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Development of the Mid-Polish Trough *versus* Late Jurassic evolution in the Carpathian Foredeep area

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Late Jurassic is the key epoch for an idea of the existence of the southeastern segment of the Mid-Polish Trough. New data on the evolution of Upper Jurassic deposits in the Carpathian Foredeep substrate provide information that there is a complete Oxfordian through Valanginian succession in the area of thick Oxfordian and Kimmeridgian deposits, proving the occurrence of the trough. Thickness of the Oxfordian and Kimmeridgian succession is twice to three times smaller than previously assumed. The facies development pattern distinguishes this area from the rest of the Late Jurassic basin. The sponge megafacies ranges up into the lowermost Tithonian in this region. Tithonian Štramberk-type reefs occur near the Carpathian thrust front and alongside. The Late Jurassic and earliest Cretaceous facies are latitudinally arranged. Starting from the latest Middle Jurassic, the study area showed strong structural and facies relations to the Tethys domain. The collected data contradict the hypothesis that the Mid-Polish Trough continues in the Carpathian Foredeep substrate.

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INTRODUCTION

The hypothesis on the continuation of the Mid-Polish Trough into the Carpathian Foredeep substrate was based mainly on the presence of thick Oxfordian and Kimmeridgian deposits occurring in this region (Pożaryski, 1957*b*; Konarski, 1974; Morycowa and Moryc, 1976; Niemczycka and Brochwicz-Lewiński, 1988).

The area of the present stratigraphic and facies analysis almost entirely belongs to that part of the Nida Synclinorium, which is covered by Miocene deposits of the Carpathian Foredeep. The Nida Synclinorium is fringed by a zone of Upper Jurassic rocks. In both the Polish Jura Chain and southwestern margin of the Holy Cross Mountains, the rocks outcrop at the surface. Unlike the Carpathian Foredeep area, knowledge on the stratigraphy and facies pattern of the outcrop areas is much more complete (e.g., Kutek, 1968, 1969; Matyja, 1977; Kutek *et al.*, 1977; Matyja and Wierzbowski, 2004; Ziółkowski, 2007).

The sedimentary cycle, to which belong the Upper Jurassic deposits, in the Carpathian Foredeep substrate started at the beginning of the late Bajocian (Moryc, 2006 — in the early Kuyavian, as in the original text) and terminated in Valanginian or maybe Hauterivian times (Urbaniec and Świetlik, 2003; Dziadzio *et al.*, 2004). Deposits of the cycle unconformably overlie an older substrate and are unconformably overlain by Upper Cretaceous rocks. Thus, they form a separate structural stage. The results of investigations in several tens of wells allowed me to present a new hypothesis on the position of the Late Jurassic basin in the Carpathian Foredeep area.

EVOLUTION OF THE VIEWS ON THE COURSE AND ORIGIN OF THE MID-POLISH TROUGH

An area showing a trend for accumulation of thick deposits and parallel to the edge of the East European Craton was a prominent palaeogeographic and structural element of the epicratonic Permian and Mesozoic of Poland. The area was first distinguished by Pożaryski (1957*a*) as the Danish–Polish Furrow. Slightly later (Pożaryski, 1957*b*) that author defined its course (see Fig. 1) and pointed to structural constraints on its evolution. The northeastern limit of the furrow was strictly re-

Fig. 1. The course (shaded gray) of the Danish–Polish Furrow after Pożaryski (1957*b*), simplified

Denticulated line is related to northern extention of Carpathian overthrust

Fig. 2. The course of the taphrogenic stage of the Mid-Polish Aulacogen (Trough) after Pożaryski and Brochwicz-Lewiński (1978, 1979)

Locations of the boreholes mentioned by Konarski (1974) are indicated; note location of Nieczajna Dolna 3, which is thought to mark a large thickness zone of the trough axis, is outside the zone

lated to the so-called lower escarpment of the East-European Craton (in the original text it was called the northeastern European plate — *op. cit.*), and the furrow itself was believed to have been of geosynclinal nature. The 1070 m thick Upper Jurassic sequence encountered in the Żółcza 1 borehole (drilled in the Carpathian Foredeep area, for location see Fig. 1) was to be indicative of the southeastern continuation of the furrow.

In the 1970s, the geological terminology of the furrow was changed (Pożaryski, 1975; Pożaryski and Brochwicz-Lewiński, 1978, 1979). The term furrow was replaced by the term aulacogen with a taphrogenic (graben) stage (see Fig. 2) with sedimentation controlled by a system of faults and flexures, and a downwarp (syneclise) stage when sedimentation of thick non-faulted sequences occurred over a vast area. The time period between these two stages corresponds to the late Early Cretaceous. Due to independent evolution of the furrow between the Danish and Polish segments, observed from the Middle Jurassic through Early Cretaceous, the term Danish–Polish Aulacogen was subsequently replaced by the term Mid-Polish Trough (Pożaryski, 1975). At the same time, its continuation towards southeastern Poland was proved by interpretations presented in papers by Kutek and Głazek (1972) and Konarski (1974). However, the problem of its further extension into the Tethyan domain (Pożaryski and Żytko, 1981) was subject to polemics (Wdowiarz, 1983). Research on deeper-seated lithospheric zones (Guterch, 1968, 1977) already indicated at that time that, within a 60–100 km wide area parallelling the Teisseyre-Tornquist line to the south-west, there is a zone where the Moho occurs at greater depths than in the adjoining areas. The zone is separated from these areas by deep fault systems. It was noticed then that the zone fairly well coincides with a syneclise stage of the Mid-Polish Aulacogen. However, it was also found out that it significantly deviates from the axis of the Triassic–Jurassic graben in southeastern Poland (Pożaryski and Brochwicz-Lewiński, 1978, 1979).

Later research of the lithosphere (Guterch *et al.*, 1984; Guterch and Grad, 2006) supported the view on the existence of an elongated crustal block between the East European Craton and the Palaeozoic platform, referred to as the Trans-European Suture Zone (TESZ) — Berthelsen (1993). The TESZ is divided by transverse fracture zones into three segments, but locations of these fracture zones are differently marked by various authors (e.g. Guterch *et al.*, 1984; Guterch and Grad, 1996; Dadlez, 1998; Figure 3).

Dadlez (1998) divided the TESZ by transverse crustal fracture zones into three segments of Pomeranian, Kuiavian and Małopolska (Fig. 3). The Małopolska segment is separated from the Kuiavian segment by the Grójec Fault. Although included in the TESZ, the Małopolska segment differs so much from the Pomeranian and Kuiavian segments that Dadlez (1997, 1998) made a conclusion that, in southeastern Poland, the TESZ not only cannot be identified with the Teisseyre-Tornquist Zone because it is wholly located on the East European Craton, but also it is at all impossible for recognition. Anyway, the crustal fracture, bounding the TESZ to the south-west, runs nearby or is a continuation of the Holy Cross Lineament in the Małopolska segment (HCL on Fig. 3). It is significant for the considerations because the Mesozoic sedimentary furrow, understood as the main depocentral axis of the Polish Basin (Stephenson *et al.*, 2003), was located above the TESZ in Northern and Central Poland (Dadlez *et al.*, 1995; Stephenson *et al.*, 2003) and it divorced from the TESZ in southeastern Poland. This observation is in line with a view of Kutek (2001) who postulated that the Mid-Polish Trough developed as an asymmetrical rift basin.

