Subsidence, Thermal and Maturity History of Late Miocene to Quaternary Formations in the Pannonian Basin*

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Abstract

Subsidence, thermal and maturity history of Late Miocene (Pannonian s.l.) to Quaternary formations has been simulated along a 70 km long regional seismic profile in the eastern Pannonian Basin (Central Europe), through 2 subbasins (from the Jászság Basin to the Northern Békés Basin) with PetroMod v11 software. Input data were based on facies, sequence- and lithostratigraphic models as well as tectonic interpretation. The studied succession varies between 2,000 - 3,000 m and is underlain by Mesozoic-Paleozoic basement belonging to the Mecsek zone of the Tisza megaunit. The hemipelagic Endrod Marl Formation lying above the base Pannonian horizon is considered to be one of the most important source rocks within the Neogene Petroleum System of the Pannonian Basin.

As the first step the paleo-water depth changes and the sediment-water interface temperature changes have been estimated. A thermal history model was constructed for the studied regional profile based on published geothermal data, tectonic, kinematic and geodynamic models, organic geochemistry data. Based on the results of the above mentioned models maturity history, migration and accumulation scenarios have been simulated using three different kinetic models. The subsidence was not uniform along the 70 km long profile. The northern (Jászság Basin) part subsided earlier and faster while the southern Békés Basin section subsided later and finally became deeper than the northern basin side. The delta system, step by step, prograded from northwest towards the southeast, gradually filling up the accommodation space.

Concluding the results, the source rocks of the Jászság Basin became matured and generated hydrocarbons (between 6.8 and 5.3 Ma) earlier than in the Northern Békés Basin (from 5.3 Ma). The Endrod Marl has mixed type (III and II) kerogene, 1.8% TOC and 208 mg/g Hydrogen Index, it generated mainly gas. According to the results of the simulation scenarios the gas generally migrated upward and occasionally sidelong. Recently the migrating gas reaches the base of the Quaternary sediments in the Jászság Basin while it is still in the Újfalu Sandstones in the Northern Békés Basin. Gas is mainly dispersed; accumulations might have been developing in possible stratigraphic and structural traps.

Introduction

The Pannonian Basin is a back-arc basin surrounded by the Alps-Carpathians-Dinarides, which was formed during the subduction of the ocean floored margin of the European Plate to the Carpathian arc from the Late Cretaceous to Late Miocene. In the Late Early Miocene (~ 18 My) the area belonged to the Central Paratethys. During this time subduction took place along the whole Carpathians, resulting in volcanic events, fast subsidence, stretching of the lithosphere by β=1.6-2 and δ = 4, and in increased heat flow up to 80-130 mW/m2 in the Pannonian basin. Earlier this time period was called "synrift phase" referring to McKenzie's rift model (1978), but it was not a real rifting event, only an extension. During this phase several pull apart type subbasins were formed, most of them can be considered as potential hydrocarbon generation areas.

From approximately 12.6 My, in the Late Miocene (postrift phase) the subduction stopped in the Western Carpathians and continued below the Eastern Carpathians. Basin subsidence slowed down, and the connection to the Eastern Paratethys and to the Mediterranean was lost, therefore a large endemic lake (called Lake Pannon) developed. The huge sediment influx from the surrounding orogens gradually filled the basin by the Early Pliocene (Horváth et al., 1988, Mattick et al., 1988, Magyar et al., 1999, Lenkey et al., 2002, Horváth, 2007).

The aim of the paper is to present the results of the simulation of subsidence, thermal and maturity history with PetroMod v11 2D software of Late Miocene – Pliocene (Pannonian s.l. in regional terminology) to Quaternary formations along a 70 km long regional seismic profile in the eastern Pannonian Basin (Central Europe). The studied regional section has NNW-SSE orientation close to one of the main coeval route of sediment supply (Figure 1 and Figure 2). It crosses two subbasins: the Jászság Basin and the Northern Békés Basin isolated by a basement high in between them. Input data were based on facies, sequence- and lithostratigraphic analysis as well as on tectonic studies.

