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Facies analysis of the Silurian shale-siltstone succession in Pomerania (northern Poland)

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The Silurian deposits of Pomerania occur in the foreland of the Pomeranian Caledonides which are the SE continuation of the Danish-North-German Caledonides. The Silurian sequence in Pomerania is represented largely by graptolitic clay- and mud-shales deposited in a hemipelagic environment. From the Wenlock through Late Ludlow, slow deposition of hemipelagic clays and muds was repeatedly interrupted by silty debris flows and turbidity currents. Many of the siltstone interbeds were reworked by bottom currents. Clastic material was sourced from the Caledonian accretionary prism stretching along the collision zone of Baltica and East Avalonia. The Silurian shale-siltstone succession in Pomerania represents a Caledonian exoflysch i.e. syn-collision clastics accumulated in a foredeep developed on the East European Craton. The diachronous appearance of siltstone interbeds in the graptolitic shales indicate that collision between Baltica and East Avalonia was associated with sinistral strike-slip movement along the edge of the East European Craton.

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INTRODUCTION

This facies analysis of the Silurian shale-siltstone succession in Pomerania is primarily based on data from the Lębork IG 1 borehole (Fig. 1) where this succession was almost entirely cored. Other boreholes are of minor significance here because little of the Silurian succession elsewhere in Pomerania was cored (Tab. 1).

The stratigraphical framework of this study is based on data from papers by Tomczyk (1963, 1968, 1974, 1976, 1982, 1989). The graptolite successions recognized in those studies were re-interpreted with reference to the Silurian stratigraphical divisions proposed for Poland by Urbanek and Teller (1997) and Szymański and Teller (1998), which correspond to standard international usage (Fig. 2, Tab. 1).

The Silurian shale-siltstone succession of the Pomeranian Caledonides foreland (Figs. 1, 2) was explored by regional subsurface investigations conducted by the Polish Geological Institute. Znosko (1962) considered the presence of this succession in Pomerania, i.e. on the East European Craton margin, to be evidence that the Caledonian orogen extended along the SW edge of the craton.This orogen was interpreted as a source of material for siltstone interbeds in the Silurian graptolitic shales (Znosko, 1962; Tomczyk, 1962).

Detailed studies on sedimentary structures showed that the Silurian shale-siltstone succession was derived from the SW, i.e. from beyond the Teisseyre-Tornquist Line, and that the siltstone beds were deposited by turbidity currents, the entire shale-siltstone succession possessing shaly flysch characters (Jaworowski, 1971).

This facies analysis of the Silurian shale-siltstone succession in northern Poland has led to a partial re-interpretation of deposition of the siltstone beds, and is relevant to recent debate between those who question (Pożaryski, 1991; Pożaryski, *et al.*, 1992) and those who support (Znosko, 1987; Dadlez *et al.*, 1994) the view on the flysch character of these deposits.

FACIES ANALYSIS

GENERAL REMARKS

The Silurian deposits of the marginal part of the East European Craton in the foreland of the Pomeranian Caledonides (Fig. 1) are primarily represented by two shale lithologies: light

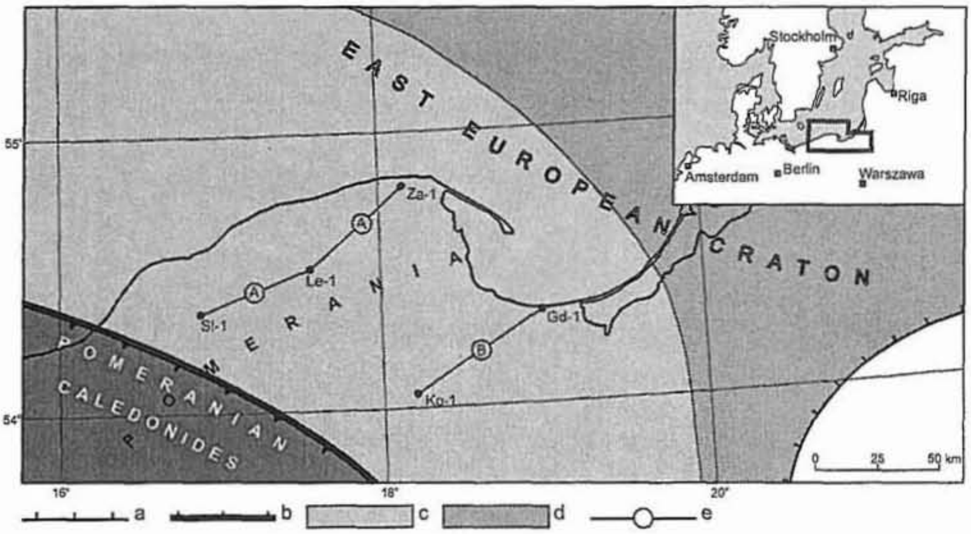


Fig. 1. Location of Silurian borehole sections

a — recent extent of Silurian deposits, b — Caledonian deformation front, c — shale-siltstone succession, d — shales and marls, e — correlation lines (see Fig. 2); boreholes: Sl-1 — Słupsk IG 1, Le-1 — Lębork IG 1, Za-1 — Żarnowiec IG 1, Ko-1 — Kościerzyna IG 1, Gd-1 — Gdańsk IG 1

grey and dark grey (almost black) (*cf.* Langier-Kuźniarowa, 1967). The light grey variety is smooth to the touch, whereas the dark grey one shows rough parting planes. The latter contains an admixture of silt material. The composition of clay minerals in both lithologies are identical. The light grey variety is represented by clay-shales, and the dark grey one by mud-shales. The two varieties alternate as beds of very variable thickness: from very thin to very thick (*sensu* Ingram, 1954). The Silurian shales discussed here resemble the facies E1.1 ("essentially structureless muds/clays with poorly defined bedding") distinguished by Pickering *et al.* (1986) among deep-water deposits. The origin of such deposits, and strictly speaking of the entire facies group E1 ("disorganized muds and clays") *sensu* Pickering *et al.* (1986), is enigmatic. As in earlier studies (Jaworowski, 1971, 1975), the Silurian clay- and mud-shales from northern Poland are considered in this paper to have been deposited through primarily slow deposition from suspension in a hemipelagic environment with anoxic bottom waters. At a certain stage in basin evolution, the slow hemipelagic mud and clay deposition was associated with submarine gravity flows of various densities which supplied silts into the basin, resulting in the deposition of a shale-siltstone succession. Jaworowski (1971, 1975) considered the Silurian siltstone beds of the Polish Lowlands to be turbidites.

In the facies classification of Pickering *et al.* (1986), the siltstone interbeds from this succession compare with the facies group D2 ("organized silts, muddy silts and silt-mud couplets") deposited by low density turbidity currents.

FACIES DESCRIPTION

The principle diagnostic features of the facies described here comprise the thickness of siltstone interbeds and the shale-siltstone ratio. Individual facies are also characterized by specific sets of sedimentary structures. Four facies have been distinguished within the shale-siltstone succession from the Lębork IG 1 borehole. They are similar, but not identical, to the facies recognized earlier in the Kościerzyna IG 1 borehole (Jaworowski, 1975). The facies in the more completely cored Lębork IG 1 borehole may be considered representative for the Silurian shale-siltstone succession in Pomerania.

FACIES F1 (FIG. 3; PL. I, FIGS. 1–3)

Alternating shale and siltstone beds, 1 to 5 cm thick. Generally, shales slightly exceed siltstones in thickness. The presence of massive siltstone beds is particularly characteristic of this facies. Their basal and top surfaces are in general sharply marked (Pl. I, Fig. 2) with frequent basal load casts and flame structures. These beds locally contain small intraclasts lithologically identical to the interbedded shales and internal deformational structures can locally be observed. Occasionally, small-scale cross bedding is observed in the upper parts of these massive siltstone beds. Facies F1 also contains massive siltstone beds with gradational tops, the transition into shales often being preceded by horizontal lamination (Pl. I, Fig. 1); such beds are characterized by erosional structures (flute marks) on their soles. Siltstones in facies F1 also occur as thin beds with horizontal lamination. One of these beds shows a feeding burrow (Pl. I, Fig. 3). This was the only trace fossil found in the material studied.

The massive siltstone beds of facies F1 were formerly interpreted as the result of rapidly decelerating turbidity currents (Jaworowski, 1971). This opinion needs revising, for they show many similarities to the massive sandstones described by Shanmugam and Moiola (1995) from the classic Carboniferous flysch of the USA (Jackfork Group). Those authors (Shanmugam and Moiola, 1997; Shanmugam, 1997) interpret such massive sandstones with no grain-size grading, as a product of deposition from sandy debris flows. The uniform siltstone beds of facies F1 may thus represent silty debris flows.

