Grzegorz PIEŃKOWSKI

EARLY JURASSIC SEDIMENTATION, SEQUENCE STRATIGRAPHY, CHEMOSTRATIGRAPHY AND CLAY MINERALOGY IN THE GORZÓW WIELKOPOLSKI IG 1 BOREHOLE (fig. 39, 41)

The borehole was drilled in the late fifties of the XX-th Century and some intervals of the core are poorly preserved and some fragments are lacking. Loss of core was mainly associated with poorly-diagenesed sandy parts of the profile (often represented by loose sands or very fragile sandstones) and poor maintenance of the core in the 70-ties and 80-ties of the XXth Century. Therefore, the profile was confronted with neutron-gamma wire-log and with previous lithological and paleontological description performed in the early sixties (Dadlez, Marcinkiewicz and Kopik, archival manuscript data, National Geological Archive, Polish Geological Institute – National Research Institute). Biostratigraphical subdivision of the Gorzów Wielkopolski borehole section, based on megaspores, was published by Marcinkiewicz (1971, her table 5), and the megaspore-based subdivision of Lower Jurassic strata in Poland was finally summarized by Marcinkiewicz *et al.* (2014). Gorzów Wielkopolski IG 1 is located outside the Mid Polish Trough, on the tectonical unit called the Gorzów Block, in the northern part of the Fore-Sudetic Monocline. Such a palaeotectonical position results in diminished subsidence and, consequently, with reduced thickness of the Early Jurassic sediments (~ 376 m) – Fig. 39 [1]. Of note is a low thickness of Hettangian strata (some 35 m), which is contrasted with thick Hettangian sediments in the Mid-Polish Trough. Thicknesses of other stages, though still reduced, are less diminished. This borehole yielded a fairly complete section through the whole Lower Jurassic series (Fig. 39), which allowed reliable sequence stratigraphic subdivision and correlation (Pieńkowski, 2004). The sequence stratigraphic framework for the well preserved and expanded Lower Toarcian section (Pieńkowski, 2004) was later supported by a high-resolution chemostratigraphic/carbon isotope study (Hesselbo, Pieńkowski, 2011; Fig. 41 [1]). The carbon isotope curve, correlated with astrochronology, allowed subdivision unpreceded in its chronostratigraphical accuracy, with each subdivision unit (isotope step) corresponding to a single orbital cycle – originally believed to represent short-term eccentricity cycles (100 kyr), now attributed to much shorter obliquity cycles (30 to 34 kyr; Boulila *et al.*, 2014). It was shown, that each carbon isotope/orbital cycle corresponds with individual progradational parasequence VIII a-f from the earlier, slightly modified sequence stratigraphical subdivision (Pieńkowski, 2004; Hesselbo, Pieńkowski, 2011). Isotope studies, along with palynomorph content (Marcinkiewicz, 1971, 1989; Pieńkowski, 2004; Pieńkowski, Waksmundzka, 2009), sedimentological studies, particularly sea-level changes expressed in succession of progradational parasequences (Pieńkowski, 2004) and clay minerals studies (Brański, 2012), led to palaeoclimatic interpretations of the Lower Toarcian section. This relatively short time (about 500 kyr) was associated with profound perturbations in carbon cycle and global climate, starting from the "initial" negative carbon isotope excursion at the Plensbachian/Toarcian boundary, and then very conspicuous negative excursions during the Toarcian Oceanic Anoxic Event (T-OAE). Perturbations in oceanic system perfectly correlate with similar perturbations of carbon cycle in the atmospheric system (Hesselbo, Pieńkowski, 2011), which proves that we are dealing with climatic events of a global scale.

[1] Figures 39 and 41 can be found in the pocket at the end of the book.

