Tectonic evolution and oil and gas generation at the border of the North European Platform with the West Carpathians (Czech Republic)

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ABSTRACT: Variscan and Alpine orogens overlap with opposite vergencies in the contact area of the North European Platform and West Carpathians in Moravia (southeastern Czech Republic). Present understanding of the geological structure is based on deep boreholes and seismic profiles through the Carpathian Foredeep, underlying Platform, allochthonous nappes of the Carpathian Flysch Belt, and the superimposed Neogene Vienna Basin. Sedimentary, tectonic and thermal evolution is simulated as a series of events of deposition, erosion and thrusting using basin-modelling software. The extent of the inferred erosion is estimated both from structural features, palaeogeography, and organic maturity data. The crystalline basement has several segments with different subsidence and uplift histories. Devonian and Carboniferous oil and gas source rocks were buried to the oil window during the final phase of the Variscan Orogeny, and later uplifted and partly eroded. Carbonate and clastic formations were deposited in the Middle to Late Jurassic, and include Malmian oil and gas source rocks. At the end of the Early Cretaceous two deep canyons were carved into the Jurassic and older formations, and were filled with clastic sediments rich in organic matter in the Palaeogene. During the Alpine Orogeny in the Ottnangian and Karpatian, the overthrust Carpathian nappes buried the Jurassic and Palaeogene source rocks to depths favourable for hydrocarbon generation. The burial was enhanced by additional Miocene to Pliocene sedimentation in the Vienna Basin. Modelling suggests that major oil and gas generation and migration has taken place since that time and is not limited to the Vienna Basin area.

KEYWORDS: *North European Platform, Carpathians, sediments, oil, gas, maturation, modelling*

INTRODUCTION

The Carpathian Foredeep, Flysch Belt, and the underlying Platform northwest and north of the Vienna Basin is an important oil and gas province in the eastern Czech Republic (Ciprys *et al.* 1995). About 260 deep boreholes have been drilled in this region, most of them (130) in the Ždánice Oil Field, and 50 in the Uhřice Field and the adjacent part of the Nesvačilka Trough. Thirty-four boreholes outside the Neogene Vienna Basin exceeded depths of 3000 m (Figs 2, 4) and five boreholes reached over 5000 m in the area of the Nikolčice-Kurdějov Ridge (Němčičky site–maximum depth 5493 m). The deepest borehole in this region is Jarošov-1 (5578 m) situated to the northeast. Several thousand boreholes have been drilled in the Czech part of the Vienna Basin. The deepest of them was Břeclav-30, at 3915 m. The numerous borehole data together with seismic profiles give an exceptional opportunity for basin analysis and modelling.

This paper gives an overview of the present understanding of the geodynamic evolution of the platform marginal basins, as well as the mechanism and timing of the Carpathian Flysch Belt overthrusting. The burial and thermal history of the autochthonous units, source-rock maturation and hydrocarbon generation is simulated using basin modelling software and organic geochemical data.

GEOLOGICAL SETTING

The geology of the autochthonous units of the southeastern Bohemian Massif was described by Dvořák (1978), Eliáš (1981), Adámek (1990), Eliáš & Wessely (1990), Jiříček (1993), Brzobohatý (1993), Krejčí *et al.* (1994), and Ciprys *et al.* (1995). For more information on the Neogene sedimentary fill of the Vienna Basin and the associated oil and gas fields, see Jiříček & Seifert (1990), Ladwein *et al.* (1991), Sauer *et al.* (1992) and Kröll *et al.* (1993). Geodynamics and petroleum geology based also on 6.5–8.5 km deep wells in northeastern Austria is summarised by Wessely (1984, 1987a, b).

The structure of the area studied comprises the following principal regional geological units (Figs 6, 7, 8):

- the North European Platform (Bohemian Massif), referred to in the text simply as the Platform, which includes the crystalline rocks covered by the autochthonous sedimentary formations;

- the Flysch Belt of the West Carpathians, comprising the Outer (Krosno-Menilite) and Magura group of nappes;
- the Miocene Carpathian Foredeep;
- the Neogene Vienna Basin superimposed on the Carpathian nappes.

There are some specific geological characteristics which make the northern (Czech) part of this region different from the southern (Austrian) one:

- thick carbonate and clastic beds of Devonian to Late Carboniferous age occur in the Czech part of the Platform;
- Middle Jurassic clastics (Gresten Fm.) are thinner and of lesser areal extent;
- the Nesvačilka and Vranovice canyons are carved deep into the Jurassic and older formations, and filled with clastics mostly of Palaeocene to Oligocene age.

The crystalline basement rocks of the southeastern Platform margin (Bruno-Vistulicum; Dudek 1980) in southern Moravia include mainly Cadomian plutonic rocks (555–600 Ma, Dudek & Melková 1975). The main petrographic types are granites to quartz diorites accompanied by rare ultrabasic rocks such as olivine hornblendite. Metamorphics overlie the plutonic rocks only at the northeastern marginal fault of the Nesvačilka block.

The autochthonous Platform formations underlying the Flysch nappes comprise Palaeozoic, Mesozoic and Tertiary sediments. During the Alpine Orogeny, the oceanic crust of Tethys, together with the attenuated Platform passive margin to the north, were gradually underthrust beneath the Carpathian–Pannonian microplate.

The Carpathian Flysch Belt is an allochthonous nappe system thrust during the Neoalpine (Palaeogene and Miocene) tectogenesis. In the area studied, the Flysch Belt comprises the Outer

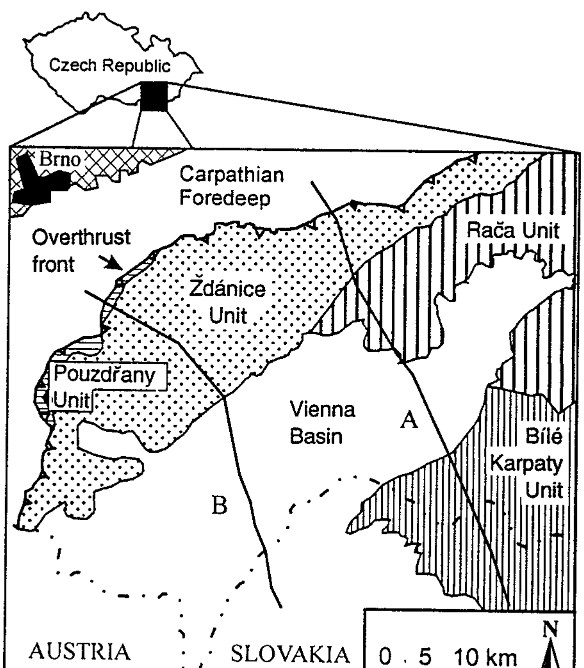

Fig. 1. Geological map of south Moravia (southeastern Czech Republic) with location of cross-sections A and B. The Outer Flysch nappes comprise the Ždánice and Pouzdřany units; the Magura Flysch nappes are composed of the Rača and Bílé Karpaty units.