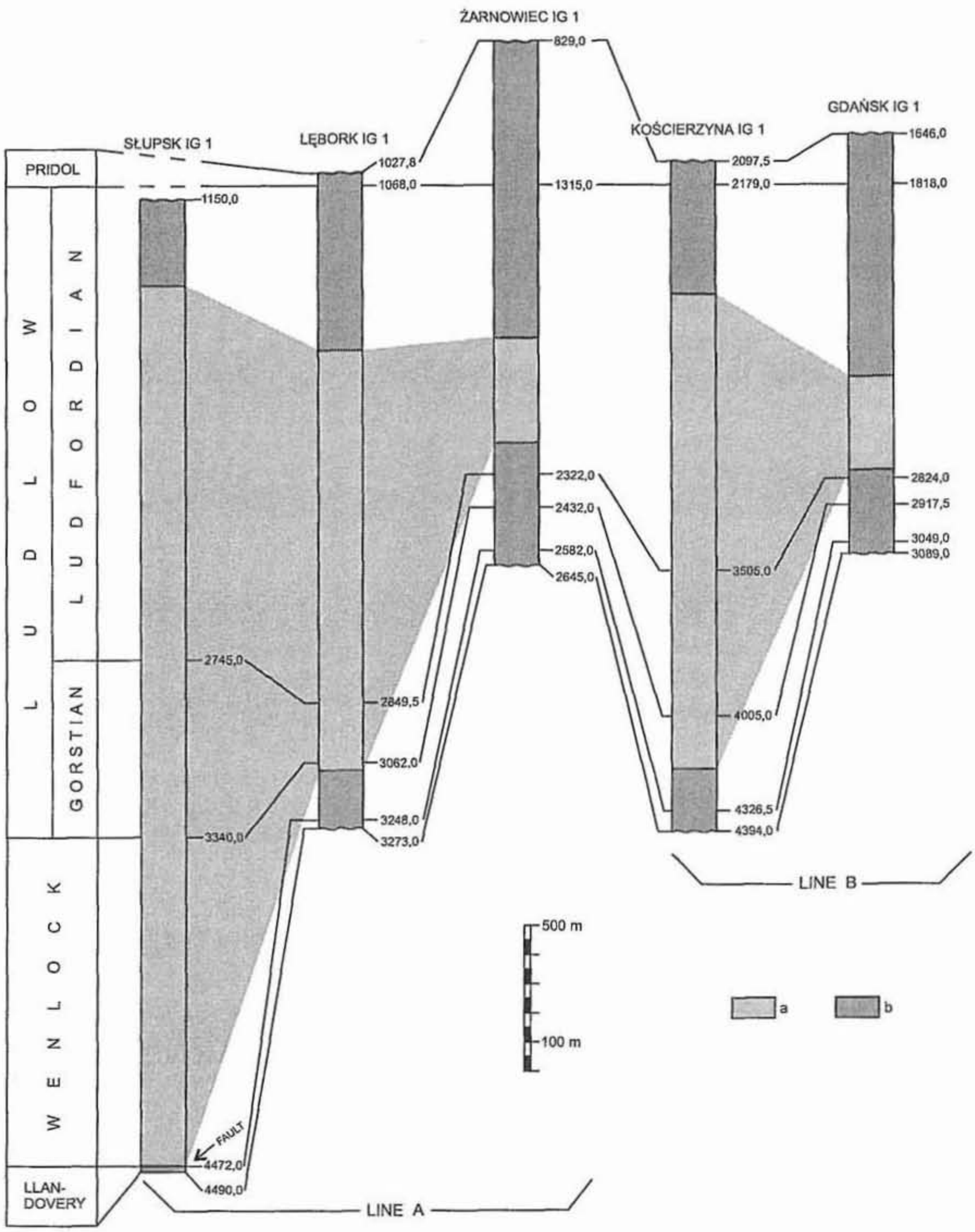


Fig. 2. Correlation scheme of Silurian borehole sections

a — shale-siltstone succession; b — shales and marls; LINE A, LINE B — correlation lines shown in Fig. 1

Massive beds that gradually pass up into shales, and/or are horizontally laminated in the upper part, would thus represent two, mutually related, depositional processes: silty debris flows giving way to turbidity currents. The turbidity currents presumably originated through mixing of part of the silty debris flow material with water. Such casual links between turbidity currents and submarine debris flows were experimentally demonstrated and explained by Hampton (1972). Traces of internal deformational structures, locally observed in the massive siltstone beds with indistinct top surfaces, are associated with post-depositional density readjustment movements of unconsolidated sediment. Small-scale cross bedding, observed in the upper parts of some massive siltstone beds with distinct upper and lower surfaces, resulted from the reworking of the sedi-

Table 1

Shale-siltstone succession in boreholes studied

Borehole	Total thickness of Silurian deposits [m] coring [%]	Thickness of the shale-siltstone succession [m] coring [%]	Stratigraphic range of the shale-siltstone succession graptolitic zone*	Stratigraphic range of the shale-siltstone succession (*cf.* Fig. 2) stages
Lębork IG 1	2245.2 94.6	1435.0 97.1	*M. lebanensis* (=*M. acer*) *Col. ludensis* ↑	upper Ludfordian (Upper Ludlow) Homerian (Upper Wenlock) ↑
Żarnowiec IG 1	1816.0 21.9	364.0 10.8	*M.* (*S.*) *balticus* *B. praecornutus* ↑	upper Ludfordian (Upper Ludlow) lower Ludfordian (Upper Ludlow) ↑
Kościerzyna IG 1	2296.5 17.0	1622.0 11.4	*N. kozlowskii* *G. nassa* ↑	lower Ludfordian (Upper Ludlow) Homerian (Upper Wenlock) ↑
Gdańsk IG 1	1443.0 10.2	325.5 10.4	*N. kozlowskii* *S. leintwardinensis* (=*C. aversus*) ↑	lower Ludfordian (Upper Ludlow)
Słupsk IG 1	3340.0 17.4	3011.0 17.7	*N. kozlowskii* *M. riccartonensis* ↑	?lower Ludfordian (Upper Ludlow) Sheinwoodian (Lower Wenlock) ↑

*Graptolitic zonation of the Polish Silurian — see Urbanek and Teller (1997) and Szymański and Teller (1998)

ment by bottom currents flowing in a lower flow regime. The same origin is assumed for thin, horizontally laminated siltstone beds.

FACIES F2 (FIG. 3; PL. I, FIGS. 4–7; PL. II, FIGS. 1–4)

This facies is characterized by the greatest thicknesses of siltstone beds. They range from 5 to 10 cm, frequently reach 30 cm and occasionally even more. Shale interbeds are 1 to 5 cm thick, although they are locally thicker. Generally, the siltstones exceed the shales in thickness. Siltstone beds are represented by two varieties. The first is characterized by sharply marked bases and gradational tops (Fig. 3; Pl. I, Figs. 5, 6; Pl. II, Fig. 3), and flute marks are observed on bed soles (Pl. II, Figs. 3, 4). The second variety shows both basal and top surfaces sharply marked (Fig. 3; Pl. I, Figs. 4, 7; Pl. II, Figs. 1, 2); linguoid current ripples are occasionally visible on top surfaces. Some of the siltstone beds are amalgamated and composed of two parts. Deposition of the upper part was preceded by erosional truncation of the underlying part and — presumably — by clay material initially being deposited on the latter. The siltstone beds of facies F2 show bedding related in the main to the lower flow regime: small-scale cross bedding, often accompanied by convolute bedding (Pl. I, Fig. 5), with transitions to flaser bedding, and horizontal lamination (Pl. I, Figs. 4, 6, 7; Pl. II, Figs. 1–3). The lower parts of some siltstone beds are massive or show horizontal lamination formed in the upper flow regime (Fig. 3). These massive parts locally contain fragments of shallow-marine shells (Pl. I, Fig. 6) which are lacking elsewhere in this facies; these were obviously redeposited by submarine gravity flows.

These siltstone beds, with sharply marked basal surfaces and gradual transitions into overlying shales, were deposited by turbidity currents. According to the Bouma model (Bouma, 1962) they correspond to Tb-e, Tc-e and Td-e sequences. The same initial origin can be ascribed to those siltstone beds of facies F2 that show sharply marked top surfaces frequently associated with current ripples (Pl. II, Fig. 2). In this case, the silt, after deposition from a turbidity current, was reworked by bottom tractional currents of the lower flow regime.

FACIES F3 (FIG. 3; PL. II, FIG. 5, 6; PL. III, FIGS. 1–4, FIG. 5, UPPER PART)

Alternating shales and subordinate siltstones. Thicknesses of shale beds range from 0.5 to 10 cm, while thicknesses of siltstones most frequently vary between 0.5 and 3 cm, occasionally reaching 5 cm. Siltstone beds, including very thin ones (Pl. III, Figs. 1, 3, 5), are characterized by sharply marked basal surfaces and gradational tops. Flute marks are commonly observed on siltstone bed soles (Pl. II, Fig. 6; Pl. III, Fig. 4). These siltstone beds contain depositional structures characteristic of the lower flow regime: small-scale cross bedding and horizontal lamination. Sharply marked basal surfaces with turbulent scours and gradual transitions of the siltstones into overlying shales indicate that the siltstone beds of facies F3 were deposited by turbidity currents. In the Bouma model (Bouma, 1962) they correspond to Tc-e and Td-e sequences. Some of the siltstone beds do not show transitions into the overlying shales and these are a product of reworking by bottom currents.

Deposits of facies F3 frequently contain small erosional channel-fills (Pl. III, Fig. 2) of turbiditic origin. Thin siltstone lenses and beds with sharp base and top surfaces locally make

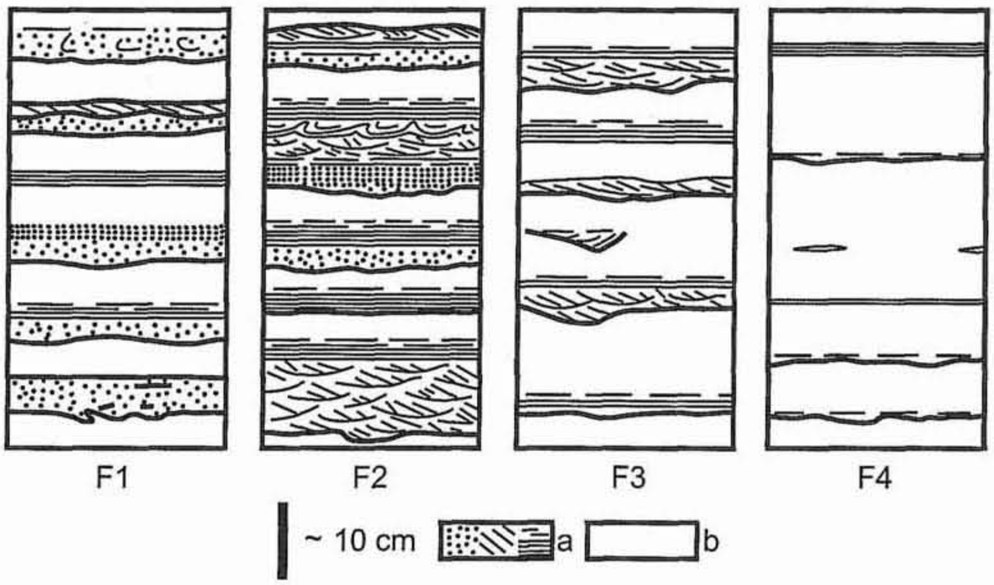


Fig. 3. Facies of the Silurian shale-siltstone succession

a — siltstones; b — shales; F1– F4 — facies symbols; see text for detailed comment

the facies F3 similar to fossil contourites (*cf.* Bouma, 1972), but, as contourites are difficult to recognize in the fossil record, this cannot be confirmed. The siltstones of facies F3, like some of those in facies F2, are more generally interpreted here as a product of bottom traction currents (tractionites *sensu* Unrug, 1977).