DEPOSITIONAL SEQUENCE I

The Lower Jurassic sediments rest on the grey mudstones of Rhaetian age. The lowermost Jurassic sediments are represented by grey sandstones and mudstones and their age is established as the Hettangian–Lower Sinemurian, based on finds of *Nathorstisporites hopliticus* Jung megaspore (Marcinkiewicz, 1971). These lowermost sediments of depositional sequence I (parasequence Ia) are disturbed by a local fault zone which was encountered at the depth 1130.0–1137.0 m, much o the core therein is missing, therefore position of the Triassic/Jurassic boundary is uncertain. Between 1125.2 m and 1132.0 m, the grey, medium-grained sandstones with trough cross-bedding prevail. This succession is interpreted as a parasequence represented by facies deposited by an alluvial (most probably meandering river) depositional system. The grey mudstones with plant remains and siderite nodules (also sphaerulites) occurring between 1122.0 and 1125.2 m represent a lacustrine depositional system and they probably correspond to the parasequence I b (Pieńkowski, 2004). The boundary between alluvial and lacustrine sediments (1125.2 m) probably represents the continental correlative of transgressive surface of the depositional sequence I. The overlying grey, medium-grained sandstones with trough cross-bedding (1118.5–1122.0 m) represent recurring alluvial sedimentation (progradation episode). Uppermost part of this section can represent a delta plain facies, as shown by palynofacies record.

The transgressive surface occurs at the depth of 1118.5 m. This transgressive surface marks the base of a set of parasequences I c–e (the individual parasequences are probably amalgamated within sandstones between 1112.0 and 1118.5 m). These well-sorted, pale-grey sandstones show tabular cross-bedding, horizontal lamination and hummocky cross-stratification and they contain brackish-marine bivalves and abundant calcareous cement both in the lowermost, 2 m thick interval, and in the uppermost section. These sandstones represent mostly a shoreface depositional subsystem. Mudstones and calcareous sandstone-mudstone intercalations with hummocky cross stratification occurring between 1107.5 and 1112.0 m point to a deeper, shoreface-offshore transition zone (parasequence I f). Dinoflagellate cyst *Liasidium variabile* Drugg has been found at the depth 1112.0 m (P. Gedl, pers. comm.). This palynomorph is generally believed as a typical form for Sinemurian, particularly Upper Sinemurian (Poulsen, Riding, 2003). However, according to Brenner (1986), this palynomorph occurs in the late Hettangian of southwest Germany. Riding and Thomas (1992) confirmed, that its first stratigraphical appearance datum in continental Europe is earlier than in England (Late Sinemurian), casting doubts on the Sinemurian age of this appearance. The appearance of *Liasidium variabile* Drugg in Gorzów Wielkopolski IG 1 is probably even earlier than in Germany (the upper limit of the Hettangian Pinuspollenites – Trachysporites pollen assemblage in this borehole is located some 12 m above the *Liasidium variabile* Drugg occurrence). Consequently, the age of this palynomorph is probably of a broader range than believed before. However, it should be pointed out that the single specimen of this palynomorph found in the Gorzów Wielkopolski IG 1 section is rather poorly preserved (J. Riding, pers. comm.) and it is possible that this palynomorph might represent a precursor form of *Liasidium variabile* Drugg. One should add in that context that short-lived connections of the Polish epicontinental basin with the Tethys domain postulated by Pieńkowski (2004) could led to a faunal or algae migration and promote appearance of new forms – it might particularly regard the dinoflagellate cysts. Possibly, connections with the Tethys could provide an explanation why some dinoflagellate cysts seem to appear earlier in the German (Brenner, 1986) and Polish basin (Pieńkowski, 2004) than in British and Danish basins (Poulsen and Riding, 2003). It particularly regards sparse appearances of some dinoflagellate cysts related to the maximum flooding surfaces – such as occurrence of *Liasidium variabile* Drugg near the maximum flooding surface of sequence I in Gorzów Wielkopolski IG 1, dated to the Middle Hettangian (Fig. 39, depth 1112.0 m) or occurrence of *Mendicodinium* sp. (Gedl, pers. comm.) at the depth of 1044.0 m, also close to the maximum flooding surface of sequence II (dated to the Early Sinemurian). Possibly, these dinoflagellate cysts evolved in the Polish and eastern German basin as endemic forms, subsequently migrating westwards. However, this supposition remains theoretical until more data are revealed. The maximum flooding surface of depositional sequence I, correlated with a mid-Hettangian age, occurs at a depth of 1111.0 m. It is thought to be associated with the parasequence I f ; accordingly, the whole succession between 1111.0 and 1132.0 m would represent the transgressive systems tract of depositional sequence I. Above the maximum flooding surface, the palynofacies show gradual shallowing and isolation of the basin resulting in development of a barrier-lagoon depositional system, topped with mudstone containing palaeosol level with plant roots and coal (marsh depositional subsystem). The overlying sediments represent mixed barrier-lagoon-marshy-delta plain deposits with three flooding surfaces associated with embayment lithofacies and they contain more abundant ichnofauna, brackish-marine bivalves, agglutinated foraminifera and Acritarcha. These strata (1096.5–1111.0 m) would represent parasequence set I g-k ? (the highstand systems tract of depositional sequence I). A sample from the depth of 1102.6 m yielded numerous miospores, including *Pinuspollenites minimus* (Couper) Kemp, *Concavisporites toralis* (Leschik) Nilsson, *Concavisporites divisitorus* Kedves et Simoncsics, *Dictyophyllidites mortoni* (de Jersey) Playford et Dettman (det. by M Waksmundzka). Collectively, these taxa point to a Hettangian age (*Pinuspollenites – Trachysporites* zone).

