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Cyclic sedimentation in the Middle Jurassic of central Poland

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Nine boreholes were drilled in the late eighties in central Poland to investigate the Middle Jurassic sedimentary successions. The boreholes were arranged in three lines (Ciechocinek, Brześć Kujawski and Wojszyce lines) running across three anticlines underlain by salt pillows. Long intervals of boreholes have been cored, often with 100% core recovery, thus enabling a detailed examination of sedimentary evolution. Sequences are composed of a full range of clastic rocks, from conglomerates through sandstones and heteroliths to shales. They are arranged in sedimentary cycles, predominantly regressive (coarsening upwards). These are interpreted as deposited in a shallow, wave/storm-dominated, shelf environment, each cycle being a result of progradation of fore-shore to near-shore heteroliths and sands over the shales of an open sea. The basin was probably non-tidal or microtidal. These essential (lower order) cycles, equivalents of the IVth order cycles in the world-wide scheme, are assembled in higher order cycles which resemble the IIIrd order cycles of that scheme. The bases of the higher order cycles are good lithostratigraphic markers, three of them being probably equivalents of chronostratigraphic boundaries (bases of the upper Aalenian, upper Bajocian and Bathonian, respectively). Correlation of borehole sections points to limited salt movement of the Ciechocinek and Wojszyce salt pillows during the Middle Jurassic. These are indicated, first of all, by thickness reductions seen in boreholes located above the tops of salt pillows. In the Ciechocinek area, the upward movement of salt occurred during the latest Bajocian/earliest Bathonian while in the Wojszyce area — during the early Bathonian. Coarser clastics were shed into the basin from the south-west, north-west (along the Mid-Polish Trough) and north-east during the Aalenian, and mainly from the north-east (from the East European Craton) in later times.

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INTRODUCTION

Nine boreholes arranged in three lines (Ciechocinek, Brześć Kujawski and Wojszyce lines) were drilled in the years 1987–1990 in central Poland (Kujawy region — Fig. 1). They were aimed at investigation of the Middle Jurassic oil and gas prospects in the area of full development of this succession and of its greatest thickness. Middle Jurassic strata range here from 400 m to nearly 1000 m in thickness. Boreholes have been cored over long intervals, often with fairly good core recovery (Figs. 2–4). In non-cored intervals the interpretation has been based on geophysical logs of good quality. Gamma ray logs have been particularly useful. All these data allowed detailed studies of sedimentation, with special attention paid to its cyclicity. Two short segments of the Middle Jurassic section have been excluded from the analysis, namely: (1) the uppermost part, belonging to the Callovian, built of mixed, clastic/calcareous rocks, and (2) the lowermost part — with initial marine ingressions — which was earlier assigned to the lower Aalenian although there is no biostratigraphic evidence for that.

Nine basic borehole sections are labelled here as follows (from south-west to north-east): Ciechocinek line — C2, C1 and C3; Brześć Kujawski line — B3, B2 and B1; Wojszyce line – W3, W1a and W4. These boreholes have been correlated with other sections over a wider area of central Poland. Coring of the latter sections is more limited but comparison of geophysical logs enabled the identification of lithostratigraphic boundaries and of the main lithofacies groups. The following additional boreholes have been taken into consideration (Fig. 1): Czernikowo IG 1 (Cz) at the northeastern extension of the Ciechocinek line; Krośniewice IG 1 (Kr) at the southwestern extension of the Wojszyce line; Gostynin IG 3 (G3), Gostynin IG1/1a (G1a) and Gostynin 4 (G4) at the northeastern extension of the Wojszyce line; finally, Zgierz IG 1 and Łowicz IG 1 situated south-east of the Wojszyce line. Generalised sections of two of these sixteen boreholes (Wojszyce IG 4 and Gostynin IG 1/1a) were used by Feldman-Olszewska (1997) as standard sections in her overview of the Mid-Jurassic palaeogeography in the Polish Lowlands.

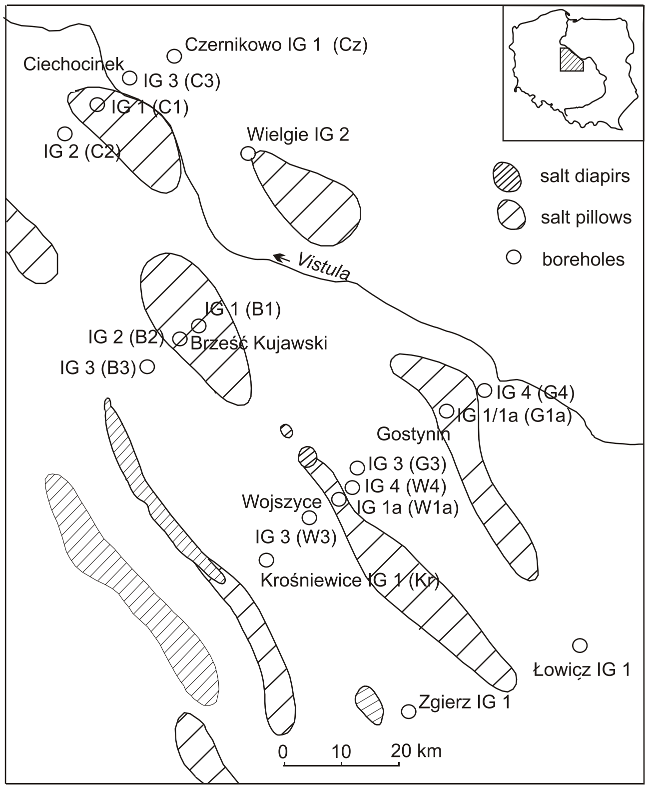

Fig. 1. Locality map

GEOLOGICAL SETTING

The area lies within the Mesozoic tectonic unit called Mid-Polish Trough (MPT), extending NW–SE across the Polish Lowlands. More exactly, it is located in the southeastern segment of the MPT (Kujawy region), characterised by the greatest thicknesses not only of the Middle Jurassic but also of all the Triassic to Lower Cretaceous interval (Dadlez, 2001). The Middle Jurassic basin subsided here most strongly, the accumulated sediments indicating its deepest part (Feldman-Olszewska, 1997).

MIDDLE JURASSIC ROCKS

A full range of siliciclastic rocks occurs in the sections investigated: from conglomerates through sandstones and heteroliths to shales. Eight essential lithofacies (labelled **A** to **H**) with several varieties have been distinguished. Since the lithofacies are arranged predominantly in coarsening upwards (reverse, regressive) cycles, the order of description below follows this arrangement. In places particular lithofacies pass gradually into other (especially within the heteroliths), so the boundaries between lithofacies are locally drawn arbitrarily.

Shales (lithofacies **H** — Fig. 5a). In the lower part of the section (Aalenian) they are black with rough surfaces of bedding planes (admixture of silt and minute mica flakes) while in the upper part (Bajocian-Bathonian) they are dark grey with smooth surfaces of bedding planes. The rocks are rich in organic matter. They contain numerous, light grey marly concretions (Fig. 5a) or light yellow and grey-brown marly-sideritic concretions. Thin interbeds of ironstones and pyrite concretions are noted in places. Well-preserved bioclasts of bivalves, and gastropods are relatively common while accumulations of crinoid plates (Fig. 6c) are less frequent. Bioclasts are either dispersed in the rock or concentrated in streaks or lenses, sometimes forming very thin lumachelle layers. Some parts of the shales contain laminae of silt or even very fine-grained sand. Shales occur in beds several metres thick, as well as in compact packages which may attain several hundred metres, as in the Aalenian-Bajocian of the Wojszyce area (Fig. 4).

The succeeding lithofacies types belong to the category of heteroliths — a rock composed of alternating layers and beds of shale and sandstone. This rock does not built separate thick packages, occurring only in thinner beds which generally do not exceed 2–5 m. Heteroliths have been subdivided into three lithofacies types according to the proportion of clay and sand.

Increasing amounts of silt and sand in shale mark the transition to **shaly heteroliths** (lithofacies **G** — Fig. 5b). They are characterised by the appearance of lenses and interbeds of silt, and very fine- to fine-grained sand within the shales described above. The shaly material prevails, constituting more than 70% of the rock. Cross-lamination is observed within the silty and sandy lenses (isolated ripples?) but more frequently they are structureless. Marly and marly-sideritic concretions occur as before. Bioturbation is rather sparse.

A further increase of the amount of sandy material in the rock leads to the next lithofacies — **shaly-sandy heteroliths** (lithofacies **F** — Figs. 5c–h) which contain from 30 to 70% of shale and 30 to 70% of sand. Structurally it represents the most diversified type of rock in the Middle Jurassic succession. Several varieties of this lithofacies may be distinguished, mainly on the basis of the intensity of bioturbation[1]. In the slightly or non-bioturbated rocks two varieties are observed: that with thick layering (layers 1 cm or more thick — Fig. 5c) and the other with thin layering (layers less than 1 cm thick — Fig. 5d). In these varieties fining upwards microcycles (storm induced?) are locally noted in which fine-grained sandstone, lying with a sharp boundary upon shale, passes up through brown silt to black shale (Fig. 5e). Coarsening upwards microcycles of the same type are less frequent. In sandstone layers and lenses either micro-hummocky cross-lamination, or wavy or parallel lamination may be present. However, structureless layers also occur. Marly or marly-sideritic concretions are less frequent than in previously described lithofacies.