FACIES F4 (FIG. 3; PL. III, FIG. 5, LOWER PART, FIGS. 6–8; PL. IV, FIGS. 1–6)

This facies includes primarily clay-shales with rare thin (up to 1 cm thick) siltstone interbeds and lenses. Even very thin siltstone beds show sharp basal surfaces and subtly gradational top surfaces. These beds are characterized by poorly marked horizontal lamination (Pl. III, Fig. 8, right side). They were deposited by small-scale turbidity currents and correspond to the sequences Td-e of Bouma (1962). Thin, usually horizontally laminated siltstone beds with sharp tops and bases are also common, indicating bottom traction current activity. Lower flow regime conditions are indicated by the parallel orientation of graptolite rhabdosomes resting on horizontal lamina surfaces (Pl. IV, Fig. 5). Thin siltstone lenses, observed in facies F4, are either small erosional channel-fills (Pl. IV, Figs. 3, 4) or separated current ripples. In the latter case, the lenses occur so close that they form a structure resembling lenticular bedding (Pl. III, Fig. 8, upper part). Separated ripples sometimes sunk into the unconsolidated clay of the sea floor (Pl. III, Fig. 7). Shales of facies F4 (Pl. III, Fig. 6) also contain thin siltstone laminae (approximately 1 mm thick) with sharply marked basal and top surfaces. They were deposited from bottom currents during redeposition of material originally supplied by turbidity currents.

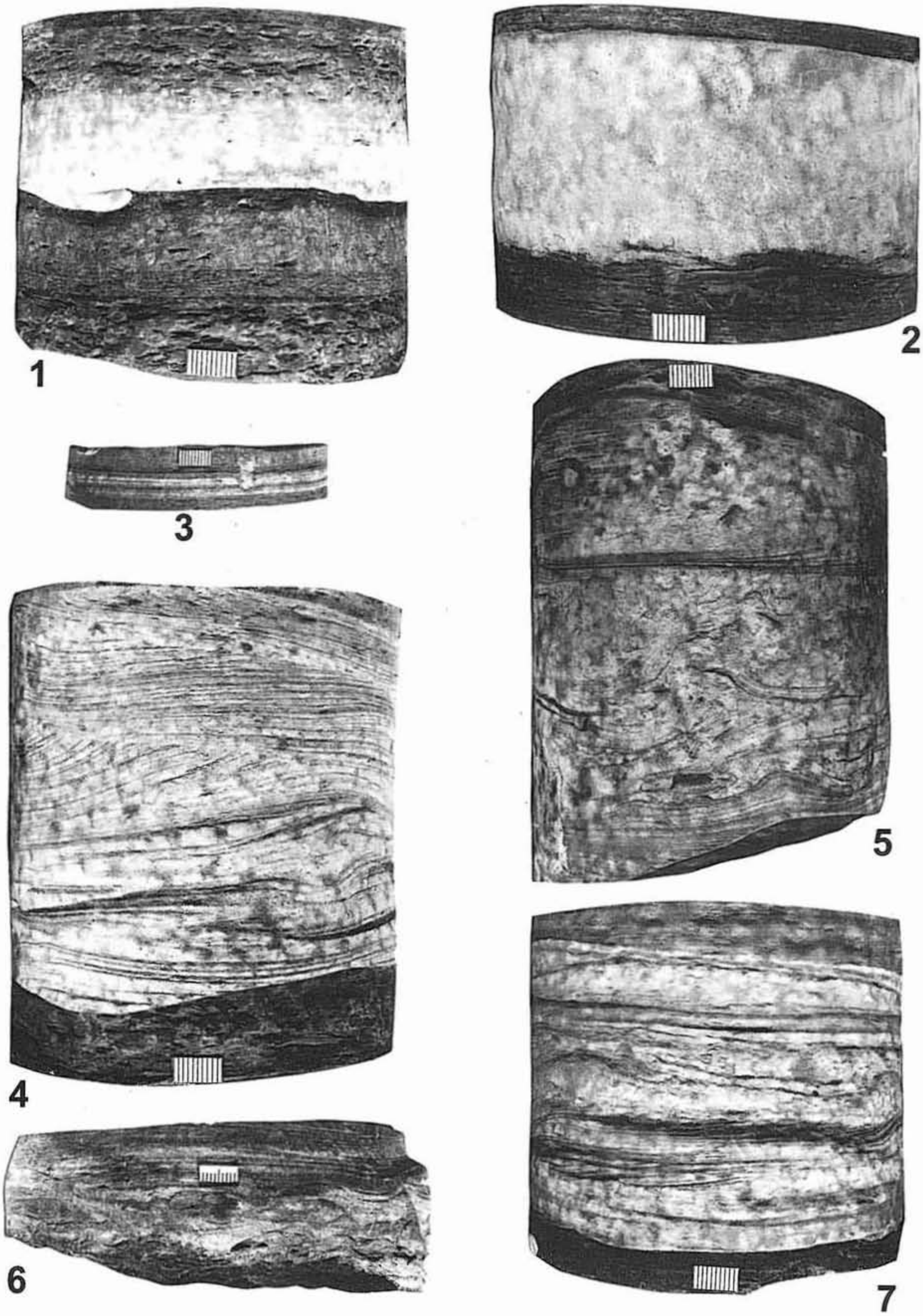
Where facies F4 was deposited, the sedimentary basin floor was affected by turbulent currents whose eroding ability was sometimes considerable, although they transported little clastic material. Deep scours locally dissect several couplets of thin siltstone and shale beds (Pl. III, Fig. 8). The resulting erosional channels initially remained free of any sedimentary fill and were later gradually filled with material supplied by bottom currents or deposited from suspension. Abundant flute and groove marks, indicating turbulent currents, occur on thin siltstone bed soles (Pl. IV, Figs. 1, 2). Siltstone lenses and sharply bounded laminae suggest derivation from bottom traction currents.

THICKNESS PATTERNS OF PARTICULAR FACIES

Table 2 contains data on the thickness of occurrences of particular facies in the Silurian section of the Lębork IG 1 borehole. It shows that F1 is the thinnest facies, which is also characterized by the lowest thickness variability, although the value of its coefficient of variability is still high. F4 is the thickest facies and shows the maximum thickness variability. The thickness distribution of facies F1 shows slightly negative skewness: the thickness of its most frequent occurrences is greater than the mean value. The other facies show positive thickness distributions, particularly facies F2. In other words, in facies F2, F3 and F4 the thickness of the most frequent occurrences is smaller than their mean values. Vertical variability in the thickness of occurrences of particular facies is illustrated by the time series shown in Figures 5, 6. An analysis of the time series is given below.

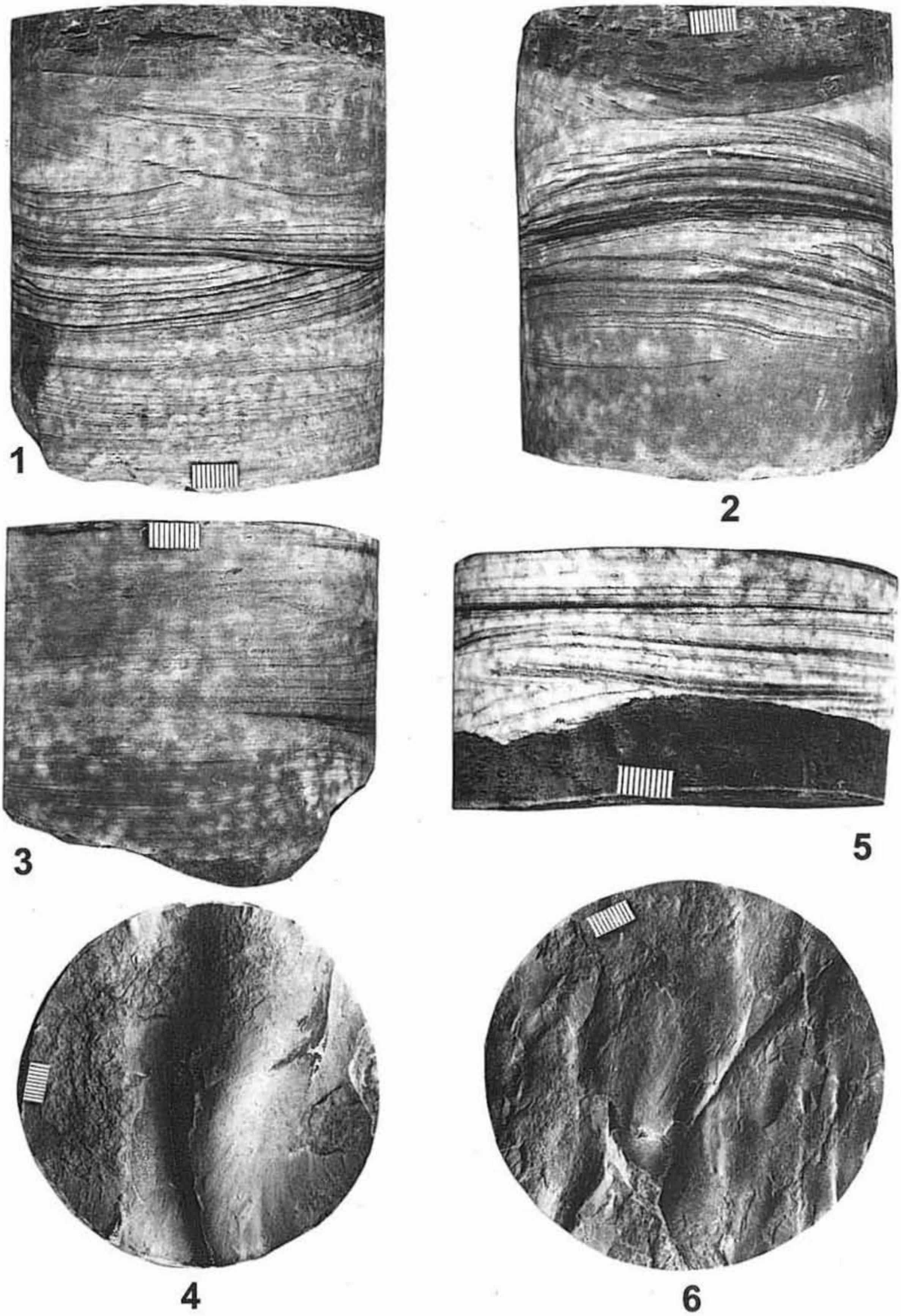
FACIES SEQUENCE

The facies sequence analysis, like the other detailed investigations, is based on the Lębork IG 1 borehole (Tab. 1, Fig. 2). The shale-siltstone succession occurs here at depths of