The section represented by continental deposits (1118.5–1132 m) have been assigned to the Zagaje Formation, and the strata representing nearshore-barrier/lagoon-deltaic deposits (1096.5–1118.5 m) belong to the Skłoby Formation. The age of the sequence I falls within the Nathorstisporites hopliticus megaspore zone (Hettangian–Early Sinemurian; zone Ho, Marcinkiewicz *et al*., 2014). Characteristic miospores of the *Pinuspollenites – Trachysporites* zone occurring in this sequence allow narrowing its age to the Hettangian.

DEPOSITIONAL SEQUENCE II

An erosional surface (1095.5 m) is interpreted as the sequence boundary. Erosion was probably significant and it removed part of the underlying sediments of depositional sequence I. The sequence boundary is covered with conglomeratic lag and coarse-grained or medium-grained, poorly sorted sandstones. This section is interpreted as the alluvial facies passing upwards into deltaic facies (parasequence II a). The erosional sequence boundary marks also the base of Ostrowiec Formation.

The core interval between 1050.0 m and 1095.5 m is poorly preserved and sedimentological interpretation is largely based on palynofacies characteristics obtained from several mudstone intercalations (palynofacies were determined by a semi-quantitative assessment, see Pieńkowski, 2004, Pieńkowski and Waksmundzka, 2009 and legend to the Fig. 39). Palynofacies point generally to the lagoonal/embayment depositional system. Sandstones may represent either the barrier-nearshore facies or deltaic-distributary facies. Better core recovery from the interval between 1028.5 and 1056.0 m allowed interpretation of these strata (wavy and lenticular heteroliths with intercalations of calcareous sandstones representing tempestites) as the facies of a nearshore depositional system, mostly offshore – shoreface transition zone. Ichnofauna is fairly rich, representing mainly deposit feeders (fodinichnia) and some domichnia (suspension feeders). Palynofacies are typical of an offshore-shoreface environment, dinoflagellate cysts including *Mendicodinium* sp. (1044 m: (Gedl, *pers. comm.*) and Acritarcha point to a marine-brackish marine conditions. The maximum flooding surface is placed on depth 1043.5 m, within the mudstone intercalation showing an open-basin, offshore palynofacies.

The nearshore depositional system is replaced by the barrier-lagoon depositional system (depth 1028.5–1033.0 m), represented by grey-brownish mudstones with siderite bands and plant detritus. These deposits terminate deposition of the depositional sequence II.

The age of the depositional sequence II falls within the *Nathorstisporites hopliticus* megaspore zone (Hettangian–Early Sinemurian). The guiding miospore *Aratrisporites minimus* Shultz indicates the same age (Rogalska, 1976). The uppermost occurrence of this miospore has been reported at the depth of 1034.0 m (Rogalska, 1976).

The whole sequence II belongs to the Ostrowiec Formation (along with the overlying sequence III).

DEPOSITIONAL SEQUENCE III

An erosional surface at the depth of 1028.5 m is identified with the sequence boundary. The sequence boundary is covered by the medium-grained, poorly sorted sandstones. A poorly preserved core does not allow recognition of sedimentary structures, but a sharp lithological contrast with the underlying lagoonal mudstones suggests a fluvial origin of the interval between 1025.0 and 1028.5 m (parasequence III a).

Mudstone intercalation occurring between 1023.0 and 1024.0 m shows the typical offshore palynofacies with dinoflagellate cysts and Acritarcha, which points that the transgressive surface occurs below this intercalation.

