al.* (1994) doubted that, suggesting that these deposits may represent epicontinental sediments accumulated under conditions not characteristic for flysch facies. Migaszewski, 1995) claimed that the Carboniferous deposits from the Ostałów PIG 2 and Opoczno PIG 2 boreholes are turbidites deposited in an intra-montane trough (*cf.* Żakowa and Migaszewski, 1995*a, b*). Migaszewski (1995) in particular concluded that Carboniferous clastic sediment was supplied to the deposition site from E to W and from NE to SW. The geochemical studies of Krzemiński (1999) show that all the material was delivered from the East European Craton (EEC). This means that the Carboniferous deposits, occurring NW of the Holy Cross Mts., accumulated outside the orogenic zone, and that the EEC was the source area. Petrographic investigations (Krzemiński, 1999) indicate that the Carboniferous sandstones represent volcaniclastic deposits: arkosic wackes and arenites. They contain faunal micro-fragments (e.g. of echinoderms), carbonate-chamosite ooids and glauconite aggregates. These components undoubtedly indicate the marine sedimentary environment. Krzemiński (1999) also underlines the "petrofacies correlativeness" of the Carboniferous sandstones from the NW border of the Holy Cross Mts. with the above-mentioned Tournaisian Gozd Arkosic Sandstones Formation (Fm). The formation represents a clastic shelf environment (Lipiec and Matyja, 1998).

Bojkowski and Dembowski (in Czermiński and Pajchlowa, 1974) hypothetically included the area located NW of the Holy Cross Mts. (north and south of the middle course of the Pilica River) within the "shelf — shallow part" and "shelf — deep part". In the lithofacies-thickness map of Westphalian deposits (these rocks were considered at that time to be of Westphalian age), Żelichowski and Jurkiewicz (1996) placed the Studzianna IG 2 and Opoczno PIG 2 boreholes within the area of basinal clay-silty lithofacies with subordinate arkosic sandstones. The Ostałów PIG 2 borehole is situated, according to those authors, within the area of the carbonate shelf. Further to the south, they suggested that clay facies with radiolarites had been deposited.

The original extent of Tournaisian deposits shown on the map by Żelichowski and Jurkiewicz (1996), as compared with the final, pre-Viséan extent of these deposits, deserves special attention. This suggests significant erosional truncation of the upper part of the Tournaisian deposits in the area situated far to NE of the Holy Cross Mts., in the marginal zone of the EEC. The erosional processes were moving from NE towards SW. This observation has important geotectonic implications (see below).

FACIES DESCRIPTION AND INTERPRETATION

Carboniferous deposits, encountered in the Ostałów PIG 2, Opoczno PIG 2 and Studzianna IG 2 boreholes, are composed of alternating sandstones, mudstones and clays (see sedimentological logs, Figs. 2–4). The following facies have been distinguished.

FACIES 1 (Figs. 5a–d, 6a, b)

Massive medium- and coarse-grained, rarely fine-grained, sandstones, most commonly with an abundant muddy matrix. Locally, these deposits contain conglomerate interbeds up to 20 cm-thick (Fig. 5d). The sandstones are arkosic wackes, locally arkosic arenites, in composition (*cf.* Krzemiński, 1999). Deposits of facies 1 are predominantly grey with a light pink tone. Arkosic arenites are commonly pink. Massive sandstones often contain mud clasts. The clasts are commonly elongate, forming concentrations in which they are arranged parallel to bedding (Fig. 6a). Mud clasts of different shapes and sizes are often randomly scattered throughout the massive sandstone bed (Fig. 5e). There are also rounded clasts originating from the disintegration of mud-supported conglomerates (Fig. 6b). Fine- and medium-grained sandstones of facies 1 are locally normally or inversely graded. Moreover, the sandstones occasionally show indistinct horizontal lamination of the upper flow regime. Rare sedimentary structures, observed in facies 1 and known only from fine-grained sandstones, comprise flaser bedding.

The common occurrence of mud clasts, several centimetres in size, in massive sandstones of facies 1 indicates a considerable density and viscosity of the currents which deposited the sandstones. Elongate mud clasts, arranged parallel to bedding planes, indicate laminar (non-turbulent) flows. The high content of muddy matrix in the massive sandstones suggests flows of considerable density and strength. All these observations suggest that the massive sandstones of facies 1 represent debris flows. Such a depositional mechanism might have also have given rise to the inverse grain-size grading observed occasionally in the sandstones. Normal grain-size grading, also present in the sandstones of facies 1, can be ascribed to turbulent flows of much lower density, i.e. turbidity currents. The indistinct horizontal lamination may also have a similar origin, although it can equally be a result of reworking by bottom currents. Such an origin may be attributed to the fine-grained sandstones with flaser bedding.

Deposits of facies 1 are typically of considerable thickness (Figs. 2–4). This results from amalgamation of sandstones deposited by successive debris flows. All the deposits of facies 1 are involved in slump structures, which are commonly incoherent slumps.

FACIES 2 (Figs. 6c, d, 7a, b)

Fine-grained (rare medium- and coarse-grained) sandstones, and siltstones. These are mainly wackes and arkosic wackes, and, less frequently, arkosic arenites. The sandstones are characterised by grey colours, locally tinged with pink. Small mud clasts were observed in some sandstone beds. The most characteristic sedimentary structures of this facies are horizontal lamination and, less frequently, normal grain-size grading and small-scale cross-bedding. Laminae surfaces are covered with parallel-arranged, indeterminate coalified flora remains (Fig. 6c). This indicates a current origin for the horizontal laminae. Such an origin is also confirmed by delicate current marks (tool marks: bounce and drag marks) observed on the soles of some sandstone laminae (Fig. 6d).

Fine-grained sandstones of facies 2, with horizontal lamination and small-scale cross-bedding, are interpreted to be a result of reworking by traction bottom currents, of the lower flow regime. The reworking affected the terrigenous material supplied to the sedimentary basin by turbidity currents. Activity of these currents is proved by the presence of sandstone beds with normal grain-size grading. The upper segments of these beds were commonly removed as a result of erosion that operated prior to deposition of the overlying sandstone bed (Fig. 7a). Therefore sandstone beds of facies 2 deposited by turbidity currents commonly represent “truncated sequences” *sensu* Bouma (1962). Deposits of facies 2 are frequently involved in slide structures (Fig. 7a) and slump structures (Fig. 7b).

