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THE OUTER CARPATHIAN – GENERAL GEOLOGY

The Polish Carpathians comprise the northern part of the Carpathian Mountains, which are parts of the Alpine mountain chain. The geology of the Carpathians (Książkiewicz 1977) can be subdivided into two zones: the Inner and Outer Carpathians. The Inner Carpathians are regarded as a prolongation of the Northern Calcareous Alps, and formed part of Apulian microplate, a promontory of the African plate. Sedimentation in the Inner Carpathians was mainly calcareous, and took place from the Early Triassic to beginning of the Late Cretaceous. They were folded during the late Cretaceous tectonic movements.

The Outer Carpathians called also the Flysch Carpathians (cf. e.g. Cieszkowski et al. 1985, Cieszkowski 2003), developed on the thinned crust of the southern margin of the Northern European plate, which contained several sedimentary basins. The sedimentation, comprised mainly of turbidites, spanned the time between the Late Jurassic and the Early Miocene, and main folding movements took place during the Miocene. Separating the Inner and Outer Carpathians mountain ranges lays the narrow, geological complicated zone - the Pieniny Klippen Belt, a shear zone that was affected by both Late Cretaceous and Tertiary tectonic phases. To the north of Outer Carpathians and partly beneath them lies the Northern European plate with its Neogene's cover. As a result of Miocene tectonic movements, the Carpathians have been overthrust onto the North European Platform for a distance more than 100 km.

THE OUTER CARPATHIAN SEDIMENTARY BASINS

The Outer Carpathian sedimentary basins are characterized by marked lateral facies changes that highlight complex paleogeography, where deep subsiding basins (trough) were separated by shallow or even emergent geanticlinal structures – ridges.). In the troughs and basins enormous sequence of flysch type sediments were deposited, the thickness of which locally exceeds more than 6 thousands meters. From the south to north the following main sedimentary basins and ridges, each with distinctive lithostatigraphic succession, are identified: the Magura Basin, the Dukla Basin, the Silesian Ridge, the Silesian Basin, the Subsilesian Ridge, and finally the Skole Basin. In the troughs and basins usually enormous sequences of flysch type sediments were deposited, the thickness of which approach up to a few thousands meters. The dominant tectonic phase that affected the Outer Carpathians was a Miocene tectonic phase. The Miocene tectonic movement took place during collision between Apulian microplate and North European plate. As a result of

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intense Neogene's orogeny the sediments filling the basins were folded and detached from their substrate and several uprooted nappes (Książkiewicz 1977) were created that reflect the original configuration of the basins. During folding and thrusting the main nappes have been partly differentiated and subdivided to smaller tectonic units. Outer Carpathian nappes, thrust one upon another, all together overthrust onto the North European Platform. During the folding and thrusting movements in front of steeply northward advancing nappes have been formed Carpathian Foredeep that was filling by the Miocene molasse deposits. Nappes overthrust partly onto the Miocene deposits lying on the North European Platform. In the front of the Outer Carpathian thrust portion of the Middle Miocene deposits were stripped from their basement, folded and also overthrust onto autochthonous molasse.

UNITS OF THE OUTER CARPATHIANS

The Outer Carpathian thrustbelt consists of several nappes sheared off from the basement. The nappes are thrust upon each other, and are themselves overthrust towards the north onto the Miocene Foredeep and its pre-Miocene platform basement. Boreholes and seismic data indicate that the distance of the Carpathian overthrust was at least 60 km. The succession of the nappes from the highest to the lowest is as follows: Magura Nappe, Fore-Magura group of nappes, Silesian Nappe, Subsilesian Nappe and Skole (Skiba) Nappe.