The varieties with trace fossils are moderately or strongly bioturbated. Burrows in both varieties (Fig. 5f, g) are of various sizes, from 1 mm to 1 cm in diameter, parallel, or (rarely) oblique to lamination. An extreme case of bioturbation is represented by a rock completely reworked by organisms. Figure 5h, portraying this variety shows a complicated system of bi-

[1]Detailed investigations of trace fossils were beyond the scope of this study. Only a few basic types of burrows have been distinguished according to their sizes and their position in relation to bedding planes.

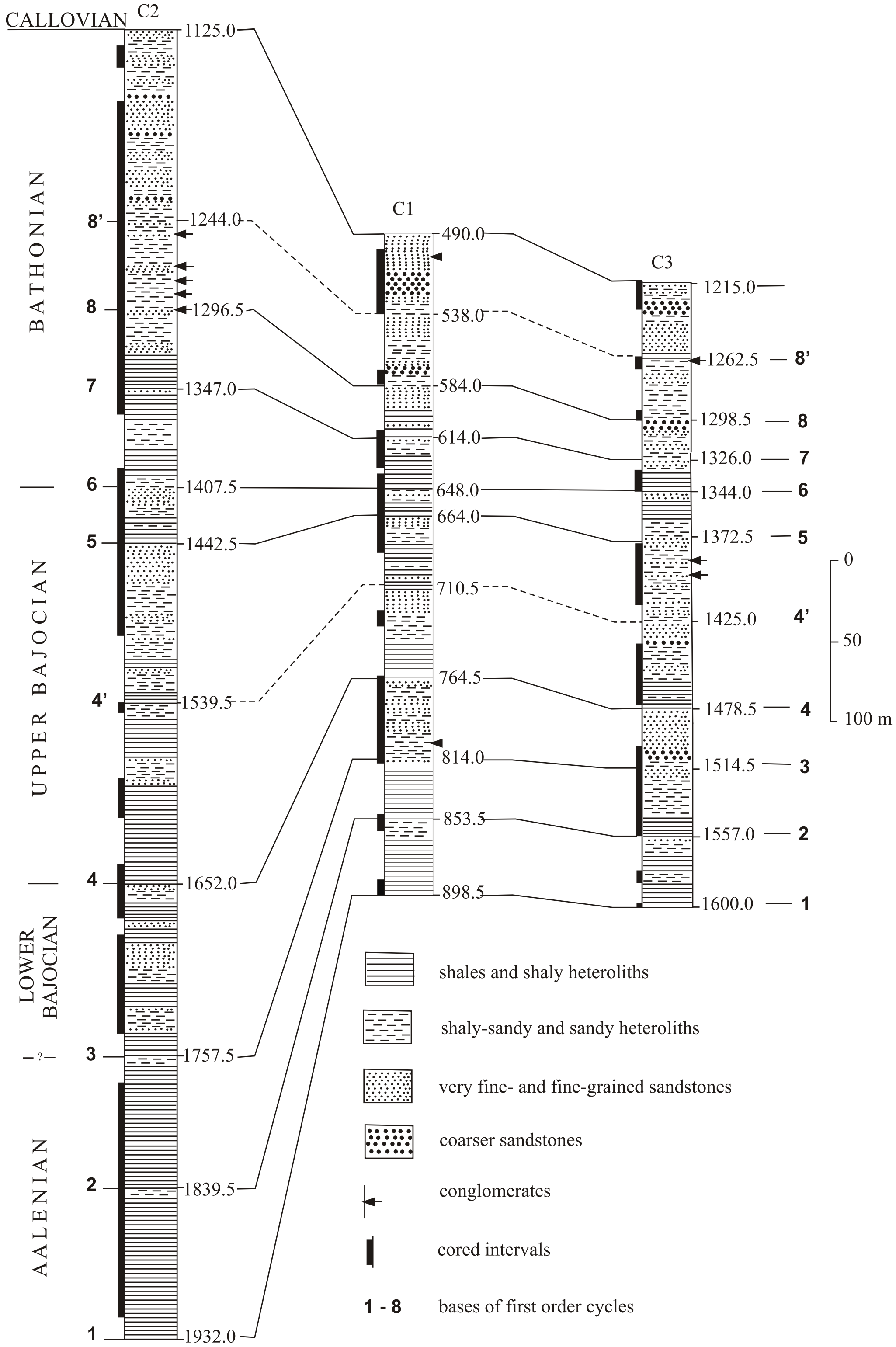

Fig. 2. Borehole columns of the Ciechocinek line (see Fig. 1 for a location and explanation abbreviated well-names)

furcated, anastomosing burrows of small diameter (1–2 millimetres), parallel to lamination. This variety occurs most often at the boundaries between shaly and shaly-sandy heteroliths. It seems that trace fossils in these rocks represent in general the Cruziana facies *sensu* Seilacher (1967), the last mentioned variety being connected with the relatively deepest waters.

The next lithofacies is a **sandy heterolith** (lithofacies **E** — Fig. 5i) in which sandy material prevails over shale constituting more than 70% of the rock. It is not frequent in the succession. Sandy parts are generally structureless or parallel laminated, shaly streaks are irregular and trace fossils are rare.