FACIES 3 (Figs. 7c, d, 8a, b)

Sand/mud heteroliths. These are thin beds and laminae of fine-grained sandstones (or siltstones) alternating with shales. Coalified flora detritus is common. Especially frequent sedimentary structures, observed in the sandstone beds, are horizontal lamination, small-scale cross-bedding and flaser bedding. Locally, the sandstones also show normal grain-size grading. In the case of steeply dipping strata, large sole surfaces of sandstone beds can be observed in drillcores (Fig. 8a, b). They are commonly covered with current marks represented by flute marks and tool marks indicating the turbulent nature of currents that eroded the bottom mud and deposited the overlying sandstone beds. Therefore, the sandstone beds should be considered as turbidites. Indeed, many of the sandstone beds of facies 3 may be classified as the Tc-e sequences of Bouma (1962). They show distinct normal grain-size grading. Where grading is absent, sandstone (and siltstone) beds of heteroliths are a result of either reworking of material — originally supplied by turbidity currents — by traction bottom currents, or deposition directly from traction bottom currents. Both these depositional mechanisms probably took place during sedimentation of the heteroliths of facies 3.

Detailed sedimentological logging of facies 3 (Figs. 2–4) enabled identification of subfacies 3A and 3B. Subfacies 3A includes sand-dominated heteroliths, whereas subfacies 3B is represented by mud-dominated heteroliths. Heteroliths of facies 3 are frequently involved in slump structures.

FACIES 4 (Fig. 8c)

Dark grey, massive shales, occasionally horizontally laminated with silt or fine-grained sand material. Floral detritus is common. Claystones and mudstones of facies 4 were deposited as a result of slow sedimentation from suspension, in a hemipelagic environment, with a small contribution from weak tractional bottom currents. These deposits are also frequently involved in slump structures.

SEDIMENTARY ENVIRONMENT

Carboniferous deposits from the Ostałów PIG 2, Opoczno PIG 2 and Studzianna IG 2 boreholes (Fig. 1, OOS area) are characterised by the following features:

— alternation of sandstones and shales;

— predominance of sandstones;

— predominance of debris flow deposits (debrites) among sandstones;

— occurrence of turbidites;

— occurrence of current marks and load casts on the soles of some sandstone beds;

— occurrence of sandstones reworked or deposited by traction bottom currents;

— occurrence of massive fine-grained deposits (claystones, mudstones) accumulated as a result of slow sedimentation from suspension in a hemipelagic environment;

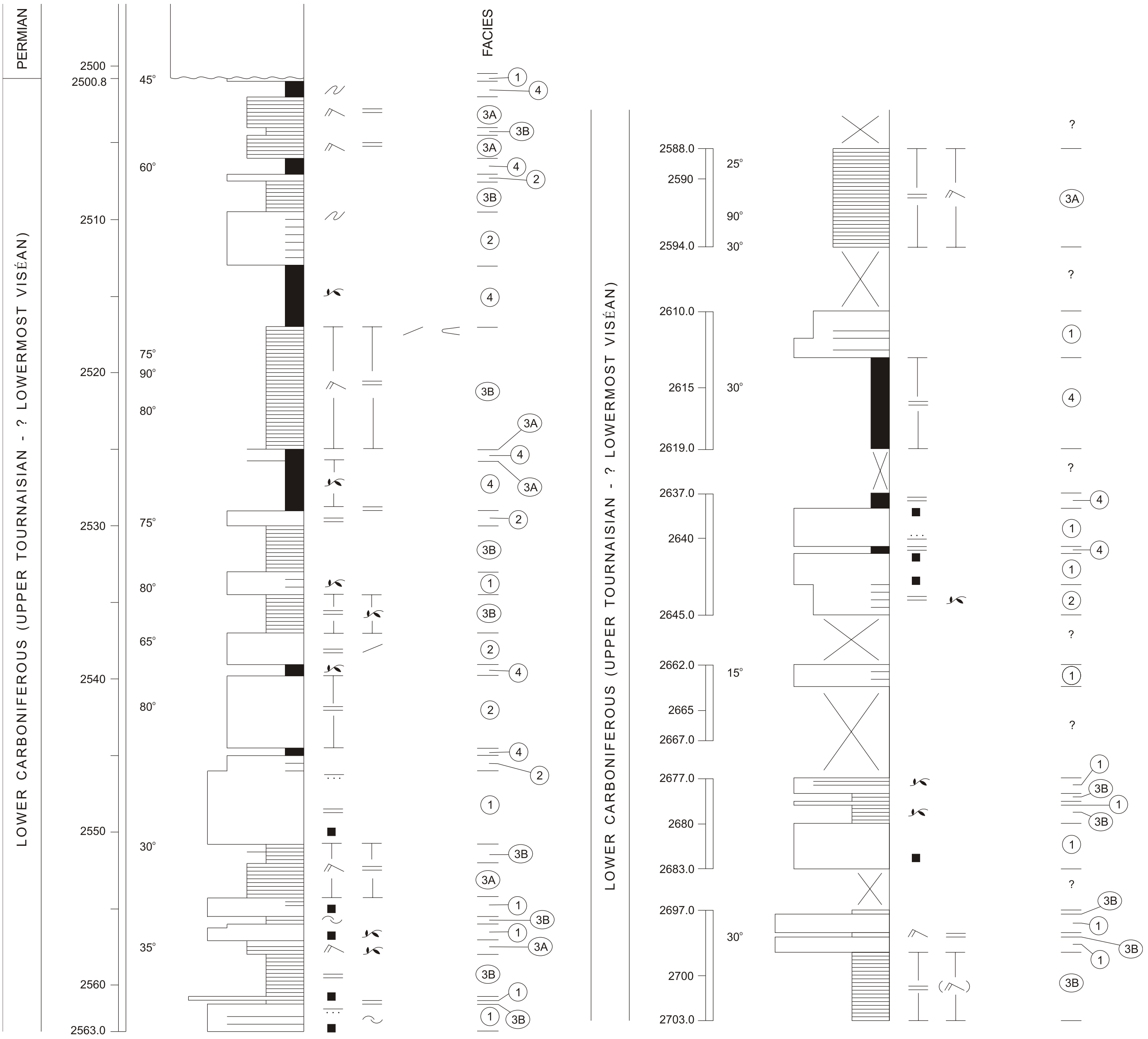


Fig. 2. Sedimentological log of Carboniferous

— occurrence of slump structures represented by incoherent slumps involving deposits of all facies;

