Early and Middle Jurassic tectonically controlled deposition in the High-Tatric succession (Tatricum), Tatra Mountains, southern Poland: a review

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The High-Tatric succession of the Tatra Mountains represents the Tatricum domain of the Central Western Carpathians, which in the Jurassic was located on the southern margin of the incipient and expanding Vahic Ocean—a branch of Western Tethys. This paper describes the various depositional consequences of extensional tectonic activity as it impacted on sedimentation in the High-Tatric succession of the Tatra Mountains during the Early and Middle Jurassic. Evidence of such impacts on depositional style and facies development are present within the Dudziniec, Smolegowa and Krupianka formations, in all the High-Tatric tectonic units. These impacts also include erosional surfaces and sedimentary gaps separating particular formations, commonly associated with minor angular unconformities. The Lower Jurassic, pre-Bajocian, Dudziniec Formation of the Komin Tylkowe (autochthonous) Unit is developed in mixed carbonate-clastic facies. The occurrence and proportion of sand-dominated and carbonate-dominated facies, as well as their thickness differences, were controlled by syndepositional tilt-block tectonics, taking place both in depositional and in neighbouring source areas. The Smolegowa and Krupianka formations (Bajocian–Bathonian) occur in all High-Tatric tectonic units, but in the Czerwone Wierchy and Giewont units they are represented mainly by laterally discontinuous bodies of crinoidal limestone of very limited thickness. The preservation of these deposits only in some areas, as well as their thickness reductions, are effects of differentiated subsidence and uplift of isolated blocks taking place in an extensional regime. Moreover, the Krupianka Formation abounds in condensed facies with ferruginous crusts and stromatolites—a feature characteristic of rapidly drowning ocean margins. Deposits of the Dudziniec, Smolegowa and Krupianka formations are also preserved as infills of extensive systems of neptunian dykes penetrating mainly the Triassic substrate, which is yet another classic symptom of synsedimentary extension. The dominant influence of tectonics on sedimentary development ceased with the onset of deposition of the Raptawicka Turnia Formation in the Callovian.

Key words: Central Western Carpathians, Vahic Ocean, Jurassic, High-Tatric series, synsedimentary tectonics.

INTRODUCTION

During the Early and Middle Jurassic, the Tatricum palaeogeographical domain constituted a part of the Central Western Carpathian (CWC) block (e.g., Michalík, 1993, 1994; Jurewicz, 2005; Płaśienka, 2012, 2013). Tatricum occupied the northern part of the block directly neighbouring a newly developing branch of the Western Tethys. In its Alpine sector this branch is referred to as the Piedmont-Ligurian Ocean (e.g., Lemoine et al., 1986; Dumont et al., 1996; Decarlis, et al., 2017), Alpine Tethys (e.g., Masini et al., 2013; Roda et al., 2019), Alpine-Mediterranean Tethys (e.g., Bernoulli and Jenkyns, 2009), and South Penninic Ocean (Frisch, 1979; McCann, 2008; Płaśienka, 2012, 2013). In the Carpathian sector, terms such as: Pieniny Basin (e.g., Birkenmajer, 1986; Golonka and Krobicki, 2004); Vahic Ocean or Vahicum (e.g., Płaśienka, 1995, Wieczorek, 2000, 2001; Jach and Reháková, 2019), Magura Ocean (e.g., Oszczypko et al., 2015) or the Pieniny Klippen Basin (Lewandowski et al., 2005) are in use as local equivalents. In the present paper this oceanic basin is referred to as the Vahic Ocean (in a more narrow, Carpathian sense) or the Alpine-Mediterranean Tethys (in a broader, regional sense). Particularly important events, constituting turning points in the evolution of the southern passive margin of the Vahic Ocean, took place in the Jurassic and are registered in the sedimentary successions of the Tatricum domain (Dumont et al., 1996; Wieczorek, 2001).

In palaeogeographical reconstructions of the Jurassic Western Tethys realm, the Alpine-Mediterranean Tethys in its Vahic (Carpathian) sector is drawn as a narrow oceanic basin with passive margins separating the Central Carpathian Block from the European Platform (Fig. 1; Thierry and Barrier, 2000a, b), although Lewandowski, et al. (2005) presented arguments that it must have attained a substantial width. During that time, breakup and disintegration of extensive shallow areas occupied by carbonate and silicielastic shelves took place. This resulted in the development of elongate and narrow basins, initially with a thinned continental crust and finally of an oceanic character (Bernoulli and Jenkyns, 2009), limited by normal faults and separated by elevated areas acting as pelagic swells and platforms or subaerially exposed land (Bernoulli and Jenkyns, 1974; Santantonio, 1994). The Vahic Ocean is one such prominent
basin (Płaśienka, 2018). Its history is often divided into a number of phases (Wieczorek, 1989; Płaśienka, 1995, 2012; Płaśienka and Soták, 2015) representing different stages of oceanic development – pre-rift (Permian to Triassic), syn-rift (Jurassic) and post-rift or syn-orogenic (Cretaceous to Paleogene). Three main rifting phases are recognized in the Jurassic of the Western Carpathians: the Zliechov, Devin and Krasin phases (Płaśienka, 2003; Froitzheim et al., 2008).

Several general reconstructions of the palaeoposition of the Central Western Carpathians and adjacent areas, and of their relation to the Alps, have been presented, based on compilations of large amounts of regional data (e.g., Płaśienka et al., 1997; Kozur and Mock, 1997; Csontos and Vörös, 2004; Golonka and Krobicki, 2004; Froitzheim et al., 2008). However, as noted by Płaśienka (2018), local sedimentary phenomena, preserved only in particular local successions, can shed much light on large-scale geotectonic and orogenic processes. This paper describes such data from the Jurassic successions representing the Tatricum domain in the High Tatra Mountains. It summarizes data, ideas and reconstructions concerning the influence of tectonic phenomena on deposition in the High-Tatric succession during the Early and Middle Jurassic. Apart from facies analysis, particular attention was paid to phenomena such as stratigraphic gaps and unconformity surfaces, neptunian dykes, condensed horizons and terrigenous admixtures in carbonate facies. All these data are discussed in terms of differences in the development and completeness of the Lower and Middle Jurassic succession within the Tatricum of the Tatra Mountains (i.e. differences between particular tectonic units), as well as in terms of comparison with neighbouring domains.

