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Late Jurassic-earliest Cretaceous evolution of the epicontinental sedimentary basin of southeastern Poland and Western Ukraine

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The following Late Jurassic depositional systems have been recognized in the W Ukrainian and SE Polish margin of the East European Platform: shelf slope/basin, open shelf, carbonate ramp, siliciclastic shelf, fluvial/playa, deltaic/swamp, restricted marine/evaporate lagoon. Three depositional megasequences have been identified. Their upper boundaries have been dated by means of targeted stratigraphic studies, compilation of existing data and reinterpretation of stratigraphic correlation concepts respectively as: lower Kimmeridgian *divisum/hypselocyclum* zones boundary, uppermost upper Kimmeridgian and lower Berriasian. Analysis of thickness and depositional system architecture within the megasequences in six regional cross-sections indicates that depocentre was located in the SW margin of the Mid-Polish Trough during Oxfordian and early Kimmeridgian times and propagated in Tithonian time to the Lviv region. This can be explained by changes in the palaeostress field. Approximately N–S oriented extension during Oxfordian and earliest Kimmeridgian times was replaced by approximately NE–SW oriented extension in Tithonian time. The thickness pattern of the megasequences as well as proximity trends of the system tracts within the sequences clearly coincide with the depocentre propagation.

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INTRODUCTION

Upper Jurassic deposits have been recognized in SE Poland (Lublin Upland) and W Ukraine (Lviv region; Fig. 1) in numerous boreholes. Their lithostratigraphy and facies development was summarized by Niemczycka (1976*a*, *b*) and Izotova and Popadyuk (1996, see also references cited therein) respectively. Recently, Zhabina and Anikeeva (2002, 2004) presented new biostratigraphic data and a sequence stratigraphic interpretation of several sections newly studied in well logs and cores in Western Ukraine which has been explored for hydrocarbon accumulations. The comprehensive biostratigraphic and sedimentological studies carried out on the Upper Jurassic deposits which crop out in the Holy Cross Mountains (HCM) and in the Polish Jura Chain (Kutek, 1968, 1994; Matyja, 1977; Matyja *et al*., 1992; Gutowski, 1992*a*, 1998) provide an effective reference framework for correlation with the successions to the east, which are largely present at depth beneath younger deposits. This correlation provides a better understanding of the sedimentary history of the basin as a whole.

The area studied was part of northern Tethyan shelf during the Late Jurassic and earliest Cretaceous. The early Oxfordian sedimentation started with carbonates of the open shelf sponge megafacies (Matyja, 1977; Matyja and Pisera, 1991; Matyja and Wierzbowski, 1995; Izotova and Popadyuk, 1996; Gutowski, 1998). Successively, starting from the mid-Oxfordian, the more proximal part of the basin became divided into two different facies regions with completely different sedimentation histories: a western region in the HCM and W Lublin Upland of Poland, dominated by carbonate and marly marine sedimentation, and an eastern region in the SE Lublin Upland and the Lviv region, where clastic continental/deltaic facies and restricted marine evaporites prevailed. Correlation of the successions between both regions remains unclear and contentious, mainly due to the lack of good biostratigraphic markers.

The western facies region. A shallow-water carbonate ramp prograded from the western Lublin Upland westwards to

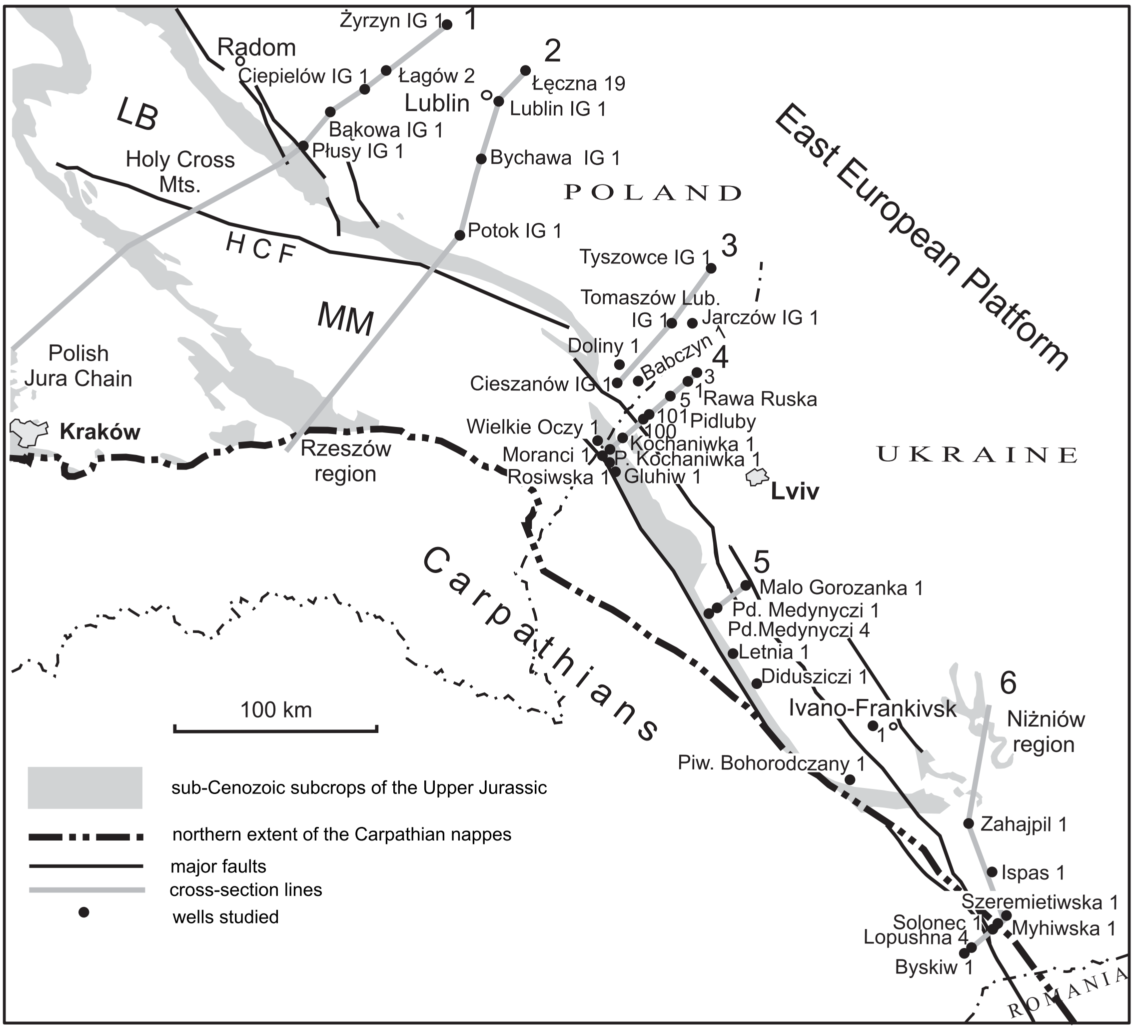

Fig. 1. Geological setting of the area studied

HCF — Holy Cross Fault, LB — Łysogóry Block, MM — Małopolska Massif; the authors have decided to use Ukrainian names in phonetic transliteration of the Cyrillic alphabet into Polish, except of the names known before in English version in the geological literature

the NE margin of the HCM in the latest *transversarium* Chron of the mid-Oxfordian (Gutowski, 1998), and then, during the latest Oxfordian/early Kimmeridgian on to the SW margin of the HCM and further to the Nida Depression (Matyja *et al*., 1989). The carbonate ramp was submerged at the boundary of the *hypselocyclum* and *divisum* chrons of the early Kimmeridgian (Kutek, 1968, 1994; Gutowski, 1992*a*, 1998). It was then overlain by oyster shellbeds and marls deposited in more open marine conditions during the time ranging up to the *eudoxus* Chron of the late Kimmeridgian. The top of the entire sequence in the HCM is clearly erosional and the Albian/Cenomanian transgressive sandstones locally directly overlie lower Kimmeridgian, namely *divisum* Zone strata (Gutowski, 1998). Younger Late Jurassic deposits are preserved on the NW margin of the HCM and further to the NW (Marek *et al*., 1989; Kutek, 1994; Kutek and Zeiss, 1994).