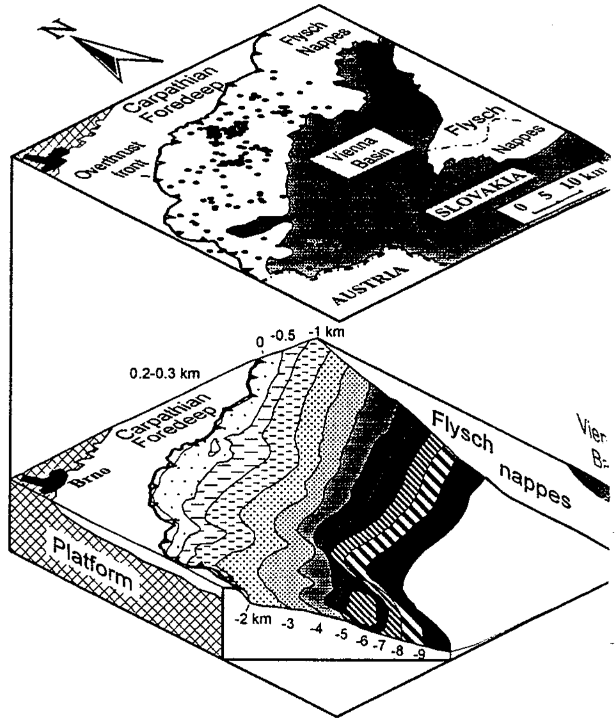

Fig. 2. Topography of the base of the Flysch nappes (in km below s level), with superimposed geological map and borehole locations.

(Krosno-Menilite) group of nappes in the northwest with Pouzdřany and Ždánice units, and the Magura group of nappe: the southeast with the Rača and Bílé Karpaty units. These a underlie the Neogene sediments of the northern Vienna Ba (Figs 1, 2). The boreholes that penetrated the Flysch base located in its shallower part in the northwest. Only less t 1000 m of the Flysch was encountered by drilling below Neogene of the Vienna Basin in the Hodonín–Gbely Horst Týnec–Cunín sites, and in the Břeclav area. The total thicknes the Flysch nappes, however, amounts to more than 5 km increases rapidly to the south-east (Fig. 2).

The Lower Miocene Carpathian Foredeep was formed in foreland of the orogenic zone during the Eggenburgian Karpatian to Lower Badenian. During the latter phase, an obli collision of the Carpathian–Pannonian plate and the Platfc took place (Tomek *et al.* 1987). As a result, the fore autochthonous Lower Miocene was separated from the Vie Basin and deposited as a "piggy back" on the moving Carpat nappes, which were partly eroded. After the Flysch Belt o thrusting stopped in the Karpatian to Lower Badenian, Vienna Basin was formed by a "pull-apart" mechanism a transtensional strike-slip faults (Burchfiel & Royden 1982). left-slip faults at the western margin of the Vienna Basin described by Roth (1980) are interpreted as an en échelon system by Tomek & Hall (1991). Considerable variability of deposition rates within the basin is due to subvertical movem along the synsedimentary faults. The maximum total thickne the Eggenburgian to Romanian sediments of the Vienna B exceeds 5000 m.

STRUCTURAL SEGMENTATION OF THE AUTOCHTHON

Fault systems segment the southeastern margin of the Platf into several tectonic blocks (Fig. 3) which have experie

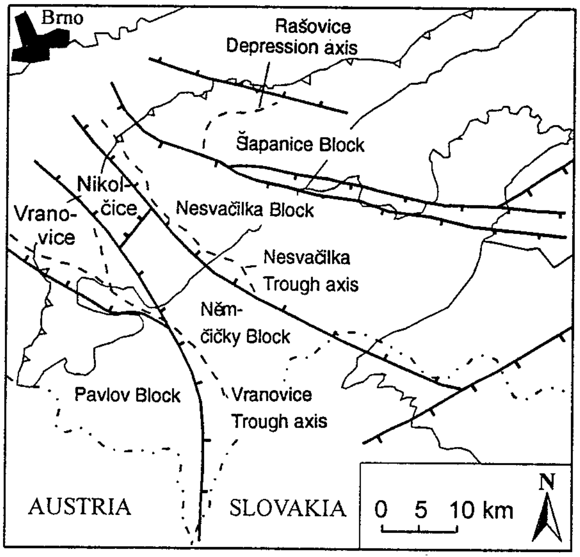

Fig. 3. Main faults cutting the crystalline surface dividing the Platform into blocks. The Měnín Block consists of the Nikolčice and Němčičky partial blocks. The parallel axes of the Vranovice and Nesvačilka troughs are related to the base of Palaeogene.