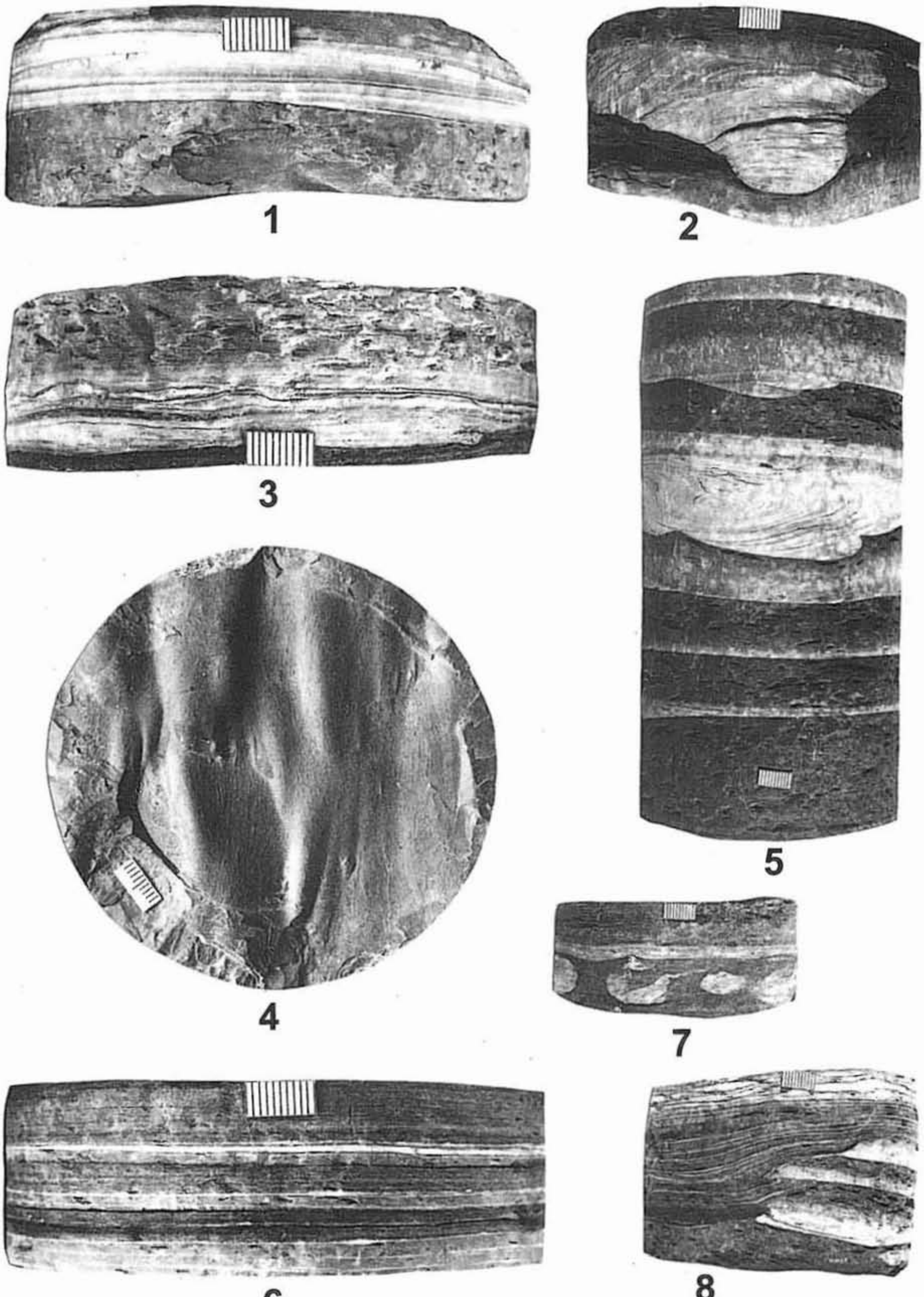


All specimens shown in Plates I–IV come from the Lębork IG 1 borehole; scale marked in mm. The photographs were taken by B. Ruszkiewicz (Pl. I, Figs. 1, 2, 4, 5, 7; Pl. II; Pl. III, Figs. 1, 3, 6; Pl. IV, Figs. 3, 4, 6) and by R. Ufnal (Pl. I, Figs. 3, 6; Pl. III, Figs. 2, 4, 5, 7, 8; Pl. IV, Figs. 1, 2, 5 — see Jaworowski, 1971) in the Photography Laboratory of the Polish Geological Institute in Warsaw

1. Facies F1; massive siltstone bed, horizontally laminated in its upper part; note the sharp base and gradual transition into overlying shale; bed deposited by silty debris flow with transition to turbidity current; depth: 2685.7 m. *2*. Facies F1; massive siltstone bed showing distinct base and top surfaces; small load casts and flame structures are visible at base; bed deposited by silty debris flow; depth: 2266.4 m. *3*. Facies F1; thin, horizontally laminated siltstone bed; a small, single feeding burrow is visible; depth: 2167.7 m. *4*. Facies F2; siltstone bed with sharp base and fairly distinct top surface; small-scale cross bedding with mud flasers (flaser bedding); low-angle and horizontal lamination is visible in its upper part; bed deposited as a result of the reworking by bottom currents; depth: 2330.4 m. *5*. Facies F2; siltstone bed with sharp base and gradual transition into overlying shale; small-scale cross bedding and convolute bedding; in the upper part of the bed transition to low-angle and horizontal lamination is visible; bed deposited by turbidity current (Tcde sequence of Bouma); depth: 2406.7 m. *6*. Facies F2; thin siltstone bed; sharp base, and gradual transition into overlying shale; note brachiopod and bivalve fragments in silty matrix in the lower part; bed deposited by silty debris flow with transition to turbidity current; depth: 1977.5 m. *7*. Facies F2; thin siltstone bed similar to that shown in Fig. 4; depth: 2111.4 m

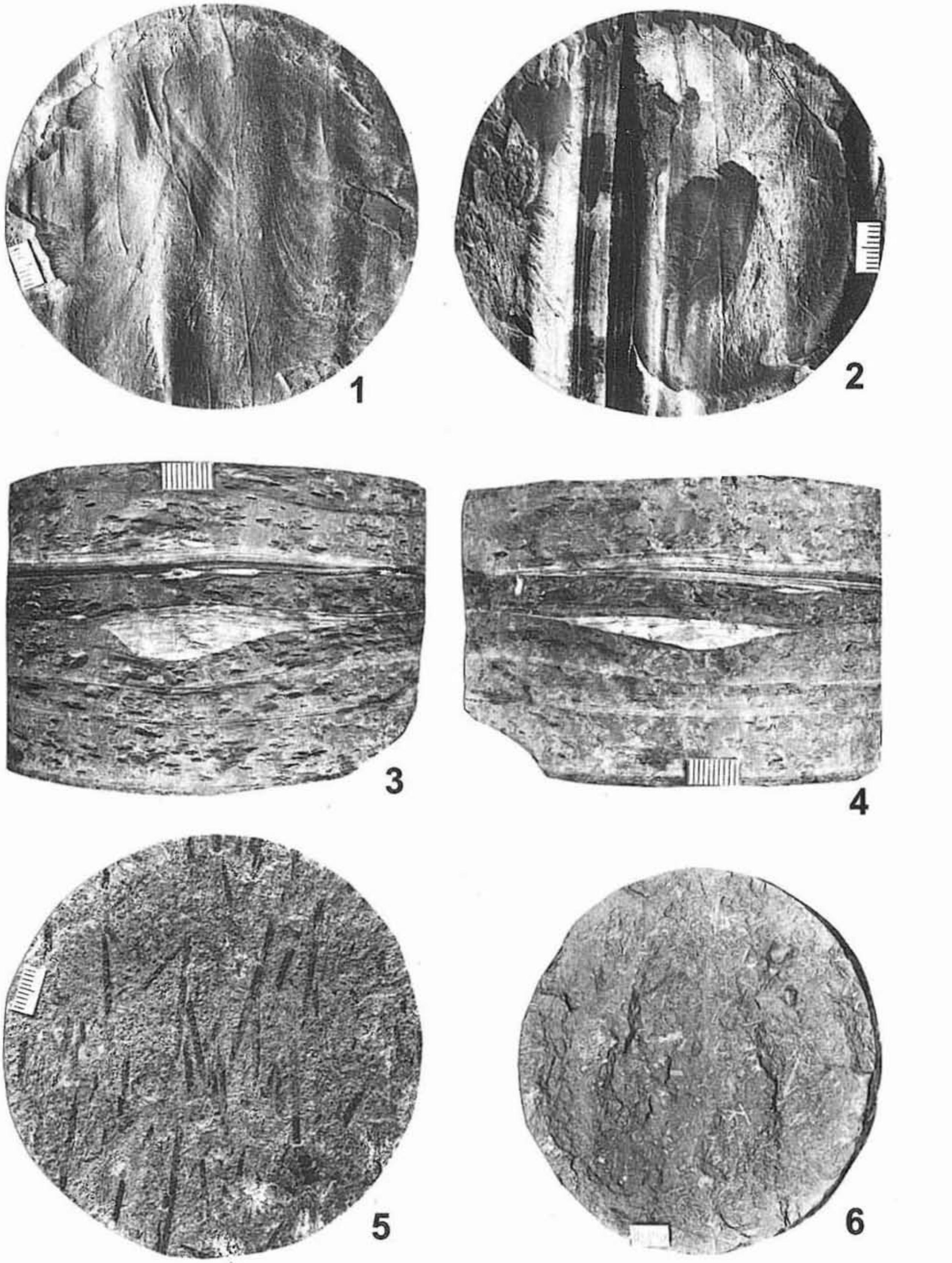


1. Facies F2; siltstone bed with fairly distinct base; horizontal lamination and small-scale cross bedding; bed deposited as a result of the reworking by bottom currents; depth: 1990.7 m. *2*. Same specimen as in Fig. 1, turned by 180°; intersection image of an upcurrent slope of linguoid ripple is visible at top. *3*. Facies F2; horizontally laminated siltstone bed with sharp base; transverse section across a flute mark is visible; gradual transition into overlying shale; bed deposited by turbidity current; depth: 2356.4 m. *4*. Facies F2; sole of the bed shown in Fig. 3 with a distinct flute mark. *5*. Facies F3; lower part of a siltstone bed; sharp, erosional base; small-scale cross bedding resembling flaser bedding; bed deposited as a result of the reworking by bottom currents; depth: 2329.4 m. *6*. Facies F3; sole of a thin siltstone bed; flute marks; depth: 2872.4 m