The eastern facies region. Clastic facies prograded from NE to SW and S over the sponge carbonates and formed used as good marker for stratigraphic correlation “multicolored” horizon (Izotova and Popadyuk, 1996). This horizon was overlain by dolomites and anhydrites in the proximal, NE part of the basin whereas carbonates of a sponge megafacies, including huge biohermal buildups, developed above this horizon in more distal parts of the basin.

This paper provides results of the integration of archive and newly obtained stratigraphic data from both Ukrainian and Polish parts of the basin and proposes new concepts regarding correlation of the Late Jurassic deposits, facies development and basin evolution.

GEOLOGICAL SETTING

The Permian-Mesozoic sedimentary basin of Poland and Western Ukraine (Figs. 1 and 2) formed the easternmost part of the epicontinental basin system that developed across Western and Central Europe (Ziegler, 1990). Its depocentral, axial part, i.e. the Mid-Polish Trough (MPT), extended along the NW–SE trending Tornquist-Teisseyre Zone (TTZ) which bordered the Precambrian East European Craton (EEC) and acreted Phanerozoic (Caledonian and Variscan) crustal structures (Pożaryski and Żytko, 1981; Guterch *et al*., 1986; Kutek, 1994, 2001). This zone is called "...the most fundamental lithospheric boundary in Europe, extending for more than 2000 km from the North Sea to the Black Sea..." (Thybo *et al*., 2002). The basin developed from Permian to Cretaceous times, being filled mainly with clastic and carbonate sediments, and was inverted during Late Cretaceous-Paleogene times (e.g. Pożaryski and Brochwicz-Lewiński, 1978; Dadlez *et al*., 1995; Kutek, 2001; Krzywiec, 2002 and references discussed therein). Its axial part was strongly uplifted and formed the Mid-Polish Anticlinorium (MPA) (Fig. 1). In the SE part of the MPA, i.e. in the HCM, the pre-Variscan (pre-Permian) basement has been exposed due to uplift and erosion. The SE part of the MPT, ranging from the HCM to Western Ukraine, was situated palaeogeographically in a transitional zone between the MPT and the Tethyan rift basins, close to the passive European margin, and was influenced by the tectonic processes acting in the Tethys ocean (e.g. Ziegler *et al*., 1995; Golonka *et al*., 2000; Kutek, 2001; Poprawa *et al*., 2002). Therefore, its history was relatively complex, included stages of extension, subsidence and accelerated sedimentation and, on the other hand, stages of contraction and non-deposition or erosion. The HCM area is cut by the WNW–ESE trending major fault called the Holy Cross Fault (HCF). The HCF runs obliquely to the MPT and separates two older Palaeozoic microplates, namely the Łysogóry Block (LB) and the Małopolska Massif (MM) (*cf.* Narkiewicz, 2002). The HCF was reactivated during the Mesozoic evolution of the basin and caused, in general, relative uplift of its southern limb. The southern limb subsided more strongly only during Late Jurassic time. Kutek (1994, 2001) proposed a model of an asymmetrical, aborted rift for MPT development. He postulated "rifting phases" taking place during the Late Permian-Early Triassic and the Late Jurassic times and a "sag phase" during the Cretaceous. However, other authors (e.g. Dadlez *et al*., 1995) consequently did not use the term "rift" as regards either the MPT or the entire Permo-Mesozoic basin of Poland and suggested that palaeostress patterns were characterized by an alternation of extensional and compressional events driven rather by far plate tectonic effects related to the geotectonic evolution of Tethyan and/or Atlantic basins (*cf.* Lamarche *et al*., 2002).

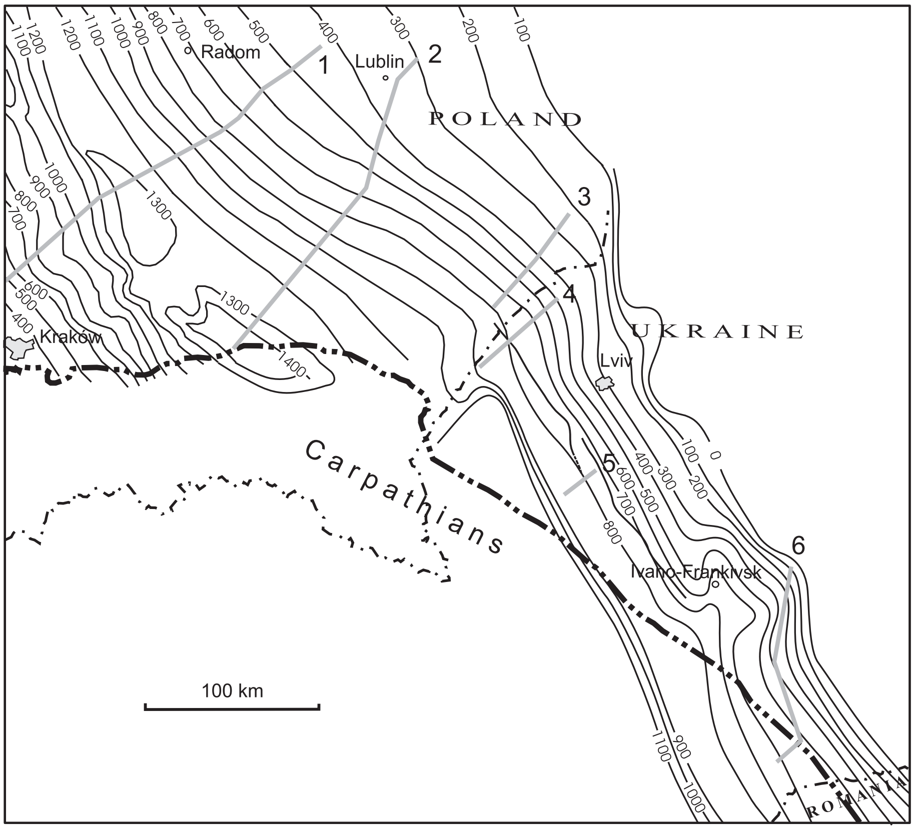

Fig. 2. Palaeothickness map of the Late Jurassic epicontinental sedimentary basin of SE Poland and W Ukraine (partly after Niemczycka and Brochwicz-Lewiński, 1988, modified)

Explanations as on Figure 1

DATA AND METHODS

This study includes a compilation of all available data within a context of whole-basin evolution and their integration using the methods and concepts of sequence stratigraphy. Additionally, we have obtained and interpreted new biostratigraphic and sedimentological data from selected type sections and have used them in our correlation and interpretation. The area studied was densely drilled during the 1960's to the 1980's by research and exploration wells of the oil industry (Niemczycka, 1976*a*; Zhabina and Anikeeva, 2002 for well location maps). We have reviewed all archive files of the wells which are stored in the Polish Geological Institute in Warsaw and the Ukrainian State Geological Research Institute in Lviv. 38 wells on the Polish side and 23 wells on the Ukrainian side (Fig. 1) have been selected as type sections, as cores of these wells are still kept in core depositories at both institutes. Collection of thin sections from these wells is still accessible. The cores and thin sections have been studied to identify/verify lithology, sedimentary structures, depositional systems and sequences. The sections studied are indicated on regional cross-sections (Figs. 6–8). Additionally, comparative sedimentological studies were carried out on the Upper Jurassic outcrops of the Niżniów region in Ukraine (*cf.* Alth, 1881); results of these observations will be given elsewhere (Gutowski *et al*., this issue). A collection of more than 200 thin sections from the Polish part of the basin were reviewed to find and identify microfossils useful for stratigraphic correlation; palaeontological and biostratigraphic aspects of the microfauna identified in the thin sections of the Lublin Upland will be presented by one of us (B. Olszewska) in a separate paper. Results of a study of more than 300 thin sections from the Ukrainian part of the basin have recently been reported by Zhabina and Anikeeva (2002, 2004).