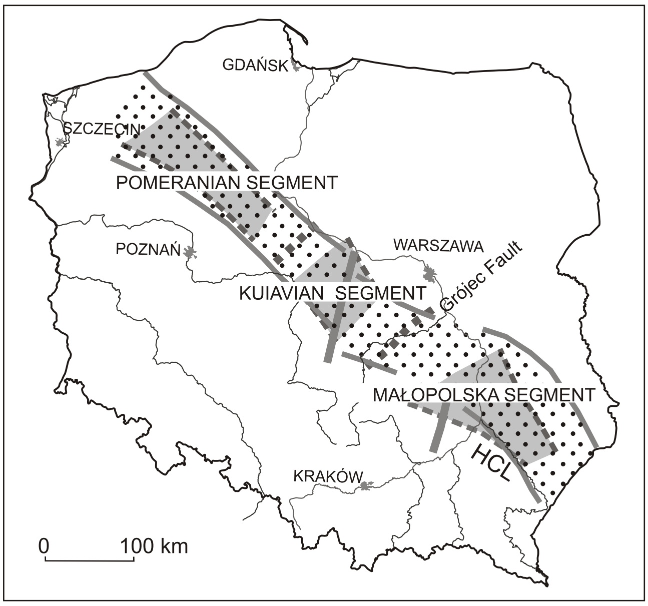

Fig. 3. Teisseyre-Tornquist Tectonic Zone after Guterch *et al.* (1984) and Guterch and Grad (1996) (spotted); and crustal fractures (shaded in grey between them) from deep seismic sounding (DSS) data after Dadlez (1997) simplified

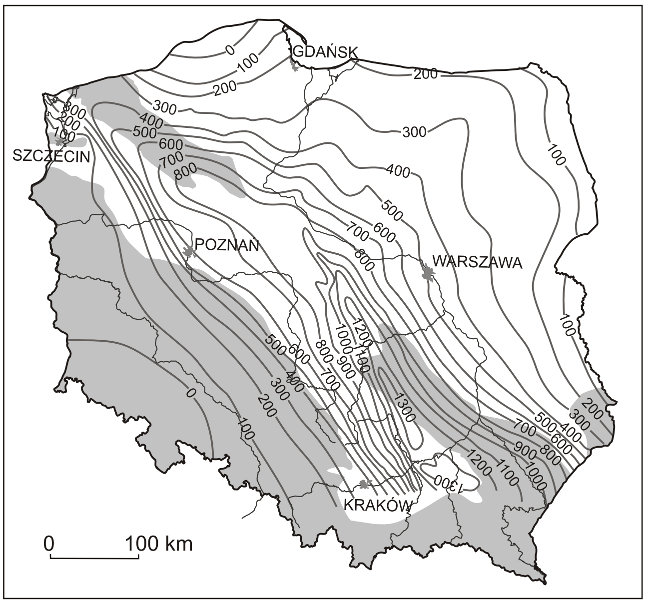

Fig. 4. Palaeoisopachs of the Upper Jurassic after Niemczycka and Brochwicz-Lewiński (1988, fig. 5) simplified

Grey-shaded areas indicate restored isopachs

The idea that the Mid-Polish Trough evolved as the Mid-Polish Rift was presented by Kutek (1989, 1994*b*, 1996, 2001). That author suggested that the southeastern part of the rift, extending south-east of the Holy Cross Lineament, evolved as a prominent rift structure during the late Middle Jurassic, being genetically related to the Carpathian rift system (Kutek, 1989). In a later paper, Kutek (1994*b*) refined his hypothesis claiming that one of the rift systems, developing in Northern and Central Poland, was bordered by the Holy Cross Lineament. The other one, the Carpathian rift system developing in the south-east, formed as a result of northward propagation of the rift zone from the Carpathian domain into cratonic areas of Western Ukraine and southeastern Poland. Both the rift systems met at the Holy Cross Lineament and amalgamated during Middle Jurassic times (Kutek, 1994*b*, p. 206). The Holy Cross Lineament started to play a role of a transfer fault at those times; hence, it was called the Holy Cross Transfer Fault.

The Mid-Polish Rift was an asymmetric rift. Its proximal part in southeastern Poland was located in a place of the present day Lower San Anticlinorium. Its distal parts were situated further south-westwards in the Nida Synclinorium, Silesia-Kraków Monocline and Upper Silesia Coal Basin (Kutek, 1996). A graben or half-graben stage of its evolution, i.e. typical rifting phase, commenced in the Callovian and the last rifting pulse occurred in the Middle and Late Albian. The transition from a synrift to sag basin stage took place at the Albian/Cenomanian boundary (Kutek *op. cit.*). The fundamental theses of the concept of Mid-Polish Rift evolution were recently recalled (Kutek, 2001) in a broader context of the Polish Basin evolution. For these considerations it is very important to identify stronger subsidence rates during the Oxfordian in areas situated at a certain distance to the west of the rift. Such strong subsidence is consistent with the simple-shear extension controlling the Mid-Polish Rift.

Hakenberg and Świdrowska (1997, p. 802), Dadlez *et al.* (1998, p. 54) and Stephenson *et al.* (2003, p. 68) made some objections regarding various aspects of the presented concept on the rifting evolution of the Mid-Polish Trough. Detailed sedimentary and tectonic evolution of the SW margin of the East European Craton from Permian to early Maastrichtian time was presented nowadays by Świdrowska *et al.* (2008).

It should be noted in conclusion that, since it has been discovered, the Mid-Polish Trough has also encompassed the area of southeastern Poland (Pożaryski, 1957*a*). In the evolution of views on the trough, from a geosyncline-type sedimentary basin (Pożaryski, 1957*b*) through an aulacogen (Pożaryski and Brochwicz-Lewiński, 1979) to a rift (Kutek, 1989, 1994*b*, 1996, 2001), the Late Jurassic evolutionary stage played an essential role.

All interpretations are based on the presence of a huge 1300 m thick deposits encountered in the substrate of the Carpathian Foredeep (Fig. 4), assumed to be of Oxfordian and Kimmeridgian age. Moreover, the deposits are situated broadly on the southeastern extension of the Mid-Polish Trough axis (Niemczycka and Brochwicz-Lewiński, 1988; Kutek 1994, 2001 and Fig. 5 here). Therefore, the problem of Late Jurassic history of the Carpathian Foredeep area seems to be especially important in terms of the above presented.