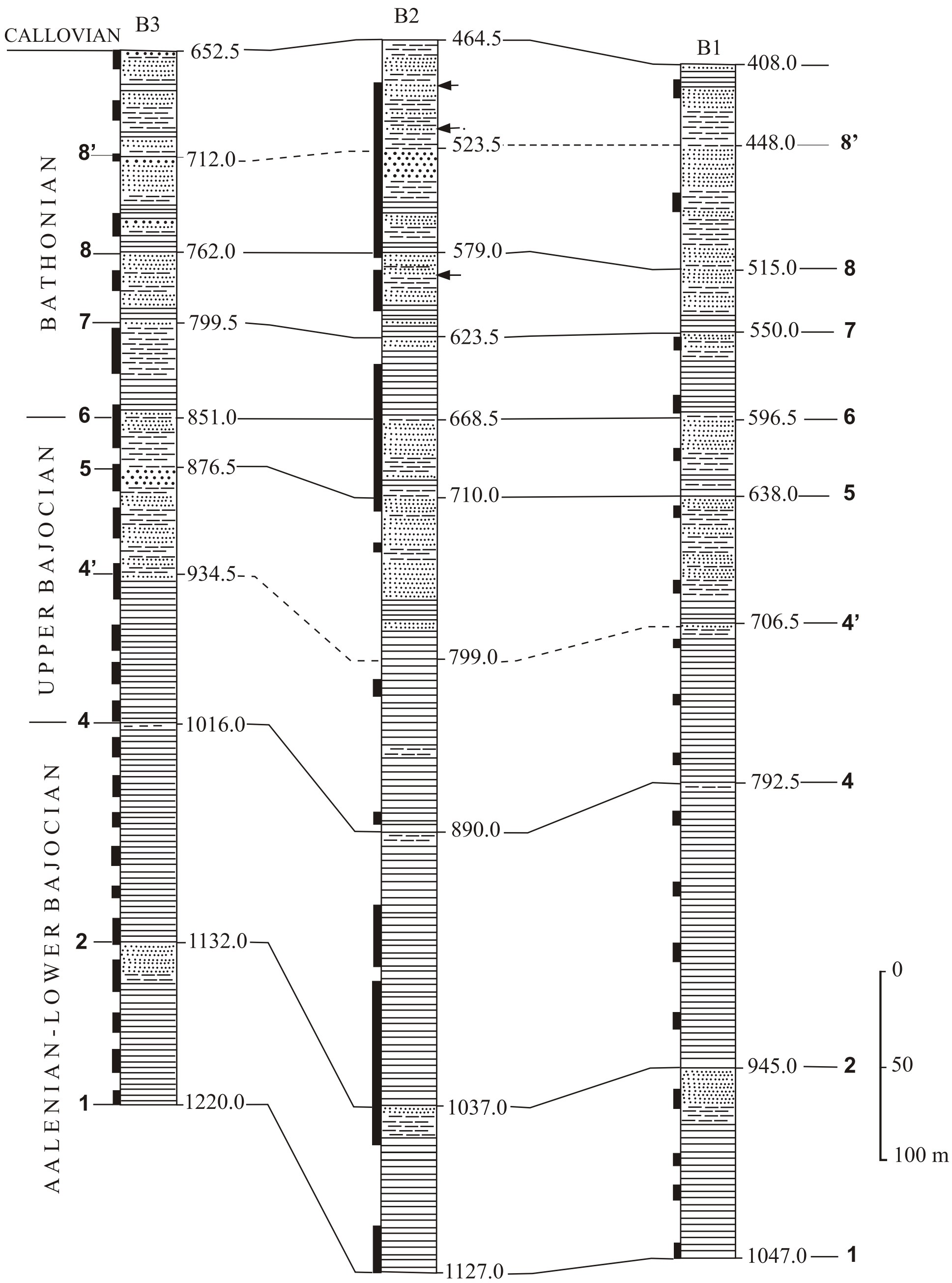

Fig. 3. Borehole columns of the Brześć Kujawski line

Explanations as in Fig. 2

Successive lithofacies are represented by sandstones. They are light grey, yellow-grey, light brown, less frequently white. Sandstones have been subdivided according to grain-size into: very fine-grained sandstones (lithofacies **D**), fine-grained sandstones (lithofacies **C**) and coarser sandstones in general (lithofacies **B**). Petrographically, they are quartz arenites with variable amount of clayey matrix. In the uppermost Bathonian, chamosite and goethite are present in the matrix. The rocks of lithotypes **D** and **C** are well sorted while those of lithotype **B** are poorly sorted. Occasionally, clay clasts are observed as well as narrow vertical burrows (Fig. 5j), suggesting the Skolithos facies *sensu* Seilacher (1967), characteristic of the shallowest waters.

Structurally, sandstones of the first two lithofacies are similar: structureless sandstones may occur (Fig. 5j), as well as parallel laminated, and wavy and cross-bedded rocks (Fig. 5k), both of planar and trough type. A few observations only were possible as to the mutual connections between structureless and cross-bedded sandstones. They revealed that both types occur: structureless rocks passing upwards into cross-bedded ones and conversely, structureless layers overlying the cross-bedded sandstones. In the lithotype **B** structureless and cross-bedded sandstones (Fig. 5l) are noted. The latter, with low-angle and