Stratigraphy

To build the models different stratigraphic and lithologic parameters, like the lithological units, their thickness, time constraints, paleo-water depths, sediment-water interface temperatures, erosional events, eroded thicknesses, etc. were created on the basis of detailed sedimentologic, stratigraphic as well as sequence stratigraphic analysis of the Late Miocene-Pliocene sedimentary succession in the study area and its neighbourhood.

Along the regional profile data of eight HC exploration wells as well as several water prospecting wells, that have been used for the interpretation. Timing of the identified horizons was based works on the correlation of the seismic network and magnetostratigraphic measurements in some continuously cored wells of the Hungarian Geological Institute (Kaskantyú-2, Bácsalmás-1, Tiszapalkonya-1, Vésztő-1, Lantos et al., 1992, Elston et al., 1994) and on sequence and integrated stratigraphic studies (Pogácsás et al., 1994, Vakarcs, 1997, Juhász et al., 2006, 2007b). The 3rd order sequence boundaries were used as horizons with more or less acceptable age data for the basin modeling.

The basin fill's lithology is based on the interpretation of the wells. The main depositional facies are time transgressive units lying above each other as can be seen on Figure 3: basinal marls at the base (Endrőd Marl Formation), deep-water turbiditic sandstones and clays (Szolnok Formation), slope facies (Algyő Formation comprising the basin slope and the slope sediments as well), delta front, delta plain and coastal plain facies (Újfalu Formation), and alluvial plain facies (Zagyva Formation).

The changes of the paleo water depth are also necessary for reconstruction of the subsidence history, in the lack of it only the depositional history could be modeled. Water depth is the result of the interaction of tectonics, lake level changes and sediment influx. In the study area the last was the main influence factor, and in the case of the 3rd order sequence boundaries (6.8 and 5.3 My old) the strike-slip tectonism as well as early inversion and uplift had also a major effect (Juhász et al., 2006, 2007a, 2007b). Estimations on water depth were based on earlier studies (Horváth et al., 1986, Magyar et al., 1999), the thickness of the slope lithofacies in wells and on the height of slopes/clinoforms deduced from the seismic profiles. In the basinal areas there were deeper waters (400-500 m), while above the central basement high lake level was much shallower. Due to the prograding delta system the water depth suddenly changed at the third order sequence boundaries (Figure 4). The sediment – water interface temperatures have been estimated with the Petromod's Global mean surface temperature calculator (based on Wygrala, 1989).

Tectonic Settings

The studied regional profile lies in the area of the Mid-Hungarian strike-slip zone, which was reactivated during the Late Miocene, Pliocene and the Quaternary also. In the surrounding area of the studied section the tectonic setting is well interpreted in previous works. Pogácsás et al. (1989) identified several compressional structures of this zone. They concluded a sinistral strike-slip fault mechanism, which has 7-8 km displacement. Some of these strike-slip structures contain discovered hydrocarbon occurrences. Detzkyné Lőrincz et al. (2002) interpreted seven tectonic phase from the Late Cretaceous to Quaternary. During these phases the dextral or sinistral strike-slip component was the dominant fault mechanism and the faults were reactivated several times. A detailed tectonic reinterpretation and mapping on 2D seismic network is in progress on the area of the Mid-Hungarian Mobile Belt in the central part of the Great Hungarian Plain (Pogácsás et al., 2011a, b).

On the map shown in Figure 5, several faults were correlated on the 2D seismic network; however, a great amount of the faults was recognized without correlation due to the long distances between the seismic sections. The structure of Upper Miocene - Pliocene sediments is dominated by NE–SW or ENE–WSW striking master faults with significant lateral displacements, rooted in the preneogene basement. The orientation of the conjugated faults seems to be controlled by the Preneogene – Early Neogene zones of weaknesses, therefore observed geometry (e.g. flower structure) is not necessarily indicative of the sense of the last displacements, and the direction of the slip may possibly be oblique (Pogácsás et al. 2011c).