1. Facies F3; thin siltstone bed with sharp base and indistinct top; low-angle and horizontal lamination; bed deposited by turbidity current; depth: 2733.0 m. *2.* Facies F3; erosional channel fill; the result of erosional and depositional activity of turbidity current(?); depth: 2558.0 m. *3.* Facies F3; very thin siltstone bed with distinct, erosional base; gradual transition into overlying shale; small-scale cross bedding and incipient convolute bedding; bed deposited by turbidity current; depth: 2113.1 m. *4.* Facies F3; sole of a thin siltstone bed; flute marks; flow direction — upwards; depth: 2786.8 m. *5.* In the lower part, facies F4 which passes upwards into facies F3; facies F4 is represented by very thin siltstone beds with sharp base and gradual transitions into overlying shales; facies F3 contains thicker siltstone beds with sharp base showing sections across flute marks; lower siltstone bed of facies F3 is characterized by distinct top surface, small-scale cross bedding and convolute bedding; this bed resulted from the reworking by bottom currents; upper siltstone bed shows gradual transition into overlying shale and was deposited by turbidity current; depth: 2664.4 m. *6.* Facies F4; very thin siltstone beds in alternating dark grey and light grey shales; siltstone beds deposited by bottom currents; depth: 3080.7 m. *7.* Facies F4; very thin siltstone bed; below, separated siltstone lenses deposited by bottom currents and loadcasted in shale; depth: 2185.5 m. *8.* Facies F4; erosional channel cutting a succession of three very thin siltstone beds showing grain-size grading and gradual transitions into overlying shales; floor-eroding turbidity current carried a part of transported material farther away; the channel was subsequently filled by bottom currents (siltstone laminae) and sedimentation from suspension; lenticular bedding in the upper part; this bedding resulted from the activity of bottom currents; depth: 3017.5 m

PLATE IV



1. Facies F4; sole of a siltstone bed. Mixed assemblage of current marks formed by turbidity current: flute marks and groove marks; flow direction — upwards; depth: 2605.7 m. *2*. Facies F4; sole of a siltstone bed; groove marks left by objects dragged by turbidity current; depth: 2959.0 m. *3*. Facies F4; erosional channel fill and siltstone laminae; the effect of bottom currents; depth: 2903.7 m. *4*. Facies F4; same specimen as in Fig. 3, turned by 180°. *5*. Facies F4; horizontal lamina surface in a thin siltstone bed; parallel orientation of graptolites indicates that horizontal lamination is of the current origin here. depth: 1719.0 m. *6*. Facies F4; dark grey variety of shale with abundant, graptolitic hash; deposit of anoxic bottom waters on a deep-water plain; depth: 3270.7 m

Table 2

Thickness variation of facies occurrences (in metres)

Facies	Total number of occurrences*	Mean x_m	Mode Mo	Standard deviation S	Coefficient of variability $v = S/x_m$	Coefficient of skewness $g_1 = (x_m - Mo)/S$
F1	67	1.83	2.0	0.95	0.52	–0.18
F2	55	2.39	1.0	2.05	0.86	0.68
F3	153	2.22	2.0	1.21	0.54	0.18
F4	160	3.30	2.0	3.76	1.14	0.35

*Facies occurrences observed immediately beneath and above uncored intervals were disregarded

1650.0–3085.0 m. The thickness percentages of particular facies and number of occurrences in the section (*cf.* Figs. 5, 6) are as follows:

F1: 11.4%; 67
F2: 12.3%; 55
F3: 31.4%; 153
F4: 44.9%; 161

It shows that the shale-siltstone succession is dominated by facies F3 and F4. For the whole of the succession, a transition count matrix has been constructed, transition being defined as the upward replacement in the section of one facies by another. In counting the number of transitions between facies, those that occur immediately beneath and above uncored intervals were discarded. As wireline log data do not allow the recognition of individual facies, the facies succession analysis refers only to cored intervals of the Lębork IG 1 borehole. The transition count matrix is illustrated in Table 3. This shows that the Silurian shale-siltstone succession is composed of a cyclic sequence, as follows:

F3-F4-F3-F4...

Element F4 of this succession is sometimes replaced by a symmetric oscillation: [F4-F1-F4], whereas between elements F4 and F3, element F2 appears to form an asymmetric oscillation: {F4-F2-F3}. The superimposition of both these oscillations over the dominant cycle F3-F4 sometimes results in the following succession:

F3-[F4-F1-{F4]-F2-F3}-F4...

STATISTICAL SIGNIFICANCE OF THE TRANSITIONS BETWEEN FACIES

This description of the facies sequence is based entirely on their transitions in the Lębork IG 1 borehole. This section was not entirely cored (Tab. 1), and so a question arises whether, and which transitions observed between the facies are statistically significant.

To answer this, the Markov chain method was used. It is assumed that the facies sequence in the section is a first order Markov chain. The usage of Markov chains in facies sequence analysis has been long known (Vistelius, 1949). The numbers of transitions between different facies form a transition count matrix in which diagonal cells have values of zero (the transi-

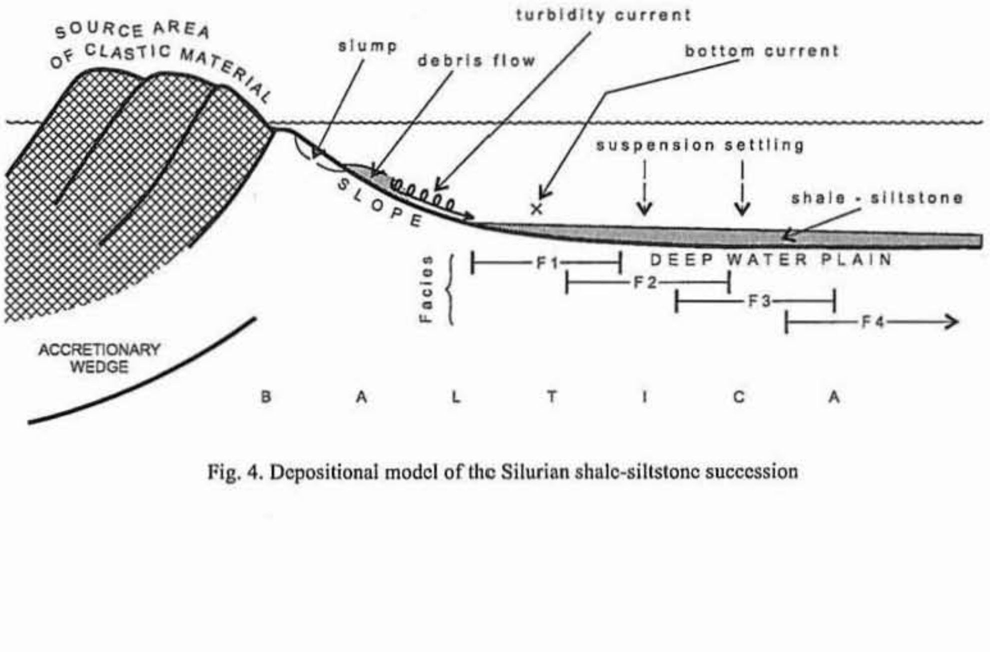


Fig. 4. Depositional model of the Silurian shale-siltstone succession

tion of a facies into itself not being considered; *cf.* Selley, 1970; Krumbein, 1967). That is why the correctness of calculation procedures of statistical significance with the use of the Markov chain method is sometimes questioned. However, it seems that the chi-square formula proposed by Gravett (in Hobday *et al.*, 1975) satisfactorily improves the procedure. Gravett's formula was applied in the statistical significance analysis of facies transitions shown below. The following symbols are used (*cf.* Miall, 1973):

n — number of facies types,

f_{ij} — number of transitions (upwards) from facies i into facies j,

s_i — number of occurrences of facies i in the section,

s_j — number of occurrences of facies j in the section,

p_{ij} — probability of transition (upwards) from facies i into facies j: $p_{ij} = f_{ij}/s_i$,

t — number of occurrences of all facies in the section,

r_{ij} — expected probability of transition (upwards) from facies i into facies j, if facies succession would be random: $r_{ij} = s_j/(t - s_i)$,

d_{ij} — probability difference p_{ij} and r_{ij}: $d_{ij} = p_{ij} - r_{ij}$.

In the statistical procedure used here, the null hypothesis *Ho* can be expressed as follows: the facies sequence illustrated in Table 3, is random. The *Ho* hypothesis was verified by means of the chi-square test using the formula proposed by Gingerich (1969):

$$\chi^2 = \Sigma(f_{ij} - s_i\, r_{ij})^2/s_i\, r_{ij}.$$

Number of degrees of freedom: $n^2 - 2n$.

The results of calculations, based on the transition count matrix (Tab. 3), are shown in Tables 4–6. Test value χ^2 = 33.507, number of degrees of freedom: 8. Limiting value χ^2 = 20.090, at confidence level $\alpha = 0.01$. This means that the *Ho* should be rejected. The facies sequence in the Lębork IG 1 borehole is not random. Facies transitions, corresponding to positive values in the difference matrix of observed and expected probabilities (Tab. 6), are characterized by the frequencies higher than random.

Gravett's formula was used to study the statistical significance of transitions between facies showing positive d_{ij} values:

$$\chi^2 = (f_{ij} - s_i\, r_{ij})^2/s_i\, r_{ij}(1 - r_{ij}).$$

Number of degrees of freedom: 1.

The results of the calculations are shown in Table 7. In this case, the limiting value $\chi^2 = 6.635$, indicating that the following transitions are statistically significant: F2 → F3 and F3 → F4. Therefore, the succession F2 → F3 → F4 can be considered statistically significant. Facies F1 appears in the succession with no statistically significant relationship to any other facies.

SEDIMENTARY ENVIRONMENT

In a comprehensive petrographic study of Ordovician and Silurian rocks in the Polish Lowlands, Langier-Kuźniarowa (1967) suggested that the Silurian shales are hemipelagites, while the siltstones were deposited from turbidity currents. The dark grey shale variety is particularly rich in pyrite and organic matter, indicating anoxic bottom waters in the sedimentary basin. The interpretation of the Silurian siltstones as turbidites was supported by Jaworowski (1971) who suggested a sedimentary environment below the wave base, in relatively deep water.

Similar Silurian (Upper Wenlock) deposits around Bornholm were studied by Bjerreskov and Jorgensen (1983), who considered the Silurian distal turbidites to have been deposited in a 1000±300 m deep basin, following analyses of tuffs occurring in that basin. Those authors also emphasized the anoxic condition of the bottom waters. According to McCann (1996), Llandovery deposits penetrated by the G-14 borehole drilled offshore in the Baltic, NE of Rügen (Fig. 8), were deposited in the hemipelagic environment interrupted by low density turbidity currents. That author considers that the basin floor was periodically above storm wave base, when "microconglomerates" and cross-bedded storm sands were deposited. McCann (1996) suggested that storm episodes were as rare as turbidity currents, and observed bioturbation in upper Llandovery deposits.