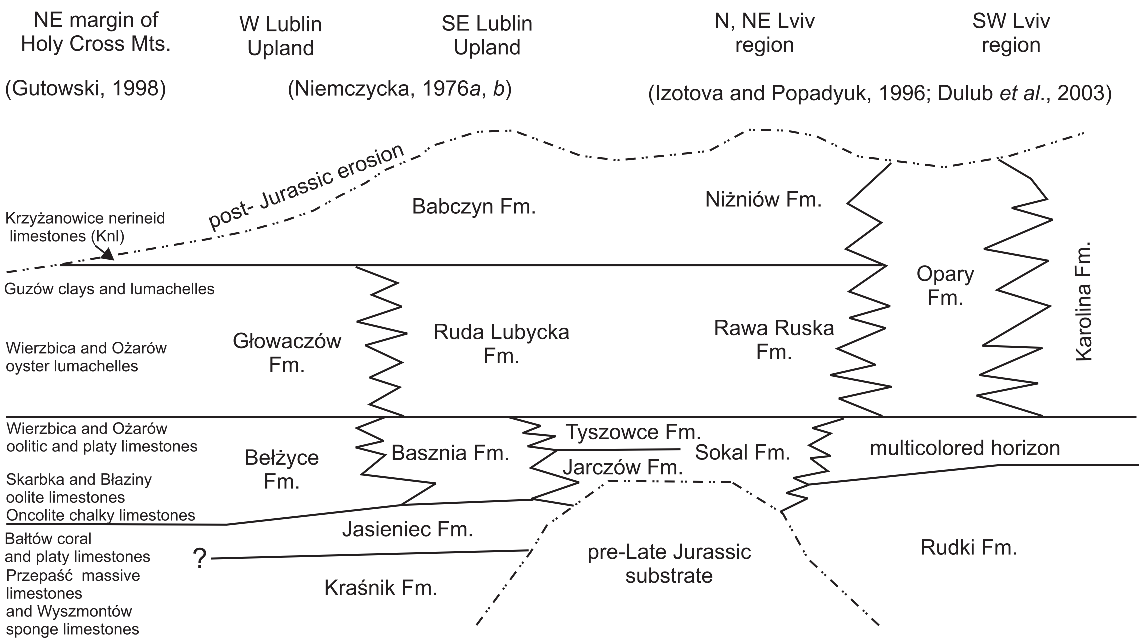

Fig. 3. Correlation of the Upper Jurassic lithostratigraphic units discussed in text

LITHOSTRATIGRAPHIC UNITS

The lithostratigraphic units discussed in this paper were defined by Niemczycka (1976*a*, *b*) in the Lublin Upland of Poland and by Izotova and Popadyuk (1996) and Dulub *et al.* (2003) in the Lviv region of Western Ukraine respectively (Fig. 3). These formations have, to date, been identified independently and have been given different names. They are, though continuous over the Polish-Ukrainian boundary. We have studied profiles of the wells situated close to the national boundary which document an exact equivalence of the Kraśnik Formation and Rudki Formation, Ruda Lubycka Formation and Rawa Ruska Formation, Babczyn Formation and Niżniów Formation. Equivalence of the Basznia Formation with the multicolored horizon, confirmed by direct correlation of the sections in the Cieszanów IG 1, Doliny 1 and Babczyn 1 wells on the Polish side and sections in the Kochaniwka, Pidluby and Rawa Ruska wells on the Ukrainian side is of first order importance for correlation of the Polish and Ukrainian successions. The Sokal Formation can be divided into a lower unit composed of mudstones, claystones and also marls and carbonates (equivalent to the Jarczów Formation) and an upper unit composed of sandstones and conglomerates (equivalent to the Tyszowce Formation). The lowermost part of the Sokal Formation is a lateral equivalent of the upper part of the Rudki Formation, according to recently obtained well data. We also assume that the lowermost part of the Jarczów Formation in Poland passes laterally into the Jasieniec Formation (Fig. 3) and therefore we have modified slightly the lithostratigraphic scheme of Niemczycka (1976*b*). A lithostratigraphic scheme of the Upper Jurassic deposits within the NE margin of the HCM (Fig. 3) has been proposed by Gutowski (1998).

BIOSTRATIGRAPHIC ANALYSIS

Biostratigraphic data from the Oxfordian and Kimmeridgian formations studied are poor and do not allow for a precise biostratigraphic age determination. The age of these formations has been identified by means of foraminifers and/or by their position relative to other formations (Niemczycka, 1976*b*; Dulub and Zhabina, 1999; Anikeeva and Zhabina, 2002, 2004; Dulub *et al*., 2003). No ammonites have been found so far in the cores studied and, moreover, the relation of the stratigraphic succession of the foraminifer assemblages and the standard ammonite zonations remains disputable. Therefore, the exact chronostratigraphic position of the Oxfordian and Kimmeridgian formations in relation to the standard ammonite zones remains more or less speculative and/or simplified both in the SE Lublin Upland and in the Lviv region. Nevertheless, some existing correlations and age indications may be revised according to the data obtained from analysis of microfaunas in thin section.

AGE OF THE BASZNIA FORMATION AND THE CORRELATIVE MULTICOLORED HORIZON

A typical foraminiferal assemblage of the Basznia Formation contains: *Alveosepta jaccardi* (Schrodt), *Paleogaudryina varsoviensis* (Bielecka et Pożaryski), *Labyrinthina mirabilis* Weynschenk, *Mesoendothyra izjumiana* Dain, *Everticyclammina virguliana* (Koechlin), *Quinqueloculina verbizhiensis* Dulub. Calcareous algae such as *Marinella lugeoni* Pfender, *Thaumatoporella parvovesiculifera* Rainieri and Codiacea are frequent. The presence of *Labyrinthina mirabilis* Weynschenk indicates that the formation is not older than uppermost Oxfordian (Fig. 4), however, a lower Kimmeridgian age for the

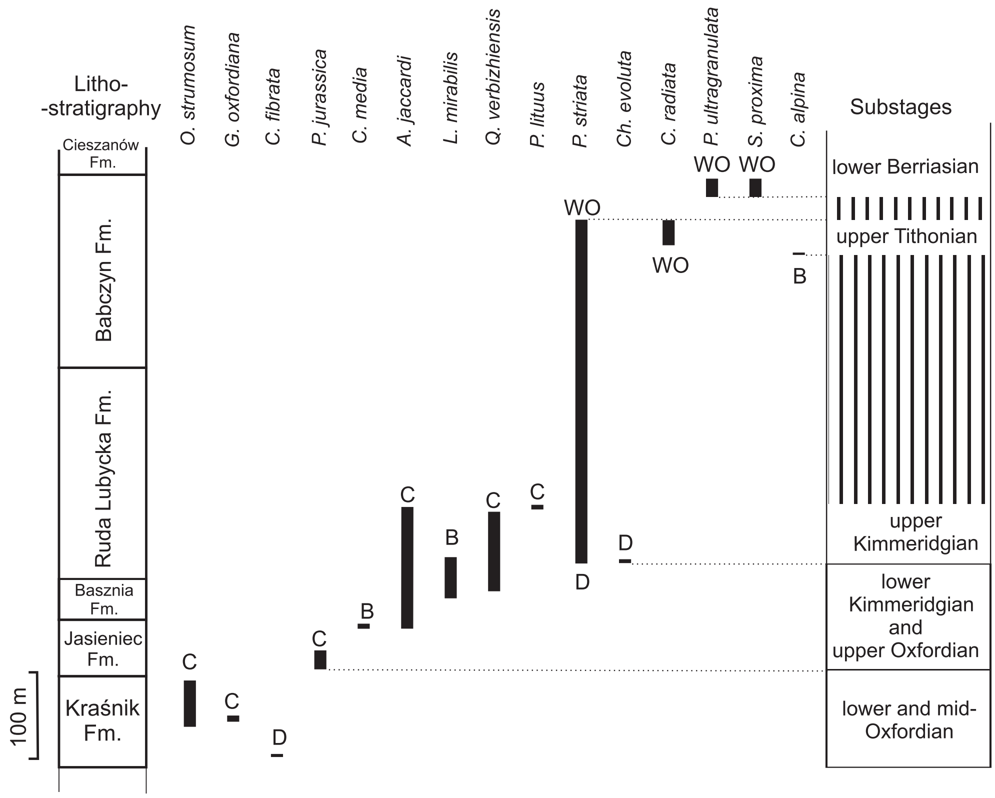

Fig. 4. Stratigraphic distribution of selected microfossils in the Cieszanów IG 1 (C), Doliny 1 (D), Babczyn 1 (B) and Wielkie Oczy 1 (WO) boreholes

formation is also possible. New data on the appearance of age-diagnostic foraminifera have recently been recovered from the multicolored horizon by Zhabina and Anikeeva (2004) from several sites in Western Ukraine. These findings include *Glomospira otorica* Romanova, which probably ranges no lower than lower Kimmeridgian, *Haplophragmoides coprolithiformis* Schwager (range from mid-Oxfordian to lower Kimmeridgian), *Chofatella tingiana* Hottinger (range from upper Oxfordian to lower Kimmeridgian). According to these data the age of the multicolored horizon has recently been assigned by Zhabina and Anikeeva (2004) as lower Kimmeridgian. Consequently, we assume that the age of its Polish equivalent, i.e. Basznia Formation, treated by Niemczycka (1976*a*, *b*) as upper Oxfordian, should likewise be reinterpreted as lower Kimmeridgian.