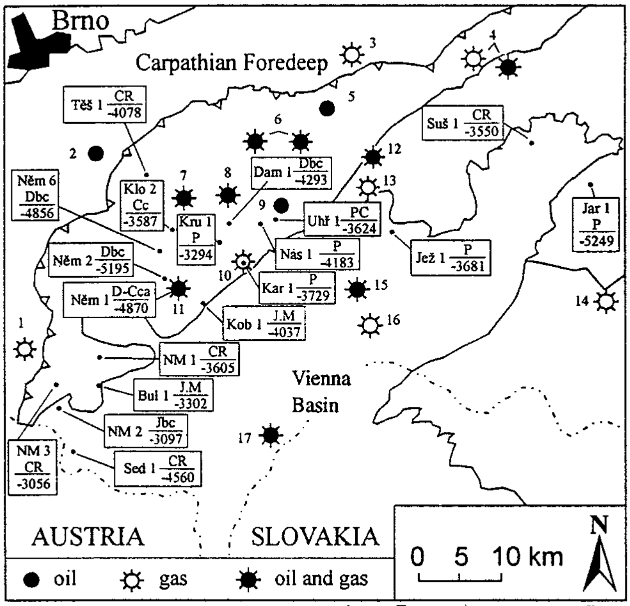

Fig. 4. Selected borehole data, oil and gas fields and occurrences. Boreholes: Bul, Bulhary; Dam, Dambořice; Jar, Jarošov; Jež, Ježov; Kar, Karlín; Klo, Klobouky; Kob, Kobylí; Kru, Krumvíř; Nás, Násedlovice; Něm, Němčičky; NM, Nové Mlýny; Sed, Sedlec; Suš, Sušice. Lithostratigraphy and depth in m at borehole bottom: P, Palaeogene sediments; J.M, Jurassic Mikulov Marlstone; Jbc, Jurassic basal clastics; Cc, Carboniferous clastics; D-Cca, Devonian and Carboniferous carbonates; Dbc, Devonian basal clastics; CR, crystalline basement (depth at top). Oil and gas fields: 1, Dolní Dunajovice (L. Miocene); 2, Měnín and Žatčany (Badenian); 3, Nítkovice (Devonian carbonates); 4, Kostelany (crystalline and Outer Flysch); 5, Letošov (Palaeozoic carbonates); 6, Ždánice (crystalline and L. Miocene); 7, Bošovice (Palaeogene); 8, Dambořice-Uhřice (Jurassic clastics (oil) and Palaeogene (gas); 9, Uhřice (Palaeozoic carbonates); 10, Karlín (Palaeogene); 11, Němčičky (Palaeozoic carbonates); 12, Koryčany (crystalline); 13, Stupava-Ježov (L. Miocene of the Carpathian Foredeep); 14, Hluk (Magura Flysch); 15, Vacenovice; 16, Ratíškovice; 17, Týnec and Cunín (15–17, Magura Flysch and overlying Miocene of the Vienna Basin).

diverse palaeogeographical and palaeotectonic evolutions since the Palaeozoic, as shown by differences in lithostratigraphy and sediment thickness in each block. Palaeozoic and Lower Miocene sediments occur in the northernmost shallow Šlapanice Block (Dvořák 1978). The Ždánice crystalline topographic high was formed prior to the Devonian transgression. In the Rašovice Depression (Fig. 3) the Lower Miocene sediments are about 100 m thick. Both structures are sealed by the Flysch and include oil and gas accumulations (Fig. 4).

In the Nesvačilka Block, the Palaeozoic sediments comprise a complete series of strata from the Devonian to Upper Carboniferous (Namurian-A). They are slightly tilted, with a maximum thickness of 2000 m below the flysch nappes. The

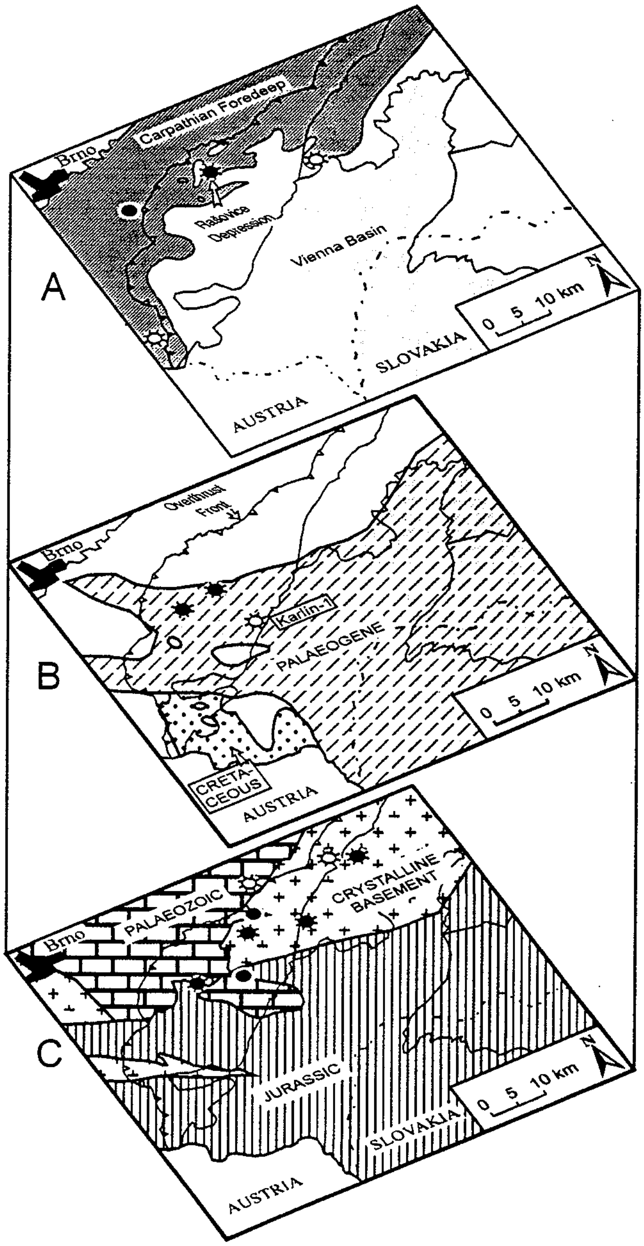

Fig. 5. Subcrop maps of geological units adjacent to and underlying the Flysch nappes. **A.** Miocene of the Carpathian Foredeep (the Vienna Basin is superimposed on the Flysch and Carpathian–Alpine nappes). **B.** Palaeogene and Cretaceous. **C.** Jurassic, Palaeozoic and crystalline. Oil and gas fields are shown in the respective stratigraphic layers where they occur.

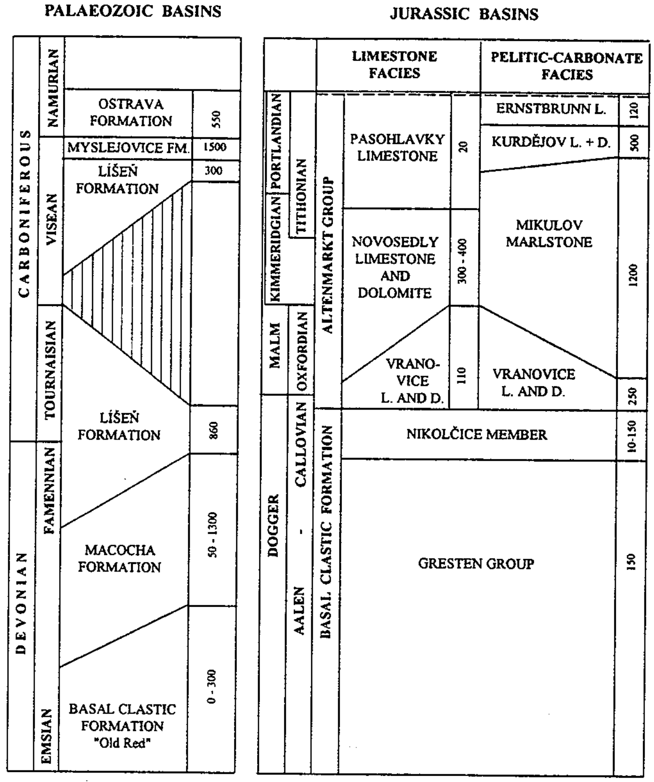

Fig. 6. Lithostratigraphy of the Palaeozoic and Jurassic sediments of the Platform.