— occurrence of tension fractures filled with clay material in sandstone beds, related to the sliding of horizontally bedded packages of sand-mud deposits;

— common occurrence of indeterminate coalified floral fragments showing parallel (sandstones) or disordered (claystones, mudstones) orientation;

— absence of bioturbation, suggesting an inhospitable basin-floor environment;

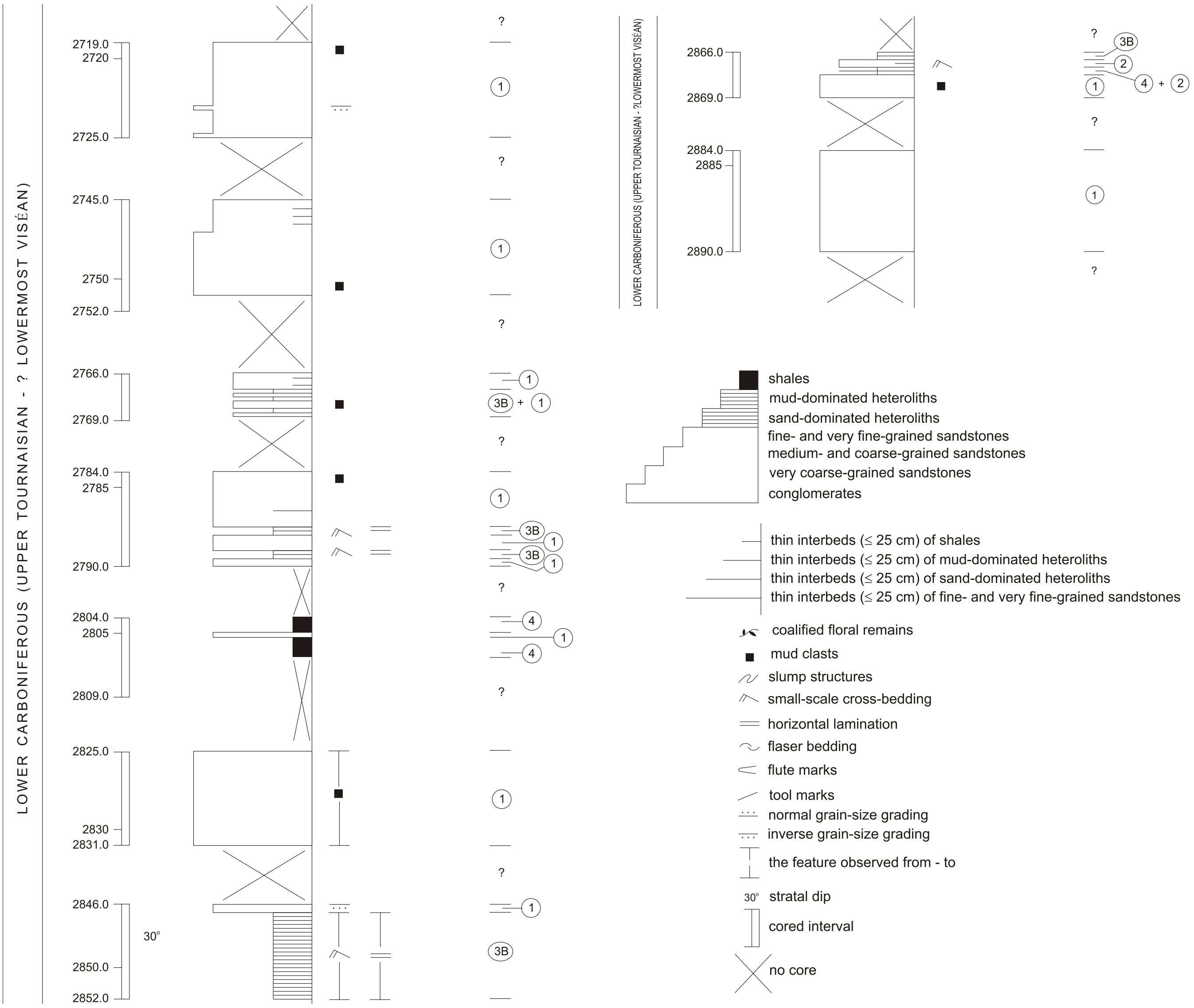
— absence of any sedimentary structures which could indicate that the basin floor was above storm or fair-weather wave-base;

— absence of any signs of large-scale erosional processes which could point to the occurrence of submarine channels;

— facies recurrence indicating facies interfingering;

— absence of any regularity in vertical facies succession.

The bathymetry of the sedimentary environment, inferred from the features listed above, is hard to estimate — first of all due to both the lack of trace fossils and preserved *in situ* organic fragments. The interpretation of a shallow-marine origin for these deposits (Krzemiński, 1999), based for example on the presence of glauconite aggregates and carbonate-chamosite ooids, is rather unlikely. The sandstones investigated were deposited as a result of mass-gravity flows (debris flows and turbidity currents), i.e. processes causing considerable displacements of sediments within the sedimentary basin. Components of the sandstones which could indicate a shallow-marine sedimentary environment were mostly redeposited. This is supported by Żelichowski and Jurkiewicz's (1996) observation



deposits from the Ostałów PIG 2 borehole

that spore assemblages also are redeposited in these deposits (e.g. in Ostałów PIG 2 borehole). As seen from the facies description, no sedimentary structures associated with the zone above storm wave-base, was observed in these deposits. Therefore, they must have been accumulated at greater depths.

Carboniferous deposits from the NW border of the Holy Cross Mts. were considered to represent flysch (Pożaryski and Karnkowski eds., 1992; Pożaryski *et al.*, 1992). The above-presented characteristics of facies indicates that the deposits indeed show features of flysch. These are features of proximal (facies 1), normal (facies 2 and subfacies 3A) and distal (subfacies 3B) flysch.