AGE OF THE BABCZYN AND NIŻNIÓW FORMATIONS

The Karolina Formation contains abundant pelagic microfossils like calpionellids and pelagic crinoids. Dulub *et al*. (2003) have reported the following fossils from this formation: *Calpionella alpina* Lorenz, *Tintinopsella carpathica* (Murgeanu et Filipescu) and *Crassicolaria intermedia* (Delga) which indicate an upper Tithonian and possibly a lower Berriasian age. The Karolina Formation is regarded by Dulub *et al*. (2003) as the age equivalent of the more proximal Opary and Niżniów Formations. An uppermost Tithonian-lower Berriasian age for the Niżniów Formation has been supported by our recent studies of microfauna collected from sections exposed in the Niżniów area (Gutowski *et al*., this issue).

The Niżniów Formation correlates with the Babczyn Formation of the SE Lublin Upland (Fig. 3) which was regarded by Niemczycka (1976*a*, *b*) as of uppermost Jurassic ("Portlandian") age. An uppermost Tithonian or even lower Berriasian age for the upper part of the Babczyn Formation was indicated by our discovery of *Calpionella alpina* Lorenz in the Babczyn 1 borehole. The Jurassic/Cretaceous boundary within the Babczyn Formation may be reasonably precisely located in the Wielkie Oczy 1 borehole. It lies somewhere between the last occurrence of *Protopeneroplis striata* Weynschenk and *Colomisphaera radiata* (Vogler) on the one hand and the first occurrence of *Protopeneroplis ultragranulata* (Gorbatchik) and *Stomiosphaerina proxima* Řehanek on the other (Fig. 4). Therefore, at least uppermost part of the Babczyn Formation in the SE Lublin Upland is of lower Berriasian age. In turn, available biostratigraphic data (Fig. 4) do not exclude the possibility that the lower boundary of the Babczyn Formation runs below the Kimmeridgian/Tithonian boundary, somewhere within the upper Kimmeridgian.

DEPOSITIONAL SYSTEMS

The following Late Jurassic depositional systems (Fig. 5) were recognized within the area studied:

A shelf slope/basin system has been identified so far only in the Ukrainian part of the basin. It is represented by the Karolina Formation and relevant part of the Moranci Formation *sensu* Zhabina and Anikeeva (2002) and consists of dark, often bituminous shales, biomicrites and mudstones which contain abun-

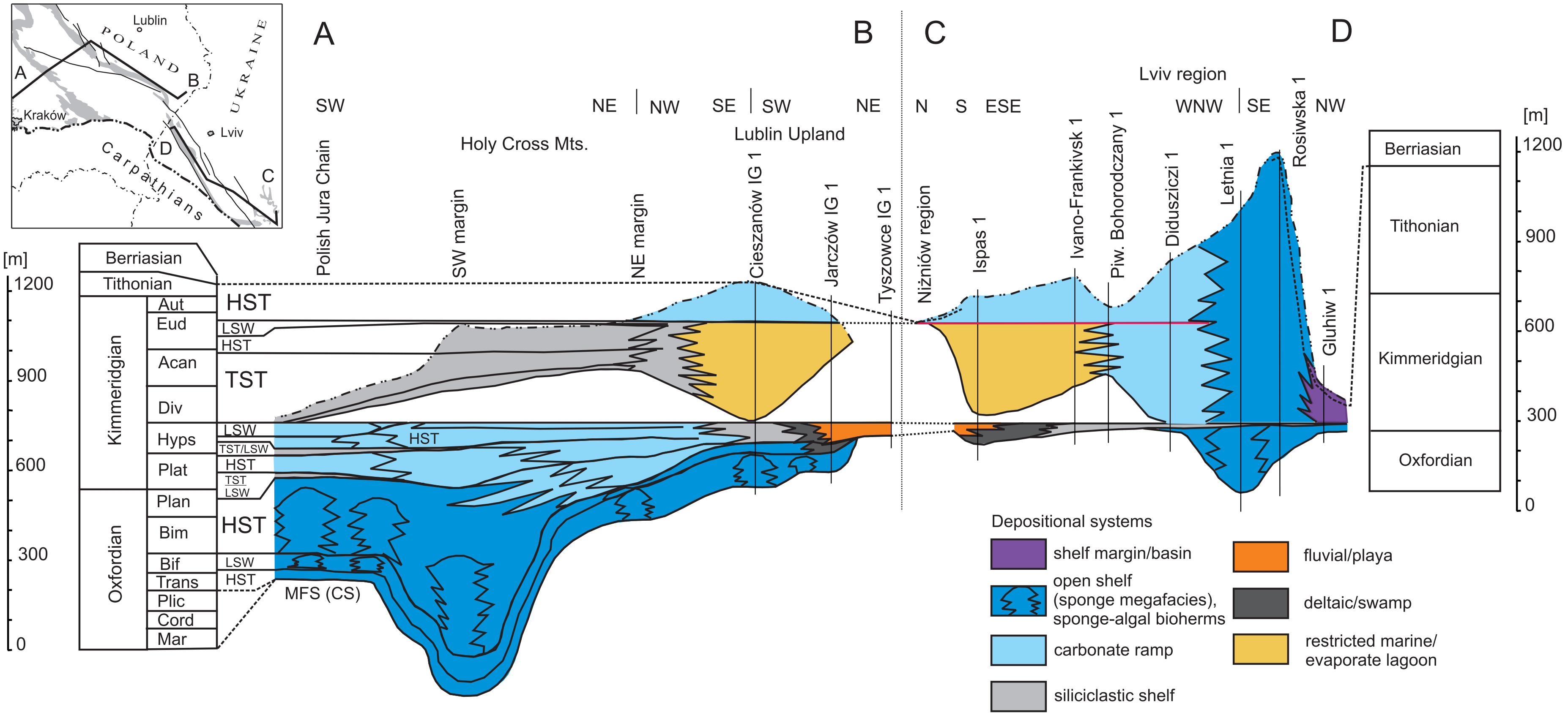

Fig. 5. Idealized cross-sections through the Late Jurassic epicontinental sedimentary basin of the SE margin of the East European Platform, flattened at tops of the sedimentary megasequences discussed in text (*hypselocyclum* and *divisum* zones boundary of the early Kimmeridgian and mid *eudoxus* Zone of the late Kimmeridgian)

Submediterranean ammonite zones: Mar — *mariae*, Cord — *cordatum*, Plic — *plicatilis*, Trans — *transversarium*, Bif — *bifurcatus*, Bim — *bimammatum*, Plan — *planula*, Plat — *platynota*, Hyps — *hypselocyclum*, Div — *divisum*, Acan — *acanthicum*, Eud — *eudoxus*, Aut — *autissiodorensis*; **system tracts**: HST — highstand, LSW — lowstand wedge, TST — transgressive, MFS (CS) — maximum flooding surface (condensed section); other explanations as on Figures 1 and 6 dant planktonic fossils, mainly calpionellids and radiolarians (Linetskaya and Lozyniak, 1983; Dulub *et al*., 2003).

An open shelf system (sponge megafacies) is defined, according to Matyja and Pisera (1991) as carbonates and marls, both bedded and biohermal, containing numerous siliceous sponges. The system is characterized by denivelations of the sea bottom ranging up to 200 metres caused by growth of microbial-sponge bioherm buildups (Matyja *et al*., 1992). The system extended widely along the northern Tethyan shelf in Europe and is commonly interpreted as having been deposited during an exceptional sea level highstand, which resulted in water depths of even up to about 400 metres within the shelf (Matyja and Wierzbowski, 1996). Therefore, it is called an "open" shelf facies (Kutek *et al*., 1984). The system is represented by the Kraśnik, Rudki and Opary Formations.