REGIONAL GEOLOGICAL SETTING

In the Jurassic, the Central Western Carpathian block was located between the incipient and expanding Vahic Ocean in the north (north-west) and the main Meliata-Vardar branch of the Tethys Ocean in the south (south-east). It constituted a relatively elevated area that was surrounded by deeper basins (Fig. 1; Thierry and Barrier, 2000a, b). The block became partly emergent during some intervals of the Jurassic, but mainly it was a place of a diverse carbonate and clastic marine deposition (Uchman, 2014a). The main palaeogeographical units representing various parts of the Central Carpathian area are the Tatricum, Fatricum and Hronicum tectono-facies domains (Andrusov et al., 1973; Kotasński, 1979). The Tatricum domain occupied the northernmost part of the Central Carpathian block, directly neighbouring the Vahic Ocean to the north. Directly south of Tatricum was the Fatricum domain, generally representing the central part of the block, and farther south the Hronicum domain, which sloped towards the main branch of the Jurassic Tethys – the Meliata-Vardar Ocean.

Each tectono-facies domain is characterized by its own sedimentary succession and its deposits are today exposed in a number of areas belonging to separate tectonic units – Tatric, Fatric and Hronic. All three units are present in the Tatra Mountains, as well as in several other core massifs of the Central Western Carpathians (Kotasński, 1979; Vozár and Káčer, 1996). The deposits of the Tatric Unit are present on the slopes of the Malé Karpaty, Považský Inovec, Malá Fatra, Veľká Fatrā, Nízke Tatry and other mountains areas, forming their sedimentary cover. This cover (in the Tatra Mountains and elsewhere) is of-
ten traditionally divided into autochthonous and allochthonous units (e.g., Kotański, 1979; Łuczyński, 2002; Uchman, 2014a).

In the autochthonous units, the sedimentary cover is usually in direct contact with its crystalline basement, whereas the allochthonous units are developed as nappes tectonically transported from the south. The term “autochthonous”, however, has to be treated only in terms of the relation of the sedimentary cover to its direct crystalline basement and not in a palaeogeographic sense, as the crystalline rocks of the Central Western Carpathians are also incorporated into tectonically transported units (e.g., Michalík, 1994).

In the Tatra Mountains, which are the northernmost core massif of the Central Western Carpathians, located on the Polish-Slovak boundary (Fig. 2A), the Permo-Mesozoic sedimentary cover is preserved on the northern slopes of the massif (Fig. 2B). Traditionally it is divided into the High-Tatric and Sub-Tatric successions or series (Kotański, 1959a, 1961; Rabowski, 1959; Lefeld et al., 1985). The Sub-Tatric succession, exposed in the lower parts of the mountains, is represented by two tectonic units (nappes) corresponding to two of the CWC tectono-facies domains: the Križna nappe (Lower Sub-Tatric) representing Fatricum, and the Choč nappe (Upper Sub-Tatric) representing Hronicum. Previously a third Sub-Tatric Unit, the Strażów nappe, was distinguished in the Tatra Mountains (e.g., Kotański, 1973), but later this term was abandoned and its deposits were incorporated into the Choč Unit (Michalík and Gażdzczyk, 1980; Iwanow and Wieczorek, 1987). The Fatricum tectono-facies domain is represented by the High-Tatric succession, which is preserved in both autochthonous and allochthonous positions in relation to the crystalline basement.

The High-Tatric succession belongs to three main tectonic units (Fig. 2C): the autochthonous Kominy Tylkowe Unit, and the allochthonous Giewont and Czerwone Wierchy units (or nappes). Exposures of Jurassic rocks occur in all three units, forming three roughly parallel latitudinal bands (Fig. 3). The Kominy Tylkowe Unit is further divided into the autochthonous unit sensu stricto, with the sedimentary rocks being undetached and lying in their original position in relation to the crystalline core of the Tatra Mountains, and parautochthonous units, in which the sedimentary rocks were detached, but probably moved only on minor distances (e.g., the Rzędy pod Ciemniakiem area; Fig. 3A). The allochthonous units are detached from their basement and overthrust northwards (e.g., Jurewicz, 2012), with the Giewont Unit undergoing the longest transport and thus palaeogeographically representing areas located farthest to the south.

In the Tatra Mountains (Fig. 4), the Jurassic deposits of the High-Tatric succession (Lefeld et al., 1985) are represented by four formations: Dudziniec, Smolegowa, Krupianka and Raptawicka Turnia. The occurrence, development and thickness of particular formations varies between particular units of the High-Tatric succession (Łuczyński, 2002). Some of the units (including the Smolegowa and the Krupianka formations, together forming the Dunajec Group) were incorporated into the lithostratigraphic division of the Tatra Mountains in the scheme earlier proposed for the Pieniny Klippen Belt (Birkenmajer, 1977), which has had controversial consequences (Wieczorek, 1988; Łuczyński, 2000).
Fig. 3. Geographic location of the main areas of exposure referred to in the text (A) and position of Jurassic outcrops in particular units of the High-Tatric succession (B)
Fig. 4. Simplified lithostratigraphic scheme of the Jurassic in the High-Tatric, Lower Sub-Tatric (Krížna), and Upper Sub-Tatric (Choč) successions in the Tatra Mountains (after Uchman, 2014a; Jach et al., 2017; simplified)
INFLUENCE OF SYNDEPOSITIONAL TECTONICS ON THE DEVELOPMENT OF THE HIGH-TATRIC LOWER AND MIDDLE JURASSIC

Early and Middle Jurassic deposition in the Tatraceut domain took place under the strong influence of synsedimentary tectonics. An extensional regime, connected mainly with rifting in the Neurakius opening Vahic Ocean, prevailed during the Middle Jurassic (e.g., Plašienka, 1995, 2012, 2018; Jurewicz, 2005). The impact of this regime is variously recognized throughout all the sedimentary successions of the High-Tatric succession; however, it included distinct culminations, considered as turning points in the area’s sedimentary development (e.g., Dumont et al., 1996; Wieczorek, 2000, 2001; Plašienka, 2003).