Moreover, these deposits show similarity to flysch deposits interpreted as deposited on deep-marine fans. According to the depositional system model of Mutti and Ricci Lucchi (1972), facies 1 could be assigned to the lower slope, facies 2 and 3 — to the outer fan, and facies 4 — to the abyssal plain. However, no signs of large-scale erosion related to the occurrence of submarine channels have been found. There are no deposits which could be considered to have represented fills of such channels, either.

The dominance of debris flows and the presence of slump and slide structures leads to the conclusion that the Carboniferous deposits NW of the Holy Cross Mts. accumulated on a clastic slope. The predominance of sand deposits and lack of any signs of large-scale erosional channels seem to indicate a non-channelised slope environment developed downdip from a sand-rich shelf. This interpretation employs the classification of debris flow-dominated depositional systems of Shanmugam (1997).

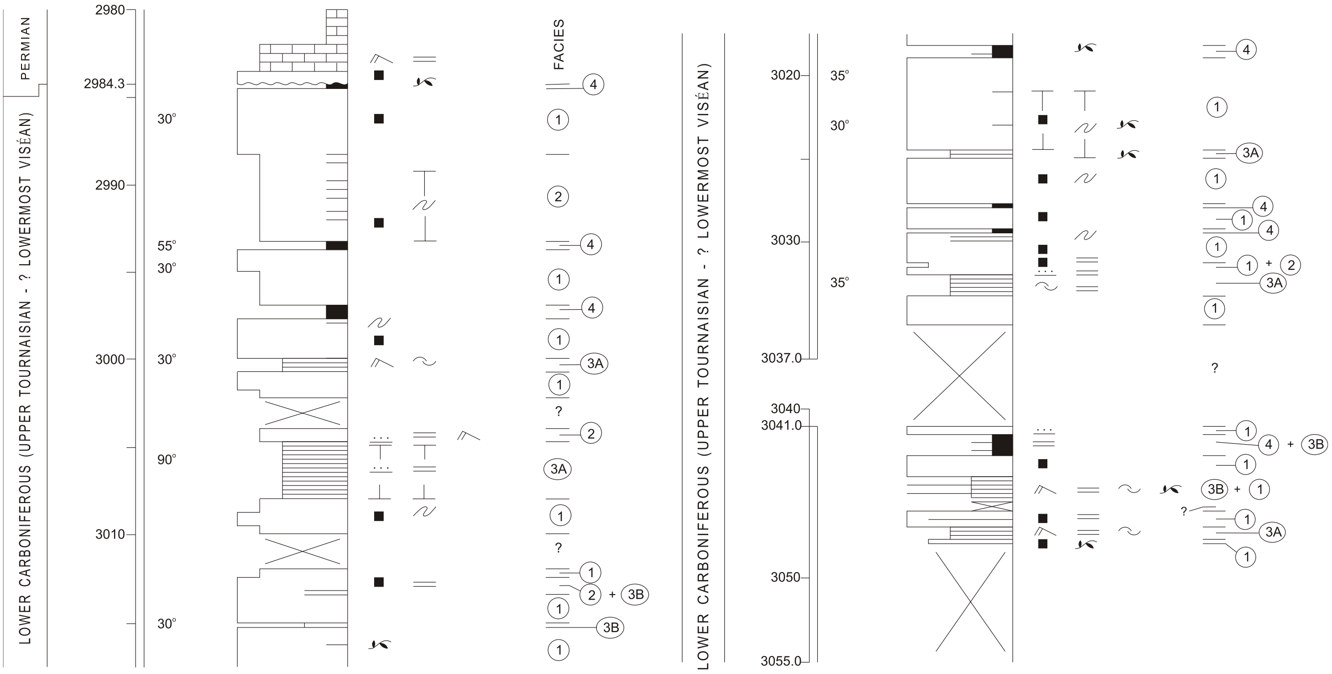


Fig. 3. Sedimentological log of Carboniferous deposits from the Opoczno PIG 2 borehole

For explanations see Fig. 2

FACIES MODEL

The facies model of deposits described in this paper is illustrated in Figure 5. It shows that the sand-dominated debrites of facies 1 accumulated mainly on the basin slope. As a result of slumps, setting in motion sand masses derived from the outer shelf margin, sand-dominated debris flows were formed. They deposited massive sandstones frequently with mud clasts scattered in the sand mass or concentrated in its top part. Material, carried down the slope, was becoming more and more diluted. Laminar flow was being transformed into turbulent flow, i.e. debris flows turned into turbidity currents (*cf.* Hampton, 1972; Shanmugam, 1997). Those currents deposited sandstone beds with normal grain-size grading. They can be observed within facies 2. Debrites and turbidites, deposited on the slope, were subject to reworking by traction bottom currents. Most sandstone beds of facies 2 and thin sandstone beds in heteroliths of facies 3 (mainly subfacies 3A) were formed in that way. Moving down the slope, turbidity currents reached the basin plain. Thin sandstone beds, deposited by turbidity currents, were also most often subject to reworking by traction bottom currents. This was the mode of deposition of sandstone beds in distal heteroliths of facies 3 (subfacies 3B). On the basin plain, away from the slope where slow deposition from suspension predominated, muds and clays of facies 3 accumulated. The lack of trace fossils within facies 1, 2 and 3 may result primarily from a high sedimentation rate on the slope. The absence of trace fossils within facies 4 indicates that on the basin-plain floor, in the deepest zone, anaerobic conditions dominated.

This facies model is consistent with the lack of a regular facies succession in the sections (Figs. 2–4). Clastic slopes are commonly associated with a “crazy pattern” facies distribution. This results from the fact that hemipelagic muds and clays can be deposited, on both slope and basin plain as can the sand deposits of turbidity currents. In an environment resembling a non-channelised slope, such currents can have the appearance of sheet-like turbulent suspensions, formed on the shelf as a result of strong storms. Those currents redeposited sand material, derived from the outer shelf, onto the basin slope (Fig. 9, see: storm-induced turbidity currents carrying sand derived from the shelf). Sheet-like turbidites, formed in that way, can occupy not only vast areas of the slope but can also reach onto the basin plain. Such deposits were described by Graham (1982) in Carboniferous flysch of Morocco.