A carbonate ramp system developed in Central Poland (Kutek *et al*., 1984) and is formed by prograding shallow-marine carbonates such as oolites, oncolites and different bioclastic and biogenic limestones (Kutek, 1968, 1969; Gutowski, 1992*a*, 1998). The system can be divided into three subsystems (Gutowski, 1992*a*):

— external carbonate ramp characterized mainly by oncomicrites, biomicrites, micritic limestones and marls with an abundant benthic fauna, often preserved in life position and/or creating patch reefs or biostromes. The faunal assemblages consist mainly of nerineids, corals, diceratids, rynchonellids, terebratulids, myids and oysters;

— oolitic barriers composed of large-scale cross-bedded oolitic/bioclastic grainstones;

— protected lagoons in which laminites and lithographic limestones were deposited. Rhizoidal, teepee and fenestral structures and also aggregations of coalified flora, including large cycadacean tree trunks, indicate extremely shallow tidal flat/beach sedimentary environments and even emergent conditions (Gutowski, 1992*a*, 1998, 2004).

The typical carbonate ramp system is represented by the variety of carbonates of the Bełżyce Formation. Carbonates of the Niżniów Formation and the Babczyn Formation of the eastern facies region are also included in the carbonate ramp system. They are accompanied by sea-shore conglomerates, sandstones and marls in an extremely proximal position in the basin where they transgressively overlie Palaeozoic basement (see Gutowski *et al*., this issue).

A siliciclastic shelf system is characterized by marls and clays, usually intercalated in different proportions with oyster-rich, mainly storm-originated, shellbeds widely distributed in Central and SE Poland (Kutek, 1968, 1994; Kutek *et al*., 1984; Gutowski, 1992*a*, 1998) and grouped by Niemczycka (1976*b*) into the Głowaczów Formation. Marls, clays and mudstones of the Basznia Formation and the multicolored horizon are also included by us into the siliciclastic shelf system.

A fluvial/playa system is represented by the upper part of the Sokal Formation recognized in W Ukraine (Slavin and Dobrynina, 1958; Zhabina and Anikeeva, 2002; Dulub *et al*., 2003) and to the corresponding Tyszowce Formation in the SE Lublin Upland (Niemczycka, 1976*b*). It is composed of red, brown, yellow, green and grey sandstones, mudstones and claystones and conglomerates, usually grouped in fining-upwards sedimentary cycles. Pebbles of metamorphic and plutonic rocks as well as Carboniferous sandstones have been identified in the conglomerates. This indicates that the alimentation zone was situated in the neighbouring area of the Ukrainian shield and surrounding Palaeozoic outcrops (Radlicz, 1972; Niemczycka, 1976*b*). The sedimentary environment of these deposits has been interpreted as continental, namely fluvial fans and plains, created most likely by ephemeral rivers in an arid climate (Niemczycka, 1976*a*, *b*; Zhabina and Anikeeva, 2002). The terrigenic rocks are intercalated, in the upper part of the sequence, with evaporites such as anhydrites and gypsum likely deposited in stagnant lakes.

The deltaic/swamp system corresponds with the lower part of the Sokal Formation (Slavin and Dobrynina, 1958; Zhabina and Anikeeva, 2002; Dulub *et al*., 2003) and the Jarczów Formation (Niemczycka, 1976*b*) respectively. More distal parts of the Sokal Formation and the Tyszowce Formation, which include marine intercalations of marls and carbonates, also belong to this system according to our interpretation. The system is built of dark grey mudstones with an abundant coalified flora and thin coal intercalations. Rhizoid structures and pebbles of metamorphic rocks were observed in these deposits (Niemczycka, 1976*b*). These deposits were interpreted by Niemczycka (1976*a*, *b*) and Zhabina and Anikeeva (2002) as deposited in swamps and "near-shore" lakes. We believe that these sediments should be interpreted at least partly as deltaic in origin due to their palaeogeographic setting in the transitional zone between the fluvial and marine systems. We also believe that this system was synchronous with the fluvial/playa system and represents the more humid environments of delta and coastal plain. According to this interpretation the differences between these deposits and the continental succession of the fluvial/playa system do not result from their different age and deposition in different climatic conditions as suggested earlier by Niemczycka (1976*a*) and Zhabina and Anikeeva (2002).

A restricted marine/evaporate lagoon system consist of anhydrites and dolomites of the Rawa Ruska Formation (Dulub *et al*., 2003) and the Ruda Lubycka Formation (Niemczycka, 1976*b*). These deposits accumulated in restricted marine or lagoonal conditions (Niemczycka, 1976*a*, *b*).

SEDIMENTARY SEQUENCES

Kutek (1994) recognized three major sedimentary sequences in the western facies region of the area studied, i.e. a Callovian-Oxfordian-Kimmeridgian (COK) sequence which includes deepening upwards, mainly clastic Callovian sediments and shallowing upwards Oxfordian and lower Kimmeridgian (*platynota* and *hypselocyclum* zones) carbonates; a lower-upper Kimmeridgian (LUK) sequence including shellbeds, marls and clays of the uppermost lower Kimmeridgian (*divisum* Zone) and the lower part of the upper Kimmeridgian (up to lower *eudoxus* Zone); and a Kimmeridgian-Volgian-Berriasian (KVB) sequence which extends from the upper *eudoxus* Zone up to the lower Berriasian and contains open marine shales and, in the upper part, evaporites and brackish and freshwater sediments of Purbeck-type. This interpretation coincides with the sequence stratigraphic scheme proposed by Gutowski (1992*b*) according to the methodology of Haq *et al*. (1987) and is adopted in this paper with minor modifications.

Recognizable regional sedimentary unconformities which bound system tracts and sedimentary sequences are indicated in Figure 5.

MEGASEQUENCE I

The Callovian/Oxfordian transition is marked by a maximum flooding surface (MFS) connected with a nodular bed, stromatolite and condensed section developed in the deep water conditions of a starved basin (Matyja and Wierzbowski, 1996; Dembicz and Praszkier, 2003). Four, third-order sedimentary sequences follow the MFS (Fig. 5). They are characterized by relatively thick highstand system tracts with clearly progradational and shallowing upward patterns of open shelf/carbonate ramp carbonates (see Matyja *et al*., 1989; Gutowski, 1992*a*, 1998) and thin lowstand/transgressive system tracts expressed by marly horizons, used as marker stratigraphic horizons (see Kutek, 1994 for stratigraphic discussion). These sequences can be grouped into one shallowing upwards, and progradational megasequence I (equivalent of the COK sequence *sensu* Kutek, 1994). Its upper boundary coincides approximately with the boundary of the lower Kimmeridgian *hypselocyclum* and *divisum* zones (*cf*. Kutek, 1994).

Closely similar shallowing upwards and progradational trends can be observed in the Oxfordian deposits of the eastern facies region, i.e. in the SE Lublin Upland and Lviv region. The open shelf carbonates are replaced by prograding clastics of marine, deltaic and fluvial/playa systems. We believe, therefore, that the discussed shallowing upwards megasequences followed by the remarkable transgressive system tract are correlatable and that their upper boundary should be used as a key stratigraphic marker horizon between the two facies regions.

MEGASEQUENCE II

Oyster shellbeds and marls which overlie the top of megasequence I in the western facies region were deposited in more open marine conditions. They can be categorized as a transgressive system tract due to their deepening upwards and retrogradational patterns observed in the HCM (Kutek, 1968; Gutowski, 1992*a*, 1998). The topmost part of the upper Kimmeridgian marls and oyster shellbeds, namely the Malenie level of the Guzów clays and lumachelles unit (see Fig. 3) of Gutowski (1998) is, on the NE margin of the HCM, of a regressive and progradational nature. The Malenie level contains quartz grains and specific black silicic pebbles which are most probably flints derived from the Carboniferous basement of the NE Lublin Upland. Their top is interpreted as the upper boundary of megasequence II (equivalent of the LUK sequence *sensu* Kutek, 1994).

The megasequence I upper boundary is overlain in the eastern facies region by definitely retrogradational and transgressive dolomites and anhydrites of the restricted marine/lagoon system, whereas the open shelf system returned in the more distal part of the basin.