The influence of synsedimentary extensional tectonics is variously demonstrated and reflected in different parts of the High-Tatric Unit. Internal differentiation of the unit in terms of completeness of the sedimentary succession has long been recognized. Kotañski (1961) distinguished a number of High-Tatric sedimentary units, based mainly on the character of the Triassic/Jurassic contact and thickness differences.

The picture provided, due to imprecise stratigraphical data and because of the scattered exposures, inevitably suffers from correlation problems, both between particular sections and with other Carpathian palaeogeographic regions. The extensional tectonic regime governed facies development during the Jurassic in areas adjacent to the Central Carpathian Block, such as the Fatricum domain, represented by the Lower Sub-Tatric (Krížna) succession (e.g., Jach, 2005; Jach et al., 2012, 2014, 2017, 2019; Jach and Reháková, 2019) and the Hronicium domain represented by the Upper Sub-Tatric Choć succession (e.g., Uchman, 1993, 2014b).

The symptoms and effects of tectonic impacts on Jurassic sedimentation in the High-Tatric Unit are recorded through:

- facies development and distribution, and particularly the occurrence and pattern of high-energy deposits;
- the quantity, character and composition of clastic terrigenous admixtures in the carbonate deposits;
- thickness differences of particular stratigraphic units and lithofacies;
- stratigraphic gaps and stratigraphically condensed horizons;
- variously developed unconformity surfaces;
- the occurrence, distribution and developmental history of neptunian dykes.

All these aspects are discussed in terms of their internal variability within the Tatraceut domain of the Tatra Mountains and as regards differences between particular tectonic units. Where sufficient availability of data permits, the emerging picture is also compared with the Jurassic of neighbouring domains.

TRIASSIC/JURASSIC TRANSITION

In the Tatra Mountains, the Triassic/Jurassic transition is marked by distinct differences between the sedimentary successions of the High-Tatric and Sub-Tatric successions. During most of the Triassic, deposition followed roughly the same course in the Tatraceut and Fatricum domains of the Tatra Mountains (see e.g., Uchman, 2014a), whereas towards its end, in the Rhaetian, this picture started to change. From this point on, and through most of the Jurassic, Tatraceut represented the generally more shallow part of the Central Carpathian area as compared with Fatricum and Hronicium.

This differentiation coincided with the onset of the syn-rift stage of development of the Vahic Ocean (e.g., Wieczorek, 1989; Plašienka, 1995, 2012; Feinst-Burkhardt et al., 2008; Plašienka and Soták, 2015).

The latest Triassic (Rhaetian) is represented by the Tomanowa Formation in the High-Tatric succession and by the Fatra Formation in the Lower Sub-Tatric succession (Fig. 4; Uchman, 2014a). The Fatra Formation is developed mainly as shallow water fossiliferous limestones and marly shales deposited near to elevated land areas (Michalík et al., 2007, 2013; Gaździcki, 2014a). Sedimentation in the Fatricum domain (Zliechov Basin) was continuous in marine facies across the Triassic/Jurassic boundary (Gaździcki, 1983). The High-Tatric Tomanowa Formation is in turn developed mainly as sandstones and mudstones with some intercalations of organogenic and oolitic limestone with abundant plant remains and terrigenous material (Radwañski, 1968; Michalík et al., 1988; Jaglarz et al., 2014).

Deposition in the Tatraceut domain took place in a morphologically diverse land area, which was periodically subject to minor marine transgressions.

Both the differences in depositional style between Tatraceut and Fatricum, and the topographic diversity within Tatraceut, were tectonically induced and associated with the beginning of rifting in the Carpathian section of the Alpine-Mediterranean Tethys (see e.g., Michalík, 1993, 1994). After Rhaetian transgression in the Zliechov Basin (Fatricum), which is recorded in the facies development of the Fatra Formation, the Tatraceut domain started to function as a relatively elevated area surrounded by deeper basins (Fig. 5) to both south (Zliechov Basin) and north (Pieniny Basin). In the Sub-Tatric succession, deposition was generally continuous across the Triassic/Jurassic boundary (Michalík et al., 2007, 2013), and the Fatra Formation is overlain by the Lower Jurassic Kopieniec Formation ("Gresten Beds") developed mainly as shales and quartzitic sandstones, with a diachronous lower boundary (Gaździcki, 1975, 2014b; Gaździcki and Iwanow, 1976).

Following deposition of the Tomanowa Formation, those parts of the Tatraceut domain in the Tatra Mountains represented by the allochthonous units were elevated and eroded, which resulted in the occurrence of a major stratigraphic gap in the Czerwone Wierchy and Giewont units, embracing the entire Upper Triassic and Lower Jurassic. It is impossible to tell the precise timespan during which the erosion of the Triassic sequences took place, and thus to determine whether deposition of the Rhaetian (and parts of the Lower Jurassic) was indeed limited only to the autochthonous unit. It is generally agreed that the main phase of subaerial erosion took place in the latest Triassic, and was followed by episodes of marine erosion in the Early Jurassic (Uchman, 2014a). A break in deposition and uplift of the allochthonous succession already in the Rhaetian is indicated by the lack of uppermost Triassic clasts in the terrigenous admixture within the Middle Jurassic deposits, which in this area rest with a stratigraphic gap on the Triassic (Luczyński, 1999; Jeziierska and Luczyński, 2016).

The erosion of the Triassic sequences reached different stratigraphical levels in particular sections, indicating tilting of the eroded blocks. This is most evident in the Kominy Tykowe Unit, in which the Lower Jurassic Dudziniec Formation rests on various parts of the Triassic succession (Kotáski, 1959a; b; Bac-Moszaszewska et al., 1979; Dumont et al., 1996). The succession is continuous across the Triassic/Jurassic boundary probably only in the Chocholowska Valley region (Fig. 3; Radwañski, 1968; Wójcik, 1981). The differences in sedimentary development between the autochthonous Kominy Tykowe Unit, with deposition of the Rhaetian Tomanowa Formation, and the prob-
ably uplifted and eroded allochthonous Czerwone Wierchy and Giewont units, marks the beginning of a new palaeogeographic situation within the Taticum domain, which prevailed during most of the Jurassic. The allochthonous units, palaeogeographically representing areas located on the southern side of the domain, began to function as an isolated uplifted block (or a number of blocks) surrounded by deeper areas to the north and south (Fig. 5).