The core interval between 987.5 m and 1023.0 m is poorly preserved and interpretation of this section is based largely on palynofacies description. The palynofacies point generally to the offshore/embayment depositional system, separated by the nearshore/barrier facies represented by sandstones. A sample taken from the depth of 997.0 m shows the typical offshore palynofacies characterised by rare palynomacerals and sporomorphs (pollens are dominating) and presence of Acritarcha and dinoflagellate cysts. This bed is interpreted as the maximum flooding surface.

The strata between 980.2 and 987.5 m are built of the heteroliths interpreted as lagoonal-embayment deposits. These strata end sedimentation of the depositional sequence III.

The whole sequence shows significant share of the facies deposited by a nearshore depositional system and due to the poorly preserved core it was only tentatively subdivided into three parasequences.

Occurrence of *Horstisporites planatus* (Marcinkiewicz)
Marcinkiewicz megaspore points to the Late Sinemurian–Pliensbachian age.

Depositional sequences II and III are assigned to the Ostrowiec Formation.

DEPOSITIONAL SEQUENCE IV

The erosional surface with mud clasts, occurring at depth 980.2 m, is conspicuous and represents the sequence boundary. The overlying trough cross-bedded sandstones and dark-grey mudstones are rich in plant fossils and they represent facies of delta plain and distributary channel depositional subsystems (this interpretation is also confirmed by palynofacies). The transgressive surface at depth 978.0 m is connected with heavily bioturbated sandstones. These sandstones commence the facies of a shoreface depositional system, developed between 969.0 and 978.0 m (parasequence IVb). Trace fossils, as well as marine bivalves, are numerous and diversified. Chamosite/chlorite is frequent. Storm cycles are also characteristic. The transgressive surface marks the lower boundary of the Gielniów Formation, characterised by domination of marine/nearshore facies. The parasequence IVb is characterised by the sediments associated with a rapid flooding, passing quickly into deposits associated with a parasequence maximum flooding surface (marine heteroliths). The maximum flooding sediments gradually pass upward into the high-energy, storm-dominated medium-grained sandstones of the upper shoreface subsystem. The next parasequence (IVc) begins with flooding surface, which commences development of the offshore deposits (lenticular to wavy heteroliths). The distal tempestite beds are frequent. Marine conditions, probably of a somewhat stressed character, are confirmed by numerous (although not very diversified) foraminifera, bivalves, Acritarcha and dinoflagellate cysts. The palynofacies point to a marine, offshore depositional system, although the relatively high frequencies of palynomorphs and spores indicate a relative proximity of shoreline and storm-induced transport of palynomacerals. The maximum flooding surface of depositional sequence IV (965.0 m) is marked by the finest fraction and the most “marine” palynofacies with dinoflagellate cysts (Gedl, pers. comm.). Upper part of the parasequence IVc (945.2–960.0 m) is represented by a shallowing, prograding succession (the offshore-shoreface transition facies passing into the shoreface facies). The core representing an uppermost part of parasequence IV c is missing, but based on archival descriptions this interval is dominated by fine-grained, well-sorted sandstones. Similarly to the parasequence IVb, parasequence IVc is built up of the type-2 parasequences (Pieńkowski, 2004).

DEPOSITIONAL SEQUENCE V

The lower boundary of depositional sequence V occurs within an interval with poorly preserved core, but presence of medium- to coarse-grained sandstones suggests occurrence of the sequence boundary with basal sediments belonging to the next depositional sequence. The overlying fragments of grey and pink (presence of iron compounds) sandstones with plant fossils and ferruginous concretions (depth 943.0–948.0 m, parasequence V a) are interpreted as facies of a delta front depositional subsystem.

Heteroliths between 941.0 and 942.0 m show basinal, offshore features (marine palynofacies and abundant trace fossils). It means that the transgressive surface of the depositional sequence V should be placed below these heterolithic strata. The whole core interval between 914.2 and 940.8 m is poorly preserved. Fragments of core with heteroliths contain palynofacies pointing to an offshore depositional system. The fine-grained sandstones prevailing in this interval represent probably a nearshore (shoreface) depositional system. The maximum flooding surface is placed at the depth 934.0–935.0 m, where palynofacies point to an offshore environment (very few palynomacerals). It allows subdivision of the depositional sequence V into the TST and HST systems tracts. The uppermost part of depositional sequence V contains more intercalation of the medium-grained sandstones, which point to a shallowing of the sedimentary basin. Two to four parasequences can be distinguished, but only tentatively due to a poorly preserved core.