Palaeozoic rocks are overlain by Jurassic sediments and by the Upper Cretaceous (?) to Palaeogene Těšany and Nesvačilka Fms. (Figs 5, 6, 7). In the central northeastern part of the Nesvačilka Trough, the Jurassic sediments were largely removed by erosion.

On the west and northwest of the Nesvačilka Block, Lower Miocene sediments extend less than 2 km below the nappes.

The Měnín Block is located further to the south and comprises the tectonically shallow Nikolčice Block in the northwest and the deep-lying Němčičky Block in the southeast. The latter is formed by a complete series of Palaeozoic strata with thick coal-bearing Upper Carboniferous clastics, relatively thick Jurassic carbonates and marls, and thin Palaeogene siltstones. The Měnín Block roughly corresponds to the morphotectonic high of the Nikolčice-Kurdějov Ridge described by Adámek *et al.* (1980). The two partial blocks are separated by a fault encountered by the Němčičky-5 borehole (Adámek 1990). This fault is interpreted as a steep reverse fault.

In the Vranovice Block the Palaeozoic carbonates and the siliciclastic sediments of Early and Late Carboniferous age are absent. The Vranovice Trough in the central part of this block was formed similarly to the Nesvačilka Trough by a deep selective erosion of Jurassic sediments at the end of the Early Cretaceous, and later filled with transgressive Palaeogene sediments (Figs 3, 5).

In the southern Pavlov Block, the crystalline basement is overlain by Devonian basal clastics and Jurassic and Cretaceous sediments (Fig. 5). There is limited or no Cretaceous in the other blocks, which may be due to both non-deposition or erosion.

LITHOSTRATIGRAPHY

The oldest autochthonous sediments deposited on the Platform crystalline basement are deltaic to fluvial clastics of the Lower Devonian Old Red facies (Fig. 6). The basal clastics are overlain by Middle Devonian to Lower Carboniferous carbonates with two different lithofacies–the Macocha and Líšeň Formations. A hiatus is assumed in the Late Tournaisian and Early Visean stages. During the Early Carboniferous, carbonate sedimentation coincided in time and space with deposition of siliciclastic Variscan flysch of the Myslejovice Formation. The Upper

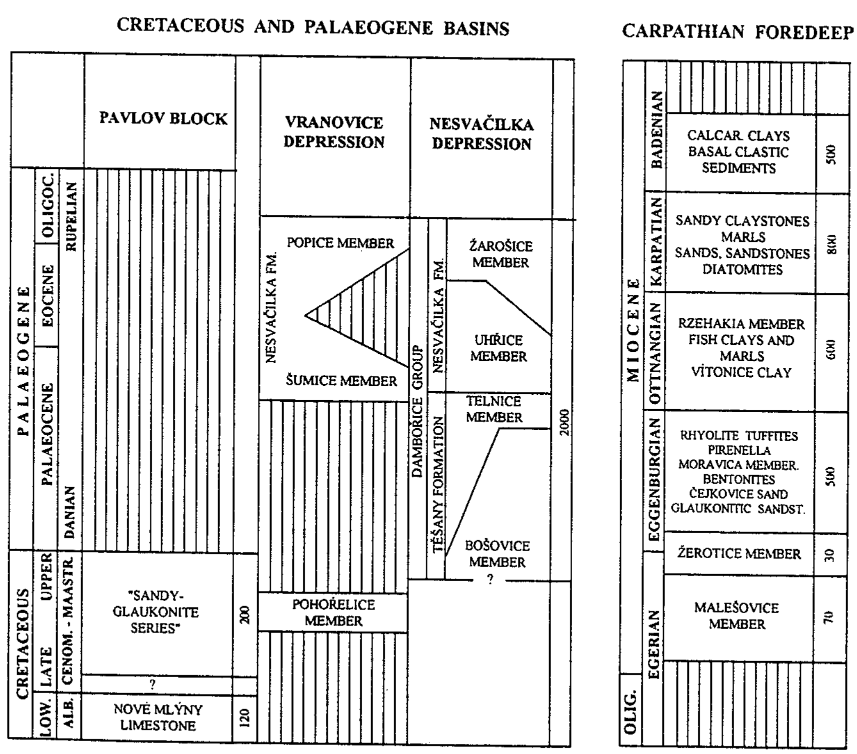

Fig. 7. Lithostratigraphy of the Cretaceous and Palaeogene of the Platform and the Neogene sediments of the Carpathian Foredeep.

Carboniferous terrigenous Ostrava Formation (Fm.) represents a Variscan molasse which closed Palaeozoic sedimentation.

The sediments of the autochthonous Jurassic are developed as carbonate facies to the west and as a pelite–carbonate facies to the east. The Jurassic transgression began in Lias and Dogger times, with basal terrigenous clastics. The lowermost Gresten Fm. locally includes coal seams. The overlying Nikolčice Fm. represents the next marine transgression. The Mikulov Marlstone of the Jurassic pelite–carbonate facies is considered to be the most important oil- and gas source rock in the wider Vienna Basin region (Ladwein 1988; Müller & Krejčí 1992; Krejčí *et al.* 1994). It forms a wedge-shaped body with thickness increasing to over 1000 m towards the southeast. In addition to its source potential, it acts as a seal for some of the underlying reservoir rocks, such as the Vranovice limestone and dolomite. More details of the stratigraphy and lithology of the Jurassic sediments are given by Eliáš (1981), Eliáš & Wessely (1990), and Adámek (1986). On the Pavlov Block, the Jurassic sediments are covered by locally preserved Upper Cretaceous sandy-glauconitic series (Řehánek 1978). In the Nové Mlýny-2 borehole it is underlain by the Albian Nové Mlýny Limestone (Adámek 1986).