The identified faults are subdivided into three groups according to their relative ages. The two younger Late Miocene (Pannonian) fault groups (9.2-6.8 My and a younger than 6.8 My) have several structural lines with N-S and NE-SW direction while the oldest group of the identified faults (older than 9.2 My) contains fewer structures. These faults correspond to the results of previous researchers mentioned above. On the section some structures are connected to the Late Miocene faults, which are possible traps, and based on their young age, they could have acted as possible migration pathways. The most of the faults do not have significant vertical components; they are probably connected to the strike-slip zones (Figure 6).

Heat Flow History

The heat flow of the Pannonian basin is increased due to the Late Miocene lithospheric extension. In the investigated area it has 90-100 mW/m2 (Lenkey et al., 2002, Horváth et al., 2004). To the exact determination of the heat flow history temperature measurements of eight wells and vitrinite reflectance data from one well (well 1, Laczó and Jámbor, 1988) has been used for the calibration. In the calibration process the heat flow history did not fit to the present temperature and to the present vitrinite reflectance data simultaneously, therefore we applied two heat flow history scenarios. The temperature calibrated history seems to fit better, because it correlates to the recent known heat flow values of the area, but in this case the maturity is overestimated. In the case of the vitrinite reflectance calibrated heat flow history the maturity fits, but the temperature seems to be underestimated. There is a 10 mW/m2 difference between the two trends of heat flow history (Figure 7).

Petroleum System

The Neogene hydrocarbon system of the Pannonian basin is fairly well known. The main source rock belongs to the Late Miocene (Pannonian) series; it is the basinal marl facies (Endrőd Marl Formation). It contains mainly type III kerogene with less amount of type II. It is generally a gas prone source rock, but it can generate oil as well. There are a limited number of TOC measurements available from the study area. However based on the analog basins (Badics et al., 2011) the average TOC content of the basinal marl is about 1%, but in locally it can be as high as 2%, and its average Hydrogen Index is 280 mg HC / g TOC (Clayton et al., 1994, Dolton, 2006).

The kinetic of this basin marl facies is not very well known, therefore the hydrocarbon generation has been calculated by three general kinetic models: Pepper and Corvi (1995) TIII DE, Pepper and Corvi (1995) TIII-IV F and Behar et al. (1997) TIII Mahak. All of these models are able to model the gas and oil generation too, from young Neogene sediments, and have been created for type III kerogen.

There is a difference between the three kinetic models in their hydrocarbon generation effect. The oil and gas generation of the Mahak model is more simultaneous like the Pepper and Corvi models, which calculate the beginning of oil generation before the gas generation. The DE model is best used for organic matter of higher order plants, while the F model is prepared and best for lignine-rich organic matters.

The possible reservoirs of the study area are the turbiditic sandstones of the Szolnok Formation and the delta front-coastal plain sandstones of the Újfalu Formation. The clays of the slope facies (Algyő Formation) and the alluvial plain facies (Zagyva Formation) represent potential seals. Structural traps could be developed in the fault connected structures and stratigraphic traps in the interfingering zones of the reservoir and seal facies (Figure 8).

Subsidence History

The subsidence was not uniform along the 70 km long profile (Figure 9). The northern (Jászság basin) part subsided earlier and faster while the southern Békés basin section subsided later and finally became deeper than the northern basin side. The delta system, step by step, prograded from northwest to southeast gradually filling the accommodation space.

Far from the sediment input the basinal areas were dominated by the deposition of pelagic marls (Endrőd Formation), overlain by deep water turbiditic sands and clays (Szolnok Formation). The prograding delta system deposited a huge thickness of turbidites (about 1,000 m) in the deep basins, particularly in the Jászság basin. The slope facies (Algyő Formation) has more or less uniform thickness along the profile.

The Jászság basin, which was closer to the sediment source areas, at about 6.8 My ago was already filled up, while the Northern Békés basin only 1.5 My later. The subsidence rate probably was connected to the sediment influx, and it has the same difference by these paleo water depth features. The alluvial plain facies (Zagyva Formation) is thickening in the Northern Békés basin presumably due to the Pliocene-Quaternary subsidence. During Late Pannonian-Quaternary the Northern Békés basin's subsidence had such extent, that it exceeded the depth of the Jászság basin.