The Magura Nappe is an innermost and largest tectonic unit of the Western Carpathians (Oszczypko 1992), thrust over the strata of various units of the Fore-Magura group of nappes and of the Silesian Nappe. The substratum of the Magura Nappe is exposed in the several tectonic windows and has also been found in several deep wells in Poland and Slovakia (e.g. Bystra IG-1, Zawoja 1, Orawska Polhora 1, Tokarnia IG-1, Sucha Beskidzka IG-1, Obidowa IG-1, Chabówka 1, Słopnice 1 and 20, Leśniówka 1). To the south it is in contact with the Pieniny Klippen Belt that bordered it from the Inner Carpathians. Flysch strata of the Magura Nappe represent mainly the Upper Cretaceous and Paleogene. Oldest, Albian-Cenomanian are known in Poland from the southern margin of Mszana Dolna tectonic window. Basing on development of facies and tectonic features, the Magura Nappe is subdivided in several subunits that follow from the south to north: the Krynica, Bystrica, Raca and Siary subunits.

The Fore-Magura Zone (after Książkiewicz 1956) includes a group of tectonic units which are folded and thrust one upon another. The Dukla Nappe (Ślęczka 1970) is the largest and most important unit of the Fore-Magura Zone. It crops out on the surface in the eastern sector of the Polish and Slovak Outer Carpathians and in Ukraine. Towards the west, together with facies changes the Dukla Nappe passes into the Obidowa-Słopnice Nappe (Cieszkowski et al. 1981) and Grybów Nappe. Both have been encountered in several deep wells below the Magura Nappe, e.g. in the Rabka - Nowy Targ area (Obidowa IG-1, Chabówka 1) and Limanowa - Słopnice area (Słopnice 1, Słopnice 20, Leśniówka 1 and others). Innermost unit of the Fore-Magura Zone, called Jasło Nappe (Koszarski 1999) has been distinguished in the surroundings of Gorlice and Jasło. In front of the Magura

Nappe two outer units are located. Those are the Fore-Magura Unit *s.s.* (Książkiewicz 1977) and Michalczowa Unit (Cieszkowski 1992). Units of the Fore-Magura Zone are tectonically covered by the Magura Nappe that has been turned from south, and all together are thrust over the Silesian Nappe. Sedimentary successions of all respective units of the Fore-Magura Zone have been deposited within the same Dukla Basin. Up to the end of the Late Cretaceous and beginning of the Paleogene it was connected with the Magura Basin. From north it was bordered by the Silesian Ridge (Cordillera) and separated of the Silesian Basin. In the Late Paleogene the Dukla Basin was separated from the Magura Basin. Then opened wide connection between the Dukla and Silesian basins which is marked in the Oligocene by presence of facies typical for Dukla succession in the innermost part of the Silesian Nappe (cf. Ślęczka 2000).

The Silesian Nappe occupies central part of the Outer Carpathians, thinning out below the most internal nappes. Sedimentary facies of the Silesian Nappe represent continuous succession of deposits of age interval from Late Jurassic to Early Miocene. During the Late Cretaceous and Paleocene in the Silesian Basin took place sedimentation of sandstone turbidites often thick- and very thick-bedded, that represent the Godula and Istebna beds. Their complete thickness in is estimated in the western sector of the Polish Carpathians for about 4500 m. All clastic material of Godula and Istebna beds was derived from southwest, from the Silesian Ridge.

The Subsilesian Nappe underlies tectonically the Silesian Nappe. In the western sector of Polish Carpathians both they thrust over the Miocene molasse of Carpathian Foredeep and in the eastern sector they thrust over the Skole Nappe. The Silesian and Subsilesian basins have been connected. Toward the north and northeast the Cretaceous and Paleogene clastic deposits typical for the Silesian Basin were in the Subsilesian sedimentary area gradually replaced, at first by variegated shales, and eventually by the marls of the Subsilesian emerged ridge. In the Paleogene time the sedimentation of variegated deposits continued up to the end of the Middle Eocene. The deposits of the Subsilesian Nappe crop out on the surface in the narrow zone in front of the Silesian thrust and arrive in several tectonic windows. In many wells they were found beneath the Silesian Nappe.