MEGASEQUENCE III

The Malenie level is overlain by the Krzyżanowice nerineid limestones (Knl) (see Fig. 3 and Gutowski, 1998) which began the transgressive system tract of the succeeding megasequence III (equivalent of the KVB sequence *sensu* Kutek, 1994).

The dolomitic-anhydritic formation is overlain in the eastern facies region by open marine carbonates of the Niżniów Formation (Izotova and Popadyuk, 1996), which definitely comprises a transgressive system tract in its lowermost part and overlies a sequence boundary developed as an erosional surface on the top of older Upper Jurassic sediments or directly upon the Palaeozoic basement (see Gutowski *et al*., this issue). Open shelf sponge carbonates were continuously deposited laterally in a more distal setting and huge organic buildups developed until and during the early Berriasian. During the Tithonian and Berriasian, corals replaced sponges in the role of main constructors of the buildup, which was transformed into a coral barrier reef (Izotova and Popadyuk, 1996). A shelf slope/basin system developed simultaneously in their foreland (Zhabina and Anikeeva, 2002). The Niżniów Formation passes laterally in SE Poland into the Babczyn Formation of Niemczycka (1976*b*). The lowermost part of this formation coincides with the Knl on the NE margin of the HCM (Fig. 3).

This episode of carbonate sedimentation in the basin can be compared with the Štramberk type carbonates which developed widely on the more southern part of the Tethyan shelf, which is overthrusted at present by the Carpathian nappes (see Kutek, 1994 for discussion of the palaeogeography). Additionally, our thin section analysis indicates a close similarity of the shelf slope/basin, radiolaria- and calpionellid-rich sediments of the Karolina Formation on one hand and the upper Kimmeridgian-Tithonian Cieszyn Shales of the Silesian extra-Carpathian nappe on the other. Sedimentary environments of the Štramberk type carbonates and a model of corresponding carbonate platform has been recently given by Hoffmann and Kołodziej (2004) from analysis of exotic material derived from the extra-Carpathian nappes. This model suggests that shales of the Cieszyn type originated in small basins which opened after breaking-up of this carbonate platform and/or earlier in its foreland basin. In our opinion, it can be supposed that the same or fairly similar late Kimmeridgian-early Berriasian facies belts, as preserved in Western Ukraine, existed in the present-day Carpathian subthrust area region further westwards. Consequently, the Cieszyn Shales equivalents, possibly still preserved in the Carpathian subthrust area, should be considered as potential source rocks for the hydrocarbon accumulations that occur in Upper Jurassic and Upper Cretaceous reservoirs both in the Carpathian subthrust area and in the Carpathian foreland. This hypothesis needs further geochemical investigation of this petroleum system both in the Polish and the Ukrainian sectors of the basin.

STRATIGRAPHIC CORRELATION OF THE SEQUENCES

Biostratigraphic data allow us to correlate higher parts of the Babczyn Formation (Niemczycka, 1976*b*), in which *Calpionella alpina* Lorenz has been recently identified by the authors, with the upper part of the Niżniów Formation, the latest Tithonian and Berriasian age of which has been recently identified by Zhabina and Anikeeva (2002, 2004) and Gutowski *et al.* (this issue). The top erosional surface of the formation is overlain directly by Albian/Cenomanian transgressive sandstones and/or marls in the NE, most proximal part of the basin. The Neocomian Stawczany Formation overlies the Niżniów Formation in the more SE part of the basin. Rare specimens of *Calpionella elliptica* Cadish have been reported from the upper part of the Stawczany Formation (Utrobin, 1962). It may suggest that the Niżniów Formation (and simultaneously megasequence III), underlying the Stawczany Formation, is older than the mid-Berriasian calpionellid Zone C (*cf.* Wierzbowski and Remane, 1992; Reháková and Michalik, 1997). A continuous stratigraphic succession ranging from the Tithonian to the Berriasian has been identified based on calpionellids in the shelf slope/basin shales within the Karolina Formation (Zhabina and Anikeeva, 2002; Dulub *et al*., 2003).

Other correlation markers may be identified using the sequence stratigraphic approach. The top of megasequence I, which coincides approximately with the boundary of the *hypselocyclum* and *divisum* lower Kimmeridgian zones, reflects the most prominent sedimentary event in the Late Jurassic history of the western facies region. This boundary is connected with rapid migrations of the ammonite fauna and mixing of faunal elements from different bioprovinces observed in several European basins and resulted from a sudden sea level rise (Gutowski, 1992*a*; Matyja and Wierzbowski, 2000 and references discussed therein). The shallow-water carbonate platform of the HCM region and neighbouring Central Poland was submerged as a result of this rise. We believe, taking this into account, that this event should be also recorded in the eastern facies region. A comparable event is observed at the top of the clastic Sokal Formation and correlative top of the "multicolored" horizon, when looking at the sedimentary record of the basin history in the eastern facies region (Izotova and Popadyuk, 1996; Zhabina and Anikeeva, 2002). The shallowing-upwards, strongly regressive megasequence is replaced at this boundary by transgressive sediments of the lowermost Rawa Ruska Formation and a return of the sponge megafacies more distally. Therefore, this boundary has been interpreted as a megasequence boundary and an important stratigraphic marker for correlation (lower flattened horizon in Fig. 5).

A second correlation horizon is established at the top of the Rawa Ruska Formation and equivalent top of the Ruda Lubycka Formation (Niemczycka, 1976*b*). The lower part of the latter formation passes laterally in the W Lublin Upland into marls and oyster shellbeds of the lower Kimmeridgian *divisum* Zone on the NE margin of the HCM, as has been demonstrated by analysis of neighbouring well logs and cores (Niemczycka, 1976*a*). The tops of all these formations are developed as sedimentary discontinuities which, according to the underlying progradational patterns, has been interpreted as the megasequence II boundary (second flattened horizon in Fig. 5). The age of this boundary is indicated by a single ammonite find in the directly overlying Knl on the NE margin of the HCM as late Kimmeridgian, excluding the upper part of the *autissiodorensis* Zone and most probably also the *mutabilis* Zone (Gutowski, 1998).

REGIONAL CROSS-SECTIONS AND PALAEOTECTONIC INTERPRETATION

Six regional cross-sections encompassing selected wells and exposures have been constructed. Their geographic location is indicated in Figures 1 and 2. All cross-sections are flattened respectively in top of one of the recognized depositional megasequences, i.e. approximately at the top of the lower Kimmeridgian *hypselocyclum* Zone (Fig. 6), within the upper part of the upper Kimmeridgian *eudoxus* Zone (Fig. 7) and approximately at the top of the lower Berriasian succession (Fig. 8). The original thickness of megasequence III, reduced due to post-Jurassic erosion, is reconstructed in Figure 6 according to regional data. The most problematic reconstruction of cross-section 1 in Figure 8 assumes that maximum original thickness of megasequence III in the HCM region was comparable to the thickness of this megasequence in the neighbouring Tomaszów Depression (NW margin of the HCM). We have also adopted the arguments of Kutek (1994) who suggested reactivation of the Meta-Carpathian Arch during part of the time span corresponding to deposition of megasequence III (his KVB sequence) and, therefore, we have assumed that the thickness of this megasequence at least slightly decreased southwards due to the relatively reduced subsidence rate in this area.