The sedimentological analysis outlined in this paper, together with the cratonic provenance of the studied deposits (Krzemiński, 1999), suggests that they were deposited on the close-to-craton slope and basin plain of the Carboniferous foredeep basin. Carboniferous sandstones, explored in the NW border of the Holy Cross Mts. (Fig. 1, OOS area), correspond thus to this basin zone (slope, basin plain) which occupied areas further towards the SW, as compared with the zone of deposition of the Gozd Arkosic Sandstone Formation (Fm) from northern Poland (clastic shelf, Lipiec and Matyja, 1998).

The close-to-craton basin floor might have been inclined at a low angle, both on the shelf and on the slope. This does not contradict the mass-gravity flow mechanism leading to deposition of sandstones of facies 1 and 2. Debris flows can spread over a distance of hundreds of kilometres across slopes inclined at an angle <1° (Damuth and Embley, 1981). Clastic material, derived from the craton, was transported from the E towards the W, and from NE towards SW across the shallow-water shelf to the slope and, in part, basin plain environment.

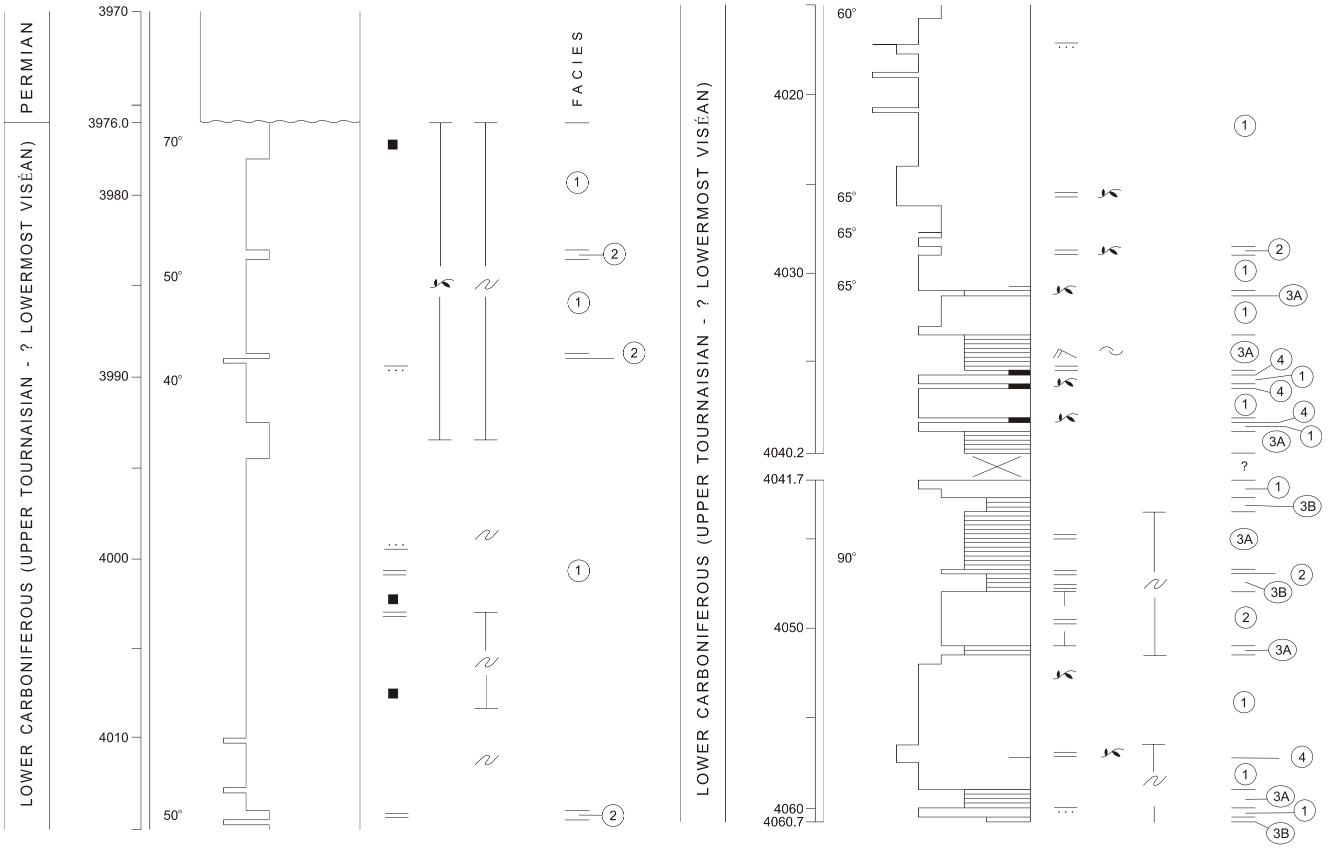


Fig. 4. Sedimentological log of Carboniferous deposits from the Studzianna IG 2 borehole

For explanations see Fig. 2

GEOTECTONIC INTERPRETATION

According to Pożaryski *et al.* (1992) "The Variscan Externides of Poland were devoid of outer foredeeps and molasses. The only exception is the Upper Silesian molasse.". Those authors were of the opinion that the zone of Variscan Externides stretches in Poland across Wielkopolska and Silesia towards Moravia. This zone is composed of Carboniferous deposits represented by the "flysch and molasse association". According to this concept, the area extending NW of the Holy Cross Mts. (including the OOS area) has been incorporated, in the map by Pożaryski and Karnkowski eds. (1992), into the younger Variscan flysch stage which was folded after the Westphalian. In that map, the front of Variscan Externides approaches the Palaeozoic massif of the Holy Cross Mts. from the NW, and farther on, it turns west and south-west (Fig. 1).