Maturity and Migration

The results derived from two heat flow models and three kinetic models, and produced six reconstructions, from which, common features can draw the best conclusions. (Figure 10, Figure 11 and Figure 12)

The temperature and the heat flow are the most important maturity factors. The difference between the two used heat flow model: according to the temperature calibrated kinetic model the hydrocarbon generation started earlier 6.8 My ago in the case of the Mahak and DE models, while in the case of the F model generation began later (5.3 My ago, Figure 10). The vitrinite reflectance calibrated heat flow model, applying lower temperature and HF values, resulted later generation (Figure 12).

The maturity zones are connected to the heat flow models. In the case of the higher heat flow scenario the oil and gas window are in higher position (DE and F model) and/or has major thickness (Mahak model). At present according to the DE scenario a relatively thick overmatured zone is being present both basin areas, while in the case of the F scenario there are much thinner overmatured zones, and in the Mahak model there are not overmatured intervals (Figure 11). Applying the lower heat flow scenario neither the DE, F nor Mahak models resulted appearing of the overmatured zones (Figure 12).

Migration was modeled by the Darcy and by the flow path method. The red arrows show the direction and the intensity of the migration, but size of the arrows is not related to the migrated petroleum volume. The generated amount of petroleum can be estimated from the transformation ratio of the source rock. The generation-migration process is different between the two basins due to the diverse basin filling; therefore the Jászság basin generated hydrocarbons earlier to the Northern Békés basin.

According to the higher heat flow model the source rock produced hydrocarbons earlier then in the case of the lower heat flow model, therefore in the first case the migration started up earlier. Based on the higher heat flow recently, the maximum intensity of the migration is within the Quaternary sediments in the Jászság basin and within the delta front sediments in the Northern Békés basin. While applying the lower heat flow model the slope sediments (Algyő Formation) can be characterized by the highest intensity migration in both subbasins.

The only exception is the model using Mahak kinetic, which calculates intense horizontal and vertical migration. Migration intensity seems to be the same in case of both the lower and higher heat flow versions of the Mahak models. Most intensive migration took place in the Quaternary sediments in the Jászság basin and in the delta front facies (Újfalu Formation) in the Northern Békés basin. The Mahak model results the most intensive migration process, connected to its lower activation energy. The DE model produced the most gas due to its highest transformation ratio.

Conclusions

Late Miocene – Quaternary subsidence, maturation and petroleum generation and migration history were simulated along a 70 km long NNW-SSE oriented composite seismic section in the central part of the Great Hungarian Plain. The 2D geological model was based on stratigraphic and tectonic analysis. Two heat flow history scenarios were applied based on the available temperature and the vitrinite reflectance data. Three different kinds of general kinetic models (developed for type III kerogens) were used. The results show that the subsidence of the Jászság basin took place earlier and faster than the Northern Békés basin, because it was filled earlier by the prograding delta system from the NW direction.

Therefore the Jászság basin heated faster, and the maturity and hydrocarbon generation was mainly affected by the temperature/heat flow and the fast subsidence. The source rock (Endrőd Marl Formation) generated hydrocarbons earlier in the Jászság basin than in the Northern Békés basin. Petroleum generation started at about 6.8 Ma (according to the higher heat flow scenario) – 5.3 Ma (according to the lower heat flow scenario) ago, depending on location. Matured productive source rocks developed in the basinal areas. Mainly gas and a smaller amount of oil were generated, but only the gas migrated.

The highest intensity of migration seems to be present within the Quaternary sediments in the Jászság basin and within the delta front facies (Újfalu Formation) in the Northern Békés basin in the case of higher temperature calibrated heat flow model. According to the lower vitrinite reflectance calibrated heat flow scenario the slope sediments (Algyő Formation) of both basins can be characterized by the highest migration intensity.