The Vranovice and Nesvačilka canyons were carved into the Jurassic sediments, partly along tectonic lineaments, during either Late Cretaceous and Early Palaeocene time (Jiříček 1993) or, more probably, at the end of the Early Cretaceous. The axes of the two troughs are shown in Fig. 3. During the global Palaeocene transgression, basal conglomerates and sandstones were deposited in the troughs, followed by dark grey siltstones with sporadic sandstone layers in the Palaeocene (Těšany Fm.), and massive clayey siltstones and silty claystones in the Eocene to Oligocene (Nesvačilka Fm.). The latter two formations are good source rocks, primarily for gas. More information about the new depositional model, the lithostratigraphic classification (shown in Fig. 7), facies analysis, biostratigraphy, and hydrocarbon prospects of the Nesvačilka Trough is given in Brzobohatý (1993), Jiříček (1993) and Řehánek (1993).

Geological mapping and borehole data show that the Miocene sediments of the Carpathian Foredeep below and in front of the Flysch nappes are of Egerian, Eggenburgian, Ottnangian and Karpatian age, with a total maximum thickness of almost 2000 m (Čtyroký 1993). The Lower Badenian sediments occur as minor relicts both below and above the Flysch nappes to the north, and thus date the time when the Carpathian thrusting ended in this region (Jurková 1979).

Lithostratigraphy of the Flysch Belt is shown in Fig. 8. For more information, see Krejčí *et al.* (1994). The Pouzdřany Unit forms a belt in front of the Ždánice Unit (Fig. 1). The sediments range from the Upper Eocene to the Lower Miocene. The lowermost Pouzdřany Marl grades into non-calcareous pelites with diatomites of the Uherčice Fm. The Boudky Marl (Egerian) was locally eroded at the boundary of the Křepice Fm., which is built up of rhythmically alternating sandstones and claystones. The Šakvice Marl (Eggenburgian) gradually develops from the Křepice Fm. and represents the youngest member of the Pouzdřany Unit.

Deposition of the Ždánice Unit began with the Upper Jurassic Klentnice Fm. and the Ernstbrunn Limestone. The latter is transgressively overlain by glauconitic sandstones and calcareous claystones of the Klement Fm. (Turonian to Coniacian) and the Pálava Fm. (Coniacian to Campanian; Stráník *et al.* 1996). The overlying Submenilite Fm. consists of variegated claystones, dark grey shales, and local sandstone and conglomerate layers. The Menilite Fm. contains calcareous pelagites to pelagic silicites and typical chert beds which can be correlated throughout the vast area of the Carpathians and the foreland of the Alps (Roth & Hanzlíková 1982). Total thickness of this formation is about 60 m in this area and increases towards the northeast. Several intervals within the Lower to Middle Oligocene formations of the Flysch are good oil and gas source rocks.

In the Late Oligocene, the facies changed from hemipelagic and pelagic, to the Krosno Flysch of the Ždánice-Hustopeče Fm. (up to 1350 m thick). The Ždánice Basin evolution ended in the Lower Miocene with the deposition of the Šakvice Marl and Pavlovice Member and Laa Fms.

The Magura Flysch comprises the Rača in the west, Bílé Karpaty in the east, and Bystrica nappes (Fig. 1). Only a few

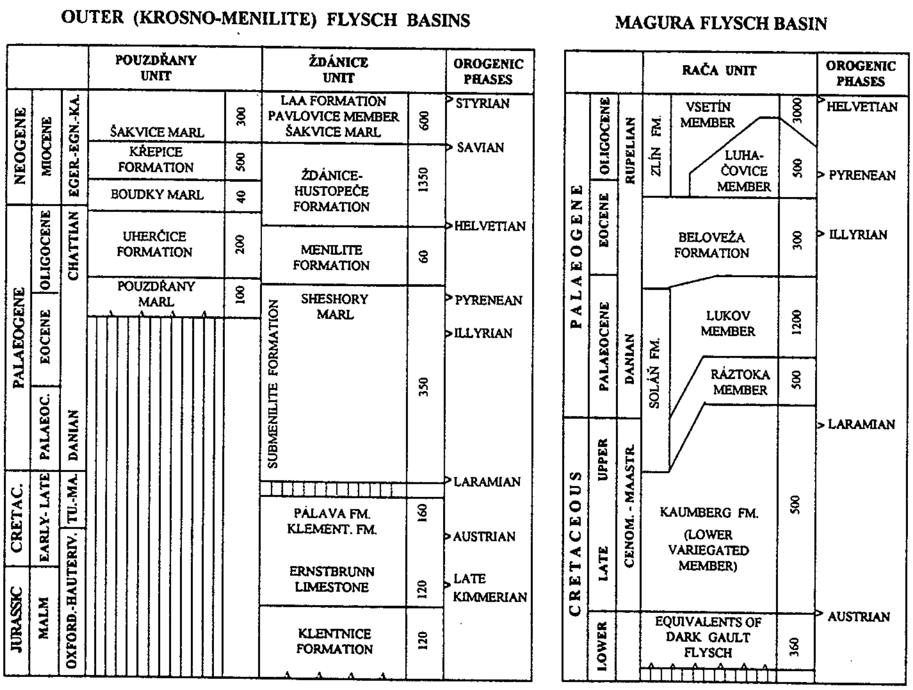

Fig. 8. Lithostratigraphy of the Flysch nappes sediments and related orogenies.

remnants of the latter extend from the northeast to the Vienna Basin. The stratigraphic age of the Rača Unit ranges from the Albian to Lower Oligocene (Fig. 8). The dark claystones of the "Gault Flysch" (Albian) and overlying Kaumberg Fm. (earlier named the Lower Variegated Member, of Cenomanian to Danian age) are followed by the flysch beds of the Soláň Fm. (Upper Cretaceous to Palaeocene) with alternating sandstones and claystones in its lower part and prevailing sandstones and conglomerates in the upper part. The Beloveža Fm. (Upper Palaeocene to Middle Eocene) consists of thin rhythmic flysch with variegated claystones. The overlying Zlín Fm. (Middle Eocene to Lower Oligocene) is a typical flysch facies with sandstones prevailing in its lower section while calcareous claystones and glauconitic sandstones prevail towards the top.

The mainly pelitic Bílé Karpaty Unit (Albian to Eocene) has been correlated with the Laab Unit of Wienerwald (Eliáš *et al.* 1990; Schnabel 1992). No important oil and gas fields have been found in this unit to date.