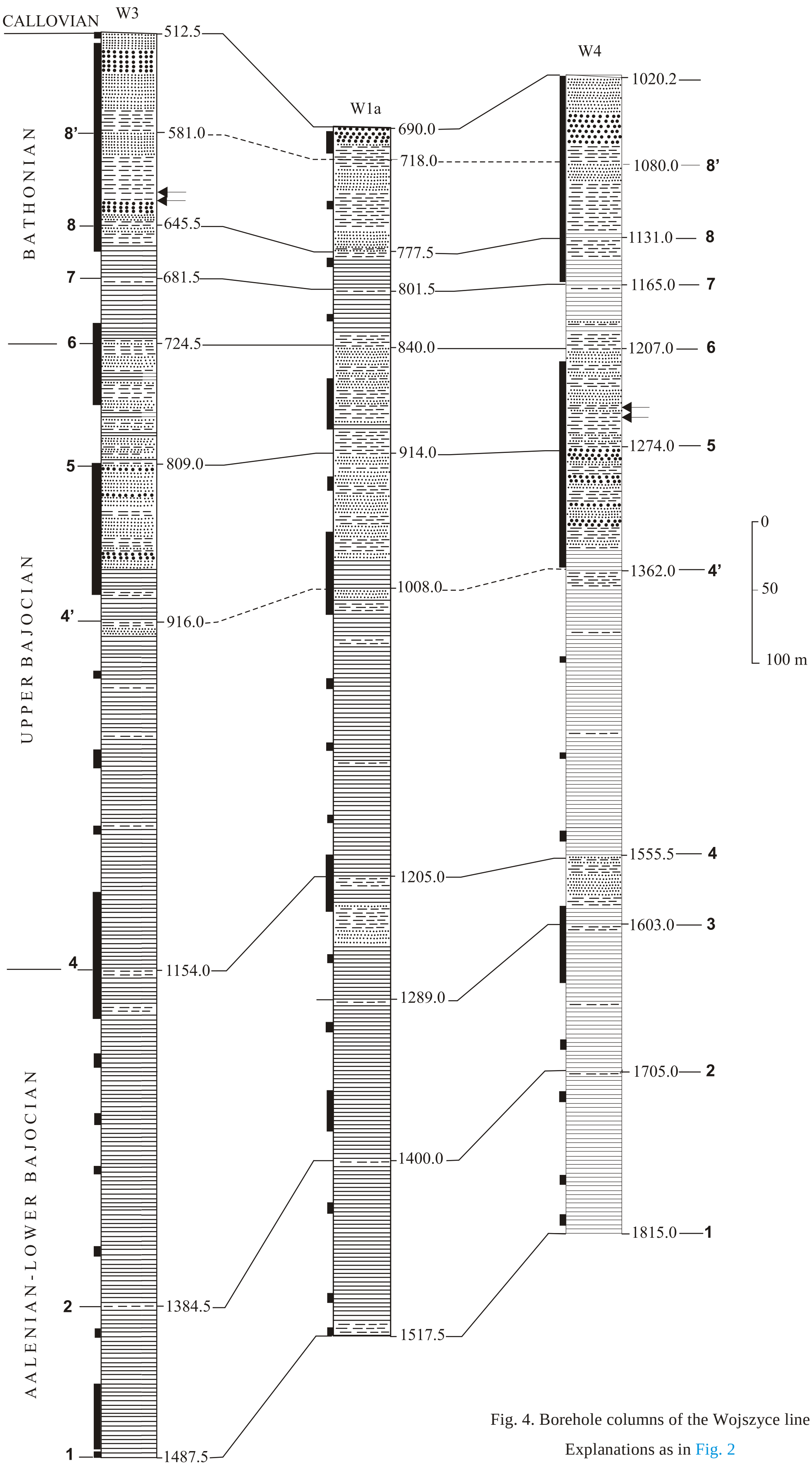

Fig. 4. Borehole columns of the Wojszyce line

Explanations as in Fig. 2

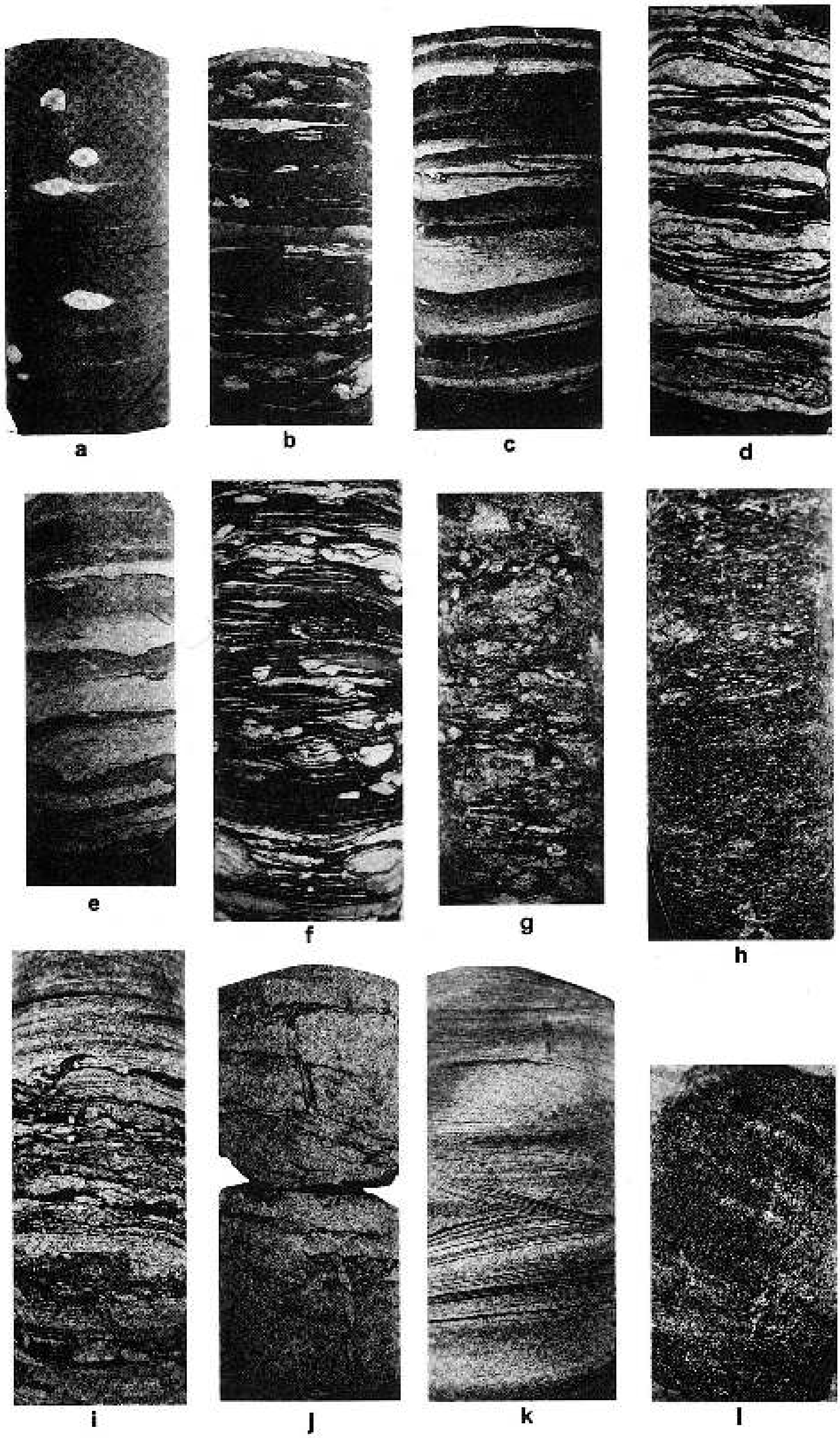

Fig. 5. Lithofacies, shale to sandstone. **a** — shale with marly concretions; Aalenian; C1, 850.5 m. **b** — shaly heterolith; lower Bajocian; C1, 791.0 m. **c** — shaly-sandy heterolith, thick layering, micro-hummocky cross-lamination in sandstone layers; upper Bajocian; W1a, 1019.5 m. **d** — shaly-sandy heterolith, thin layering; upper Bajocian; W4, 1337.2 m. **e** — shaly-sandy heterolith, fining upward microcycles; upper Bajocian; C1, 682.5 m. **f** — shaly-sandy heterolith, weakly bioturbated; lower Bajocian; W4, 1591.5 m. **g** — shaly-sandy heterolith, strongly bioturbated; upper Bathonian; W3, 623.4 m. **h** — shaly-sandy heterolith, strongly bioturbated, with small horizontal burrows; upper Bajocian; B2, 670.2 m. **i** — sandy heterolith; upper Bajocian; W1a, 893.4 m. **j** — very fine-grained sandstone, structureless, straight vertical burrows of small diameter; upper Bathonian; W4, 1065.6 m. **k** — fine-grained sandstone, cross-bedded; upper Bajocian; W1a, 1008.7 m. **l** — unequigranular sandstone, cross-bedded; upper Bathonian; C3, 1228.2 m

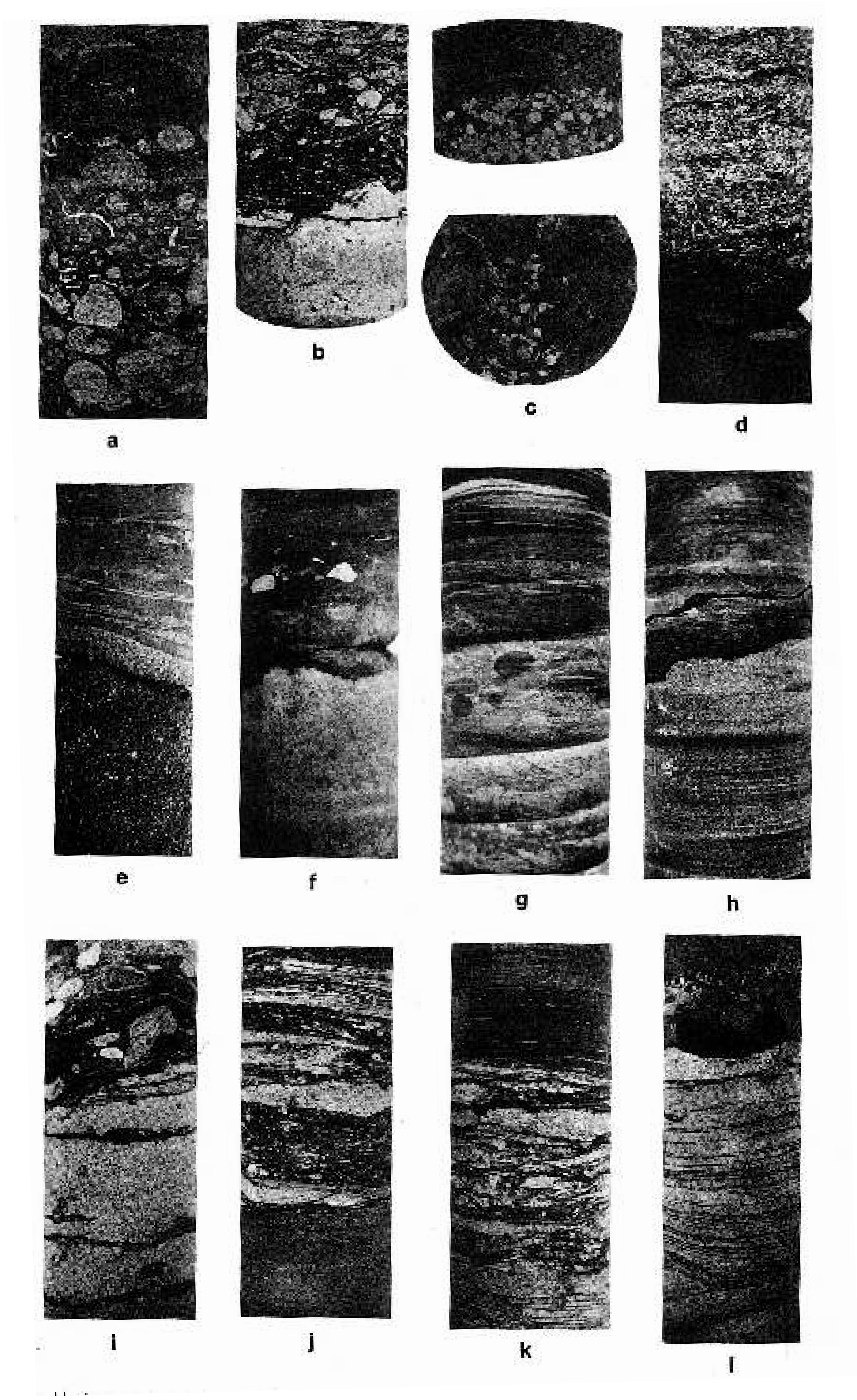

Fig. 6. Conglomerates, bioclasts, contacts between cycles. **a** — conglomerate, poorly sorted, pebbles of calcareous sandstones, bioclasts of thick-shelled bivalves, shale-sand matrix; upper Bajocian; W4, 1256.7 m. **b** — isolated pebbles in shale; upper Bajocian; W1a, 876.0 m. **c** — crinoid plates in shale; Aalenian; B3, 1213.0 m. **d** — lumachelle, composed of thin-shelled bivalves; lower Bathonian; W3, 711.4 m. **e** — contact H/B between shale (upper part) and coarse-grained sandstone; lower Bajocian; C1, 775.0 m. **f** — contact H/C between shale (upper part) and fine-grained sandstone; upper Bajocian; C2, 1542.5 m. **g** — contact F/A between shaly-sandy heterolith (upper part) and conglomerate; lower Bajocian; W1a, 1214.1 m. **h** — contact G/C between shaly heterolith (upper part) and fine-grained structureless sandstone; base of Aalenian; W1a, 1517.5 m. **i** — contact F/C: shale at the base of shaly-sandy heterolith with pebbles of calcareous sandstone (upper part) in contact with structureless fine-grained sandstone; upper/middle Bathonian; W3, 645.5 m. **j** — contact F/B between shaly-sandy heterolith (upper part) and unequigranular sandstone; upper Bajocian; W3, 845.3 m. **k** — contact H/F between shale (upper part) and shaly-sandy heterolith; Aalenian; W3, 1469.8 m. **l** — contact F/C between shaly-sandy heterolith (upper part) and fine-grained, cross-laminated sandstone; upper Bajocian; W4, 1270.0 m