Depositional sequence V falls within *Horstisporites planatus* megaspore zone (Marcinkiewicz, 1971), which points to the Late Sinemurian–Pliensbachian age.

The depositional sequences IV and V show mostly a marine/nearshore character and they build up the Gielniów Formation.

DEPOSITIONAL SEQUENCE VI

Depositional sequence VI is relatively thin. Sedimentation of this sequence was preceded by significant erosion. The erosional surface occurring at the depth 914.2 m is very conspicuous. The erosional surface is covered by a conglomeratic lag composed of large mud clasts deriven from eroded underlying mudstones. This surface is correlated with the lower boundary of depositional sequence VI. Similarly to the other regions in Poland, this erosion is probably associated with significant non-depositional/erosional hiatus. The beginning of sedimentation followed a rise of base-level, leading first to the initial fluvial sedimentation. The whole succession between 903.5 and 914.2 m (parasequence VIa) is dominated by the medium-grained, trough-cross bedded sandstones with plant detritus and local horizons with mud clasts. This succession (parasequence VIa) represents an initial deposition, probably in eroded valleys. Depositional system is interpreted as an alluvial (meandering river) or a coarse-grained deltaic (distributary channel) depositional subsystem. Above 903.5 m (transgressive surface), the sandstones are more fine-grained and the horizontal bedding and tabular cross bedding replace through cross bedding. Moreover, trace fossils (both domichnia and fodinichnia) appear in these strata. Based on these features, the complex between ~894.2 m and 903.5 m (parasequence VIb) is interpreted as the nearshore (shoreface) facies followed by the lagoonal-embayment heteroliths, containing abundant plant fossils and fodinichnia burrows. The maximum flooding surface (897.2 m) is placed within these heteroliths. The age of depositional sequence VI still falls within the *Horstisporites planatus* megaspore zone (Marcinkiewicz, 1971), which points to the Late Sinemurian–Pliensbachian age. The prominent erosional base of this sequence is also regarded as the lower boundary of Komorowo Formation.

DEPOSITIONAL SEQUENCE VII

The overlying sandstone strata (879.0–895.5 m) are not preserved in the core material. Based on the neutron-gamma wire-logs and archival description (Dadlez 1960 unpubl.), the sequence boundary can be tentatively placed at the depth of about 894.0 m. The overlying strata (860.0-879.0 m) are represented by homogenous, grey mudstones and lenticular heteroliths with siderite bands, pyrite concretions and fodinichnia burrows. Palynofacies point to an embayment-lagoonal depositional system with developing upward shallowing/isolation tendencies. The flooding surface at depth 860.0 m commences the parasequence VIId deposits represented by wavy heterolithic-sandstone facies. These strata are characterised by numerous *Diplocraterion parallelum* dwelling structures and dinoflagellate cysts (Gedl, *pers. comm.*). The *Diplocraterion parallelum* Torell burrows show both the protrusive and retrusive character, even if occurring at the same horizon. This feature points to very unstable sedimentary conditions, i.e. rapid shifts from the erosion stages to rapid sedimentation periods. The unstable sedimentary conditions and other features (such as regular rhytmites observed in this section), may suggest that this section was deposited in a tide-influenced shore zone. The maximum flooding surface of the whole depositional sequence VII is associated with subtidal sandstones with hummocky cross-stratification, while the heteroliths would represent a shallow subtidal/tidal flat environment. Presence of *Diplocraterion parallelum* Torell, foraminifera and Acritarcha points to a marine salinity, while palynofacies indicate rather nearshore-marginal marine (lagoonal) conditions. Collectively, it fits well the tidal interpretation.

Depositional sequence VII shows the increasing marine influences towards the top, a transgressive systems tract builds a larger part of the sequence VII (mostly a barrier-lagoonal depositional system). The highstand systems tract represented by tidal plain deposits is thin. The uppermost part of sequence VII could have been removed by erosion, associated with the sequence boundary of the next sequence. Depositional sequence VII still falls within the *Horstisporites planatus* megaspore zone (Marcinkiewicz, 1971; Late Sinemurian–Pliensbachian age) and they belong to the upper part of the Komorowo Formation.