The following features are characteristic of the Lębork IG 1 borehole:

— thin siltstone beds deposited by sediment gravity flows: both debris flows and turbidity currents;

— thin and medium (*sensu* Ingram, 1954) siltstone beds reworked by bottom traction currents;

— shales deposited from suspension and partly from turbidity currents in a hemipelagic environment;

— an abundance of pyrite and organic matter in dark grey shales;

Table 3

Vertical facies sequence; transition count matrix

	F1	F2	F3	F4	
F1	–	13	22	28	63
F2	7	–	33	16	56
F3	18	17	–	110	145
F4	39	25	95	–	159
					423

Table 4

Vertical facies sequence; transition probability matrix

	F1	F2	F3	F4
F1	–	0.21	0.35	0.44
F2	0.12	–	0.60	0.28
F3	0.12	0.12	–	0.76
F4	0.24	0.16	0.60	–

— the presence of a nektonic fauna (mostly cephalopods) and — en masse — of a planktonic fauna (graptolites) in shales;

— the presence of a benthic fauna represented exclusively by redeposited fragments in the lower parts of some siltstone beds deposited by sediment gravity flows;

— a general lack of any trace of biogenic structures formed by bentic organisms;

— a lack of any sedimentary structures indicating that the basin floor was above the fairweather or storm wave base.

Most of these features were also observed in the Silurian shale-siltstone succession from other boreholes (Figs. 1, 2). However, these were more poorly cored than the Lębork IG 1 borehole (Tab. 1). On the whole, the Silurian shale-siltstone succession from the foreland of the Pomeranian Caledonides was deposited in a hemipelagic environment, most probably at the foot of the slope and on the deep-water plain of the basin. It is difficult to estimate here precisely the water depth of the sedimentary basin. It consistently exceeded the depths of both fairweather and storm wave base. Debris flows may travel hundreds of kilometres over slopes inclined at an angle < 1°. Assuming such a low slope angle, the basin depth could be fairly small.

The shale-siltstone succession shows many similarities to submarine fan deposits and, in particular, to outer fan deposits. However, the presence of siltstone beds deposited by debris flows (facies F1) suggests an analogy with the non-channelized debris flow system model of Shanmugam (1997). The debris flow deposits and siltstone beds reworked by bottom traction currents are acompanied, though, by turbidity current deposits in the shale-siltstone succession. These currents were generated by slumps and debris flows moving down the slope of the sedimentary basin. Thus, the deposits discussed probably formed

Table 5

Vertical facies sequence; independent trials matrix

	F1	F2	F3	F4
F1	–	0.16	0.40	0.44
F2	0.17	–	0.40	0.43
F3	0.23	0.20	–	0.57
F4	0.24	0.21	0.55	–

Table 6

Vertical facies sequence; difference matrix

	F1	F2	F3	F4
F1	–	0.05	–0.05	0.00
F2	–0.05	–	0.20	–0.15
F3	–0.11	–0.08	–	0.19
F4	0.00	–0.05	0.05	–

vast accumulations of terrigenous material extending along the foot of the slope and over the deep-water plain of the basin.

A depositional model for the Silurian shale-siltstone succession is shown in Figure 4. According to this model, facies F1 has formed close to the marginal part of the sedimentary basin and source areas of terrigenous material, whereas facies F2, F3 and F4 have developed farther away towards the deep-water plain of the basin. Therefore, proximity to source areas decreases from facies F1 to facies F4.

Table 7

Chi-square tests on positive values from the matrix shown in Tab. 6

Upward transition	Chi-square test value
F1 → F2	1.007
F2 → F3	8.360
F3 → F4	21.047
F4 → F3	1.448

VERTICAL VARIATION IN THE THICKNESS OF FACIES OCCURRENCES

Variation in the thickness of occurrences of particular facies in the Lębork IG 1 borehole section is shown in the form of time series (*cf.* Miller and Kahn, 1962). The thickness of occurrence of a facies is meant here to be the thickness of a section fragment represented by this facies. Unsmoothed and smoothed thickness time series have been compiled for each facies using 5-unit and 11-unit moving averages. The smoothed time series were used to observe small-scale and large-scale tendencies of changes in facies thickness. Graphs illustrating the time series of particular facies are shown in Figures 5, 6. The axis of ordinates of each graph represents consecutive numbers of facies occurrences in the section (the numbering corresponds with the order in which particular occurrences of a given facies appear, from oldest to youngest). The axis of abscissae represents common logarithmic values of thickness of occurrences in metres. The stratigraphical range of occurrences of each facies is given on the left.

The unsmoothed time series for facies F1 (Fig. 5a) shows oscillations with no clear trend of thickness changes. The time series smoothed with a 5-unit moving average reveals the presence of the groups of occurrences showing an increased thickness, close to the occurrences labelled 15, 23, 32, 40 and 58. The time series smoothed with an 11-unit moving average contains groups of increased thickness of facies F1 near the occurrences labelled 15, 40 and 60. Occurrence 15 is within the *scanicus parascanicus* + *invertus* Zones, while occurrence 23 is within the *leintwardinensis* Zone. Occurrence 32 also belongs to the *leintwardinensis* Zone. Occurrence 40 is within the *praecornutus* Zone, and occurrences 58 and 60 are within the *auriculatus* Zone. Thus, distinct thickness fluctuations within the time series of facies F1 occur in the Gorstian (*scanicus parascanicus* + *invertus* Zones) and lower Ludfordian (*praecornutus* and *auriculatus* Zones).

The unsmoothed time series of facies F2 (Fig. 5b) shows two distinct fluctuations in thickness distribution. Both these fluctuations are blurred by oscillations that disappear in the smoothed time series. In both smoothed time series, the groups of occurrences showing an increased thickness of facies F2 appear close to the occurrences labelled 16 and 45. Occurrence 16 is within the *praecornutus* Zone, while occurrence 45 is within the *inexpectatus* Zone. Both these thickness fluctuations in facies F2 are lower Ludfordian in age.

The unsmoothed time series of facies F3 (Fig. 6a) shows a number of oscillations with no clear trend of thickness changes. The time series smoothed with a 5-unit moving average shows small fluctuations expressed by the groups of occurrences showing an increased thickness of facies F3. These occur near the occurrences labelled 6, 27, 52, 92, 130 and 147. The time series smoothed with an 11-unit moving average is characterized by the groups of occurrences showing an increased thickness of facies F3 near the occurrences labelled 27, 52, 92 and 130. Occurrence 6 is within the *hemiaversus* Zone, and occurrence 27 and 52 are within the *leintwardinensis* Zone. Occurrence 92 is within the *praecornutus* Zone, and occurrence 130 is within the *inexpectatus* Zone. Thus, distinct thickness fluctuations within the time series of facies F3 fall within the lower Ludfordian (*leintwardinensis, praecornutus* and *inexpectatus* Zones), with a further example close to occurrence 147, within the upper Ludfordian *balticus* Zone.

Both the unsmoothed and smoothed time series of facies F4 (Fig. 6b) show thick occurrences of this facies both in the lowermost and uppermost parts of the shale-siltstone succession, combined with a trend of upwardly increasing thickness of facies F4 occurrences. Numerous oscillations are visible in the unsmoothed time series, while weakly expressed fluctuations are revealed by the smoothed time series. The time series smoothed with a 5-unit moving average is characterized by thickness peaks of facies F4 near the occurrences labelled 20, 40, 65, 95 137 and 157. Similar, weakly developed fluctuations occur within the time series smoothed with an 11-unit moving average near the occurrences of facies F4 labelled 15, 40, 65, 95 and 137. Occurrence 15 is within the *scanicus parascanicus* Zone or *invertus* Zone, occurrence 20 is within the *hemiaversus* Zone, and occurrence 40, 52 and 95 are within the *leintwardinensis* Zone, whereas occurrence 137 is in the *inexpectatus* Zone. This shows that thickness fluctuations in facies F4 occur in the Gorstian (*scanicus parascanicus* + *invertus* Zones and *hemiaversus* Zone) and lower Ludfordian (*leintwardinensis* and *inexpectatus* Zones), with a further thickness peak close to occurrence 157 in the upper Ludfordian *balticus* Zone.

This time series data reflects the distance from source areas of clastic material and its supply to the sedimentary basin. The depositional model (Fig. 4) suggests that facies F1 and F2 represent a proximal zone of siltstone deposition. The thickness peaks of facies F1 and F2 may suggest relatively close proximity to source (*cf.* Fig. 4). Fluctuations in the time series of facies F1 and F2 clearly show a decreasing distance to source in the *praecornutus* Zone (lower Ludfordian), and to a lesser extent,

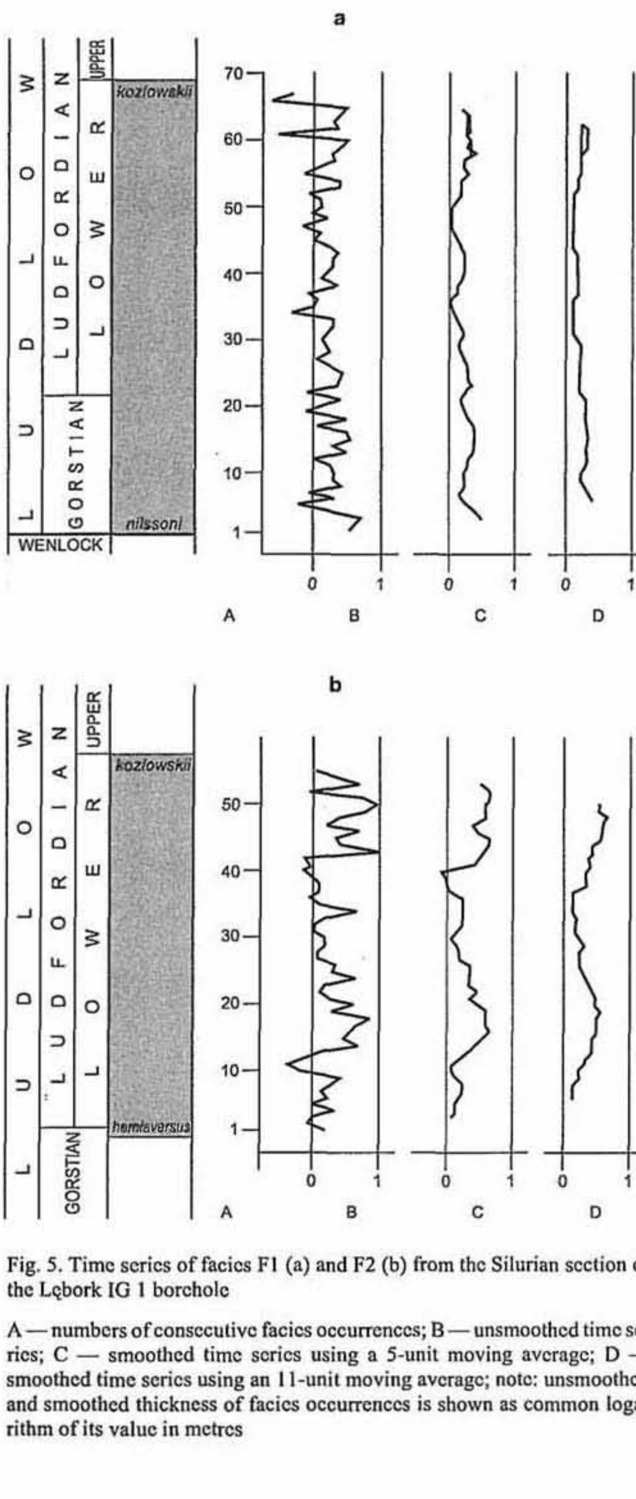


Fig. 5. Time series of facies F1 (a) and F2 (b) from the Silurian section of the Lębork IG 1 borehole