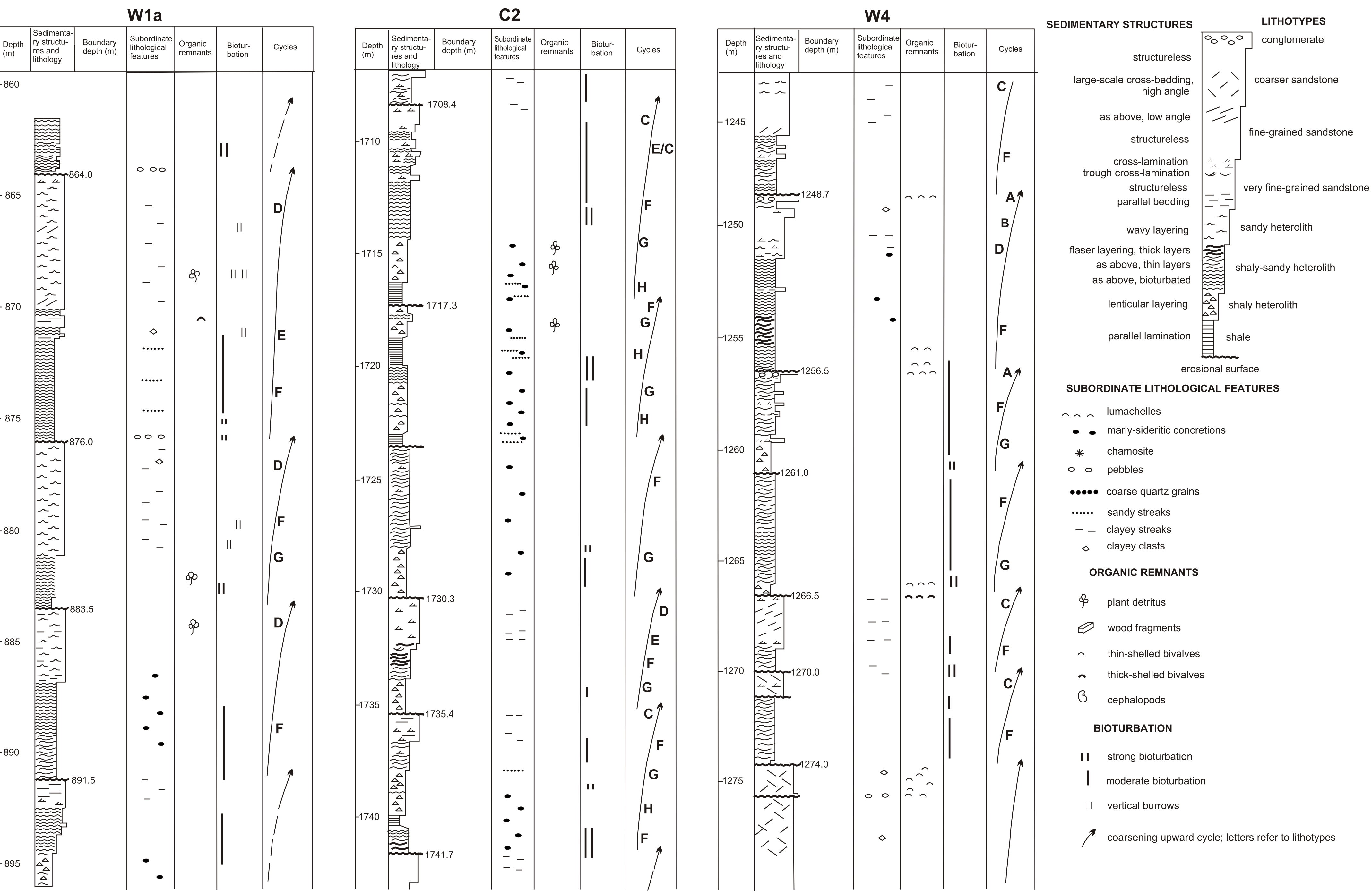

Fig. 7. Examples of essential (lower order) sedimentary cycles in the Bajocian

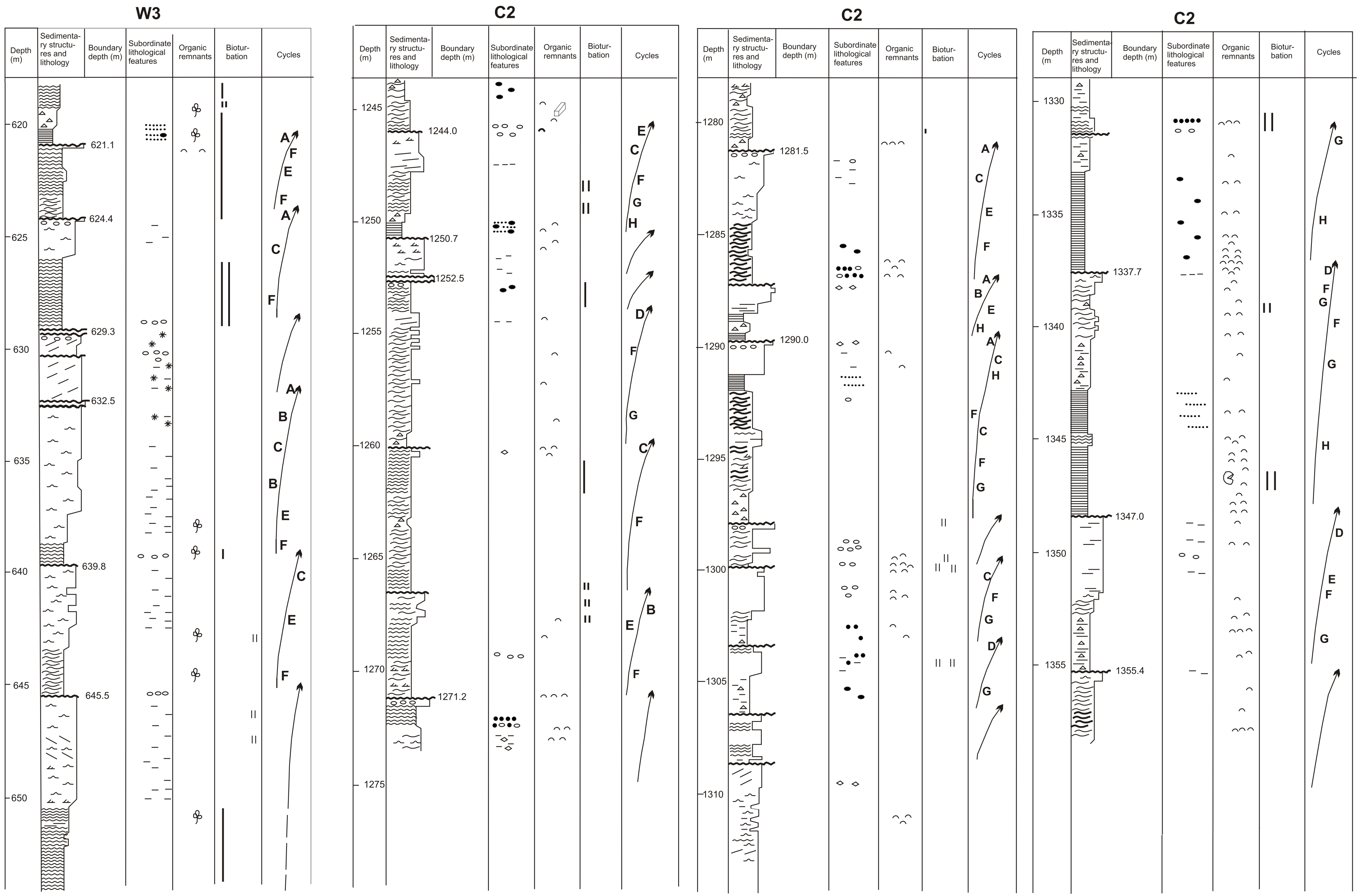

Fig. 8. Examples of essential (lower order) sedimentary cycles in the Bathonian

high-angle bedding, are most frequent. Sandstones, like shales, may occur either in beds a few metres thick, or in packages of greater thickness, as in the uppermost Bajocian and in the Bathonian where they may attain several scores of metres (Figs. 2–4).

The last member of the clastic sequence comprises **conglomerates** (lithofacies **A** — Fig. 6a). It is a subordinate component of the section (less than 1%) but it is very characteristic and significant indicating longer breaks in sedimentation. Conglomerates occur in beds, from a few centimetres to 25 cm thick, more frequently in the Bathonian than in the lower parts of the succession. They are built of fine- to medium-grained pebbles, rather poorly sorted, with variable roundness and variable composition. Pebbles are composed of cemented fine-grained sandstones (calcareous, dolomitic or sideritic), ironstones and clay clasts. Packing of the pebbles is also variable, the matrix of the rock may be abundant, silty-clayey and sandy-clayey, often with an admixture of coarse quartz grains, locally irregularly cemented with carbonates. The bioclasts of thick-shelled bivalves are a common component. Conglomerates do not always occur as separate beds. In places isolated pebbles are immersed either in the rocks of the uppermost part of a given cycle or in the lowermost part of the shale or shaly heterolith of the overlying cycle (Fig. 6b).

An additional lithofacies, not included in the clastic sequence, consists of thin lumachelle beds (lithofacies **M** — Fig. 6d). These occur mostly within shales or shaly heteroliths and are composed of fine, tightly packed bioclasts of thin-shelled bivalves, frequently cemented with carbonates.

CYCLIC SEDIMENTATION

The Middle Jurassic succession has been divided into sedimentary cycles. Essential, lower order cycles are assembled in cycles of a higher order. A set of *ca.* 120 lower order cycles has been analysed in all nine basic borehole sections. However, statistical approach is limited because the distribution of cored intervals is irregular — they are concentrated in the Bathonian and uppermost Bajocian (Figs. 2–4). Examples of lower order cycles at a larger scale are shown in Figures 7 and 8. These illustrations are prepared according to sedimentological standards with the following modification: the width of the column represents the grain-size in sandstones but in heteroliths it shows the lithofacies (**G, F** and **E**). Within the column the sedimentary structures are shown, while beyond it the subordinate lithological features, organic remnants, degree of bioturbation and cycles are given. Higher order cycles are visible in Figures 2–4. The lower order cycles are, almost without exception, coarsening upwards (reverse, regressive) cycles. A few cycles only in the whole set are fining upwards cycles. All the higher order cycles are coarsening upwards cycles. Their bases are used as lithostratigraphic boundaries (see below). They are characterised by a gradual upward thickness increase of the sandy or heterolithic portions in the sequence.