Dadlez *et al.* (1994) question this view. They claim that the outer limit of the Variscan orogen extends much farther to the west of the Holy Cross Mts (Fig. 1). A similar course of the "…limit of the folded Caledonian and Variscan basement…" is shown in the *Tectonic Map of Poland* (Znosko ed., 1998). In that map, the OOS area belongs to the zone of a sedimentary cover overlying the Caledonian basement deformed by Variscan tectonic movements that resulted in "fold-block tectonics". Krzemiński (1999) placed the Variscan Deformation Front in an intermediate position between that suggested by Pożaryski *et al.* (1992) and that proposed by Dadlez *et al.* (1994) and Znosko ed. (1998). Krzemiński (1999) claims that the Carboniferous deposits from the MRB area (Milianów IG 1, Radwanów IG 1 and Budziszewice IG 1 boreholes), extending farther to the west of the OOS area, represent flysch of the Variscan Externides.

In this place it should be emphasised that the term "flysch" is often ambiguously used, i.e. its descriptive (sedimentological, facies) and interpretational (palaeotectonic, geodynamic) meanings are not always consistently discriminated. All the terms concerning different types of flysch, used hereafter, originate from the classification of Contescu (1964).

Facies features of the Carboniferous deposits from the Ostałów PIG 2, Opoczno PIG 2 and Studzianna IG 2 boreholes point to flysch in terms of sedimentology. However, these deposits cannot be considered typical flysch (orthoflysch) because they were derived from a cratonic source. Therefore, they cannot be considered as exoflysch, either. Exoflysch, formed in foredeeps, is sourced from areas situated within the orogen. Source areas of the Carboniferous deposits here discussed were located within the East European Craton. Therefore these deposits are not exoflysch. They represent pseudoflysch i.e. deposits which show facies features of flysch and, simultaneously, are of cratonic provenance.

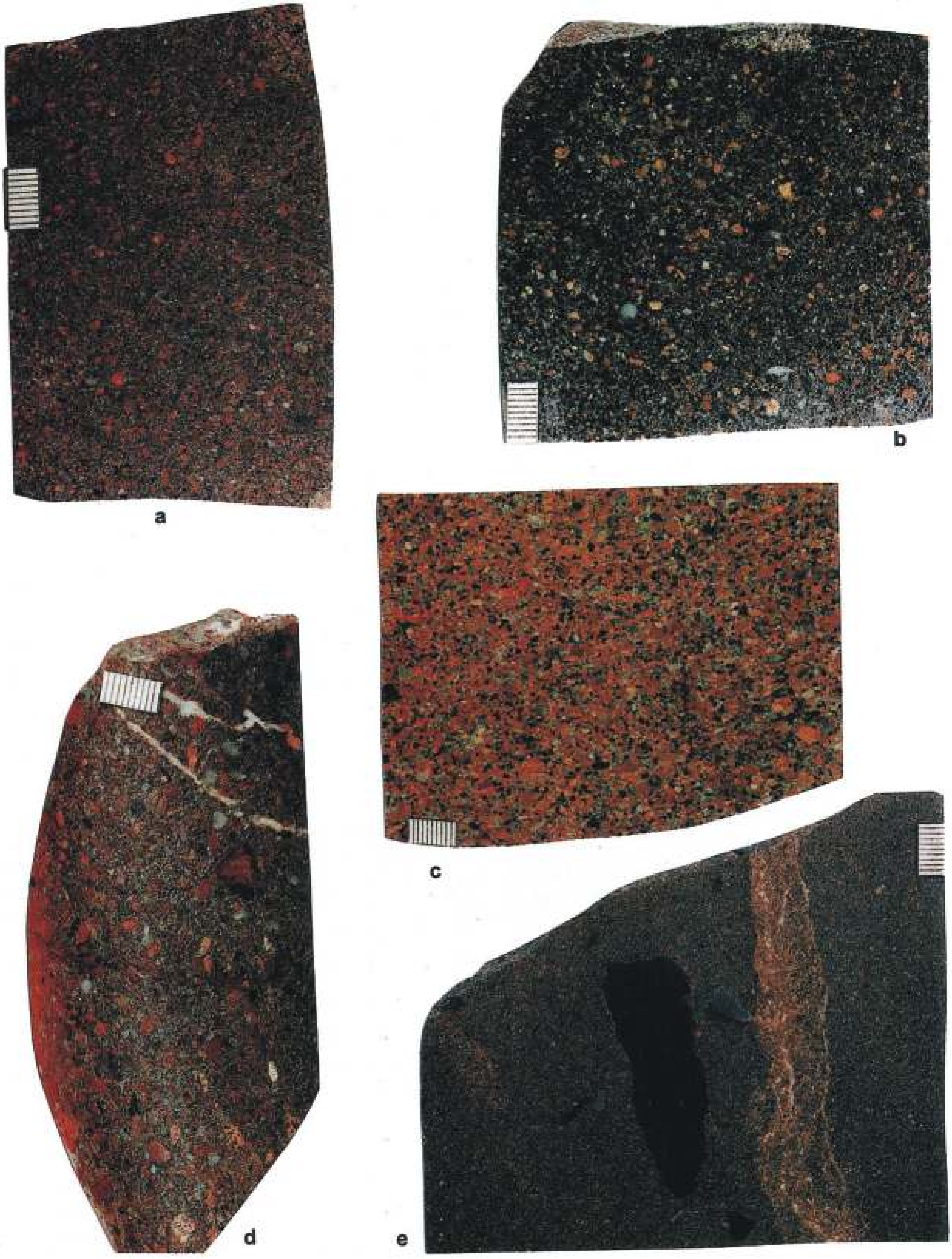


Fig. 5. **a** — facies 1; massive sandstone: medium- and coarse-grained arkosic wacke; note small mud clast immediately above scale bar; Ostałów PIG 2; depth 2746.6 m. **b** — facies 1; massive sandstone: coarse-grained arkosic wacke with much muddy matrix; Ostałów PIG 2; depth 2697.5 m. **c** — facies 1; massive sandstone: coarse-grained arkose; Ostałów PIG 2; depth 2826.3 m. **d** — facies 1; massive sandy conglomerate, arkosic in composition; note subrounded feldspar grains; Studzianna IG 2; depth 4017.2 m. **e** — facies 1; massive sandstone: fine-grained wacke with randomly scattered mud clasts of different sizes; Ostałów PIG 2; depth 2555.2 m. All photographs shown in Figs. 5–8 were taken by B. Ruszkiewicz and R. Kościelniak (Photography Laboratory of the Polish Geological Institute in Warsaw). Bar scaled in millimetres