In the Smytnia Valley, being an extension of the Koœcieliska Valley (Fig. 3), the top of the Norian limestones, which are the youngest Triassic deposits in the section, is corroded and abraded, and a palaeocliff structure with large boulders at its foot is preserved (Radwañski, 1959a). The Norian is overlain by the Lower Jurassic carbonate-clastic Dudziniec Formation, which indicates emergence of the area, followed by a subsequent transgression (Radwañski, 1959b). The boulders are covered by borings of the polychaete Potamilla, within which Rhaetian sediments are preserved (Radwañski, 1959a). This indicates that deposition of the Rhaetian Tomanowa Formation probably took place at least across most of the autochthonous unit, including the Koœcieliska Valley region. In Smytnia, the whole Rhaetian (~65 m) has been removed (Kotañski, 1959a, b; Radwañski, 1968), and the thickness of the Norian has been reduced from ~130 to 30 m (Radwañski, 1959a). Erosion of the Norian limestones is indicated by the lack of Potamilla borings on the tops of the layers, and their limitation only to boulders. The Kopieniec Starorobociañski and Bobrowiec sections in the Chocho³owska Valley, with continuous marine deposition at that time, are located at a distance of just 4–5 km from the Smytnia Valley, and this relation has not changed markedly since the Triassic. This shows the magnitude of the uplift of the Koœcieliska Valley region in the east in relation to the Chocho³owska Valley region in the west, due to syndepositional faulting (at least more than 100 m). Such faulting activity, and the similar general relation of the two regions, prevailed through the Early Jurassic.

The top of the Norian limestones in the Smytnia Valley, close to the cliff structures, is cut by clastic dykes and veins filled by Early Jurassic material (Radwañski, 1959a). The development of the voids took place after the deposition of the Rhaetian shales (absent from the voids) and after lithification of the host Norian limestones, but prior to the deposition of the Dudziniec Formation. This was the first of many episodes of the development of sedimentary dykes in the High-Tatric succession during the Jurassic (Łuczyński, 2001a; Łuczyński and Jezierska, 2018). The dykes cutting the Norian are filled mainly by sandy limestones and sandstones identical to the overlying deposits. However in some places, particularly in their more remote parts, the dykes are filled by fine dolomitic marls. The formation of such infills may result from a sieve effect in the veins, although Radwañski (1959a) interpreted them as alluvial residues of dissolved Norian host rocks, transported in suspension and reprecipitated within the voids. Dissolution of subaerially exposed carbonate sequences might have taken place directly in the vicinity of the dykes within the autochthonous unit, but also could have occurred in the uplifted allochthonous units, the dissolved material being washed down to the Kominy Tylkowe Unit area of marine deposition.

**TIME OF DEPOSITION OF THE DUDZINIEC FORMATION (HETTANGIAN–AALENIAN)**

The Dudziniec Formation occurs only in the Kominy Tylkowe Unit, in which it rests on various Triassic strata, predominantly the Rhaetian (Rabowski, 1959; Kotañski, 1959a; Radwañski, 1959a; Dumont et al., 1996). It is developed in mixed sandy-carbonate deposits, represented by a wide range of facies, from sandstones to crinoidal limestones. In detail these deposits have been described by Horwitz and Rabowski (1922), Siemiradzki (1923), Rabowski (1954, 1959), Radwañski (1959b), Wójcik (1959, 1981) and Jezierska et al. (2016). Several members and beds are distinguished within the formation (Lefeld et al., 1985). Its total thickness varies greatly,
and reaches over 500 m in the Chocholowska Valley in the western part of the unit (Fig. 3; Wójcik, 1981; Lefeld et al., 1985), but does not exceed ten or so metres in its eastern part (east of the Kościeliska Valley), in the Kraków Gorge (Fig. 3; Jezińska et al., 2016) and in parautochthonous folds in the Rzędy pod Cierniakiem area (Fig. 3). However, in the latter locations the thickness of the formation is probably tectonically reduced. The Dudziniec Formation occurs also as infillings of sedimentary dykes penetrating the Triassic substrate (Rądwanis, 1993a), as well as hosting neptunian dykes itself (Luczyński and Jezińska, 2016).

The exact chronostratigraphy of the Dudziniec Formation remains unclear. Originally, based on scarce and mainly poorly preserved belemnite and brachiopod faunas, Horwitz and Rabowski (1922) determined the age of these deposits as Hettangian (Sinemurian?) through Bathonian. Based on the presumed Bajocian age of the overlying Smolegowa Formation, documented mainly in the Pieniny Klippen Belt (Birkemajer, 1977), the upper limit of the formation is supposted to be the Hettangian-Sinemurian.

The onset of deposition of the Dudziniec Formation took place in a Tataricum domain already characterized by pronounced topographic variety. The base of the formation lies unconformably and erosively on the Triassic (Jezińska and Luczyński, 2016). The allochthonous Giewont and Czerwone Wierchy units probably remained elevated through the whole Early Jurassic and acted as source areas for the carbonate lithoclastic components of the Dudziniec Formation that was deposited on the autochthonous unit (Rabowski, 1959; Katarzynski, 1961; Luczyński, 2002). No Early Jurassic deposits have been recorded from the High-Tatric allochthonous units. In individual exposures, in the terrigenous component of Middle Jurassic crinoidal limestones (the Smolegowa Formation in the Ciemniak section of the paraautochthonous area of the Kominy Mountains, it is overlain by shallow marine quartzitic limestones of the Hettangian–Synemurian (?) Kopieniec Formation with a diachronous lower boundary (Gazdzicki, 1975, 1983, 2014b; Gazdzicki and Iwanow, 1976; Gazdzicki et al., 1979), representing shallow shelf settings. In the eastern part of the Tatra Mountains, it is overlain by shallow marine quartzitic limestones of the Koperszady (Med’odóly) Sandstone Formation (Lefeld et al., 1985; Popiolek et al., 2010; Uchman et al., 2014a) with its lower part referred to as the Baboš Quartzite Member (Iwanow, 1973; Popiolek et al., 2010). The provenance of quartz grains in these facies is not unequivocally determined, and may be associated with magmatic and metamorphic rocks; however, most probably they underwent a multistage history and are derived from erosion of Triassic clastic deposits from exposed parts of Tataricum or Hronicum (Turnau-Mórawska, 1953, 1955; Popiolek et al., 2010). Once again, this underlines the topographic diversity within the Central Carpathian area during the early stages of the Early Jurassic.