Lithofacies defined above represent the successive phases of sedimentation. If denoted in the same manner as lithofacies, the full lower order cycle should contain eight phases: **HGFEDCBA**. Such an ideal cycle has not been found. The most complete cycle contains six phases (**HGFEDC**). Cycles composed of three or four phases are most common, the former making 34% and the latter 27% of the whole population. Less frequent are two-phase cycles (17%). Among the three-phase cycles the sequences **GFD** (e.g. W1a below 876.0 m — Fig. 7), **FEC** (e.g. W3 below 639.8 m — Fig. 8) and **GFC** (e.g. C2 below 1300.0 m — Fig. 8) prevail, while among the four-phase cycles the most common are the sequences: **HGFD**, **GFED** (e.g. C2 below 1730.3 m — Fig. 7) and **GFEC**, making together about a half of this group. In two-phase cycles over 50% of the population is occupied by the sequences **FD** (e.g. W1a below 883.5 m — Fig. 7) and **GF** (e.g. W4 below 1261.0 m — Fig. 7).

Succession of lithofacies (phases) in cycles is not always gradual and regular. Both the omissions of individual phases (e.g. **FDBA** — W4 below 1248.7 m — Fig. 7; **GFA** — W4 below 1256.5 m — Fig. 7) and repetitions of one or more phases (e.g. **HGFGFD** — C2 below 1337.7 m — Fig. 8; **FEBCBA** — W3 below 632.5 m — Fig. 8) have been recorded.

Initial phases of the cycles are most frequently represented by lithofacies **F**, **G** or **H**. They comprise together *ca*. 90% of the population. In the final phases the lithotypes **D**, **C** and **A** prevail (76% total) while lithotype **B** is less frequent (13%).

There are small differences between these proportions when the individual lines of boreholes are compared. This may be an evidence that the general conditions of the sedimentation along the basin were only slightly differentiated. No regularity has been observed in the vertical arrangement of specific cycle types. Exceptionally only, two neighbouring cycles are of the same type (as **FC** in W4 — Fig. 7). Elsewhere cycles of various thickness and various formulae alternate. This feature proves that local sedimentary conditions — within the same environment — changed significantly from place to place.

Contacts between cycles are — almost as a rule — marked by sedimentation breaks (Figs. 7 and 8). These are identified as: (1) either a conglomerate bed or an accumulation of loosely packed pebbles; (2) admixture of coarser quartz grains and/or clay clasts; (3) pyrite concretions; (4) bioclasts of thick-shelled bivalves. Contact surfaces may be flat or uneven.

As far as lithofacies straddling the boundaries are concerned, contacts with four phases missing (23%) or with three or two phases missing (22% of each of them) are most frequent. This makes together about 2/3 of the whole set. In the case of four-phase contacts the contact **G**/**C** is noted most often (Fig. 6h). Three-phase contacts are represented by the types **G**/**D** and **F**/**C** (Fig. 6i, l) while in the case of two-phase contacts the type **F**/**D** predominates. The five-phase contacts are sparser (20%) with the **F**/**A** type prevailing (Fig. 6g). As in the case of cycle types, the types of contacts are distributed chaotically — various contact types are recorded in various parts of the succession.

Some higher order cycles (e.g. those dominated by shales in the lower part of the succession — Figs. 3 and 4) are not divided into lower order cycles. The latter are best developed in the uppermost Bajocian and in the Bathonian. In these intervals they are predominantly less than 10 m thick. In the Ciechocinek area 75% of cycles are 3–7 m thick while in the Wojszyce area 55% of cycles are 5–8 m thick.

How long did the cycles of both orders last? According to recent geochronological schemes (Harland *et al.,* 1989; Gradstein *et al*., 1994) the duration of the Aalenian-Bathonian time span was nearly 14 my. Subtracting 2 my for the early Aalenian we obtain 12 my for the Middle Jurassic part of the sequence analysed. Eight higher order cycles have been distinguished in this part. Thus, the average time for one such cycle is about 1.5 my. In turn, higher order cycles are composed of 8–12 lower order cycles in the above-mentioned intervals of their best development. Consequently, the duration of a lower order cycle is 0.1–0.2 my. Obviously, this is an approximate estimation, because the duration of sedimentary breaks at their boundaries is impossible to define. Comparing these values with the durations of standard cycles (Miall, 2001), it may be concluded that the higher order cycles in this study are equivalents of the third order standard cycles and lower order cycles resemble the fourth order standard cycles. The former lasted 0.5–3 my and the latter 0.08–0.5 my (Miall, 2001).

STRATIGRAPHY

Biostratigraphic evidence in the Middle Jurassic of the MPT is variable (see Feldman-Olszewska, 1997, table 2). Index ammonites of the lower Aalenian have been found in the Mesozoic cover of the Holy Cross Mts. only (SE of our area). upper Aalenian ammonites were recorded in the Kujawy region while lower Bajocian ones are known from the Cracow-Wieluń Range only (SW of our area). Upper Bajocian and lowermost Bathonian ages are fairly well represented in the Kujawy area. Finally, the biostratigraphic documentation of the higher Bathonian beds in the same area is rather doubtful.

Cores of the nine reported sections yielded two specimens of ammonites only (Feldman-Olszewska, pers. comm.): one is characteristic of the upper Bathonian (in C2 borehole) and the other is indicative of the lowermost Bathonian (in B2 borehole). However, the analysed sections of the Wojszyce line can be easily compared with the Łęczyca area, where a dense net of shallow, fully cored boreholes was made in the late fifties during the exploration for iron ores. Many index ammonites were then found (Znosko, 1957, 1958), especially in the upper Bajocian (Strenoceras, Garantiana, and Parkinsoni beds) and lowermost Bathonian (Ferruginea Beds). The same ammonite horizons were seen in the Pomeranian segment of the MPT (Dadlez, 1957).

No lithostratigraphic scheme has been proposed so far for the Middle Jurassic. In the borehole sections reported here the most distinct lithological boundaries occur at the bases of higher order cycles (Figs. 2–4). They have been labelled with Arabic numbers **1**–**8**. The extra boundaries **4’** (within the upper Bajocian) and **8’** (in the Bathonian) have been fixed with less probability. A lithological subdivision can be made on this basis. In the pure sense of the term it is then not a lithostratigraphic but rather an allostratigraphic subdivision.

Boundary **3** is not widespread. It was recorded in the Ciechocinek region (Fig. 2), disappeared in the Brześć Kujawski area (Fig. 3) and appeared again (with reservations) in the sections of the Wojszyce area (Fig. 4). The remaining basic boundaries (**1**–**2** and **4**–**8**) are easily correlated in all borehole sections. Judging from the general knowledge of Middle Jurassic stratigraphy in the Polish Lowlands, four of these boundaries coincide with chronostratigraphic boundaries. Boundary **1** marks the start of the Mid-Jurassic transgression in the Aalenian (late Aalenian?). Boundary **4** is equivalent to the base of the upper Bajocian, boundary **6** — to the base of Bathonian[2] and boundary **7** — most probably to the base of the middle Bathonian. All of the main boundaries mark the successive steps of Middle Jurassic transgressions.

It is characteristic that the boundaries **4** and **6** were recognised also in the peri-Baltic part of the Pomeranian segment of the MPT (Dadlez, 1963). It is true that at that time no cycles of a higher order were distinguished. Nevertheless, borehole correlations presented in the cited paper clearly show that the then identified base of member 1 (Strenoceras Beds) resembles boundary **4** in this report and the boundary between the members 10 and 11 (base of Ferruginea Beds) is an equivalent of boundary **6**. The former marks the initial Middle Jurassic transgression in the Pomeranian segment (which came here later than in the Kujawy segment) and the latter shows the basin widening at the start of the Bathonian.

The sandstone lying below the boundary **4** has so far been ascribed to the lower Bajocian. Whereas its top may be actually considered as the top of the lower Bajocian, the problem of the Aalenian/Bajocian boundary is more complex. This boundary lies within a higher order cycle with gradational transitions between the successive lithotypes. Moreover, the thickness of this sandstone markedly decreases in some boreholes (C2 — Fig. 2; W4 — Fig. 4) and — finally — it disappears in all of the remaining sections of the Brześć Kujawski and Wojszyce lines. So, this boundary is meaningless and — consequently — the Aalenian and lower Bajocian are here not separately distinguished.

Boundaries **1**, **4** and **6** are equivalents to the bases of cycles J3-I, J3-II and J3-IV, respectively, according to Feldman-Olszewska (1997). She distinguished them in terms of sequence stratigraphy and correlated them with the scheme of Haq *et al.* (1988). Some remarks are necessary in this connection.