A — numbers of consecutive facies occurrences; B — unsmoothed time series; C — smoothed time series using a 5-unit moving average; D — smoothed time series using an 11-unit moving average; note: unsmoothed and smoothed thickness of facies occurrences is shown as common logarithm of its value in metres

in the *scanicus parascanicus* + *invertus* (Gorstian) Zones, and *auriculatus* and *inexpectatus* Zones (lower Ludfordian).

The proximal facies F1 and F2, as well as facies F3 representing the transition to a distal zone of siltstone deposition, provide information on the terrigenous supply to the basin. The thickness fluctuations described above reflect such changes in supply. The time series of facies F1, F2 and F3 show the greatest silt supply during the early Ludfordian (*leintwardinensis–praecornutus* Zones and *inexpectatus* Zone). A comparable analysis of the Silurian shale-siltstone succession from the Kościerzyna IG 1 borehole (Jaworowski, 1975) was interpretated in terms of tectonic activity in the source areas. The data in that study, though, was poorer than that from the Lębork IG 1 borehole, enabling a revision, in the present paper, of that study. Nevertheless, the conclusion then expressed, that the strongest tectonic uplift of source areas took place immediately above the *leintwardinensis* Zone, requires only partial modification. The greatest supply of terrigenous material occurred in the *leintwardinensis–praecornutus* Zones, with the most proximal setting in the *praecornutus* Zone. In other words, particularly strong uplifting took place in the source areas during the early Ludfordian. The total thickness of the Ludlow deposits is shown in Figure 7 (*cf.* Fig. 2).

Facies F4, representing the distal zone of siltstone deposition characterized by shale domination, shows a general trend of upward-increasing in thickness, showing a gradually decreasing intensity of processes stimulating silt supply. Thickness trends in facies F4 in the lowermost part of the shale-siltstone succession indicate a gradual increase in silt supply during the early stages of deposition of this succession. Thickness peaks of facies F4 occur in the *leintwardinensis* and *inexpectatus* Zones (lower Ludfordian). As shown above, silt supply to the sedimentary basin was enhanced in these zones. It may be supposed that the simultaneous enhanced deposition of clay was associated with the same depositional mechanism. Subaqueous gravity mass flows of unconsolidated deposits occurred then on the clastic wedge slope of the sedimentary basin margins. Thin intervals of facies F4 in the *praecornutus* Zone (lower Ludfordian) reflect the relatively close position to source at that time, when there was a dominance of the proximal facies F1 and F2.

The fluctuations in both proximity and supply to the sedimentary basin are interpreted here as due to tectonic events, primarily uplift in the source areas. This uplift caused increased erosion and sedimentary transport from source areas, the development of a clastic wedge in the marginal part of the basin, an increase in its slope gradient, and, finally, this initiated submarine gravity flows. Because the shale-siltstone succession developed in deep-waters (below wave base) and distant from shore, the influence of eustatic sea-level changes on sedimentary variability through time can be considered insignificant.

FLYSCH OR NOT FLYSCH?

The similarity of the Silurian shale-siltstone succession of the Polish Lowlands to shaly flysch has been suggested (Jaworowski, 1971), based on comparison with diagnostic features of flysch given by Dżułyński and Smith (1964).

But, flysch deposits are commonly considered to be involved in fold deformations of the orogen with which they are directly connected. The deposits here are unfolded and lie nearly horizontally as the fill of the foredeep of the Pomeranian Caledonides stretching SW of the Teisseyre-Tornquist Zone, having formed at the margin of Baltica. Pożaryski (1990) and Pożaryski *et al.* (1992) questioned the flysch character of this shale-siltstone succession, suggesting rather that it represents a Caledonian molasse. Dadlez *et al.* (1994) though, favoured the

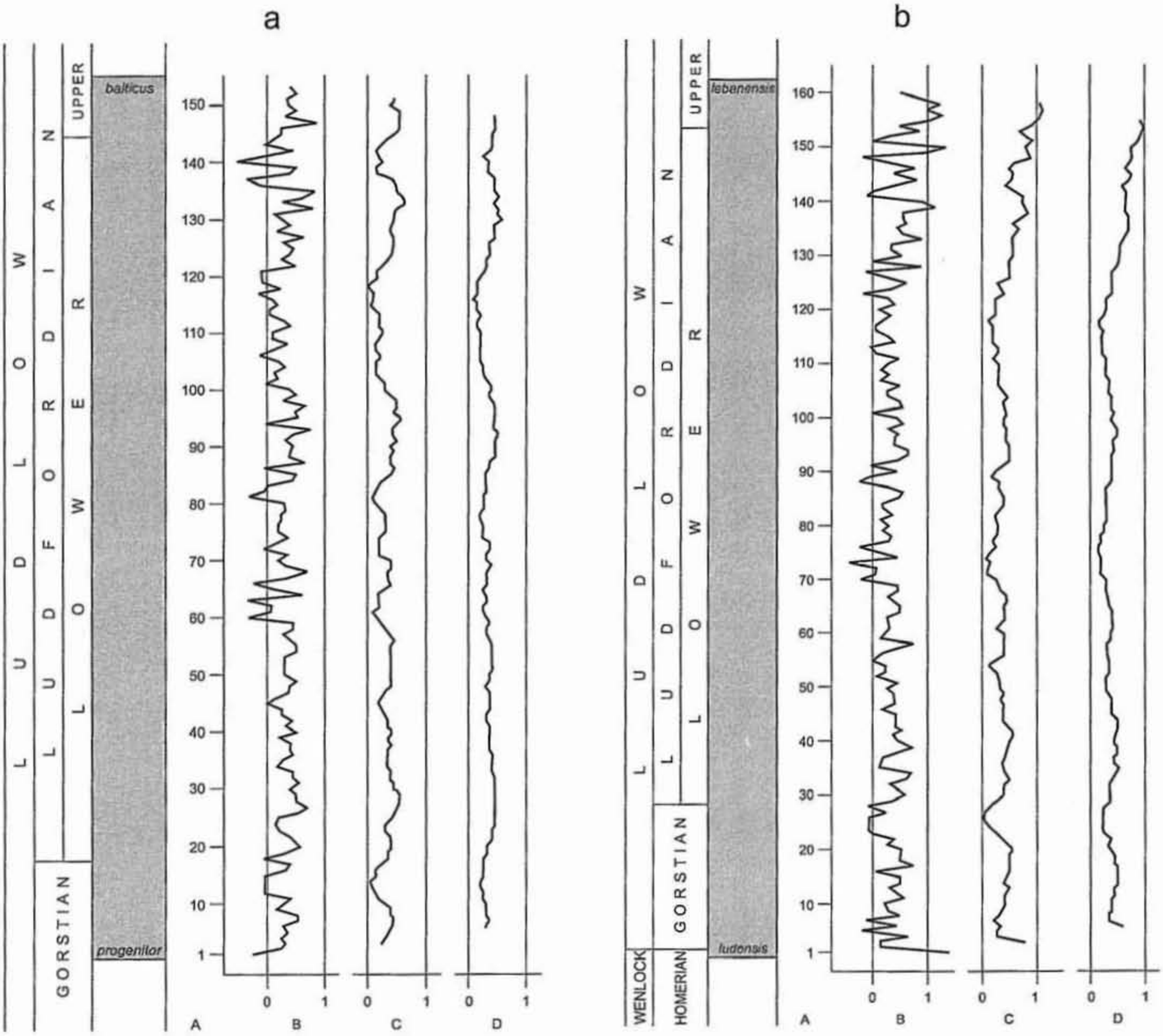


Fig. 6. Time series of facies F3 (a) and F4 (b) from the Silurian section of the Lębork IG 1 borehole

For explanations see Fig. 5

earlier views of Jaworowski (1971), considering the shale-siltstone succession, as a syn-orogenic deposit, as flysch. The lack of involvement of this succession in later deformation was explained (Dadlez *et al.,* 1994), in terms of the plate tectonics theory.

These different views reflect ambiguity in the terms flysch and molasse. Homewood and Lateltin (1988, p. 2), though, after an analysis of the classic Alpine area, unequivocally stated that "...flysch and molasse are meaningful and useful words when used to denote fillings of sedimentary basins evolving under given geodynamic contexts". Difficulties in understanding the terms flysch and molasse arise from the fact that many depositional successions, resembling flysch sedimentologically, occur in basins which, from a geodynamic point of view, are molasse basins (Homewood and Lateltin, 1988). An example is the Annot Sandstones of the French Alps, described as flysch in the classic paper of Bouma (1962). Dżułyński and Smith (1964) noted that flysch facies may also occur within molasse. Those authors emphasized that „...there is a need for the term flysch to be clearly understood as a facies term". Homewood and Lateltin (1988), though, considered the term flysch geodynamic term combining sedimentation and tectonics.