Acknowledgements

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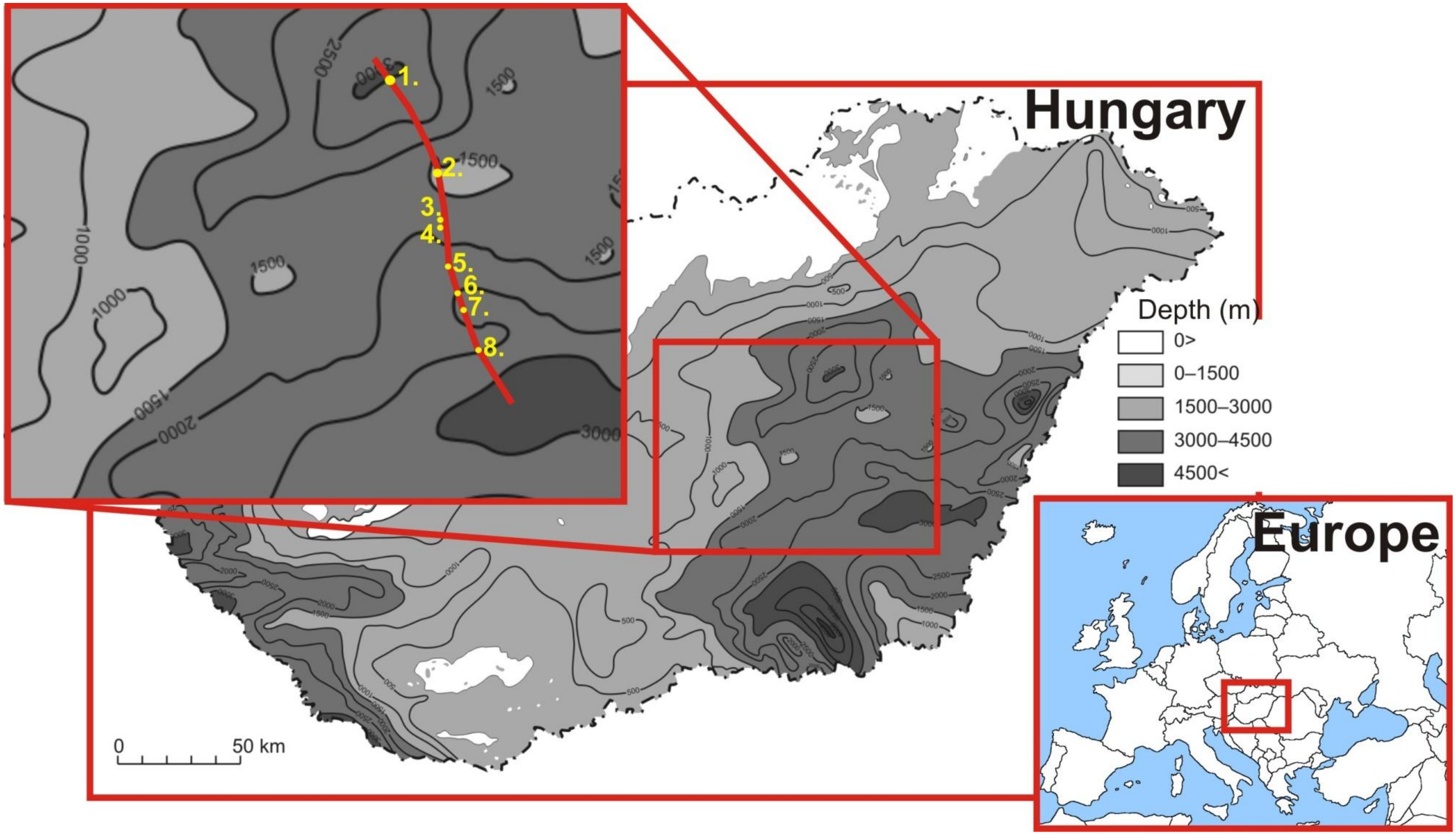

Figure 1. Location of the studied section and the eight wells on the isopach map of Late Miocene – Pliocene (Pannonian s.l.) sediments in Hungary (after Csíky et al., 1987).