The Skole Nappe occupied large area in the northeastern part of Polish Outer Carpathians. Towards the east on the territory of Ukraine it goes be wider but towards the west its width diminishes until it eventually disappears from surface, plunging beneath the Silesian and Subsilesian Nappes. The Skole Nappe consists of several narrow elongated thrust folds. There is predominance of the Oligocene Krosno beds cropping out on the surface in the inner zone of this unit while outer is mainly build of Upper Cretaceous strata. In the Polish part of the Outer Carpathians there is no evidence of the most external unit known from the Ukrainian Carpathians as the Borislav-Pokuty Nappe. Its occurrence beneath the Skole Nappe in the Polish Outer Carpathians has been supposed but evidence from deep boreholes (e.g. Paszowa 1, Cisowa IG-1) suggests that Borislav-Pokuty Nappe do not continue to the west of Polish-Ukrainian Border.

In the western sector of Polish Outer Carpathians **the thickness of the nappes** overthrusting flatly the North European platform is steeply growing towards the south. Many deep wells located on a distance up to 40 km to south from the northern margin of Outer Carpathians reached the platform substratum on a depth from 1000-3500 meters. In more inner zone (Cieszkowski et al. 1985) some of deep wells did not drilled through the flysch up to the depth 4000-5000 meters (e.g. Obidowa IG-1, Chabówka 1, Słopnice 1, Słopnice 20, Leśniówka 1). Basing on the results of deep boreholes and on the seismic and magnetotelluric data, depth of the platform in peri-Klippen zone of the Magura Nappe is estimated for about 6000 meters.

In the eastern sector the total thicknesses of flysch units growth up quickly more. There in the Kuźmina 1 deep borehole the platform was drilled on the depth about 7000 m. The next borehole Paszowa 1, located several km south-east of Kuźmina 1 did not drill through the Skole Nappe up to 7200 m. More to the south the thickness of the Outer Carpathian units could reach ten thousands meters or more.

SILESIA NAPPE

Sedimentary facies of the Silesian Nappe represent continuous succession of deposits of the age interval from Late Jurassic to Early Miocene. The oldest Carpathian basin was created within the central part of the rift forming nascent Silesian Basin. The Silesian Basin was infilled by sediments of the **Cieszyn Beds** derived from the adjacent calcareous platforms. The Cieszyn beds, up to 700 meters thick, are divided to three lithostratigraphic divisions. The sedimentary succession begins in the Kimmeridgian with dark red, bluish, black, and brown calcareous mudstones partly redeposited with subordinate layers of limestones called **Lower Cieszyn Shales**. The age of the Lower Cieszyn Shales is Kimmeridgian-Tithonian. These black sediments beginning of an euxenic cycle which lasted without major interruption until the Albian. Lower Cieszyn Shales have been covered by the Tithonian-Berriasian **Cieszyn Limestones**, vast submarine fans build of calcareous turbidites, and the Valanginian - Hauterivian **Upper Cieszyn Shales** which consist of grey and black calcareous shales intercalated by thin and medium bedded sandstones. During the Hauterivian and the **Grodziszczce Sandstones**, developed as several coarse grained submarine fans, were deposited. In the Hauterivian the calcareous sedimentation pass upward into black clayey and siliceous shales of the **Verovice Beds**.

In the early Albian within the black shales, turbiditic sedimentation of the **Lgota Beds** started. The sequence, up to 450 meters thick, usually begins with thick-bedded sandstones passes upward into thin and medium bedded quartzitic sandstones. Its sedimentation continued up to Early Cenomanian. In the western sector of Polish Carpathians, the uppermost part of sequence is locally developed as spongiolites called **Mikuszowice Cherts**. Along the northern margin of the Silesian basin and in the Sub-Silesian basin upper part of siliciclastic sequence was replaced by specula turbidites of the **Gaize Beds**, up to 250 meters thick.

During the Cenomanian, a period of slow and uniform sedimentation embraced all the Carpathian basins, and well-oxygenated conditions began develop. The Cenomanian is represented by a typical sequence that begins with the **Radiolarian Beds** developed as green radiolaritic shales and radiolarites, intercalated with black shales containing manganiferous concretions, and in upper part with calciturbidites. These are overlain by the Turonian red and green, **variegated shales**, widespread mainly in the northern part of the Silesian Basin and in the Sub-Silesian Basin. In the area of Beskid Śląski and Beskid Mały during Turonian and Coniacian took place sedimentation of **calciturbidites**, later partly eroded during dynamic sedimentation of following those deposits.