UPPER JURASSIC AND LOWER CETACEOUS DEPOSITS OF THE CARPATHIAN FOREDEEP SUBSTRATE

The Upper Jurassic data are based on the most recent stratigraphical investigations. Their preliminary (Matyja and Barski,

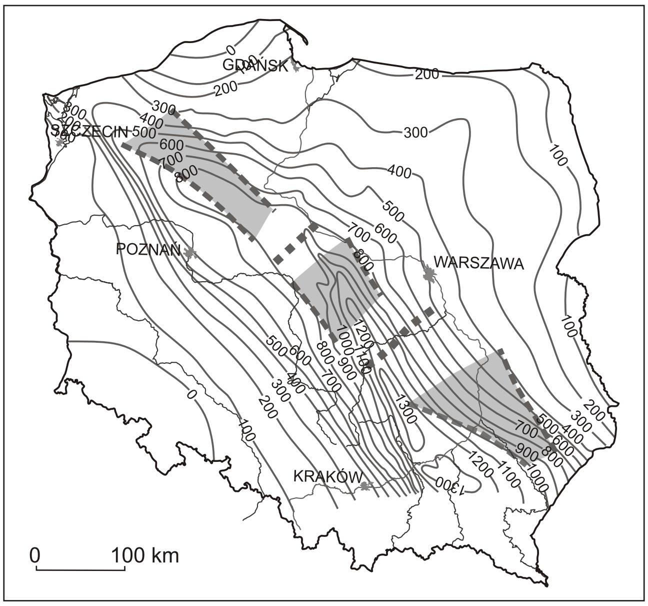

Fig. 5. Upper Jurassic isopachs (after Niemczycka and Brochwicz-Lewiński, 1988; see also Fig. 4) superimposed on the Trans-European Suture Zone (TESZ) (after Dadlez, 1997; see also Fig. 3)

2007) or final but briefly presented (Barski and Matyja, 2008*a*, *b*) results have already been published. A comprehensive report on the stratigraphical studies is currently under preparation.

A number of lithostratigraphic units, holding the rank of formations and members, have been established within the entire continuous Upper Jurassic–Lower Cretaceous sequence. However, these are informal units and thus are used with uncapitalized lithologic and unit-terms (Salvador, 1994). If possible, the previously used unit names have been maintained because some of the successions in individual sections from the study area were very thoroughly analysed (Morycowa and Moryc, 1976; Golonka, 1978; Zdanowski *et al*., 2001; Bobrek *et al*., 2002). Due to the limited coverage of the paper, research history and synonymy of the lithostratigraphic units are not presented.

The two oldest formations, Łękawica sponge limestone Formation and Niwki limestone-marly formation, occur throughout the whole Carpathian Foredeep area. The remaining formations are located in the northern or southern regions. The boundary between them runs longitudinally south of Dąbrowa Tarnowska (see Fig. 6). Earlier reports on the variability within the Upper Jurassic deposits, with regard to the Algal-Oolitic Series, between the north and south were given by Golonka (1978).

ŁĘKAWICA SPONGE LIMESTONE FORMATION

The lower portion of the Upper Jurassic succession of the Carpathian Foredeep substrate is composed, like much of the epicontinental Polish Basin, of the so-called Sponge Megafacies. The Sponge Megafacies corresponds here to the Łękawica sponge limestone formation of very variable thickness resulting from both facies variability (bedded and biohermal limestones) and its different stratigraphical ranges in individual sections. The Łękawica formation is commonly overlain by the Niwki limestone-marly formation. In areas of strong development of biohermal facies, it is immediately overlain either by the Swarzów limestone formation (northern region) or by the Pilzno coralliferous limestone formation (southern region). An interfingering of the Łękawica sponge limestone formation with the Niwki limestone-marly formation is observed in a number of sections. There are also sections where sponge limestones overlie the Niwki formation. Therefore, the upper sponge limestone member has been established for this part of the Łękawica formation that overlies the Niwki formation. The spatial relationships between these formations are illustrated in Figure 7.

Thickness[1] of the Łękawica formation is variable and ranges from 68 m to 570 m.

NIWKI LIMESTONE-MARLY FORMATION

The limestone-marly formation was established by Morycowa and Moryc (1976). Golonka (1978) called these deposits the Niwki series. It is composed of marls, marly limestones and pelitic limestones containing rare organic remains.

The Niwki limestone-marly formation overlies or interfingers the Łękawica formation, but is overlain by different lithostratigraphic units: the Pilzno coral limestone formation or upper sponge limestone member in the south, and the Swarzów limestone formation in the north.

As mentioned above, the Łękawica formation can occur as a lateral equivalent to the Niwki formation. It is manifested by the occurrence of sponge limestone interbeds in a number of borehole sections in different parts of the Niwki formation. Thickness of the Niwki formation varies from 0 to 587 m.

SWARZÓW LIMESTONE FORMATION

This formation was established by Morycowa and Moryc (1976) as the coralliferous-algal formation in the Dąbrowa Tarnowska region. It consists mostly of various types of grained limestones (e.g., organodetrital, oolitic and oncolitic limestones) with abundant corals and algae. More detailed lithological and well-log characteristics is given by Morycowa and Moryc (*op. cit.*). Thickness of the Swarzów limestone formation ranges between 118 and 177 m.

SMĘGORZÓW COQUINA FORMATION

This formation was established by Morycowa and Moryc (1976) as the limestone-dolomitic coquina formation in the

[1] The values refer to complete thicknesses preserved within the Upper Jurassic–Lower Cretaceous succession. If part of the formation's deposits was removed by subsequent erosion, it is clearly stated.