The base of her J3-I cycle (= the base of LZA-1 cycle in the scheme by Haq *et al*., *op. cit.*), being coeval with the boundary **1**, supports the idea that it is the base of the upper Aalenian. However, the lower boundary of the LZA-1 cycle is based on a local transgression in the North Sea area (see Miall, 1997, p. 236). Thus, the comparison seems irrelevant because these basins were not connected at that time. Higher in the succession the correlation is also not perfect:

1. The beginning of the J3-II cycle (= boundary **4**) is delayed in comparison with the start of the LZA-2.1 cycle.

2. The start of the LZA-2.2 cycle is not unequivocally recorded in our area — possibly it may correlate with the additional boundary **4’**. However, in the Pomeranian segment the base of the member (4)+5 (base of the Parkinsoni Beds) is al-

[2] The most recent subdivision based on dinoflagellates (Barski, 2000) suggests that the Bathonian base runs somewhere lower, nearer boundary **5.**

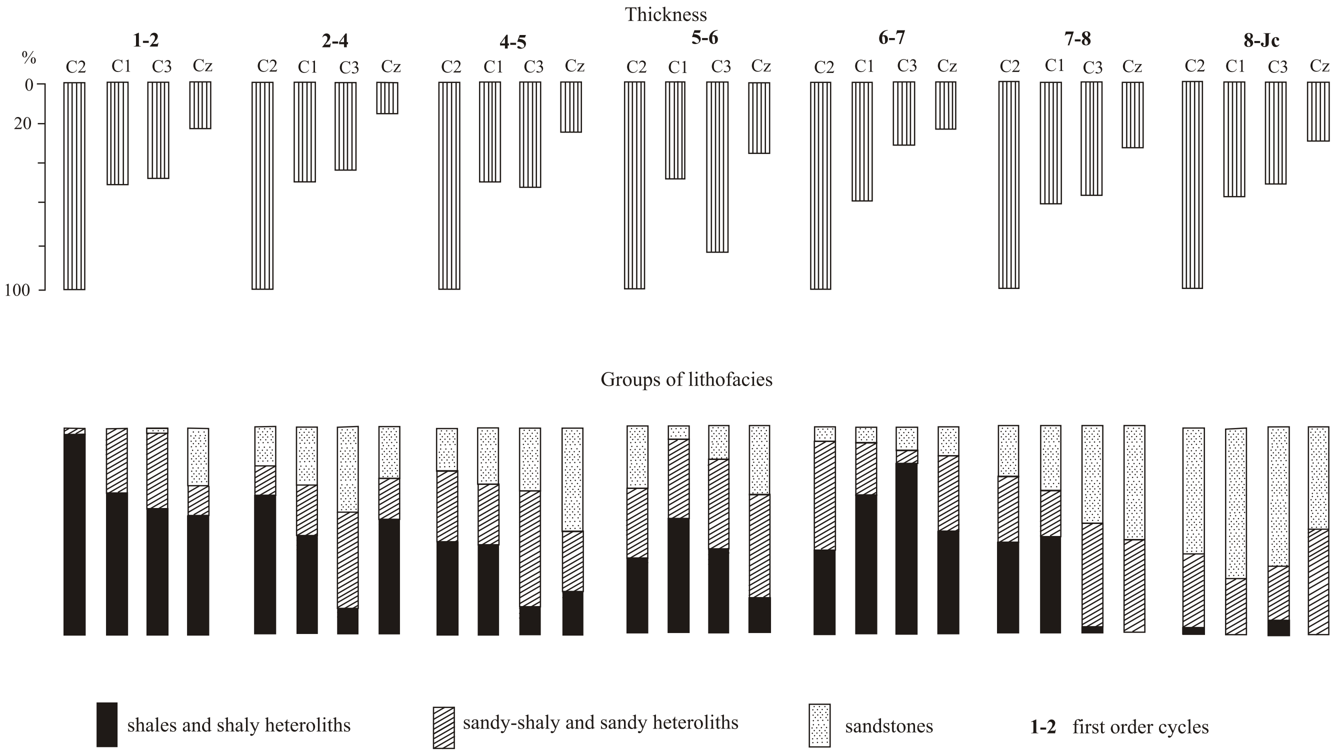

Fig. 9. Correlation of thickness and lithofacies percentages — Ciechocinek line

most exactly the equivalent of the base of this cycle. The onset of Polish cycle J3-III (boundary **6**) has no counterpart in the scheme of Haq *et al.* (*op. cit.*).

3. The base of the LZA-2.3 cycle falls within the cycle J3-III — in the subdivision proposed here it may correlate with boundary **7**.

4. The base of the J3-IV cycle (= additional boundary **8'**) is not visible in the curve of Haq *et al.* (*op. cit.*).

All these discrepancies in relation to the standard, world-wide cycles may be caused by local tectonic events in the MPT.

New elements in the subdivision proposed here — in comparison with earlier results — are: boundary **2** which falls within the Aalenian, boundary **5** in the uppermost Bajocian and boundary **8,** somewhere in the higher beds of the Bathonian.

SEDIMENTARY ENVIRONMENT

The faunal content, lithological features of the sediments and the pattern of coarsening upward cycles suggest that they originated in a shallow shelf environment of an intracontinental basin. The principal disputable question is, whether there were tides in this basin or not. Characteristic heterolithic lithofacies are very similar to those known from the contemporaneous tidal flats (Evans, 1965; Reineck and Wunderlich, 1968). However, they lack some features of this environment such as: bimodal cross-bedding, frequent desiccation cracks and fining-upward sequences terminated with shales containing abundant plant detritus. According to Miall (2001) such lithotypes and similar cycles may occur also in a siliciclastic, wave/storm-dominated shelf.

The general palaeogeography of the Middle Jurassic basins in the Polish Lowlands shows that during the Aalenian and early Bajocian it was a very narrow (30–40 km) and very long (*ca.* 500 km) embayment connected with the Tethyan realm (by a narrow strait?) and closed from the north-west. The occurrence of tides in a basin of such dimensions seems unlikely. During the late Bajocian the sea transgressed southwestwards and northwestwards (along the MPT into Pomeranian segment) but the width of its axial zone did not change significantly. It was only in the Bathonian that the sea markedly crossed the border of the trough and overflooded the vast areas to the north-east and south-west. At the same time wide communication was opened with the epicontinental basins of the Western Europe. Only then did conditions set in when the tides (microtides?) might dominate the basin.

These arguments, and some features of rocks (e.g. micro-hummocky cross-lamination — Dott and Burgeois 1982), suggest that the essential (lower order) cycles in the investigated area may be interpreted in terms of progradation of the fore-shore and near-shore sands of an inner shelf onto the shales of an outer shelf along a wave/storm-dominated shoreline. Eustatic transgression was not necessarily a continuous process (Vail *et al.*, 1977). Periods of its progress were separated by periods when it decelerated or even stopped. It was at those times when the sheets of alongshore sands prograded onto the shales of distal shelf.

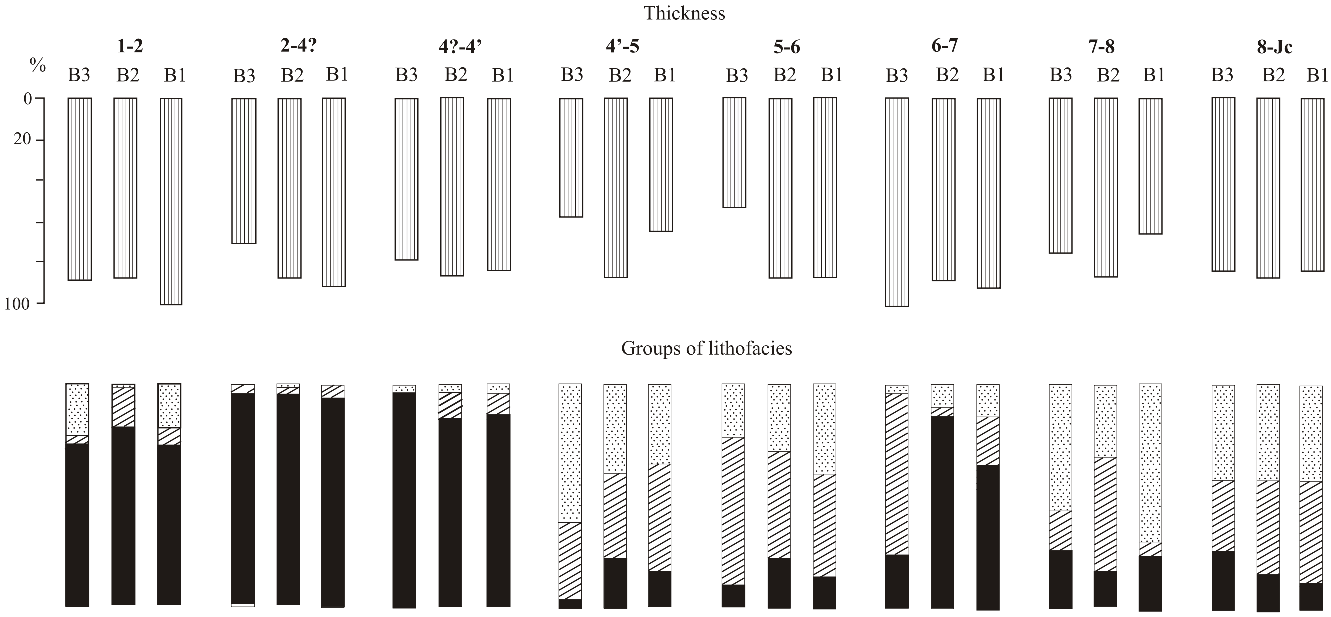

Fig. 10. Correlation of thickness and lithofacies percentages — Brześć Kujawski line