The higher part of Lower Jurassic succession of Fatrium is represented by spotted limestones and marls of the Sołtysia
Marlstone Formation (Lefeld et al., 1985; Uchman et al., 2014b) – an equivalent of the Alpine Fleckenmergel facies (Wieczorek, 1995). Initially sedimentation was more unified and represented mainly by deep water facies then, not later than the Pliensbachian, the Križna Basin became divided into horsts and grabens by syndepositional block faulting. These events may be simultaneous and related to the episodes of faulting in the High-Tatric domain recorded by facies changes and the occurrence of neptunian dykes, although the exact correlation of particular events is not currently possible. Since the Pliensbachian, the horsts became places of variable sedimentation of specific facies, that differed from the Fleckenmergel variety prevailing in deeper areas. These deposits belong to the Huciska Limestone Formation (Lefeld et al., 1985; Jach, 2014). Their differentiation and associated history are yet further reflections of the prevailing influence of syndepositional extensional tectonics on sedimentation and basin morphology during the Early Jurassic and the Early/Middle Jurassic transition on the Central Carpathian Block. The succession starts with spiculites (Jach, 2002) which, due to shallowing of some areas, were replaced by crinoidal limestones deposited in the vicinity of crinoidal meadows (Głuchowski, 1987) and interpreted as tempestites (Jach, 2005). A spectacular facies example of the Huciska Limestone Formation, the deposition of which was related to syndepositional tectonic activity, is the Upper Toarcian manganese layer with stromatolites that outcrops between the Chochołowska and Lejowa Valleys. Based on characteristic their faunal and mineralogical features, these deposits are interpreted as related to submarine hydrothermal vents associated with faults and fissures (Jach and Dudek, 2005). They are overlain by condensed Ammonitico Rosso-type red nodular limestones deposited on a submarine swell(s) (Wieczorek, 1983; Gradziński et al., 2004). Wieczorek (2001) considered these condensed horizons as one of the “turning points” in the passive margin evolution. Jurassic deposits of the Hronicum domain are preserved in the Choć (Upper Sub-Tatric) Unit of the Tatra Mountains only sporadically (Fig. 4; Uchman, 2014b). The Jurassic is almost entirely represented by the variously developed Sinemurian to Pliensbachian limestones of the Miętusia Formation, resting directly on the Triassic (Uchman and Tchoumatchenko, 1994). Their formation is interpreted to have been controlled by syndepositional tilting of fault-bounded blocks, the rotation of which lead to emergence and erosion of Triassic rocks (Uchman, 1993). Bahamian-type shallow water tropical carbonates are typical of the Lower Jurassic of the Western Tethys (Rychliński et al., 2018). The youngest deposits of the Upper Sub-Tatric Unit comprise red bioclastic limestones, most probably of Aalenian age (Uchman, 1988, 2014a). All these features indicate that, during the Early Jurassic, extensional syndepositional tectonics connected with opening of the Vahic Ocean controlled deposition in all palaeogeographical domains represented in the Tatra Mountains.

THE TIME OF DEPOSITION OF THE SMOLEGOWA FORMATION (BAJOCIAN?)

The Smolegowa Formation is uniformly developed across the High-Tatric succession. In all units it is represented by light grey to pink, coarse-grained crinoidal limestones with a minor admixture of Triassic lithoclasts and quartz grains (Lefeld et al., 1985; Łuczyński, 2002, 2014a). Traditionally, these deposits have been termed “white Dogger crinoidal limestones” by Uhlig (1897) and “white Bajocian crinoidal limestones” by Horwitz and Rabowski (1922), Andrusov (1958, 1959), Rabowski (1959) and Kotasinski (1959a, 1961). A Bajocian age has been determined by Horwitz and Rabowski (1922) based on their brachiopod fauna. Jurassic crinoidal limestones are a common facies in the Jurassic of various Tethyan basins (Jenkyns, 1971). Similarly
The Smolegowa Formation is developed as massive limestones, with faint bedding observed only in parts of the Kominy Tylkowe Unit (Rządy pod Ciemniakiem and Chochołowska Valley; Fig. 3), in which it attains its maximum thickness of up to 30 m (Kotański 1959a). In parts of the autochthonous unit (Dolina Chochołowska, Wąwóz Kraków), the Smolegowa limestones occur in a continuous succession of the Dudziniec Formation (Wójcik, 1981; Lefeld et al., 1985; Łuczyński, 1999). In the Giewont and Czerwone Wierchy units, the formation is preserved only in places as laterally discontinuous lenticular bod-
area of deposition of the Smolegowa limestones was larger than their present distribution, and that the lenticular shape of most of the lithosomes is an erosional phenomenon. On the other hand, if the High-Tatric allochthonous units are interpreted to be the source areas of the terrigenous admixture present in the crinoidal limestones, at least some parts of the area must have remained uplifted during some periods of their deposition.

Compilation of these observations leads to a relatively complicated regional palaeogeographical picture of the High-Tatric area during the Bajocian, which however due to lack of precise stratigraphical evidence cannot be more closely constrained in time (Fig. 9). The Bajocian transgression, which most probably flooded the whole High-Tatric area, was preceded by rotation of substrate blocks, as is indicated by a paraconformable contact of the Smolegowa Formation with the underlying deposits, most clearly visible in the Giewont Unit. Another period(s) of tectonic instability is marked by the formation of neptunian dykes. The formation of extensional fissures took place in the Triassic solid substrate under the cover of recently deposited loose crinoidal deposits, which were injected into them at the moment of their opening (Łuczyński, 2001a; see Winterer et al., 1991). Formation of the neptunian dykes was associated with the activity of syndepositional extensional faults, responsible for the differen-
tiation of the basin’s topography during deposition and for the lateral thickness variations in the Smolegowa crinoidal limestones.

The stratigraphy and sedimentology of the Middle to Upper Jurassic of the Lower Sub-Tatric (Krížna) Unit has been summarized by Jach et al. (2014) and by Jach and Reháková (2019), who referred to the Patricium domain at that time as a pull-apart basin with a thinned continental crust, emphasizing the influence of tectonic activity on its sedimentary history. In the Bajocian, sedimentation differed between the eastern and western parts of the area (Jach and Uchman, 2014). In the west (exposures in the Western Tatra Mountains) the discontinuous succession represents elevated horst areas (Uchman, 2014a) and is represented by shallow water crinoidal and Bositra limestones (Jach, 2007).