Analysis of thickness and depositional system architecture within the megasequences in the regional cross-sections (Figs. 6–8) indicates that the depocentre, understood as a maximum subsidence zone, was located at the SW margin of the MPT (present day SW margin of the MPA) during Oxfordian and early Kimmeridgian times, and propagated to the Lviv region in Tithonian-early Berriasian times. Simultaneously, the open shelf system (sponge megafacies) was replaced by shallow marine sediments in Central Poland not later than in the earliest Kimmeridgian whereas the huge sponge-microbial buildups developed in the Lviv region until and including the early Berriasian and, accordingly, a shelf slope/basin system developed more distally in this part of the basin. A carbonate ramp system overstepped onto older Jurassic deposits or even directly on to Palaeozoic basement in more proximal parts of the basin in W Ukraine. These changes in basin palaeogeography and thickness patterns can be explained, in our opinion, by reorientation of the palaeostress field. The local Tethys margin was composed of microplates, namely the LB and MM, which interacted with the EEC as solid crust blocks during Late Jurassic-earliest Cretaceous times in a generally extensional regime (e.g. Kutek, 1994). Their bounding zones are at present expressed as inverted fault systems (Figs. 1 and 2) which were reactivated as normal or transtensional fault systems (Krzywiec, 2002; Gutowski *et al*., 2003*a*, *b*) depending on the direction of the palaeostress field. According to the analogue models of rift

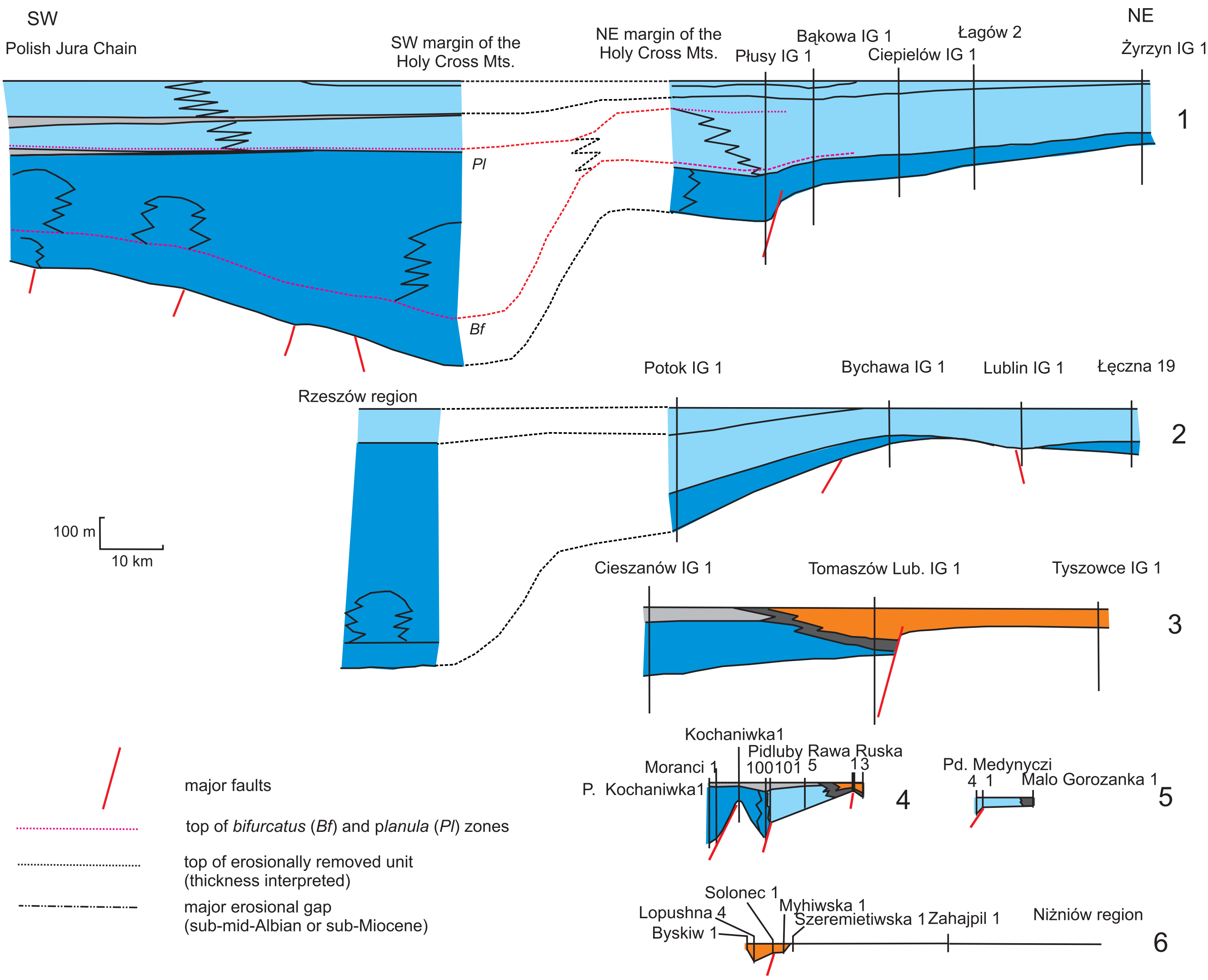

Fig. 6. Regional cross-sections flattened at the top of the megasequence I (approximately top of the lower Kimmeridgian *hypselocyclum* Zone)

For location see Figure 1; colours of the depositional systems as on Figure 5

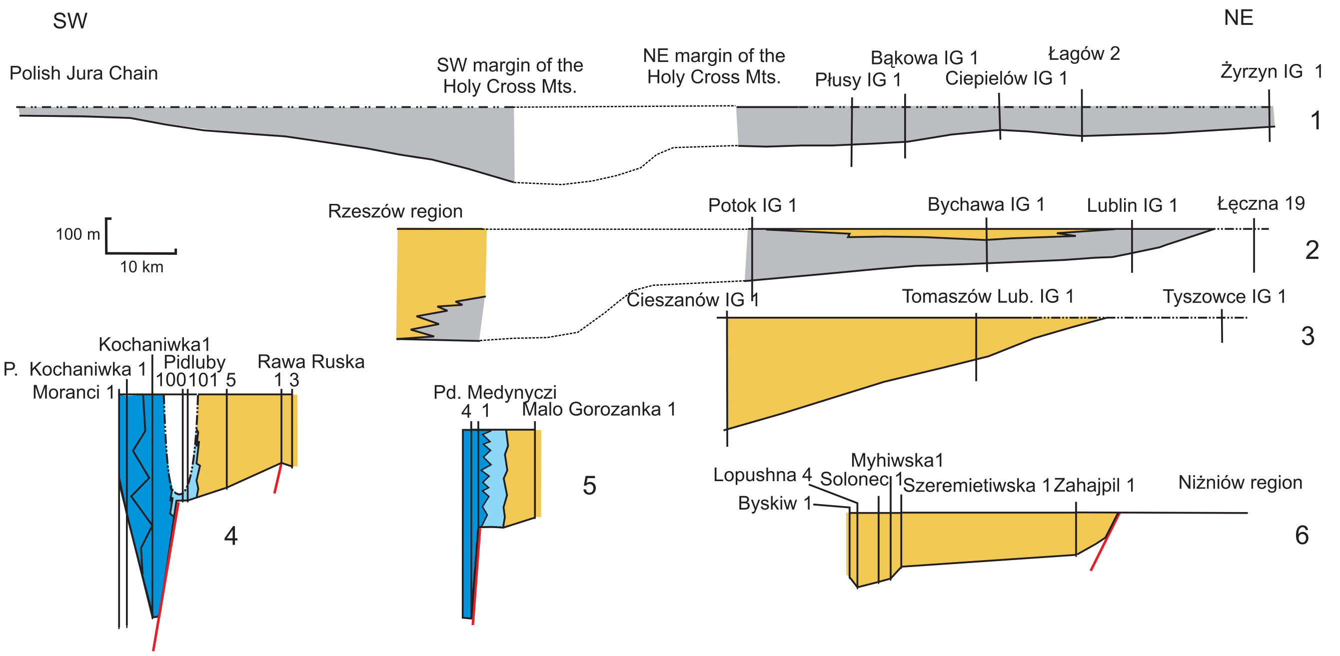

Fig. 7. Regional cross-sections flattened at the top of the megasequence II (mid *eudoxus* Zone of the upper Kimmeridgian)