Within the Silesian basin, above variegated shales and calciturbiditic sedimentary sequence several complexes of generally noncalcareous turbidites and fluxoturbidites were deposited. During the Early Senonian the **Godula Beds** developed mainly in the western part of the Silesian basin, were deposited. These deposits that consist of several series of thin to thick-bedded glauconitic sandstones could be thick up to 2000 meters or more. During Late Senonian and Paleocene took place the sedimentation of the **Istebna Beds**. The **Lower Istebna Beds (Lower Istebna Sandstones)**, thick up to 1500 meters or locally more, consist of thick and very thick-bedded sandstones and conglomerates. Within the **Upper Istebna Beds**, the thick turbidite and fluxoturbidites complex (the **Upper Istebna Sandstones**) underlies and overlies thin bedded turbidites (the **Lower Istebna Shales** and the **Upper Istebna Shales**). The thickness of sandstone sequence of both Godula and Istebna beds in Beskid Śląski could extremely reach about 5000 m.

The Early Eocene is marked in the Silesian Basin by the sedimentation of the **variegated shales**, interrupted by deposition of the coarse, thick bedded **Ciężkowice Sandstones**. The Ciężkowice Sandstones, as well as occasionally the Upper Istebna Sandstones are important reservoirs of hydrocarbons. In the Middle Eocene was formed thin and medium bedded, shale-sandstone, rhythmic flysch of the **Hieroglyphic beds**.

During the Late Eocene and Oligocene, up to Early Miocene in all Outer Carpathian basins, with exception of the Magura basin, unification of sedimentation could be observed. In the Silesian Basin took place sedimentation of the **green shales**. Later, at the end of the Eocene, marls with abundant planctonic foraminifera were deposited. These are so-called **Globigerina Marls**, which corresponded to a global drop in the CCD that occurred in the latest Eocene.

The Oligocene sequence commences in all basins (except the Magura Basin) the **Menilite Beds** developed as dark brown bituminous shales (the **Menilite Shales**) with **cherts** and siliceous marls and sporadic sandstone complex in their lower part (the Sub-chert sandstones). These sediments represent a new phase of euxenic conditions, but this time owing to the closure of deep-marine connections with the Tethys Sea. In the Carpathian basins, „Black Sea” conditions rapidly developed. Within the shale sequence of the Menilite bed there are several sandy fans. The **Cergowa Sandstones**, typical for the Dukla basin, arrive in the southernmost part

of the Silesian basin. There are developed also **Magdalena Sandstones**, an important reservoir of hydrocarbons in the external sector of Polish Carpathians.

The Menilite beds pass gradually upwards through a transitional facies into the **Krosno Beds** developed as a series of micaceous, calcareous sandstones and grey marly shales. The development of the Krosno beds varies considerably, but on the whole they display overall thinning up sequence. The lower part is formed usually of the thick-bedded sandstones, the middle part sandstone alternating with grey marly shales, and the upper part of the marly shales with subordinate, thin-bedded sandstones. These lithofacies are diachronous across the Silesian, Sub-Silesian and Skole basins. Towards the southeast the thick bedded sandstones steeply wedge out. A thin isochronous horizon of the Oligocene, nannofossil **Jasło Limestones** it makes possible to correlate different lithofacies through the Outer Carpathian basins. In the inner zone of the Silesian Nappe, between Biała and Wisłoka rivers, the Krosno beds passes up to the chaotic deposits of the Early Miocene age.

In the area of Beskid Śląski and Beskid Mały within the Silesian Nappe are divided two tectonic subunits: Cieszyn Nappe and Godula Nappe. The Cieszyn Nappe is built of the Cieszyn, Grodziszczce and Verovice beds, while overthrusting it the Godula Nappe is represented mainly by Upper Cretaceous rocks.

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