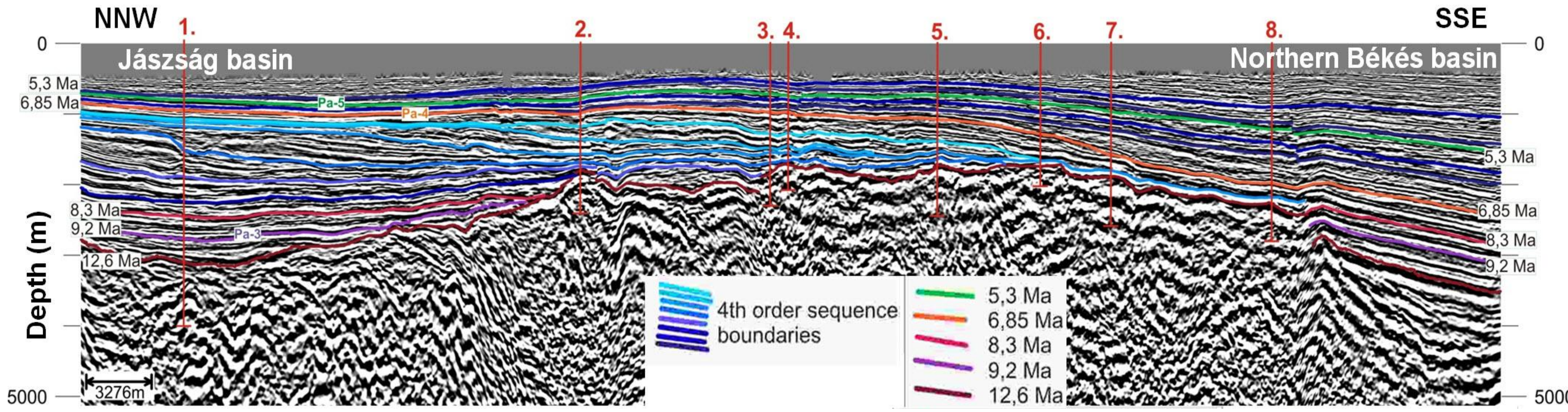

Figure 2. Sequence stratigraphic interpretation of the Late Miocene (Pannonian) basin fill sediments.

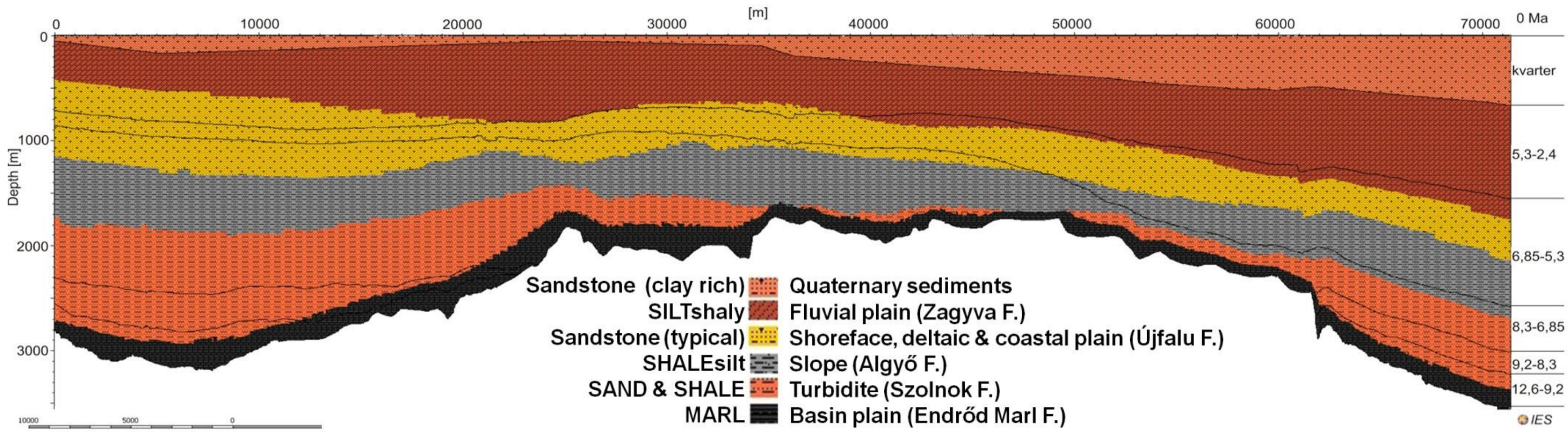

Figure 3. Prevailing lithology of the different prograding depositional facies vs. lithostratigraphic units as well as the 3rd order sequence boundaries of the studied regional profile. Irregularity of the prograding succession is due to the undulatory nature of the profile.