Other explanations as on Figure 6

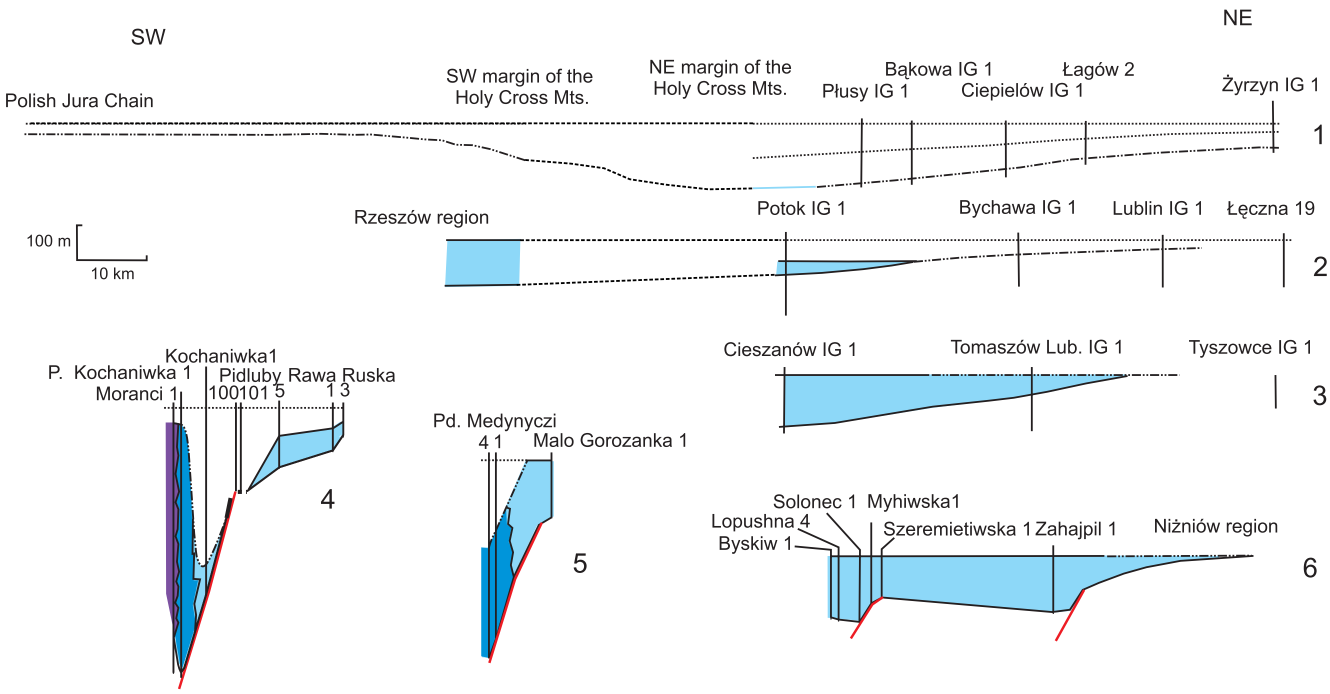

Fig. 8. Regional cross-sections flattened at the top of the megasequence III (approximately top of the lower Berriasian)

Other explanations as on Figure 6

structures (e.g. McClay *et al*., 2002) especially well-expressed depocentres are located along bounding fault systems in an orthogonal extension regime. On the other hand, oblique extension results in a mostly slight subsidence pattern along transtensional fault systems. Therefore, it can be supposed that, during Oxfordian-early Kimmeridgian times, the extension was oriented approximately N–S (up to NW–SE), i.e. perpendicular to the HCF and parallel to the East European Platform (EEP) margin fault zone in Western Ukraine (Figs. 1 and 2). Such an extension direction is supported by Oxfordian-early Kimmeridgian palaeothickness maps of the Nida Depression situated SW from the HCM, in which rapid thickness changes are visible along palaeostructures running W–E or WNW–ESE (Z. Złonkiewicz, pers. comm.). This could result in stronger subsidence along the HCF and its accompanying fault arrays which accommodated this underlying deep structure into an MPT (NW–SE) direction, and also in the location of the Oxfordian depocentre on the SW margin of the HCM. On the other hand, such an orientation of extension could have resulted in a transtensional regime along the EEP margin fault zone in Western Ukraine and slight subsidence in this part of the basin. This proposed orientation of the palaeostress field may have been connected with a slight counter-clockwise rotation of the MM.

Approximately N–S oriented extension was successively replaced during the late Kimmeridgian by approximately NE–SW (up to ESE–WNW) oriented extension, i.e. approximately parallel to the HCF and perpendicular to the EEP margin fault zone in Western Ukraine, probably connected with a slight clockwise rotation of the MM. These tectonic patterns could eventually have resulted in the location of the Tithonian depocentre in the Lviv region, along the EEP marginal fault zone.

DRIVING MECHANISM OF THE SEDIMENTARY MEGASEQUENCES

The thickness patterns of the particular megasequences as well as the proximity trends of the system tracts within the megasequences clearly coincide with the described depocentre propagation. This suggests strongly that the sequences were driven by relative sea level changes resulting from regional tectonic events, possibly related to oscillation of the East European continental margin due to alternation of interplate stresses according to the model of Cloetingh (1988). This mechanism was suggested by Kutek (1994) as controlling the Late Jurassic tectonic events in SE epicontinental Poland. Although this mechanism did not have a global effect, its fairly isochronous results can be observed in distant sedimentary basins of epicontinental Europe which were situated close to the Tethyan shelf. For example, the distinct extensional event in the late Oxfordian *Bimammatum* Chron that resulted in enhanced thicknesses on the SW margin of the MPT (see cross-section 1 and 2 in Fig. 6) coincides with the similar event in the Swiss Jura Mountains (see fig. 15 in Allenbach, 2002). This event corresponds strictly with the mixing and sudden invasions of ammonite fauna from different bioprovinces of Europe during the *Bimammatum* Chron, which is connected with a major relative sea level rise (Matyja and Wierzbowski, 1995). A similar phenomenon has been observed at the turn of the *hypselocyclum* and *divisum* early Kimmeridgian chrons (Matyja and Wierzbowski, 2000). It can be correlated with the megasequence boundary and tectonic event marking the beginning of the depocentre shifting toward the Lviv region (see Fig. 5). It is also worth noting in this context that the stratigraphic age of the top of megasequence III in Western Ukraine, which is dated as early Berriasian but older than the mid-Berriasian calpionellid Zone C, corresponds with the age of the top of the KVB sequence of Kutek (1994), identified on the NW margin of the HCM. The uppermost part of the KVB sequence is developed in the NW segment of the MPT in Purbeck-type facies and is overlain, unconformably in part, by marine sediments of the upper Berriasian (Dembowska and Marek, 1975; Marek *et al*., 1989).

Correlation of the depositional megasequences recognized with the global standard sea level curves proposed by Haq *et al*. (1987) and Hallam (1988) would be misleading when done in a simple, direct way because several difficulties and misunderstandings exist in correlation of the Submediterranean ammonite zonal scheme, used as a standard in this paper, and the Subboreal/Boreal zonal scheme used in both curves (e.g. Matyja and Wierzbowski, 1995; Zeiss, 2003). Moreover, a clear tectonic cause for these sequences and events suggests rejection of a global sea level model as a norm for interpreting the sedimentary cyclicity observed in the basin studied.

CONCLUSIONS

1. The following Late Jurassic depositional systems have been recognized in the Ukrainian and Polish margin of the East European Platform: shelf slope/basin, open shelf, carbonate ramp, siliciclastic shelf, fluvial/playa, deltaic/swamp, restricted marine/evaporate lagoon. A shelf slope/basin system has been identified so far only in the Ukrainian part of the basin. It consists of dark, often bituminous shales, biomicrites and mudstones which contain an abundant planktonic fauna, mainly radiolaria and calpionellids. These deposits can be considered as potential source rocks for the Late Jurassic hydrocarbon system.

2. The interval ranging from the uppermost Tithonian to the Berriasian has been documented biostratigraphically based on calpionellids and foraminifers in the shelf slope/basin system (Karolina Formation) in W Ukraine (Dulub *et al*., 2003). One specimen of *Calpionella alpina* Lorenz indicating an uppermost Tithonian-Berriasian age was identified in the Babczyn Formation in SE Poland.

3. Three depositional megasequences have been identified. Their upper boundaries have been dated respectively as: the top of the *hypselocyclum* Zone of the lower Kimmeridgian (megasequence I), the *eudoxus* Zone of the upper Kimmeridgian (megasequence II) and the top of the lower Berriasian (megasequence III), are correlated in the two western and eastern facies regions. The megasequences were driven by relative sea level changes resulting from regional tectonic events, possibly related to oscillation of the East European continental margin due to alternation of interplate stresses according to the model by Cloetingh (1988).

4. Analysis of thickness patterns and depositional system architecture within the megasequences in six regional cross-sections (Figs. 6–8) indicates that the depocentre was located on the SW margin of the MPA during Oxfordian and early Kimmeridgian times and propagated to the Lviv region in Tithonian time. This may be explained by reorientation of the palaeostress field. Approximately N–S oriented extension during Oxfordian and earliest Kimmeridgian times was successively replaced by approximately NE–SW oriented extension in Tithonian-early Berriasian time.

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