Fig. 6. **a** — facies 1; mud clast concentrations in fine-grained sandstone (wacke); elongate clasts are oriented parallel to the bedding; Ostałów PIG 2; depth 2562.7 m. **b** — facies 1; massive sandstone: medium- and coarse-grained wacke with mud clasts similar to those in Fig. 6a; in the top right, a fragment of mud-supported conglomerate is visible; Ostałów PIG 2; depth 2682.7 m. **c** — facies 2; horizontally laminated fine-grained sandstone; upper surface of one lamina with fragments of indeterminate coalified flora; the fragments are set parallel, indicating current origin of laminae; Ostałów PIG 2; depth 2644.3 m. **d** — facies 2; sole surface of horizontal lamina in fine-grained sandstone; small tool marks (bounce and groove marks) indicate current flow; Ostałów PIG 2; depth 2539.0 m

Fig. 7. **a** — facies 2; two thin beds of normally graded fine-grained sandstone; lower bed represents a Ta-c Bouma (1962) sequence truncated at the top; the distinct lower boundary of this bed is characterised by load casts; note sedimentary tension fractures caused by slow sliding of parallel-bedded deposits; one of the fractures is partly filled with upward-squeezed mud (arrowed); Opoczno PIG 2; depth 3004.5 m. **b** — facies 2; slump structure: randomly arranged fragments of broken and deformed siltstone and claystone beds in a sandy-clay matrix; Opoczno PIG 2; depth 2990.2 m. **c** — facies 3; sand/mud heterolith, subfacies 3A: sand-dominated heterolith; horizontal lamination, single sandstone lense and erosional scour filled with cross-laminated sandstone; Ostałów PIG 2; depth 2504.0 m. **d** — facies 3; sand/mud heterolith, subfacies 3B: mud-dominated heterolith; thin sandstone and siltstone beds with small-scale cross lamination; numerous tension fractures are visible; some fractures are filled with mud, squeezed out of mudstone interbeds; the arrowed fracture is filled with mud and calcite; Studzianna IG 2; depth 4045.0 m

Fig. 8. **a** — facies 3; sole surface of thin fine-grained sandstone bed from sand/mud heterolith; mixed assemblage of current marks is visible: indistinct flute marks and tool marks, indicating turbulent flow depositing the sandstone bed; Ostałów PIG 2; depth 2518.5 m. **b** — facies 3; sole surface of sandstone bed from sand/mud heterolith; distinct tool mark is visible; overlying sandstone bed is visible at the bottom, owing to the cylindrical shape of the drillcore fragment; the bed shows small-scale cross lamination, resembling flaser bedding; Ostałów PIG 2; depth 2517.5 m. **c** — facies 4; dark clayey shale; Ostałów PIG 2; depth 2525.0 m

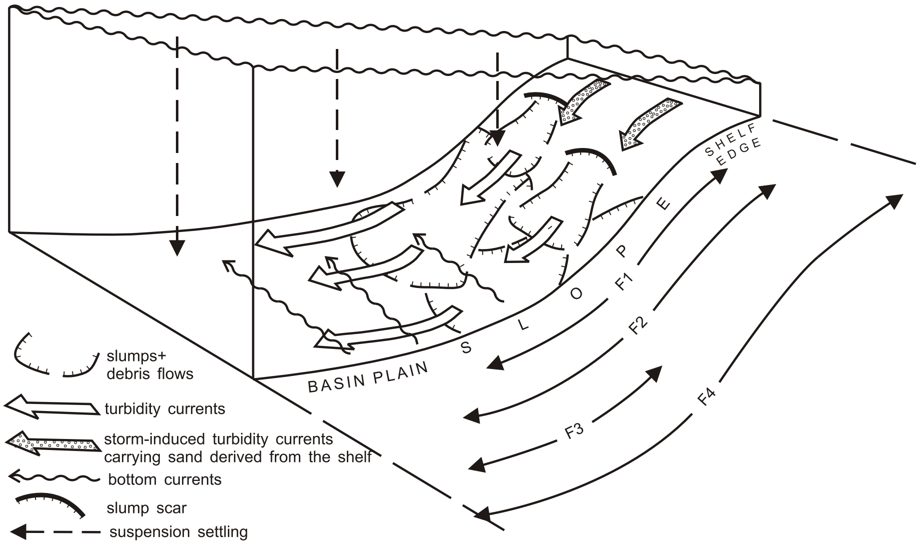


Fig. 9. Facies model of Carboniferous deposits from Ostałów PIG 2, Opoczno PIG 2 and Studzianna IG 2 boreholes (OOS area, see Fig. 1)

F1–F4 — extent of facies F1–F4

The sedimentary basin, developed in the marginal part of EEC, continued towards the SW as far as the front of the Variscan Externides. Exoflysch was deposited in the proximal (in relation to the front position) part of the foredeep (Fig. 10). These deposits possess features of flysch and originate from wearing down of the Variscan Externides, i.e. clastic material was derived from completely different areas and with opposite transport directions (SW→NE), than deposits which are the subject of the paper. The Carboniferous deposits, known from the Milejów IG 1, Radwanów IG 1 and Budziszewice IG 1 boreholes (MRB area), accumulated in areas of the Variscan exoflysch deposition. The Carboniferous deposits from the Ostałów PIG 2, Opoczno PIG 2 and Studzianna IG 2 boreholes (OOS area) represent pseudoflysch of cratonic provenance (with transport direction from NE to SW), interfingering with the exoflysch. The pseudoflysch was deposited in the opposite, distal (in relation to the Variscan front position) part of the foredeep (Fig. 10). That foredeep was formed in the marginal part of the East European Craton and on a basement composed of a crustal collage of pre-Variscan age (*cf*. Dadlez, 1997).