Explanations as in Fig. 9

SEDIMENTATION RATES, THICKNESS AND FACIES CHANGES

Taking into account the geochronological tables quoted earlier (Harland *et al.*, 1989; Gradstein *et al*., 1994), the following estimate can be made of the duration of individual ages: late Aalenian+early Bajocian — 4 my, late Bajocian — 5 my and Bathonian — 5 my. Thicknesses of sediments deposited during these ages in the most complete section W3 are: 333.5, 429.5 and 212 m, respectively. Consequently, the sedimentation rates are: 84, 86 and 42 m/my. Thus, sedimentation rates decreased twice in the Bathonian. This difference is even greater if the compaction of the Aalenian-Bajocian section (dominated by shales) is considered. This deceleration of sedimentation (and subsidence) rates are coeval with the Bathonian widening of the basin.

Lateral changes in thickness and facies in the studied area are illustrated in Figures 9–11, separately for each borehole traverse. Thicknesses of the higher order cycles (with simplifications between the boundaries **1** and **4**) have been presented in each section as a percentage in relation to the section with the greatest thickness of the given interval. Lithofacies have been grouped in assemblages easily discernible in geophysical logs (lithofacies **H**+**G**, **F**+**E** and **D**+**C**+**B**; lithofacies **A** is not identifiable on geophysical logs because of the small thickness of beds). The cumulative thickness percentage of each group in relation to the thickness of the whole cycle is shown.

An overview of these diagrams leads to the following conclusions. The axis of sedimentation and subsidence during the entire Middle Jurassic was located generally along the line: C2–B2–W3–Zgierz IG 1 with the most distinct axial zone in the C2 and W3 sections where the cumulative thickness and percentage of shales are the greatest. The location and width of this zone fluctuated with time as e.g. during the **1**–**2** interval when the axis was shifted into the W1a and B1 sections or during the **1**–**5** (**4'**) interval when the belt of shaly sedimentation was broader than in later times.

The axial zone was bordered from the south-west by an area with smaller thickness and subordinate clastic influx, represented by the Krośniewice section. However, it is disputable whether it is a slope of the MPT because the sedimentary processes might have been influenced here by a local uplift of the Kłodawa Salt Diapir. The opposite slope of the MPT is more distinct. It is marked by greater thickness gradients and stronger clastic input during the entire Middle Jurassic, visible especially along the Ciechocinek and Wojszyce lines (Figs. 9 and 11 — the Brześć Kujawski line did not reach this slope). The most distinct thickness gradient is noted between the Cz and C3 sections (Fig. 9) in the former area (except for the earliest Bathonian), and G1a and G3 sections (Fig. 11) in the latter area (except for the interval **7**–**8** when it shifted to the north-east). These small deviations prove that northeastern border of the MPT was not stable.

Local thickness and facies changes are superimposed on this regional background. They are caused by episodic upward salt movements in the Ciechocinek and Wojszyce salt pillows. This is shown by thickness reductions in the C1 and W1a sections (Figs. 9 and 11) when compared with thicknesses in the neighbouring boreholes. These both sections are located precisely above the tops of salt pillows as detected by seismic sec-

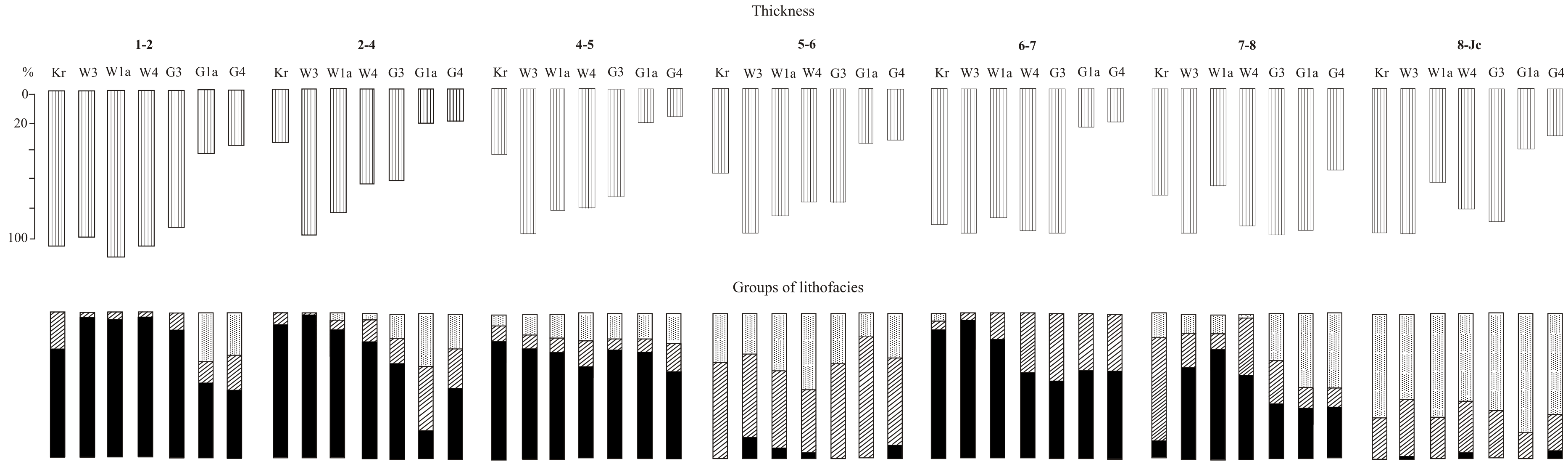

Fig. 11. Correlation of thickness and lithotype percentages — Wojszyce line

Explanations as in Fig. 9

tions. In the first case a thickness decrease is observed between the boundaries **4** and **6**, in the second case it occurs between the boundaries **6** and **8**. This means that the Ciechocinek Salt-pillow uplifted slightly during the latest Bajocian and earliest Bathonian while the Wojszyce Salt-pillow uplifted somewhat later, during the early and mid-Bathonian. Thickness changes are accompanied by small modifications of the facies pattern: in both sections lying above salt pillow tops the percentage of shales in these time intervals is greater than in the neighbourhood.

Contrary to the Ciechocinek and Wojszyce salt pillows, there are no signs of the Gostynin Salt-pillow mobility during the Mid-Jurassic. The Gostynin IG 1a section situated above the top of the salt pillow shows thicknesses intermediate between the neighbouring sections (Fig. 11). Data from the Brześć Kujawski line are inconclusive since the boreholes are not located above the culmination of the salt pillow.

CONCLUSIONS

1. Borehole sections which were fully cored over long intervals yielded good material for the reconstruction of Mid-Jurassic sedimentary evolution. The limitations of this analysis result from long distances between the three main borehole traverses and from the irregular distribution of cores which are concentrated in the Bathonian and uppermost Bajocian.

2. Eight main lithofacies have been distinguished in the siliciclastic Middle Jurassic succession, from conglomerates through sandstones and heteroliths to shales.

3. Dominating, coarsening upwards, essential (lower order) cycles are composed of these lithofacies. They are interpreted as a result of autocyclic sedimentation on a wave/storm-dominated proximal shelf in a non-tidal or micro-tidal basin. They reflect the progradation of near-shore and fore-shore sands and heteroliths over the shales of an open sea.

4. Cycles of lower order are assembled into higher order cycles. Their bases are good markers for the lithostratigraphic/allostratigraphic subdivision of the Middle Jurassic succession. They can be correlated over a wider area of central Poland, some of them even over the entire Mid-Polish Trough. These cycles mark the successive steps of the Mid-Jurassic episodic, eustatic transgression at the onsets of the late Aalenian, Bajocian and Bathonian.

5. The northeastern boundary of the Mid-Polish Trough is well-defined by sharp thickness reductions and facies changes. The sedimentary conditions at the opposite boundary are modified by the local influence of salt anticline mobility.

6. Local thickness changes point to episodic, slight mobility of salt pillows in the area discussed. The Ciechocinek Salt-pillow was active during the latest Bajocian and earliest Bathonian while the Wojszyce Salt-Pillow moved during the early and middle Bathonian.

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