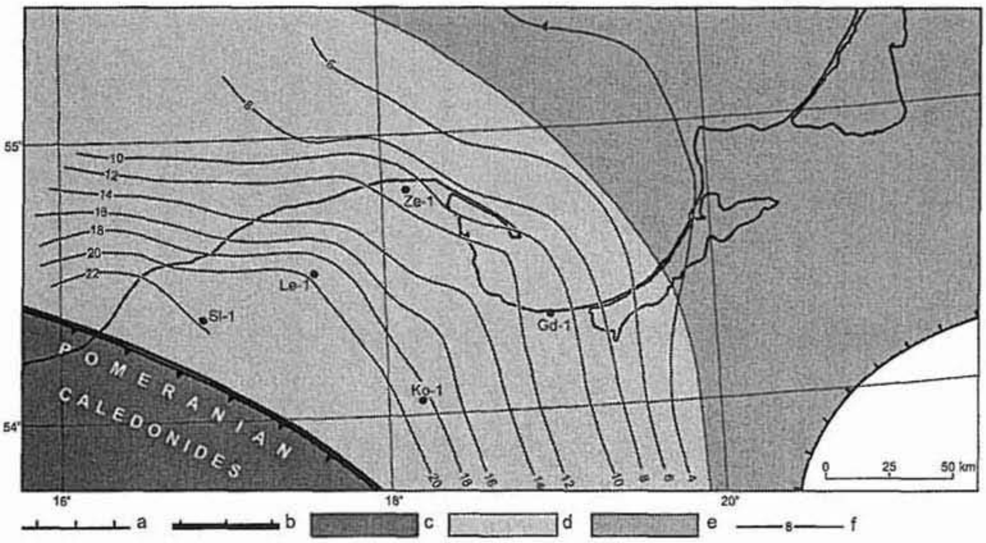


Fig. 7. The thickness of Ludlow deposits

a — recent extent of Silurian deposits; b — Caledonian deformation front; c — source area of clastic material; d — Silurian shale-siltstone succession; e — Silurian shales and marls; f — isopachs (in hundreds of metres); for borehole symbols see Fig. 1

From a sedimentological point of view, the Silurian shale-siltstone succession from Pomerania can be considered shaly flysch (Jaworowski, 1971), and there seems no reason to change this opinion, despite the detailed revision of this paper. This revision, inspired by the views of Shanmugam and Moiola (1995, 1997) and Shanmugam (1997), indicate that some of these Silurian siltstone beds were deposited not from turbidity currents, but from either debris flows or as a result of the reworking by bottom currents. Nevertheless, the Silurian shale-siltstone succession, sedimentologically still represents distal flysch.

The tectonic and geodynamic context of the Silurian shale-siltstone succession remains to be discussed. Does this succession represent flysch in these terms? The siltstone beds in the Silurian shales of the Polish Lowlands have long been considered as evidence that the Caledonian orogen extended along the Teisseyre-Tornquist Line, i.e. along the SW edge of the East European Craton (Znosko, 1962). This orogen was considered as a source area of clastic material, implying that this material was transported from SW towards NE. This transport direction was later supported on the basis of sedimentary structures in the siltstones (Jaworowski, 1971). The present study confirms clastic supply from SW towards NE, from beyond the Teisseyre-Tornquist Line, i.e. from the Pomeranian Caledonides (Figs. 1, 7, 8). These are interpreted as either a fragment of the fold-and-thrust Caledonian orogen (*cf.* Znosko, 1985, 1987, 1997; Dadlez *et al.*, 1994) or as a result of Caledonian accretion (Pożaryski, 1990, 1991; Pożaryski *et al.*, 1992).

The Pomeranian Caledonides are the southeastern continuation of the Danish-North German Caledonides, recently also interpreted in terms of Caledonian accretion. According to this idea (Giese *et al.*, 1994; Maletz *et al.*, 1997; Poprawa *et al.*, in press), a collision between Baltica and East Avalonia took place in the Late Ordovician and Early Silurian. The accretionary prism of the Danish-North German-Polish Caledonides was thrust over the East European Craton margin, and the Pomeranian Caledonides are a fragment of this orogen. The Silurian shale-siltstone succession of northern Poland was deposited in a basin developed in their foreland, clastic source areas (Fig. 4), being located within the Caledonian accretionary prism. The prism is thrust over the East European Craton margin and stretches along the zone of the Late Ordovician-Early Silurian collision between the Baltica continent and East Avalonia microcontinent (Fig. 8).

The existence of the Pomeranian Caledonides and the position of the Caledonian deformation front along the SW margin of the East European Craton seems unquestionable (*cf.* Znosko, 1985, 1987, 1997; Dadlez *et al.*, 1994). There is also no doubt that the Silurian shale-siltstone succession represents, in terms of plate tectonics, an orogenic, syn-collision clastic complex and, as such, represents flysch. Homewood and Lateltin (1988, p. 1–2), referring to the Alpine area, state: "In the case of the Alps, flysch can be called pre-collision to syn-collision orogenic clastics". The possibility that flysch may occur in a foredeep area was indicated in a largely overlooked paper by Contescu (1964). That author suggested that flysch can be divided into three categories: orthoflysch, paraflysch and pseudoflysch. Paraflysch develops in foredeeps and intramontane depressions, that deposited in foredeeps being called exoflysch (Contescu, 1964). It corresponds to deposits of the "deep (Flysch) Phase" distinguished by Stockmal *et al.* (1992, p. 115, fig. 7) in the evolution of foredeeps. In those terms, the Silurian shale-siltstone succession developed in the foreland of the Pomeranian Caledonides represents exoflysch, or, more precisely, shaly exoflysch.

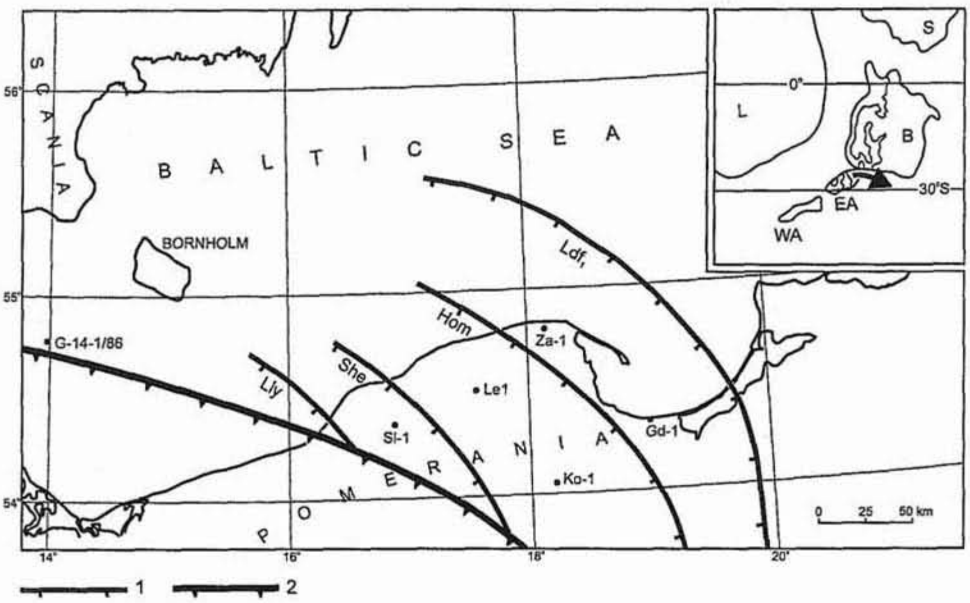


Fig. 8. First occurrences of siltstone interbeds in Silurian shales

1 — extent of first siltstone occurrences in: Lly — Llandovery, She — Sheinwoodian (Lower Wenlock), Hom — Homerian (Upper Wenlock), Ldf_1 — lower Ludfordian (Upper Ludlow); 2 — Caledonian deformation front; for borehole symbols see Fig. 1; inset map: distribution of palaeocontinents in the Llandovery (after Scotese and McKerrow, 1990, simplified and modified); B — Baltica; EA — East Avalonia; WA — West Avalonia; S — Siberia; L — Laurentia; arrow denotes sinistral movement of Avalonia in the collision zone with Baltica

DEVELOPMENT OF SILURIAN EXOFLYSCH AND COLLISION BETWEEN BALTICA AND EAST AVALONIA

The correlation scheme (Fig. 2) and Table 1 show that the extent of the Silurian exoflysch in northern Poland was increasing trough time from SW to NE (Fig. 8). It first appeared in the Silurian section of the borehole Słupsk IG 1 — in the Sheinwoodian (Lower Wenlock, Fig. 2). Later, in the lower Ludfordian (lowermost Upper Ludlow, Fig. 2), exoflysch appeared in the Silurian sections of the boreholes Żarnowiec IG 1 and Gdańsk IG 1. This progression indicates growing intensity of the uplift and thrusting of the Caledonian accretionary prism. The strongest movements, as indicated by the time series analysis, took place during the early Ludfordian, which was the time of the greatest extent of the shale-siltstone succession to the NE (Figs. 1, 8).

The extent of the shale-siltstone succession also increased from the NWW towards the SEE, i.e. along the present-day Caledonian deformation front. This is seen when comparing data from the Slagelse 1 (Bjerreskov and Jorgensen, 1983) and G-14 (McCann, 1996) boreholes with information from the Słupsk IG 1 and Kościerzyna IG 1 boreholes. In the areas located farther SEE, the exoflysch appears later (Tab. 1, Fig. 8). As demonstrated above, the source area for the Silurian shale-siltstone succession was the accretionary prism related to the collision between Baltica and East Avalonia (Fig. 8). This means that the collision was accompanied by sinistral strike-slip movements along the SW edge of the present day East European Craton (*cf.* Pożaryski, 1991).

CONCLUSIONS

1. The Silurian shale-siltstone succession was deposited in a hemipelagic environment at the foot of the basin slope and on the deep-water plain.

2. The siltstone beds alternating with graptolitic shales of this succession were deposited by submarine silty debris flows and turbidity currents. Many were reworked by bottom currents.

3. The graptolitic shales of this succession were deposited primarily as a result of hemipelagic sedimentation from suspension, and partly from low density turbidity currents.

4. The Caledonian accretionary prism, stretching along the collision zone between the Baltica and East Avalonia continents, was the source of the silt.

5. The strongest uplift and thrusting of the accretionary prism took place during the earliest Late Ludlow (early Ludfordian).

6. The Silurian shale-siltstone succession in Pomerania is represented by Caledonian shaly exoflysch, i.e. syn-collision clastics deposited in a foredeep developed on the East European Craton.

7. Passing from the SW edge of the East European Craton towards the NE, the Silurian exoflysch appears progressively later in the foreland of the Pomeranian Caledonides. A similar phenomenon is observed along the edge of the East European Craton from the NNW towards the SSE.

8. Thus it follows that sinistral strike-slip movements along the SW edge of the East European Craton, together with thrusting, accompanied the collision between Baltica and East Avalonia.

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