This interpretation helps place in context the results of Krzemiński's (1999) investigations which show that the petrographic-geochemical character of the MRB area deposits indicates their derivation from Variscan orthoflysch. The latter, formed prior to the main orogenic (collision) stage, is incorporated into an orogen (accretion/thrust wedge). So it is easy to understand the "orogenic" (or rather postorogenic) character of the Carboniferous deposits of the MRB area. Subject to short-distance and rapid transportation by mass-gravity flows, typical of flysch facies, these deposits (debrites, turbidites) are conspicuous through a petrographic-geochemical composition similar to the composition of rocks from the source areas, i.e. to Variscan orthoflysch. The sedimentological analysis given above and the resulting geotectonic conclusions suggest that, in central Poland (Fig. 1), the front of Variscan Externides ran to the west of the MRB area (approximately as suggested by Dadlez *et al*., 1994; Znosko ed., 1998 and Kotański and Mizerski, 2000).

Erosion of the cratonic area, which was the source of clastics deposited as pseudoflysch in the OOS area, was associated with uplifting movements in a far forefield of the Variscan Externides. Those movements accompanied stresses exerted by the accretion/thrust wedge advancing up the EEC margin. They resulted in the formation of a peripheral bulge (Fig. 10). Clastics, being erosionally removed from the peripheral bulge, were deposited further to the SW on the shelf of the basin extending along the EEC edge, on the slope, and — in part — on the basin plain. As the thrusting movements intensified, the peripheral bulge with accompanying erosional processes was moving towards the accretion/thrust wedge, i.e. south-westwards. This must have caused the foredeep to become narrower. The moving of the erosion zone towards the SW is shown in the map illustrating the original and final, pre-Viséan extent of Tournaisian deposits (Żelichowski and Jurkiewicz, 1996).

All these facts indicate that, during accretion and Variscan thrust movements, the EEC margin was flexured according to the model of "...flexural response of a viscoelastic plate overlying an inviscid fluid..." (*cf*. Stockmal *et al*., 1992).

The Variscan foredeep from the area NW of the Holy Cross Mts. was probably a fragment of a foredeep developed outside of the presumed pra-Carpathian-Dobrogea Variscan belt. Referring to Nowak's (1927) suggestions, the existence of this belt with its accompanying foredeep was postulated by Znosko (1997).

The present study, revealing the occurrence of the Variscan foredeep in the area NW of the Holy Cross Mts., also allows one to explain the above-mentioned problem of the flysch-like character of Carboniferous deposits across vast areas of south-western and central Poland (*cf*. Pożaryski and Karnkowski, 1992). These deposits show sedimentological features of flysch and they are very alike over the whole area. Despite this alike-

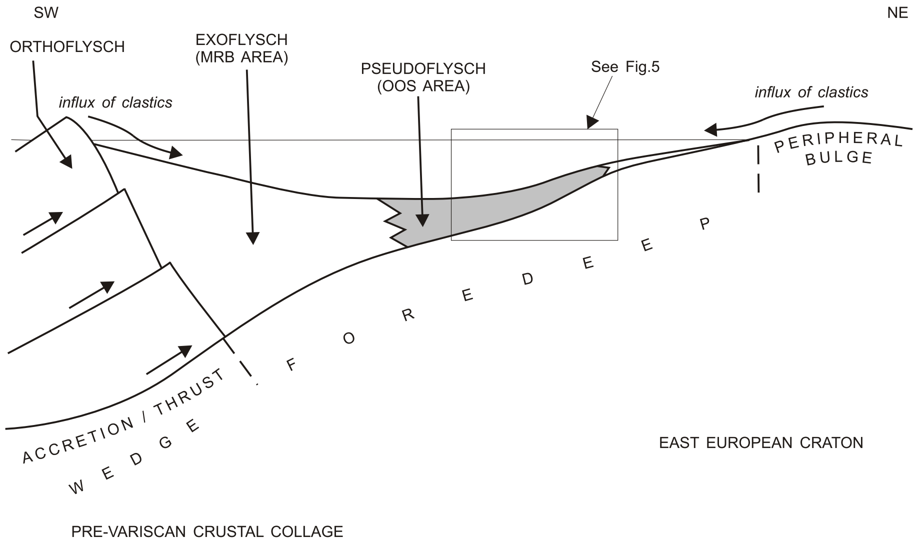


Fig. 10. Schematic reconstruction of Variscan foredeep in the area located NW of the Holy Cross Mts. (central Poland)

ness, they differ much with regard to the geotectonic setting. They developed in zones which differed in both the position in relation to the front of the Variscan Externides, and the provenance of Carboniferous clastics. The study shows that, moving from the SW towards the NW from the Fore-Sudetic Monocline to the EEC, there is a successive appearance of Variscan ortho-, exo- and pseudoflysch (Fig. 10). The foredeep was the deposition site of interfingering exo- and pseudoflysch which — from the geodynamic point of view — are equivalent to an outer molasse. This is a good example of a convergence of tectonic associations: deposits with sedimentological features of flysch are deposited in a foredeep, i.e. in a basin showing geodynamic features of a molasse basin (*sensu* Homewood and Lateltin, 1988).

CONCLUSIONS

1. Carboniferous sandstones and shales, encountered in deep boreholes drilled in central Poland, NW of the Holy Cross Mts. (Ostałów PIG 2, Opoczno PIG 2 and Studzianna IG 2 boreholes), were deposited in a marine basin, below storm wave-base, on a clastic slope and, in part, on a basin plain.

2. It was a non-channelised environment, developed on a slope beneath a sand-rich shelf.

3. Sandstones are represented mostly by debrites and turbidites. Some thin sandstone beds were reworked by traction bottom currents.

4. The deposits represent pseudoflysch. They show facies features of flysch and, simultaneously, are of cratonic provenance.

5. Clastic sediments were derived from a peripheral bulge, formed within the East European Craton as a result of stresses exerted by the accretion/thrust wedge advancing up the marginal part of the craton.

6. In central Poland, NW of the Holy Cross Mts., a Variscan foredeep existed. It was developed in the marginal part of the East European Craton and on a basement composed of a crustal collage of pre-Variscan age.

7. The foredeep was the deposition site of interfingering exo- and pseudoflysch which — from a geodynamic point of view — are equivalent to an outer molasse.

8. Huge masses of Carboniferous deposits from southwestern and central Poland (showing facies features of flysch) successively represent, moving from the SW towards the NE, Variscan ortho-, exo- and pseudoflysch.

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