DEPOSITIONAL SEQUENCE VIII

Based on continuous abundant occurrence of the *Paxillitriletes phyllicus* megaspore assemblage (Marcinkiewicz, 1971), this sequence was dated to the Toarcian age. The Toarcian sediments are assigned to a single unconformity-bounded depositional sequence VIII, which has been subdivided into six parasequences VIIIa–f (Pieńkowski, 2004). The oldest deposits of the sequence comprise alluvial and deltaic sediments, assigned to the Komorowo Formation. In contrast, the bulk of the sequence is assigned to the Ciechocinek Formation, which is present across the whole Polish Basin, comprising grey-green mudstone, heterolithic silty mudstone, and siltstone with intercalation of fine sand and sandstone. The sequence boundary (depth 852.2 m) is associated with a sharp lithological contrast. The core interval between 848.3–852.2 m is poorly preserved, but it shows occurrence of coarser fraction (sandstones) and plant roots. This indicates an emersion (supra-tidal, probably delta plain environment).

The transgressive surface at the depth 848.3 m marks the beginning of sedimentation of wavy heteroliths with *Diplocraterion parallelum* and fodinichnia burrows (parasequence VIIIb). Abundant dinoflagellate cysts (*Nannoceratopsis* spp., M. Hodbod, *pers. comm*) point to a marine environment, while other palynofacies features point to proximity of shore. Such a mixture of “marine” and “non-marine” palynofacies characteristics may point to the palynofacies inversion (Pieńkowski, Waksmundzka, 2009), associated with storm activity. The overlying mudstones/

claystones are grey in their lowermost part (839.9–842.7 m) and grey-greenish higher up in the profile (817.0–837.2 m). This marked change in colour may indicate that the lower part of the section representing grey claystones, mudstones and heteroliths (839.9–843.3 m) belong to a separate parasequence from the mudstones located above. It is difficult to judge if the parasequence boundary is located somewhere between 837.2 and 839.9 m as the core there is not preserved. However, Dadlez (1960, unpubl.) noted siderite sphaerulites at the depth of about 838.0 m and as such concretions are typically related to paleosols, one can put the upper boundary of parasequence VIIIb there. It is also supported by carbon isotope changes, therefore such amendment to previous location of the range of parasequence VIIIb (Pieńkowski, 2004) was accepted (Hesselbo, Pieńkowski, 2011). On that way the parasequence VIIIb would be of much smaller thickness that in Mechowo borehole (Pomerania), further pointing to changes in subsidence rate and sediment delivery between Gorzów block and Pomerania area. Mudstones of parasequences VIIIb and VIIIc contain typical offshore palynofacies with foraminifera and dinoflagellate cysts (mainly *Nannoceratopsis*), but sometimes features of marginal-marine palynofacies can be observed (825.0–834.0 m). Such a "mixed" palynofacies characteristic is probably associated with the type 2 palynological inversion (storm events) – Pieńkowski (2004), Pieńkowski and Waksmundzka (2009). The maximum flooding surface was placed at the depth of 842.0 m, where the palynofacies show a most marine, distal character. On the other hand, continuous presence of continental miospores indicates proximity of the coastal zone. Presence of siderite bands and dispersed siderite, together with the lack of heteroliths and other wave-generated features, point to an isolation of the sedimentary basin. The characteristic greenish colour is caused by chlorite content. It must have been an extensive basin of embayment character, showing many similarities to the recent Maracaibo Bay (Hyne *et al.*, 1979). The succession between 817.0–838.0 m represents the parasequence VIIIc and is topped with the palaeosol level with plant roots. Sandy facies with dolomitic cement occurring at the top of this parasequence are very thin and represent incipient, submerged barrier belts. The palaeosol level occurs in the claystones of similar character to those occurring in the deeper parts of the basin. It indicates that the wave energy in the sedimentary basin was weak. The shore zone of this basin was of a flat, muddy/marshy coastal plain character. It is yet another argument supporting the view that the whole basin of depositional sequence VIII was extensive but generally very shallow.

The next parasequences VIIIc, VIIId, VIIIe and VIIIf represent recurred flooding-progradational successions, each one ending with marsh deposits. *Diplocraterion parallelum* Torell burrows occurring in the parasequence VIIId (depth 778.5 m) points to a short-lived marine water ingression, while the rest of sediments are typical of a shallow, lagoonal basin. In the middle part of the parasequence VIII c one can find few strata with micro-hummocky cross lamination interpreted as tempestites, which points to periodically higher wave energy. However, for its most part the parasequence set VIIIc–e is dominated by the deltaic/coastal plain/marshy facies.