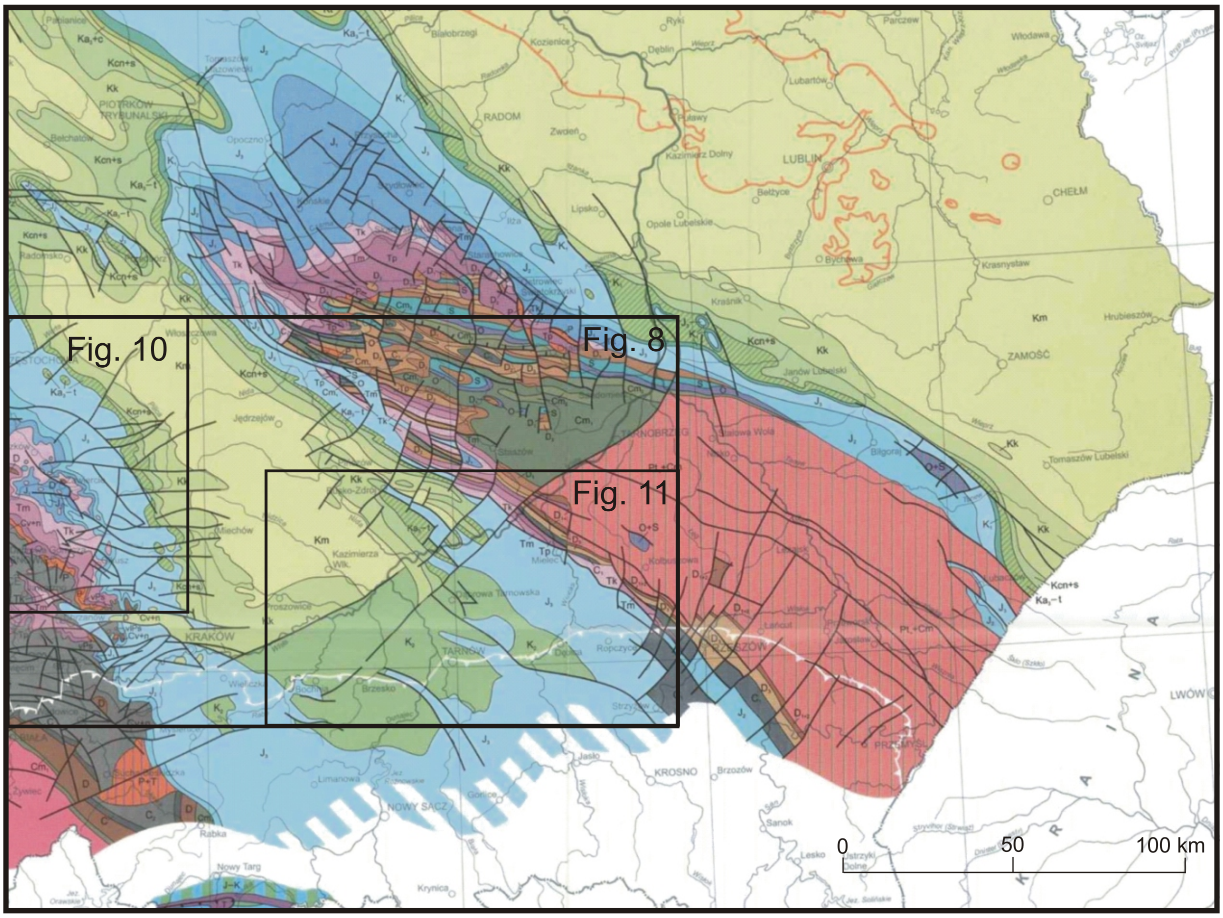

Fig. 6. Location map of area illustrated in Figures 8–10 in the Geological Map of Poland without Cainozoic Deposits (Dadlez *et al*., 2000)

Dąbrowa Tarnowska region. The lower part of the formation commonly contains a 2–5 m thick marl bed, mostly slightly sandy and with glauconite. Above, there is a series of organodetrital limestones containing abundant bivalves and crinoids, with interbeds of detrital and oolitic limestones. This series is overlain by a more marly coquina layer composed mostly of unbroken shells representing mainly oysters.

The uppermost portion of the succession consists largely of coquina limestones and marls with abundant *Exogyra* individuals. These deposits represent the Smęgorzów coquina formation with its lithological and well-log characteristics given by Morycowa and Moryc (1976). The extent of the Smęgorzów coquina formation is limited to the northern facies region. The formation is nowhere preserved in full; its upper boundary is erosional. The maximum preserved thickness of the formation is 160 m.

PILZNO CORAL LIMESTONE FORMATION

This formation, established by Matyja and Barski (2007) is represented by a few hundred metres thick reef-forming coralliferous limestones. This formation occurs in the southern region and forms a latitudinally extending zone near the Carpathian Thrust front between the areas located about 20 km east of Dębica and about 15 km west of Tarnów (Fig. 8). Their western and eastern boundaries are erosional. This formation generally overlies the Niwki formation or the Łękawica formation, and is overlain by the Ropczyce formation. There are also areas where the Pilzno formation laterally interfingers with part of the Niwki formation.

Thickness of the Pilzno formation varies from 0 to 466 m.

ROPCZYCE LIMESTONE FORMATION

Golonka (1978) defined the Ropczyce formation as a dolomitic-limestone series (Ropczyce series). This formation is clearly bipartite and thus subdivided into two members (Zdanowski *et al*., 2001; Maksym *et al*., 2001). The lower member, referred to as the limestone-dolomitic member, is composed mainly of limestones and dolomites containing pseudomorphs after gypsum, evaporite-solution collapse breccia, *Clypeina* biomicrites and laminated bird's-eye limestones (Maksym *et al*., 2001). The upper member, so-called limestone-marly member, is characterized by a considerable increase in clay content and admixture of detrital quartz grains (*op. cit*.).

Thickness of the Ropczyce formation is 312–423 m. Thicknesses of the limestone-dolomitic and limestone-marly members are 92–319 m and 66–114 m, respectively.

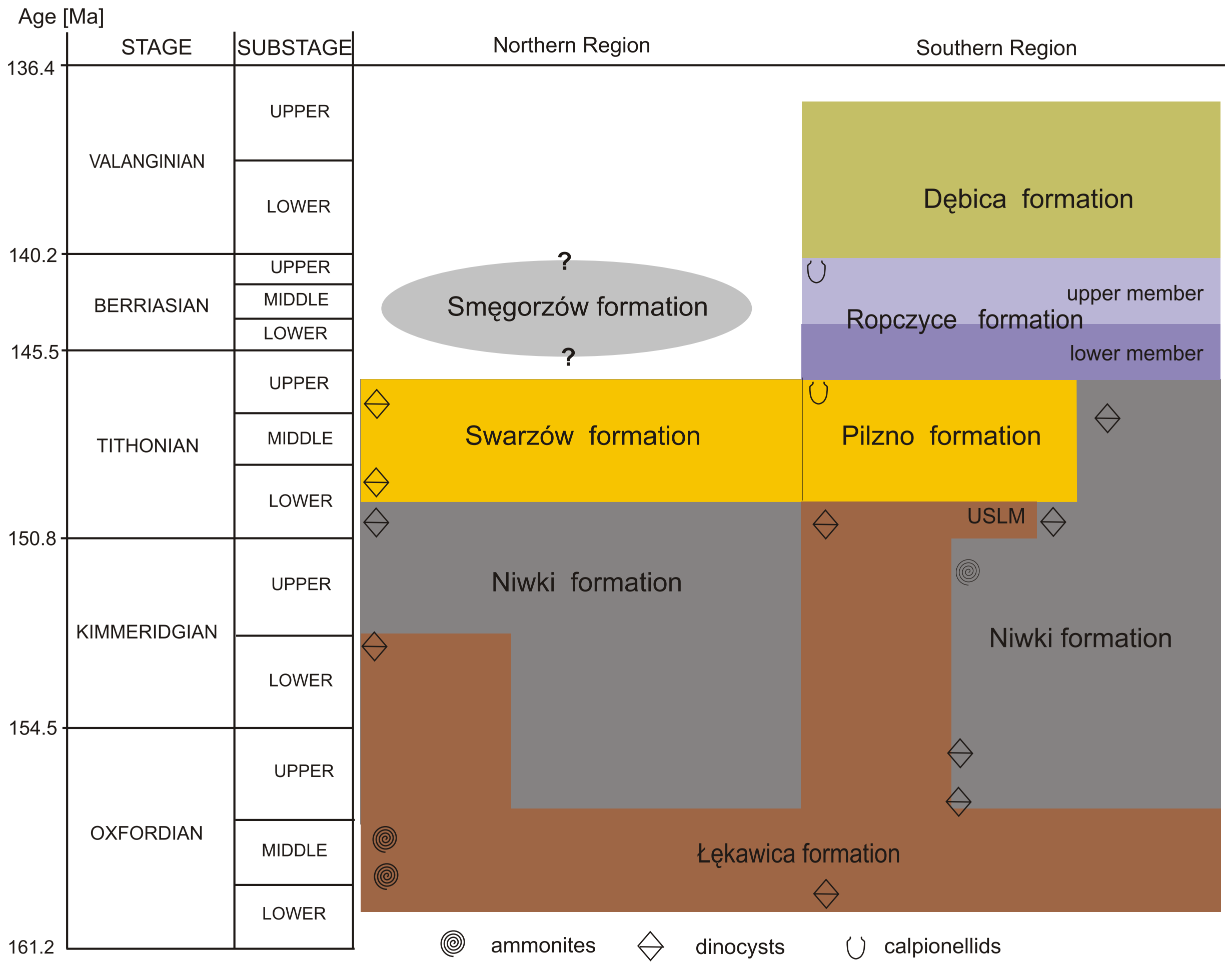

Fig. 7. Chronostratigraphic position of the Upper Jurassic and Lower Cretaceous lithostratigraphic units in the Carpathian Foredeep area (based on Barski and Matyja, 2008*b*)

USLM — upper sponge limestone member

DĘBICA LIMESTONE FORMATION

The Ropczyce formation is overlain by the upper algal series (Dębica series) identified by Golonka (1978). It is represented by organogenic algal limestones and grainstones. The complete thickness of the Dębica formation is unknown due to its erosional upper boundary. The maximum preserved thickness is 94 m.