TECTOGENESIS OF THE FLYSCH BELT

Sediments of the Carpathian Flysch Belt were deposited on the northern margin of Tethys. During the Neo-alpine orogeny they were detached from the basement and, as thrust nappes, pushed to the north to the Platform foreland where the final composite thrust structure was created (Fig. 9). The total distance of the overthrusting to the north and northwest in the Cenozoic probably exceeded 200 km (Roth 1986). At least 40 km overthrust of the Flysch and Calcareous Alpine zones can be confirmed in the Berndorf-1 borehole in northeast Austria (Wachtel & Wessely 1981). The palaeogeographical and geodynamic model of the Vienna Basin evolution at the contact of the Eastern Alps w the Western Carpathians (Seifert 1992) and the palaeomagne data of Krs *et al.* (1993) suggest that the probable depositio basins of the Magura Flysch were situated on the north margin of the African plate.

Deposition of the lowermost Klentnice Fm. of the Ždán Basin was associated with the Late Kimmerian orogeny (Up Jurassic; Eliáš 1992). Hardground occurrences on top of Ernstbrunn Limestone (Late Tithonian to Hauterivian?) sugg a possible continuous marine environment with almost no se mentation after the Hauterivian. The Klement Fm. (Turonia Middle Coniacian) was deposited after the Austrian phase (Ea to Late Cretaceous). The Laramian phase in the latest Cretaceo to Palaeocene initiated an increased input of coarse clas material into the Soláò and Submenilite Fms. Accumulations coarse clastics in the Middle- to Upper Eocene horizons of Submenilite Fm. reflect Illyrian (Middle/Upper Eocene) a Pyrenean (Eocene/Lower Oligocene) thrusting in Carpathians. During the Helvetian Orogeny (after the Lov Oligocene) the sedimentary fill of the Magura basin was fol and detached. The embryonic Magura thrust structure suppl clastic material into the Ždánice-Hustopeče Fm. (Stráník *et* 1991).

During the Savian phase (Eggenburgian), the sediment fill was detached from the Ždánice Basin, and a nappe wit shearing character was formed. Tectonic effects of this orog are evident mainly in the internal (eastern) part of this unit, wh in the outer part thin Lower Miocene sediments were deposit During the Styrian phase (Karpatian/L. Badenian), the lead

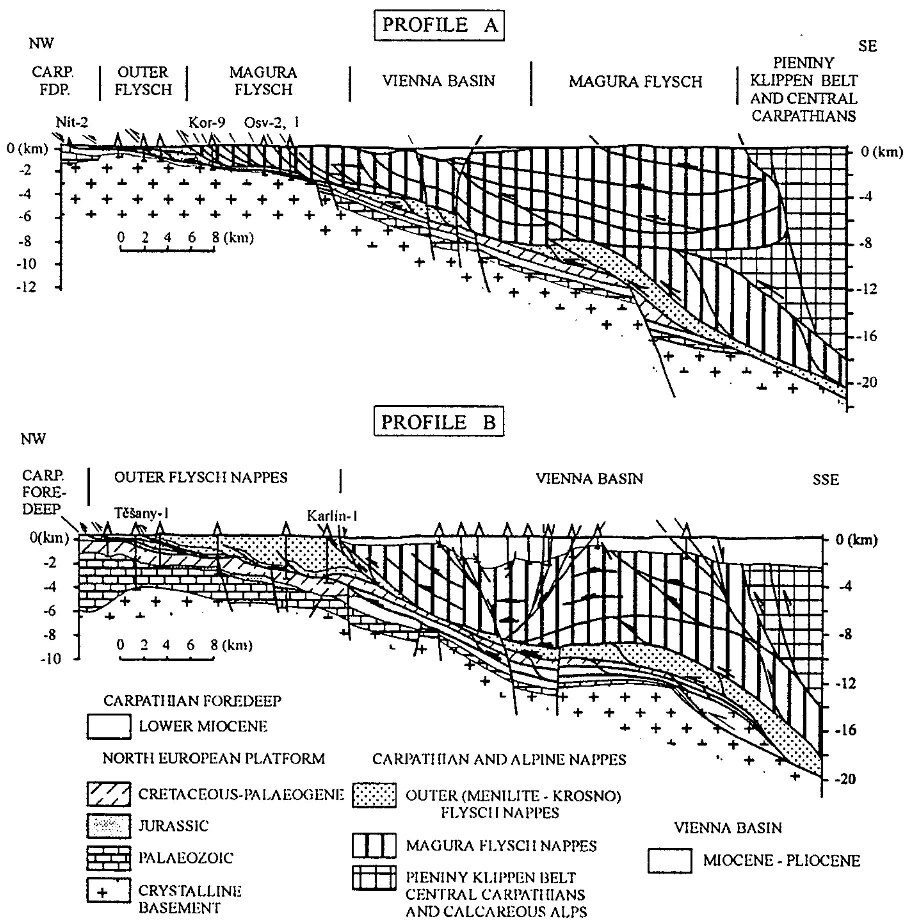

Fig. 9. Geological cross-sections A an (location in Fig. 1) through the Flysch B

imbricate fan of the Ždánice Nappe was formed by "piggy-back" mechanism, with the principal movement along the basal-nappe plane and only minor movements along internal thrust planes, typical of the overstep-type mechanism of Boyer & Elliott (1982). To the northwest the Ždánice Nappe was thrust over the Pouzdřany Nappe and the Lower Miocene of the Carpathian Foredeep (Fig. 1), while it was in turn overridden by the Magura Nappe to the southeast.

At the base of the Flysch nappes the Platform formations were often tectonically incorporated into the duplex system. This tectonic enhancement of thickness affected the autochthonous Palaeozoic, Jurassic, Palaeogene and Miocene formations, and possibly also the crystalline basement in the deeper parts to the east (Fig. 9).

The horizontal distance of the Styrian overthrust, proved by the borehole northeast of the study area (close to Zlín), exceeds 20 km. The total overthrust of the Outer Flysch nappes, including the Pouzdřany Unit in front of the Ždánice Nappe, is estimated to be about 100 km.