Deposits of the Ciechocinek Formation of the sequence VIII show more muddy character and less sandstone intercalations than deposits of the same age in Pomerania or Holy Cross Mountains (Pieńkowski, 2004). It points to regional changes in sedimentary delivery. Similarly to the Pomeranian region, the Lower Toarcian Ciechocinek Formation is truncated from the top by extensive erosion. The Ciechocinek Formation marks the maximum extent of Jurassic sediment accumulation in the Polish Basin, and Dadlez (1969) and Pieńkowski (2004) have suggested a relation to Early Toarcian sea-level rise that is also recorded from other European basins (Hallam, 2001). Environmental conditions in the Polish Basin at this time, also in the area of the Gorzów Block, were not fully-marine; fauna are uncommon and of low diversity, composed mostly of ostracods, foraminifers, gastropods, bivalves, and fish teeth (Kopik, 1962; Kopik, Marcinkiewicz, 1997). Trace fossil assemblages are also of low diversity and dominated by simple forms such as *Planolites* (Pieńkowski, 2004; Leonowicz, 2009).

Sedimentation of depositional sequence VIII is associated with one of the most profound global environmental changes in the Jurassic (and more generally, Phanerozoic) times. This is known as the Toarcian Oceanic Anoxic Event (T-OAE), which started about 182.8 Myr ago and lasted for some 300,000–500,000 years (Boulila *et al.*, 2014). Gorzów Wielkopolski IG 1 section, along with six other Polish profiles, yielded an extensive (>400 samples) new carbon-isotope dataset generated from terrestrial plant organic matter in expanded Toarcian sections (Hesselbo and Pieńkowski, 2011). A comprehensive sequence stratigraphic scheme and inferred relative sea-level history, based on detailed sedimentological, and palaeontological study of boreholes and outcrops (Pieńkowski, 2004), served as a framework and in the same time the Lower Toarcian sequence stratigraphy was tested by chemostratigraphical methods. Carbon isotopes were analysed in separated wood particles (compound-specific analyses), and the carbon-isotope composition is an integrated representation of the standing vegetation, and thus indirectly also of the contemporaneous atmospheric carbon dioxide (cf. Hasegawa *et al.*, 1997; Jahren *et al.*, 2008). Similarly to the other contemporaneous strata, the Gorzów Wielkopolski IG 1 profile shows well-developed excursion towards lighter isotopic values through the Lower Toarcian (Fig. 41). The magnitude of the excursion as expressed in $\delta^{13}CC_{V-PDB}$ ranges from ~4 to ~7‰. This pattern is perfectly compatible with previous reports of the negative carbon-isotope excursion in organic matter from the T-OAE. One particularly notable feature of all the isotopic profiles reported here is the development of a number of abrupt steps leading up to the peak of the negative excursion. The stepped nature of the excursion is now very well documented from a number of wholly marine successions in Europe, and has been described from both organic matter and carbonate (Jenkyns *et al.*, 2001; Kemp *et al.*, 2005; Hermoso *et al.*, 2009; Sabatino *et al.*, 2009). These steps occur as inflections on the rising limbs of quasi-sinusoidal isotope profiles and thus cannot be explained simply as an artefact of sedimentary hiatus. Each step has been interpreted, controversially, by some previous workers as a phase of rapid and voluminous input of isotopically light carbon from an external source such as marine gas hydrate, with pacing modulated by climatic forcing at astronomical frequency (Kemp *et al.*, 2005; Wignall *et al.*, 2006). On the basis of analysis of high-resolution magnetic susceptibility data, Boulila *et al.* (2014) have assigned these regularly cyclic steps in the negative carbon-isotope excursion to the 30 to 34 kyr astronomical obliquity cycles. As argued by Kemp *et al.* (2005), evidence for astronomical control is important because an isotopic signal of global significance under astronomical control would rule out a key alternative mechanism for input of isotopically light carbon to the atmosphere, namely methane vented from the metamorphic aureoles of giant sills within older organic-rich sediments during the formation of the Karoo-Ferrar large igneous province (McElwain *et al.*, 2005; Svensen *et al.*, 2007). The new dataset obtained from Gorzów Wielkopolski IG 1 and other boreholes in the Polish basin (Hesselbo, Pieńkowski, 2011), is particularly significant in this regard because it demonstrates that the stepped pattern was characteristic not just of the shallow sea, where it might be argued the signal only represents localized oceanographic processes, but also the contemporaneous atmosphere, where localized systematic anomalies matching those in the ocean are inconceivable. The four cyclic steps in the carbon-isotope curve (Fig. 41) match the number of parasequences previously defined by lithological cycles, which record four phases of progradation (Pieńkowski, 2004; Fig. 41). The only minor change regards Gorzów Wielkopolski IG 1 profile, additional parasequence (VIIIb) was added in the interval 839.9–843.3 m (Hesselbo, Pieńkowski 2011) – this amendment was associated with the mentioned poorly preserved core in that section. In all the cases progradational phases culminate in the deposition of shoreface, barrier island, deltaic or lagoonal sediments, with the most regressive deposits evincing root traces or palaeosols. In several cases, but not all, the steps in the isotope curve occur at flooding surfaces commencing every parasequence. This coincidence is clear in the lower parasequences, but less clear in the upper ones. It was probably connected with enhanced weathering, transport and sedimentation processes during the heights of T-OAE and greenhouse effects, which led to reduction of accommodation space, obliterating and delaying the flooding events.