STRATIGRAPHIC POSITION OF THE LITHOSTRATIGRAPHIC UNITS

The most serious disadvantage of the previous reports on the Upper Jurassic deposits from southeastern Poland was the lack of stratigraphical analyses. Studies of ammonites, as orthostratigraphic fossils, enabled both establishing the stratigraphic position and making a very thorough correlation between different facies types within the Upper Jurassic succession of the Kraków–Częstochowa Upland (see Matyja and Wierzbowski, 2004) and the southwestern margin of the Holy Cross Mountains (see Kutek, 1968; Matyja 1977), i.e. outcrop areas fringing the Nida Synclinorium.

Ammonite finds are not numerous in these rocks, neither are illustrations of the specimens (e.g., Król, 2004). Middle Oxfordian ammonites have been reported by Król (2004). From a pelitic limestone series, that author reports the presence of *Cardioceras* (*Plasmatoceras*) sp., whereas *Perisphinctes* (*Dichotomosphinctes*) sp. is known from the lowermost part of the sponge limestone succession. The former specimen documents the lower part of the Plicatilis Zone, while the latter one — the Middle Oxfordian Transversarium Zone. Both the mentioned lithologies correspond to the lowermost part of the Łękawica formation. All these data indicate that the lower part of the Łękawica sponge limestone formation occupies the same stratigraphic position as the Częstochowa sponge limestone formation from the Polish Jura Chain (e.g., Matyja and Głowniak, 2003) and the southwestern margin of the Holy Cross Mountains (Matyja, 1977).

Only two ammonites have been cited, but not illustrated, from younger deposits. One of them was found in the lower part (member "b") of the limestone-dolomitic coquina forma-

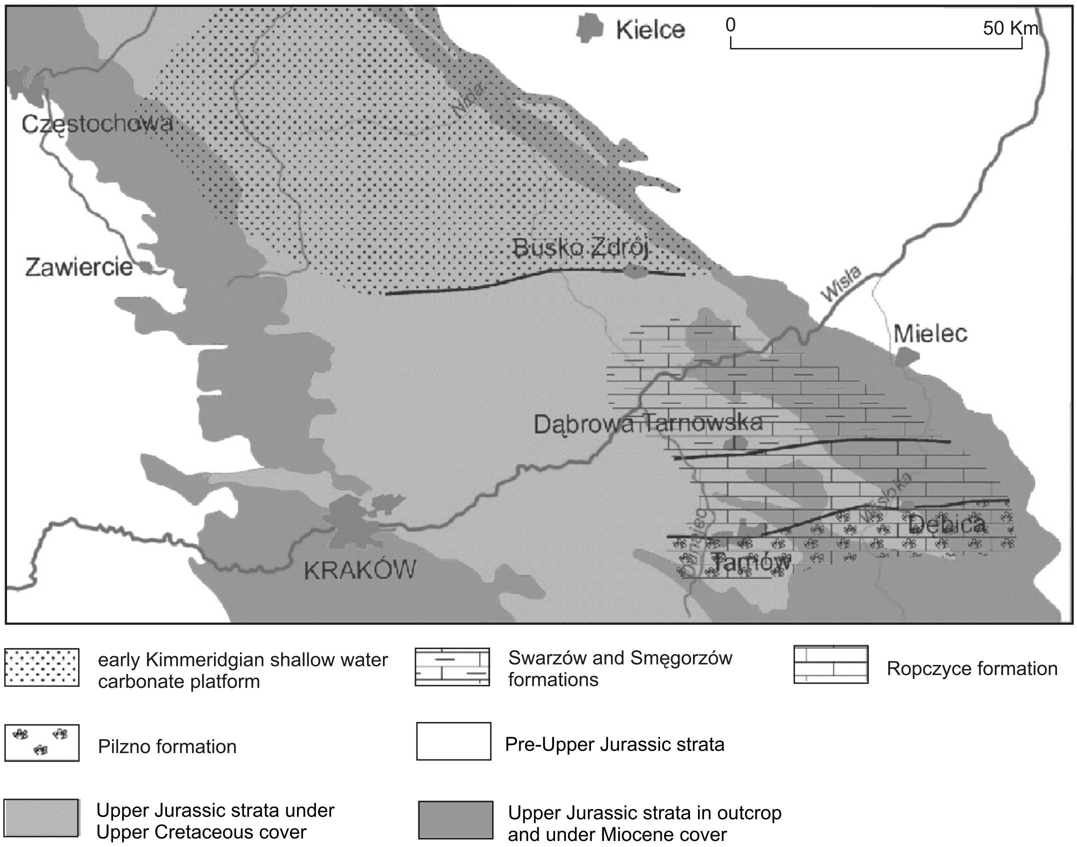

Fig. 8. Distribution of Early Kimmeridgian shallow water carbonate platform and selected formations

For area location see Figure 6

tion (Smęgorzów formation in this report) — see Morycowa and Moryc, 1976. This ammonite was identified by Cimaszewski (pers. comm. Moryc) as *Ataxioceras* sp. indicating the lower Kimmeridgian. The stratigraphic position of these deposits is in a dramatic contradiction to the remaining age determinations presented in this paper (see below). The other ammonite specimen was found 30 m beneath the top of the Niwki formation. It was identified as *Orthosphinctes* sp. by Gutowski (Gutowski *et al*., 2007) and is actually identified as representative of much younger evolutionary lineage of *Discosphinctoides–Sarmatisphinctes–Ilowaiskya* occurring from the upper Kimmeridgian Autissiodorensis Zone through the lower Tithonian (see Kutek and Zeiss, 1997). The preserved specimen resembles individuals of the former genera.

Previous biostratigraphic determinations of other microfossils enable augmenting or supporting the Upper Jurassic stratigraphy of the Carpathian Foredeep area, presented in this paper.