In the east (Kopy So³tysie region and Bielskie Tatry), the facies are characteristic of deeper basinal settings and are developed as spotted limestones and marls of the So³tysie Marlistone Formation (Fleckenmergel facies), the deposition of which continued across the Lower/Middle Jurassic boundary (Lefeld et al., 1985; Uchman, 2014a). From this time on, due to gradual deepening of the whole area, and because of cessation of syndepositional tectonic activity, the deposition became more unified across the Krížna Unit (Jach and Reháková, 2019). This deepening and facies unification precedes similar processes (although differently expressed) in the High-Tatric Unit.

The stratigraphic column of the Upper Sub-Tatric Unit lacks Jurassic deposits younger than Aalenian (Lefeld et al., 1985; Uchman, 2014a).

THE DEPOSITION OF THE KRUPIANKA FORMATION (BATHONIAN)

The interval with most profound evidence of the variable influence of syndepositional tectonic activity on the depositional development of the High-Tatric succession is the timespan between the deposition of the Smolegowa Formation encrinites and the onset of deposition of the Raptawicka Turnia pelagic limestones. In the sedimentary record this is represented by the Krupianka Formation. Traditionally its deposits have been referred to as “red Dogger crinoidal limestones” by Uhlig (1897) and as “red Bathonian crinoidal limestones” by Horwitz and Rabowski (1922), Passendorfer (1936, 1938), Rabowski (1959), Kotanís (1961) and Szulczewski (1963a, 1968). Based on the rich ammonite fauna from Wielka Świstówka, the Czerwone Wierchy Unit (Szulczewski, 1963b; Łuczyński, 1963b), one of the Krupianka limestones (Fig. 7) and due also to the occurrence of the Dudziniec Formation only in the autochthonous unit. Therefore, in various areas, the Bathonian rests directly on the Triassic (all three tectonic units; e.g. the Wążów Kraków – autochthonous unit, the Wulka Świstówka–Czerwone Wierchy Unit, and the Zawrat Kasprowy–Giewont Unit), on the Dudziniec Formation (only the autochthonous unit; e.g. Wążów Kraków 1), or on the Smolegowa Formation (two tectonic units; e.g. the Rzędy pod Ciennikiem – autochthonous unit, and the Giewont – Giewont Unit). In all cases the contact shows an erosional character, emphasized by the lenticular shapes of the lithosomes, and in many places the Bathonian deposits fill local depressions.

The differentiation of the High-Tatric area in the Bathonian, caused by syndepositional fault activity, is reflected by facies differences between particular tectonic units. In the Giewont Unit, the Krupianka Formation is represented by red crinoidal limestones (Lefeld, 1957; Sieciarz, 1963; Łuczyński, 2002), in the Czerwone Wierchy Unit mainly by condensed ferruginous deposits commonly with stromatolites and occasionally with an abundant ammonite and belemnite fauna (Grochocka-Renko, 1963; Kostiukow, 1963; Szulczewski, 1963b; Łuczyński, 1963b), whereas in the Kominy Tynkowe Unit in most exposures it is developed as (stylo)nodular limestones (Łuczyński, 2002). All three lithofacies have been subjected to strong pressure dissolution and chemical compaction (Łuczyński, 2001b), the intensity and character of which differed between different tectonic units. Although the present facies differences are accentuated by late diagenesis, all the varieties are characterized by a red colour and the occurrence of crinoids. Their present-day development is partly an effect of these processes, with the crinoidal limestones being the least altered, and thus their pre-compactional differences were less evident than they are today.

The Krupianka Limestones of the Giewont Unit and particularly of the Czerwone Wierchy Unit include abundant evidence of internal breaks in deposition, such as erosional surfaces and condensed horizons (Lefeld, 1957; Grochocka-Renko, 1963; Kostiukow, 1963; Szulczewski, 1963b; Łuczyński, 2002; Jezińska and Łuczyński, 2016). For example, in the Wrótka Pass section of the Giewont Unit (Fig. 3), a condensed belemnite- and crinoid-rich deposit is truncated by an intraformational flat abrasion surface (Łuczyński, 1995). The character of the surface, that evenly cuts the sediment and the belemnite rostra, indicates abrasion of completely lithified deposits, which in turn indicates that the non-depositional and/or erosional episodes...
were long-lasting. In a number of areas (e.g., Giewont, Mała Świstówka, Wielka Świstówka; Fig. 3)stromatolite horizons occur, marking condensation episodes (Szulczewski, 1963a, b, 1968; Łuczyński, 1999, 2002). Moreover, in the Świstówka Pasendorfera section in Wielka Świstówka, the stromatolite horizon is overlain by a condensed layer rich in ammonites. The occurrence of such condensed horizons at certain levels of the sedimentary successions is often considered to represent crucial turning points in the depositional development on passive margins of various Tethyan basins (Dumont et al., 1996; Wieczorek, 2001).

The Krupianka Limestones in all their lithological varieties contain a fairly rich terrigenous admixture (Łuczyński, 2002; Jezierska and Łuczyński, 2016). It is much more abundant and coarser than in the Smolegowa encrinites, which indicates that the erosion was more intense, and the source areas were closer. The admixture is composed of limestone and dolomite lithoclasts, which can be identified as derived from the High-Tatric Triassic, quartz grains probably coming mainly from erosion of the Dudzińec Formation in the Kominy Tykowskie Unit, and ferruginous clasts indicating intraformational erosion and reworking. Reflecting differences in the main source areas, the composition of the clastic admixture differs between different tectonic units (Jezierska and Łuczyński, 2016). As compared with the entire High-Tatric Bathonian, the quartz grains are proportionally more abundant in the autochthonous unit (direct vicinity of the carbonate-clastic Lower Jurassic deposits), whereas ferruginous clasts are especially common in the Czerwone Wierchy Unit (area of most prominent evidence of condensation and/or non-deposition). In the Giewont Unit, the composition of the terrigenous admixture is very similar to that calculated for the whole High-Tatric succession.