The Gorzów Wielkopolski IG 1 profile and other Polish Basin successions are also particularly useful in yielding further data on palaeoclimatic conditions prior to, during, and after the OAE. Palynofacies from the Late Pliensbachian show strong pollen-over-spore dominance, in contrast to palynofacies from the Early Toarcian which show dominance of spores over pollen; this has been interpreted by Pieńkowski and Waksmundzka (2009) as a shift from cold and dry conditions prior the T-OAE to very warm and humid conditions. Data from expanded Mechowo IG 1 and Gorzow Wielkopolski IG 1 boreholes (Marcinkiewicz, 1971; Hesselbo, Pieńkowski, 2011; Fig. 41) also show close correlation of megaspore abundance and development of the negative isotope excursion; because megaspores are derived from the hydrophilic plant groups Lycopsida (club mosses) and Isoetaceae (quill worts) – Marcinkiewicz (1971, 1989), these data strongly support the inferences made by other authors that the negative excursion corresponded to a time of extremely warm climate and very high atmospheric CO_2 content (Jenkyns, 2003). Additionally, clay mineral assemblages may be expected to respond to changes in palaeoclimate, with an increase in the formation of kaolinite over illite during hot humid weathering of source terrains. In an incomplete and relatively low resolution study of Early Jurassic strata in Europe, including the Toarcian, Dera et al (2008) have reported prevalence of kaolinite in the Early Toarcian with a distinct palaeolatitudianal distribution which these authors related to the development of a humid belt north of the Tethys ocean. Clay mineral distributions in fraction <2μ have been documented from the Polish Basin, including Gorzów Wielkopolski IG 1 profile (Brański, 2012; Fig. 41). Although this dataset from Gorzów Wielkopolski IG 1 is incomplete (measurements from the upper part of the profile are missing), there is a correlation (although not so clear) between some negative carbon isotope excursions and kaolinite content (Fig. 41). One should bear in mind that kaolinite content may depend also on the pace of erosion, which was much enhanced during the most negative steps in carbon isotope perturbations. Enhanced erosion rate may lead to a quick removal of rock substrate before kaolinisation process (requiring some time) is fully developed.

DEPOSITIONAL SEQUENCES IX AND X

Overlying an erosion surface at the top of the sequence VIII (sequence boundary of the sequence IX; Fig. 41 – 767.4 m) sediments of ? Middle–Late Toarcian age belong to the Borucice Formation, comprising fine to medium sandstones laid down in alluvial or deltaic channel systems. The sequence boundary is certainly associated with an erosional hiatus, as the uppermost parasequences of the sequence VIII (known from Brody-Lubienia and Parkoszowice profiles – Hesselbo, Pieńkowski, 2011) are absent from the Gorzów Wielkopolski IG 1 profile. The coarse-grained, in places conglomeratic lithofacies occurring between 756.5 and 767.2 m represent amalgamated alluvial deposits belonging to the sequences IX and X and probably to the lowermost part of the next depositional sequence of a latest Toarcian or an early Middle Jurassic age. The sample taken from the mudstone intercalation at the depth of 761.3 m (Fig. 39) contains delta plain palynofacies, which can point to facies separating the sequence IX from sequence X. Alluvial/deltaic sedimentation is characteristic for the final period of Late Toarcian sedimentation in the Polish basin.