Since the 1970s, there has been a lot of information about the occurrence of tintinnids in the Algal–Oolitic Series (corresponding to the Swarzów and Pilzno formations in the present paper) from which Golonka (1978) reported the presence of a specimen representing "...probably the genera of *Crassicolaria*...". Morycowa and Moryc (1976) also illustrated "...microfossils resembling tintinnids..." (*op. cit*., p. 250, pl. 14, fig. 1a–e, h and fig. 2) from the member "d" of the Coralliferous-Algal Limestone Formation (Swarzów formation in this report). In the light of the new data, those previously recognized occurrences create a suprisingly coherent image of the stratigraphy (Matyja and Barski, 2007; Barski and Matyja, 2008*a, b*).

Among other microfossils used as biostratigraphic indicators, calcareous dinocysts, foraminifers (Garlicka, 1974; Olszewska, 1998, 1999; Bobrek *et al*., 2002); and recently organic dinoflagellate cysts (Matyja and Barski, 2007; Barski and Matyja, 2008*a*, *b*) are the most important.

Analysis of organic associations of dinoflagellate cysts indicates that most samples contain rich and well-preserved palynological material. The most abundant associations were found in the Niwki formation and part of the Łękawica sponge limestone formation. With few exceptions, poor but especially important results have been obtained from younger deposits.

The results of biostratigraphic analyses are presented below (see also Fig. 7).

The onset of marly sedimentation of the Niwki formation falls on the late Oxfordian Bifurcatus Chron. The documented upper boundary of the Niwki formation runs within the lower Tithonian in most of the borehole sections. The only area where it ranges up at least to the upper Tithonian is the south-east of the southern region. It is worth noting that at least 200 m thick part of the Niwki formation was assigned by Golonka (1978) to the Kimmeridgian, based on foraminifera studies. Analysing, among others, calcareous dinocysts, Olszewska (1998) placed the upper boundary of the Niwki formation within the upper Kimmeridgian.

The stratigraphical range of the Łękawica formation is variable. Its lower boundary runs within the lower Oxfordian whereas the upper one can range up into either the upper Oxfordian Bifurcatus Zone or even the lower Tithonian.

Dinocyst determinations, made on the Swarzów limestone formation, document a stratigraphic interval comprising the upper lower Tithonian to upper Tithonian, and probably uppermost upper Tithonian–Berriasian.

The age of the Smęgorzów coquina formation remains unclear. It cannot be precluded that it is late Tithonian or Berriasian.

The age of the Pilzno coral limestone formation was directly determined by the presence of an upper Tithonian tintinnid assemblage (Barski and Matyja, 2008*a*). Because the Pilzno formation overlies in general both the Niwki and Łękawica formations, which range up into the lower Tithonian, it can be assumed that the Pilzno formation started to be deposited not earlier than during the early Tithonian.

The upper boundary of the Pilzno formation is defined by the age position of the Ropczyce formation. In the Zagorzyce 6 borehole, in the limestone–marly member of the upper part of the Ropczyce formation, the so-called small form of *Calpionella alpina* was found at a depth of 2836 m (Olszewska, 1999). Such forms first occurred at the base of the calpionellid "zone B" and persisted through the calpionellid "zone D" corresponding to the uppermost Tithonian–lowermost Valanginian interval (Remane, 1985). Between the limestone–marly member of the Ropczyce formation and the Pilzno formation there is the limestone–dolomitic member of the Ropczyce limestone formation (92–319 m in thickness) representing an extremely shallow-marine, locally lagoonal environment. Assuming that the environment's development resulted in a breaking of the marine communication with the basin in Central Poland, and knowing that it occurred precisely in the zarajskensis horizon of the late Tithonian Scythicus Chron (Kutek, 1994*a*), I lean to the opinion that the stratigraphic position of the Pilzno coral limestone formation at the current stage of study falls between the upper part of the lower Tithonian and the lower part of the upper Tithonian (Fig. 7).

The stratigraphical analysis has shown that the stratigraphic position of the Upper Jurassic deposits in the Carpathian Foredeep substrate is characterized by a strong peculiarity in relation to lithologically similar Upper Jurassic deposits from the margin of the Holy Cross Mountains and Nida Synclinorium, which they were previously correlated with. The most important attributes of the peculiarity are as follows:

— A much greater stratigraphic range of the Łękawica sponge limestone and Niwki limestone-marly formations. In the southern region of the Carpathian Foredeep, the sponge megafacies, represented by the Łękawica formation, ranges up into the lower Tithonian, whereas towards the north i.e. in the SW margin of the Holy Cross Mountains it is replaced in the uppermost Oxfordian by a shallow water carbonate platform (Kutek, 1968; Matyja *et al*., 1989). In the Wieluń Upland, the megafacies also covers lower Kimmeridgian deposits (Wierzbowski *et al*., 1983). The Niwki formation was supposed to be of Oxfordian (Morycowa and Moryc, 1976; Gliniak *et al*., 2004; Gutowski *et al*., 2007) or partly Kimmeridgian age (Golonka, 1978; Olszewska, 2004), but it ranges up into the lower Tithinian or even into the upper Tithonian in some sections.

— Development of the Tithonian shallow water carbonate platform. Carbonate platform facies of the northern region (Swarzów limestone formation) were so far considered late Oxfordian (Morycowa and Moryc, 1976) or Kimmeridgian in age (Golonka, 1978; Olszewska, 1999, 2001, 2004; Gutowski *et al*., 2007).

— Development of reefal deposits (Pilzno formation) representing the uppermost lower Tithonian through upper (but not uppermost) upper Tithonian as an equivalent of the Štramberk limestones.

The new biostratigraphic data served both for a modification of previously developed Late Jurassic palaeogeographic reconstruction and for a verification of the distribution and thickness pattern in individual Jurassic stages.

Stratigraphically, most of the Upper Jurassic sequence in the basement of the peri-Carpathian Foredeep is composed of two formations:

1. The Łękawica formation represented by bedded limestones and thick microbialite-sponge bioherms;

2. The Niwki formation represented by marls and marly limestones, locally by micritic limestones.

The Oxfordian portion of the sequence is similar to that found in adjacent areas. Essential changes are observed at the base of the Kimmeridgian succession. In the SW margin of the Holy Cross Mountains, a shallow marine carbonate platform developed in late the Planula Chrone of the late Oxfordian (Matyja *et al*., 1989), and continued in the early Kimmeridgian (Kutek, 1968, 1969). However, it did not reach the foredeep area (Figs. 8 and 9). Only in the northernmost sections, the Niwki formation contains thin interbeds of detrital limestones supposedly representing a distal part of the platform.

In the Polish Jura Chain, erosional processes removed almost all Kimmeridgian deposits. Limestones, containing colonial corals, are preserved in a number of sites only in the easternmost areas of the outcrops (see Fig. 8). These limestones correspond in age to the uppermost Oxfordian or, more likely, to the lowermost lower Kimmeridgian (see Matyja and Wierzbowski, 2006*a*).