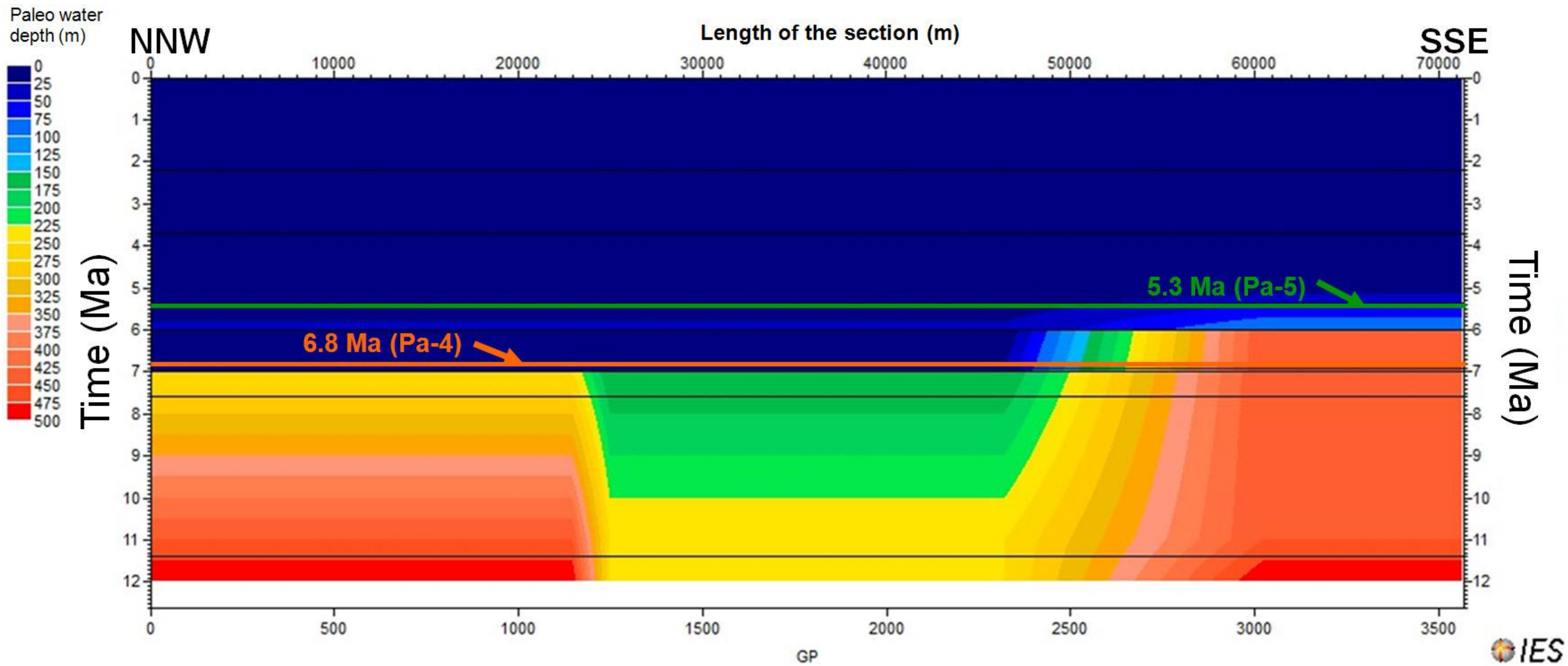

Figure 4. The estimated paleo water depth changes along the investigated section. Probably there were water level falls on the third order sequence boundaries at 6.8 and 5.3 Ma ago.