The reconstruction of the palaeogeographic and palaeotectonic history of the High-Tatric area during the Bathonian is too a great extent based also on the analysis of neptunian dykes filled with deposits of the Krupianka Formation. As noted above, the Krupianka limestones are preserved only sporadically in the normal stratigraphic column, both laterally and in vertical sections. In such an incomplete record, characteristic of times of fragmentation of carbonate platforms during rifting, the study of unconformities and neptunian dykes can shed light on the processes that took place in the intervals hidden in the gaps (Clari et al., 1995; Marino and Santantonio, 2010). Commonly the infills of dykes are the only preserved deposits representing particular episodes of an area's development, yielding unique information (e.g., Lehner, 1991; Winterer and Sarti, 1994; Aubrecht and Kozur, 1995; Schłögl et al., 2009; Aubrecht and Schłögl, 2011; Wendt, 2017).

Dykes with variously developed deposits associated with the Krupianka Formation are present in all the High-Tatric tectonic units (Łuczyński, 2001a). Systems of interconnected dykes and sills are hosted mainly by the Middle Triassic carbonates and in the Kominy Tykowskie Unit; they occasionally penetrate also the topmost part of the Dudzińec Formation. To this group belong fissures and voids containing red caproloid limestones, but also extensive systems of structures filled with very fine red, unfossiliferous carbonate silt—the "rot pelit". The origin of the latter is not entirely clear, however, most probably these are the finest fractions of the Krupianka Limestones that penetrated deep into the voids and were depleted from coarser fractions due to the sieve effect. Such an interpretation is suggested by the shapes and dimensions of the very thin interconnected networks of thin fissures penetrating deep into the underlying Triassic strata. In the Czerwone Wierchy Unit, structures filled with red micrite occur >150 m below the base of the Jurassic (Łuczyński, 1999). Often they are developed as sills running along bedding planes within the Triassic (Anisian) limestones and dolomites (Fig. 8), and pass laterally into fissures filled with calcite cement (presumably in those parts of the fissures which the sediment did not reach) or fade away as pressure solution structures, such as dissolution seams (Łuczyński, 2001a, b; see also Mišlik, 1998).

In some localities the dykes associated with the Krupianka Formation are interconnected with dykes filled with Smolegowa caproloid limestones, which points to repeated opening of the same fissures. Recurrent opening of the void systems and movement within them, associated with repeated fracturing of the brittle substrate due to episodic tectonic instability, is indicated also by the occurrence of internal breccias (Fig. 8). Nests of such breccias occur in places that are particularly densely cut by consecutive systems of dykes filled with various deposits. All this marks episodes of intense substrate fracturing associated with extensional tectonic movements taking place in the Tatricum domain. At least two such profound episodes took place—after the deposition of the Smolegowa limestones and during the deposition of the Krupianka limestones.

In contrast to the dykes filled with the deposits of the Smolegowa Formation, the dykes associated with the Krupianka limestones are often characterized by smooth walls devoid of sharp edges, which suggests an important role of dissolution processes in their formation. However, more prolonged subaerial exposition seems unlikely, as is indicated by the stable oxygen and carbon isotopes of deposits that infill them. The δ^{13}C values are between 3.2 and 3.3‰, and the δ^{18}O is around −2‰ for both the Smolegowa and the Krupianka limestones filling the dykes (for detailed data see Łuczyński, 1999, 2001a). These results fall within the range characteristic of marine waters of normal temperature and salinity (e.g., Gruszczynski, 1998; Kasting et al., 2006; Prokoph et al., 2008). This indicates good communication between the dykes and the sea bottom at the time when they were being filled with deposits.

On the other hand, other infillings of the fissures, such as red micrite (carbonate silt) and various kinds of palisadic, radiaxial and blocky calcite cements, are depleted in δ^{18}O (ranging between −2.5 and −8‰) in relation to other Middle Jurassic neptunian dykes described from other regions (e.g., Winterer et al., 1991; Winterer and Sarti, 1994; Mišlik et al., 1994; Wall and Jenkyns, 2004). This may result from three co-occurring processes. Firstly, the fine carbonate silt and calcite cements occupy the more remote parts of the extensive systems of fissures deeply penetrating the substrate, that could have been subjected to circulation of hydrothermal waters (Hsi, 1983; Matyszkiwicz et al., 2016). In this case, the strongly negative δ^{18}O values of the cements would indicate elevated temperatures of their precipitation. Secondly, depletion of the heavy oxygen isotope can be an effect of late diagenesis, particularly of pressure dissolution that took place mainly along horizontal planes. This is supported by the strongly negative δ^{18}O results (−12‰) obtained for the residue of dissolution seams into which the sills laterally pass. Thirdly, the timespan represented by the dykes described (Bajocian/Bathonian boundary interval) is coeval with the most profound isotopic excursion in the Jurassic (Gruszczynski, 1998; O'Dogherty et al., 2006), characterized by particularly low δ^{18}O and δ^{13}C values. The distinctly positive δ^{13}C values of red silts and calcite cements (between 2.4 and 2.9‰) excludes their speleothem and karstic origin.

The base of the Krupianka Formation is an erosional unconformity in all High-Tatric tectonic units (Jezierska and Łuczyński, 2016), regardless of the underlying deposits (Triassic, Dudźiniec or Smolegowa Formations). Removal of the Bajocian caproloid limestones from large parts of the Tatricum
domain is indicated by the occurrence of neptunian dykes filled with the Smolegowa Formation in areas that lack the Bajocian in the normal stratigraphic column. Most probably, the whole High-Tatric area became subaerially exposed and subjected to erosion, which reached various levels. Some parts of the High-Tatric area remained emergent also after the following onset of deposition and became sources of the terrigenous admixture present in the Krupianka limestones (Fig. 9). During the entire time of sedimentation of the Krupianka Formation, the High-Tatric area acted as a constantly changing patchwork of elevated and submerged areas. Periods of deposition were interrupted by episodes of intraformational erosion, indicated by internal erosional surfaces, and also by the occurrence of reworked intraformational ferruginous clasts (Łuczyński, 2002). Recurrent tectonic instability led also to the formation of neptunian dykes and internal breccias, some of which are composed of multiple generations of sediments and cements. The occurrence of neptunian dykes filled with sediments associated with the Krupianka Formation also in those areas in which the Bathonian is missing in the normal stratigraphic column is yet another symptom of the intertwining of episodes of erosion and deposition. The topographic differentiation of the area is reflected also by the replacement of uniformly developed crinoidal limestones of the Smolegowa Formation by diverse facies of the Krupianka Formation.