In the area located further to the south along the Upper Jurassic outcrops there are Pilica formation deposits at the Oxfordian/Kimmeridgian boundary, represented by micritic limestones with subordinate marl interbeds (Matyja and Wierzbowski, 2004). In the reconstructed Late Jurassic palaeogeographic image (*op. cit*.) this facies change is observed in an area between the Kroczyce biohermal complex and Pilica interbiohermal basin (see Fig. 10). It seems probable that the zone of facies changes was associated with activity of the latitudinally trending Zawiercie Lineament identified by Kutek (1996, 2001). Kutek (1996, p. 60; 2001, p. 220) reported a number of features discriminating the areas situated to the north and south of the lineament in both the Silesian–Kraków Monocline and the eastern margin of the Mid-Polish Anticlinorium. An additional feature is that other facies changes are observed also in the Juras-

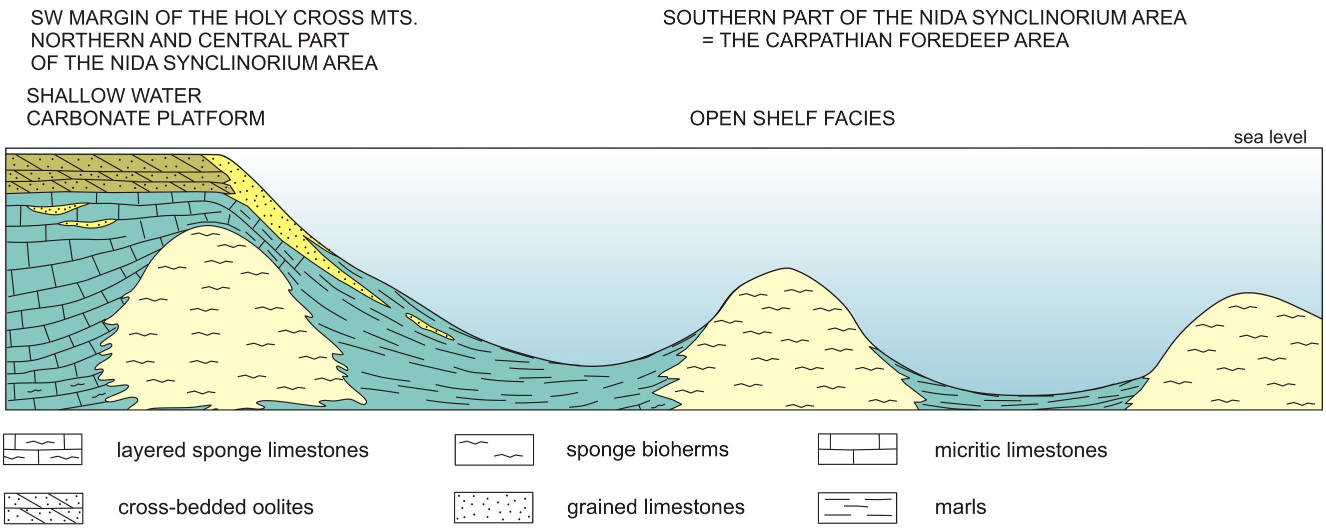

Fig. 9. Facies and bathymetry relationships in the early Kimmeridgian between the SW margin of the Holy Cross Mountains and the northern and central area of the Nida Synclinorium, and the peri-Carpathian Foredeep area

sic succession of this area. Describing the Middle and early Late Jurassic facies, Różycki (1953) situated the boundary between the major facies units (northern region of Częstochowa–Zawiercie and southern region of Olkusz–Kraków) slightly to the south of Zawiercie. Another change is observed in the distribution trend of Oxfordian biohermal complexes along a line crossing Zawiercie. South of Zawiercie, the biohermal complexes show a latitudinal extent, whereas north of Zawiercie, NE–SW trends are also observed (see Fig. 10). The extents of biohermal complexes are related to the orientation of substrate elevations developed both prior to and during Oxfordian times (Matyja and Wierzbowski, 2004).

The upper part of the Upper Jurassic–Lower Cretaceous sequence also exhibits latitudinal facies variability. The Tithonian shallow marine carbonate platform (Swarzów formation) and the overlying coquina-marly deposits (Smęgorzów formation) are typical of the northern facies region in the peri-Carpathian Foredeep. Latitudinally extending Tithonian coral reefs of huge thicknesses (Pilzno formation) are observed in the southern region near the present-day Carpathian thrust front. They are overlain by calcareous peritidal deposits (limestone-dolomitic member of the Ropczyce formation) followed by very shallow marine and continental marly deposits (limestone-marly member of the Ropczyce formation — Zdanowski *et al*., 2001) representing the Berriasian stage (Olszewska, 1998). The preserved part of the succession is topped by shallow marine carbonate platform deposits (Dębica formation) assigned to the Valanginian (Bobrek *et al*., 2002; Dziadzio *et al*., 2004). The boundary between the northern and southern regions, delineated by the southern extent of the formations, runs roughly latitudinally slightly to the south of Dąbrowa Tarnowska (see Fig. 8).

The Oxfordian-Valanginian succession, formerly assigned to the Oxfordian and Kimmeridgian (Niemczycka and Brochwicz-Lewiński, 1988), is 1247–1373 m thick. The Żółcza 1 borehole, referred to by Pożaryski (1957*b*), Grobla 28, Nieczajna Dolna 3 boreholes (Konarski, 1974) and a number of sections described by Morycowa and Moryc (1976) were drilled through the sequence in the Carpathian Foredeep substrate. All of the sections were used by Pożaryski and Brochwicz-Lewiński (1978, 1979), Niemczycka and Brochwicz-Lewiński (1988) and Kutek (1994*b*, 2001) for reconstructions of the Mid-Polish Trough.

New stratigraphic data indicates that the total thickness of the Oxfordian and Kimmeridgian strata in the Carpathian Foredeep substrates varies from 371 up to 799 m (see Fig. 11)[2]. These figures are twice or three times smaller than those which were used for the reconstructions of the extend of the Mid-Polish Trough in the Carpathian Foredeep area.

A RELATION OF THE RECOGNIZED DEPOSITIONAL SUCCESSION TO THE TETHYS OCEAN DOMAIN

The Upper Jurassic deposits of the Carpathian Foredeep substrate are included into two panregional facies patterns, both related to the Tethyan area. The older facies pattern is represented by the sponge megafacies defined as bedded or biohermal carbonate deposits (limestones and marls) containing Lithistida and Hyalospongea (Hexactinosa and Lychniscosa) siliceous sponges preserved as calcareous "mummies" (Matyja and Pisera, 1991). In this sense, the sponge

[2] Figure 11 illustrates the total thicknesses of the Łękawica and Niwki formations as roughly corresponding to the thicknesses of the Oxfordian and Kimmeridgian. The real thickness of the Oxfordian and Kimmeridgian deposits is lower because the upper boundary of the Kimmeridgian succession commonly runs several metres to a few tens of metres below the upper boundary of these formations, as evidenced by data from some borehole sections. Thickness values are given only for individual sections because drawing isopachs requires obtaining more comprehensive data on structural constraints, which is outside the scope of the present paper.

Fig. 10. Distribution of the Oxfordian biohermal complexes (b.c. — in brown) and interbiohermal basins (i.b-b. — in blue) in the Kraków–Częstochowa Upland (after Matyja and Wierzbowski, 2004)

megafacies was widespread in the northern Tethyan shelf and can be traced from Portugal through the Spain's Celtiberic and Praebetic provinces, Jura Mountains in France and Switzerland, across Swabian Alb, Franconian Alb, Moravia and Poland towards Ukraine. The maximum development of the sponge megafacies in Europe took place during the Oxfordian (see Matyja and Wierzbowski, 1995, Fig. 1), but local occurrences are observed in all the Upper Jurassic stages (e.g., Ziegler, 1977; Leinfelder, 1993).