OIL AND GAS FIELDS

Outside the Miocene of the Vienna Basin, most of the oil and gas pools are situated in the autochthonous sediments underlying the Flysch nappes (Figs.4, 5). The most important commercial accumulations occur in the northern margin of the Nesvačilka Trough with pay horizons in the clastics of Jurassic (Dambořice) and Palaeogene age (Uhřice and Karlín). Reservoirs of the Ždánice oil and gas field are situated on a topographic high in the weathered quartz diorite and Lower Miocene clastics of the Rašovice Depression. The Dolní Dunajovice Gas Field and the Měnín Oil Field are situated within the Miocene of the Carpathian Foredeep northwest of the Flysch Belt. Minor pools are known within the Flysch nappes underlying the Vienna Basin (Týnec-Cunín, Vacenovice, and Ratíškovice; Fig. 4).

MODEL OF HYDROCARBON GENERATION

The model of hydrocarbon generation is based on the general experience that kerogen is converted to oil and gas if the source rocks are sufficiently heated for a necessary "cooking" time (Tissot & Welte 1984). Measured organic maturity, as a record of the total thermal history, is used for calibration of a simulated burial and thermal history using the 1-D PD^{TM}-PC (IES) modelling software based on the principles of Welte & Yükler (1981) and Welte *et al.* (1981). Oil and gas generation is modelled applying chemical reaction kinetics (Tissot & Espitalié 1975) with respect to kerogen type in each source rock. Present steady-state or corrected subsurface temperature and heat-flow data are from Čermák (1979). Maturity data were measured on numerous core samples from deep boreholes in the contact area of the Platform and the Carpathians, and include vitrinite reflectance (R_o), T_{max} from Rock-Eval pyrolysis, and biomarker ratios.

The conceptual model is based on a series of stratigraphic and tectonic events discussed above, i.e. deposition, erosion, non-deposition, and thrusting in this area. Some of the depositional and erosional events are inferred from palaeogeography and tectonics, and their extent and duration are estimated mainly from organic maturity.

The hydrocarbon generation history in the region is determined by the following facts and assumptions. Lower to Upper Carboniferous clastic formations include oil (?) and gas source rock intervals with mixed kerogen type III/II, III and genetic potential up to 2 kg of hydrocarbon per tonne of rock. It is inferred that Palaeozoic sedimentation ended with additional deposition of Upper Carboniferous formations younger than those known from the deep boreholes. Possible additional thrusting of Variscan nappes from the west over the Namurian and/or younger formations is assumed to increase the burial depth mainly in the northwestern part of the region. Both types of additional overburden were removed by Late Palaeozoic to Early Mesozoic erosion. Organic maturity (R_o) in the Carboniferous formations increases from the southeast, where they now plunge under the Carpathians, to the northwest, where they outcrop in the mountains of the Bohemian Massif. This suggests that the maximum palaeotemperatures and inferred eroded Variscan overburden also increased from the southeast to the northwest (Dvořák 1979; Müller & Krejčí 1992). The Carboniferous source rocks entered the oil window first during the Late Palaeozoic burial (Fig. 10) but some of the oil and gas was probably lost during subsequent uplift. In the southeastern part of the region these source rocks were still not entirely depleted by that time.

After a hiatus in the Triassic, and rifting and basin opening during Early/Middle Jurassic, the Upper Jurassic marls were deposited. Recent analyses of these source rocks show that the reactive part of kerogen is type II, while the abundant inertinite makes the bulk hydrogen index lower, as if the kerogen was type II/III given by Ladwein (1988). The genetic potential (S1 + S2 of Rock-Eval pyrolysis) of these rocks ranges from 2 to 10 kg of hydrocarbons per tonne of rock. Burial of Jurassic source rocks was not sufficient to generate hydrocarbons.

Deposition of the Upper Cretaceous sediments with very low source potential had no special impact on hydrocarbon generation. It was followed by local carving of two deep canyons (Nesvačilka and Vranovice Troughs) into the Jurassic and Palaeozoic formations. During the Palaeocene to Oligocene, these were filled with siliciclastic sediments rich in organic matter (Nesvačilka and Těšany Fms., Fig. 10). Their maximum thickness is about 2000 m, and the kerogen is mostly land derived humic matter enriched in liptinite (type III and III/II). This is the second most important source rock, with mainly gas potential. Due to facial changes it is more oil-prone in the southeast. Maturity increases with depth along an almost identical trend both in the Palaeogene (Fig. 11) and Jurassic rocks, which suggests that deposition of the Palaeogene merely compensated the preceding local erosion and did not cause any additional maturation of the Jurassic source rocks.

The Menilite Formation of the Krosno-Menilite Flysch is the stratigraphic equivalent of the upper part of the autochthonous

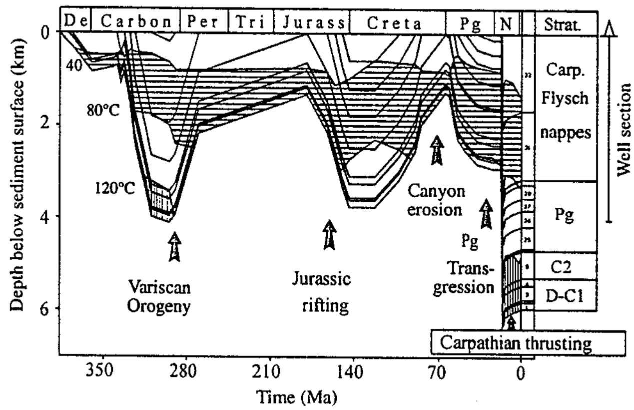

Fig. 10. Model of the burial and thermal history of the Karlín-1 borehole section (extended to the crystalline basement based on seismics surveys and adjacent boreholes). Location of Karlín-1 is shown in Figs 4 and 5.