The internal palaeogeographic picture of the High-Tatric domain during the deposition of the Krupianka Formation, emerging from the facies distribution, completeness of the sections and occurrence of neptunian dykes, is very complicated. Lack of precise stratigraphy hinders the possibility of accurate correlation of the sections, and thus of putting all the phenomena into proper stratigraphical order. Nonetheless, the sedimentary record of the times between the end of deposition of the Smolegowa limestones and prior to the onset of deposition of the Raptawicka Turnia limestones provides plentiful evidence of intense extensional tectonic activity on the southern side of the Vahic Ocean occupied by the Tatricum domain.

In the Lower Sub-Tatric Unit, the overall deepening pulse, which started in the Bajocian, continued during the Bathonian, when it became more distinct and uniform. A variety of different facies ascribed to various settings of a diverse palaeotopographic environment (see above) was replaced by spotted and nodular limestones followed by radiolarites (Jach, 2007; Jach and Uchman, 2014; Jach and Reháková, 2019). The radiolarite sedimentation of the Sokolica and Czajakowa formations (sensu Lefeld et al., 1985) and of the Ždiar Formation (sensu Polák et al., 1998), starting in the Bathonian and lasting until the Upper Kimmeridgian (Jach et al., 2012; Jach and Reháková, 2019), was uniform across the whole Zliechov Basin (Krížna Unit). These facies mark the cessation of the syndepositional tectonic activity in the area. Both these processes (deepening and facies unification) preceded similar phenomena taking place in the Tatricum domain, in which they started probably not earlier than in the Callovian.

MIDDLE JURASSIC PERIOD OF DEPOSITION OF THE RAPTAWICKA FORMATION (CALLOVIAN)

The variously developed deposits of the Krupianka Formation are truncated by a prominent unconformity surface in all High-Tatric tectonic units (Łuczyński, 2002; Jeziorska and Łuczyński, 2016). The formation’s discontinuous character of preservation, which in some areas is limited only to in fills of neptunian dykes, points to a break in deposition and/or erosion following the sedimentation of red crinoidal, ferruginous and nodular limestones across the whole area. After that episode, the Tatricum domain was subjected to rapid drowning, which is reflected by a distinct facies contrast with the overlying deposits of
Fig. 10. Time and space distribution of tectonically induced phenomena and features recorded in the High-Tatric Jurassic of the Tatra Mountains
SUMMARY

The entire depositional history record of the Tatrnicum domain during the Jurassic can be described and interpreted in terms of the influence of various effects of tectonic activity on sedimentation, facies development and preservation of the deposits. Three main areas can be distinguished within the High-Tatric succession (Fig. 10), characterized by different occurrences and intensities of synsedimentary tectonic phenomena, particularly in the Middle Jurassic (1) an autochthonous succession of the Kominy Tylkowe Unit, (2) the paraautochthonous succession of the Czorsztyn Tylkowe Unit, and (3) the Czerwone Wierchy and Giewont units.

The record of influence of syndepositional tectonics on the sedimentary record falls into several categories (Fig. 10). One of the most prominent is the occurrence of neptunian dykes, which are present in all three areas studied, and which host deposits ranging from the Early Jurassic (probably Sinemurian or Plenusbachian) to the Bathonian. The second broad category are the various expressions of synsedimentary block tectonics, such as block tilting demonstrated by angular unconformities, evidence of submarine and subaerial erosion, and rapid lateral thickness changes. Also these symptoms are present with various intensities in all the areas studied, commencing mainly in the Bajocian and the Bathonian of the parautochthonous successions and the Czerwone Wierchy and Giewont units. The third category is the occurrence of substantial amounts of terrigenous admixture composed of clasts of local origin, indicating the proximity of elevated source areas. Such admixtures are most abundant in the Dudziniec Formation of the autochthonous succession, and in the Krupianka Formation. And finally, the fourth category comprises various symptoms of non-deposition or condensation, such as ferruginous crusts,stromatolites, cephalopod limestones, etc., particularly common in the Bajocian of the foldic units and also in the Bajocian of the paraautochthonous succession.

All these manifestations of Jurassic syndepositional extensional tectonic activity in the High-Tatric succession of the Tatra Mountains correspond well to the broader picture of the evolution of the Vahic Ocean’s southern margin during the Jurassic, based on compilations of regional data. The main three postulated rifting phases that took place in the Jurassic of the Western Carpathians – the Zliechov, Devin and Krasin phases (Płasiennik, 2003; Froizheim et al., 2008) – can also be recognized in the material studied. Most profoundly developed are the effects of the Bajocian/Bathonian Krasin phase, which correspond to the time of deposition of the Smolegowa and Krupianka formations, and is reflected by a whole variety of sedimentary and erosional phenomena (Fig. 10). More difficult is the recognition of the Zliechov and Devin phases (respectively Hettangian–Sinemurian and Toarcian); that is due to the imprecise internal stratigraphy of the Dudziniec Formation, but these probably can be linked to the episodes of neptunian dyke formation and/or increased input of terrigenous material into the basin.

The history outlined of the southern rim of the Vahic Ocean generally follows the same path as in the Alpine sector of the Alpine-Mediterranean Tethys. However, the exact relation between the Alpine and Carpathian Mesozoic oceanic realms is still a matter of long-lasting controversy (cf. Mahel, 1981; Froizheim et al., 2008; Płasiennik, 2012), and exact correlation is hindered by a lack of precise dating of some crucial events and phenomena. Nevertheless, notable analogues in the successions, and particularly in the positions of erosional events.
and associated stratigraphic gaps, can be found between the Central Western Carpathians and the Northern Calcareous Alps of the Austroalpine Domain (e.g., Mandl, 2000; Gawlick et al., 2009), as well as with the French Western Alps of Dauphiné (Dumont et al., 1996). Somewhat surprisingly, the closest analogue in terms of sedimentary development of the High-Tatric succession, with similar Bathonian facies with stromatolites, can be found in the Villany Mountains of southern Hungary (Radwañski and Szulczewski, 1966; Géczy and Galácz, 1998).

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