The development of the sponge megafacies was preceded by a considerable deepening of the marine basin. In biostratigraphically well-dated Upper Jurassic sections of the Polish Jura Chain, the deepening is marked within the middle Callovian–lowermost Oxfordian interval (Giżejewska and Wieczorek, 1977; Dembicz and Praszkier, 2003). The effect of the deepening is observed also in Northern and Central Poland. Among the three major Permo-Mesozoic tectonic subsidence events, the middle one occurred in the Late Jurassic (Dadlez *et al.*, 1994). Initially (Dadlez *et al.*, 1994), no synchroneity was seen between event II (extensional event) and geological processes in the Carpathian Basin, as evidenced by the results of Birkenmajer's studies (1985) who did not consider the Middle/Late Jurassic transition as the main rifting phase in the Carpathians. Although the event occurred during intensification of crustal extension within the Arctic-North Atlantic rift system (Ziegler, 1990), the event was also supposed to have been related to the development of rifting processes at the northern flank of the Tethys (Dadlez *et al.*, 1995). It was noticed then (Dadlez *et al.*, 1998, p. 52) that the Late Jurassic increase in subsidence rate is very weakly marked in the NW portion of the trough, more distinct in its central part, and best pronounced along the profile LT-5 situated in the south-easternmost part of the study area. In its later reconstruction of the Tethyan Ocean evolution, Birkenmajer (1986) postulated the extensional regime and the formation of an oceanic crust for the Pieniny Klippen Basin and the Magura Basin "...during Late Liassic or even Mid-Late Jurassic times..." (*op. cit.*, p. 23).

The stage of rapid spreading of the Tethys Ocean basins occurred at the Middle/Late Jurassic transition. The range of the spreading was determined mainly by palaeomagnetic data from the Pieniny Klippen Belt of southwestern Ukraine (Lewandowski *et al.*, 2005) and Slovakia (Lewandowski *et al.*, 2006). Matyja and Wierzbowski (2006*b*) reported the relationship of these dynamic extensional processes at the turn of Mid-

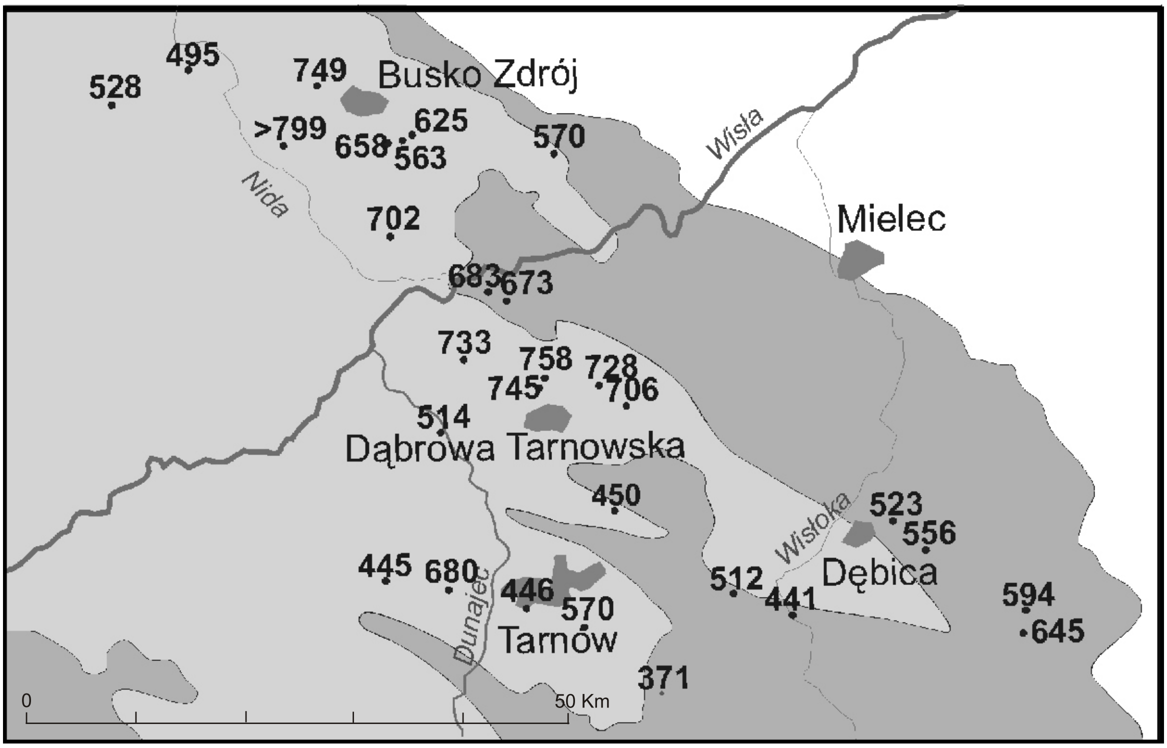

Fig. 11. Total thickness in metres of the Łękawica and Niwki formations in the Carpathian Foredeep area

For area location see Figure 6, explanations as in Figure 8

dle/Late Jurassic in the outer basins of the Tethys Ocean to the processes that occurred in the adjoining shelf area, calling it the Metis Geotectonic Event.

The younger panregional facies pattern is represented by the Štramberk limestones. This facies was better studied in the western part of its range and treated as a belt fringing (delimiting) the Tethys shelf area (Mišik, 1974). The identification of the eastward continuation of this belt (Pilzno formation) to the outside of the Bohemian Massif margins allows considering the Štramberk limestones as a facies that rimmed the shelf. It is worth adding that the Pilzno formation reefs formed a very prominent latitudinally elongated belt. There was no dependence of the reef location on the earlier basinal differentiation into biohermal and interbiohermal basins. The reefs are situated both in areas of development of the Łękawica formation basinal facies, and upon previously formed microbialite-sponge bioherms of considerable thicknesses.

CONCLUSIONS

The Upper Jurassic and Lower Cretaceous deposits of the Carpathian Foredeep substrate show a number of distinctive palaeogeographic features discriminating the area from areas located to the north. These are the following features:

1. Lack of the early Kimmeridgian shallow marine carbonate platform identified in the southwestern margin of the Holy Cross Mountains (Kutek, 1968) and in the central area of the Nida Synclinorium (Jurkiewicz *et al*., 1969).

2. Much greater stratigraphic range of the sponge megafacies (reaching into the lower Tithonian) than in the remaining area of Poland.

3. Latitudinal pattern of the Tithonian and Early Cretaceous facies in the Carpathian Foredeep area.

These features, along with data on the total thickness of the Oxfordian and Kimmeridgian succession (twice to three times smaller than previously assumed) and the variable thickness distribution, contradict the presence of a NW–SE-trending zone (i.e. in line with the Mid-Polish Trough axis) of increased subsidence in the Carpathian Foredeep area during Late Jurassic and earliest Cretaceous times.

The same features, supported by the presence of a latitudinal belt of coral reefs of the Štramberk facies (Pilzno formation), suggest that the study area is related to the Tethyan domain.

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