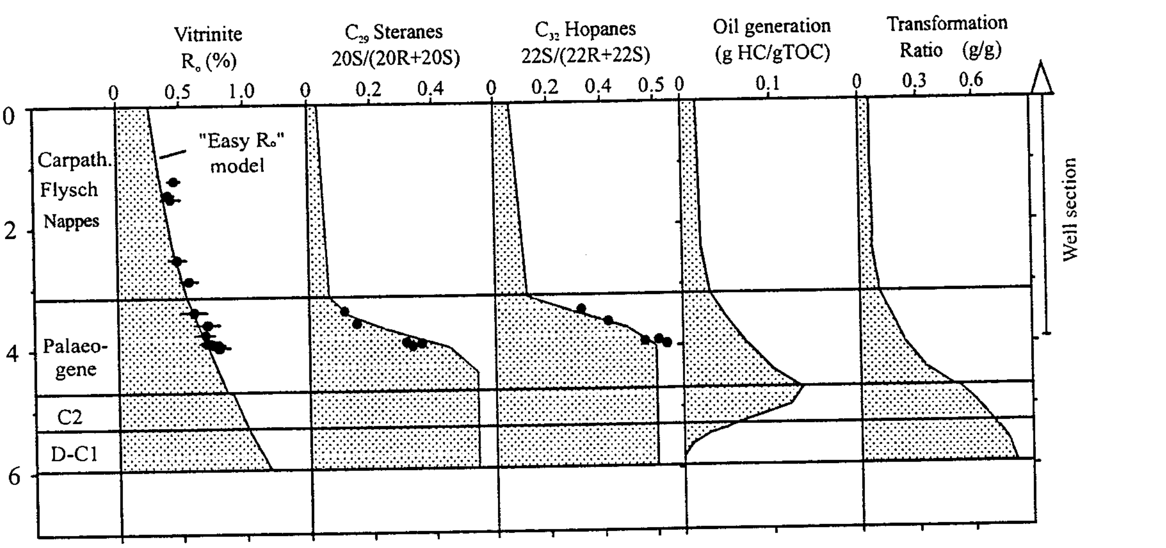

Fig. 11. Depth plot of measured and calculated organic maturity in the Karlín-1 borehole, simulated oil generation from kerogen type III, and t formation ratio quantifying the conversion of kerogen to oil and gas.

Nesvačilka Fm. It has good oil and gas genetic potential (S1 + S2 up to 18 kg hydrocarbon per tonne of rock) which is similar to or even better than that of the Malmian source rocks (Mikulov Marl). Its original thinness is partly compensated by multiple tectonic thickening in the nappe system.

During the Styrian phase of the Alpine–Carpathian orogeny (16–17 Ma), the Flysch nappes buried the Platform sedimentary units and partly also the Carpathian Foredeep (Molasse Zone). As in adjacent Austria (Ladwein *et al.* 1991) this was the decisive mechanism for burial and maturation of the Jurassic and Palaeogene source rocks, which was enhanced by continuing sedimentation in the Vienna Basin. In the Carboniferous source rocks underlying the southeastern part of the Carpathian nappes, the oil and gas generation restarted for the second time at depths of over 5 km.

Simulation of burial due to thrusting requires precompaction of the nappe formations before emplacement on top of the autochthonous sequence. This is achieved by modelling of sedimentation and burial in the original Flysch basin as a first step, followed by burial and partial catagenesis due to overthrust by the earlier-formed (Magura) nappes. Then the precompacted sediments can finally be emplaced on top of the Platform formations. In the final phase of thrusting, the autochthonous formations are partly tectonically thickened by a duplex mechanism. The model of burial and the thermal history of the Karlín-1 borehole (Fig. 10) shows the principal events that are characteristic for the e region; the extent of these events, however, varies consideral the different Platform blocks. This example represents the ce part of the Nesvačilka Trough where the Jurassic formations mostly eroded and where the thickness of the Palaeogene is to maximum. Simulation is calibrated by vitrinite reflectanc biomarker ratios (Fig. 11), and suggests that the oil gener presently occurs at a depth of 3.5 to 5.5 km and gas generati the deeper zones.

Based on modelling of a series of boreholes, matur zonality is shown in a regional cross section in Fig. 12 higher maturity data (R_o) of the Flysch compared wit simulation trend of the autochthon occur in many bore (e.g. Fig. 11) and suggest that these formations were b deeper in the past. The uneven top of the oil window in F reflects partial uplift of the Flysch nappes due to thru Overthrusting and rapid burial of the autochthon to th window within one or a few million years suggests the po for overpressuring at depth. This is proved in numerous wel in Karlín-1, where at depths of about 3980 m the formation sure attained 106% over hydrostatic (80 MPa; Benada & 1991). Active faulting during further evolution of the enabled migration of oil and gas along faults to reservoirs are mostly situated in the immature zone of the Vienna Bas the autochthonous formations of the Platform.

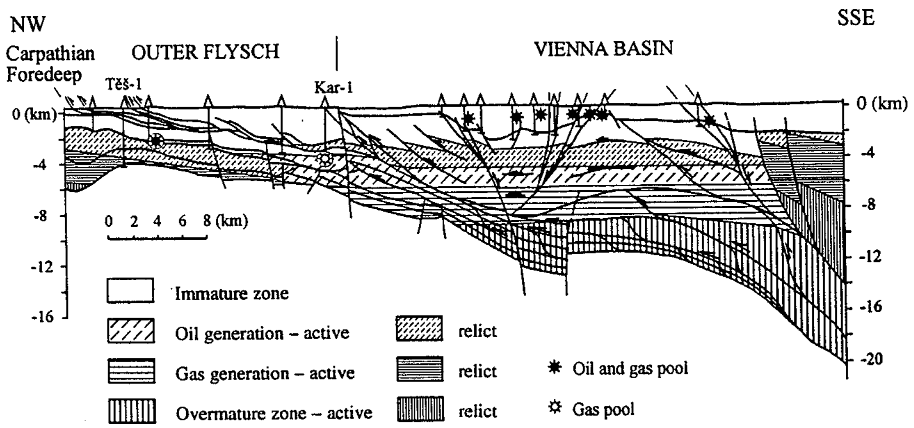

Fig. 12. Source-rock maturity zon the geological cross-section B (locat Figs 1 and 9) based on a series of models.

CONCLUSIONS

Basin analysis of the contact area between the West Carpathians and the Bohemian Massif (North European Platform) provides a deeper insight into the complexity of source rock deposition and thermal maturation throughout the geological history. Potential source rocks occur partly within the Late Palaeozoic and mainly the Malmian, and Palaeogene formations of the autochthon and in the Oligocene of the Outer Flysch. All these source rocks were buried sufficiently to generate oil and gas in some parts of the region during the Alpine–Carpathian orogeny. The Palaeozoic formations lost some of their potential during the Variscan orogeny.

Precise analysis of the structure and geodynamics of the Flysch thrusting shows that maximum source-rock burial took place during very late Karpatian and early Badenian. Several tectonic processes had to be simulated within the model of the basin evolution related to an overthrust belt. These comprise partial precompaction of the allochthonous sediments of the Flysch nappes prior to emplacement over the Platform, tectonic doubling of some of the autochthonous units by duplex mechanisms, and their incorporation into the lower part of the nappe system. These factors influenced the thermal history and hydrocarbon generation during the last phases of the Carpathian orogeny.

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