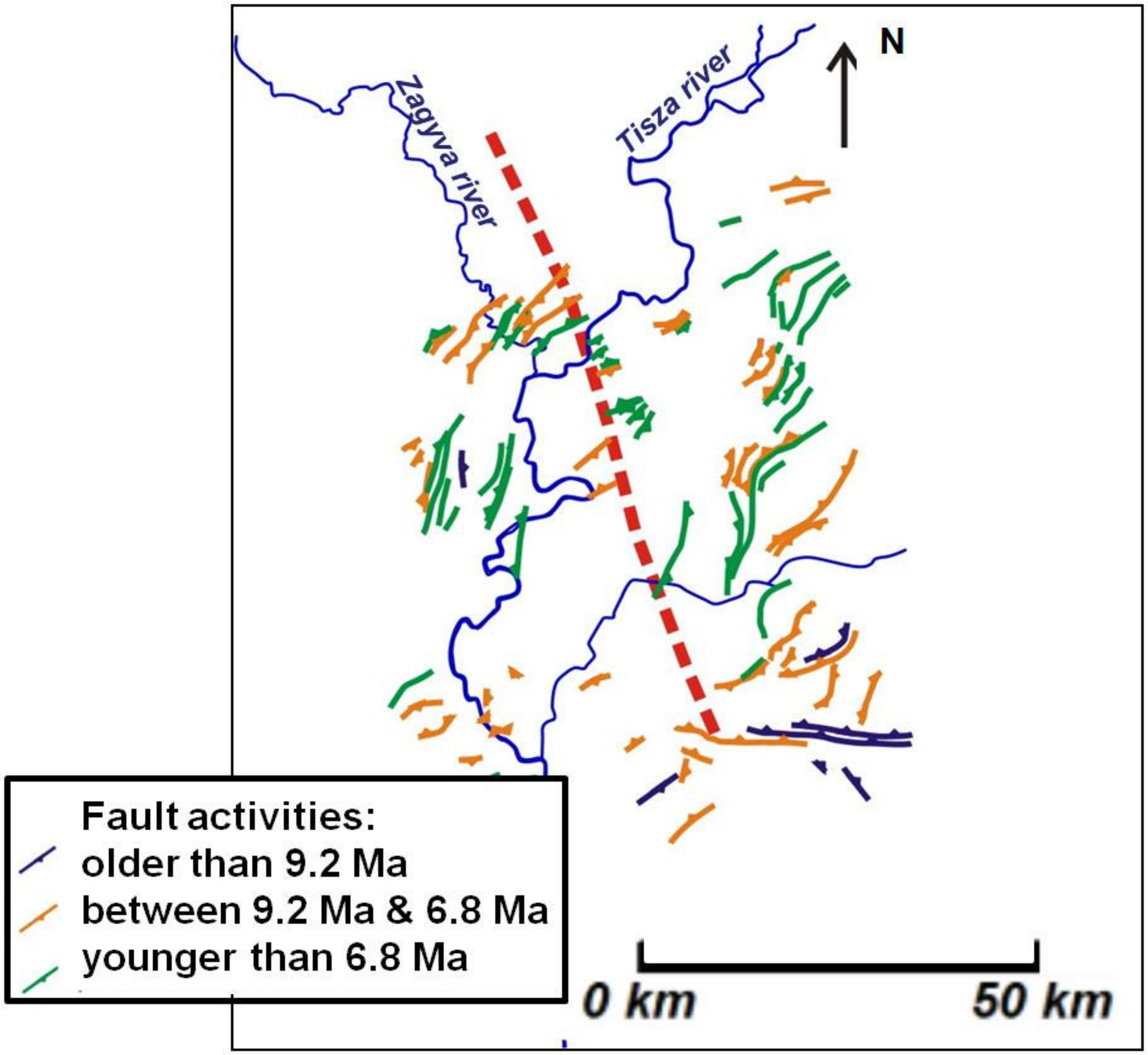

Figure 5. Mapped tectonic lines based on the 2D seismic network. The dashed red line indicates the approximate position of the studied section.

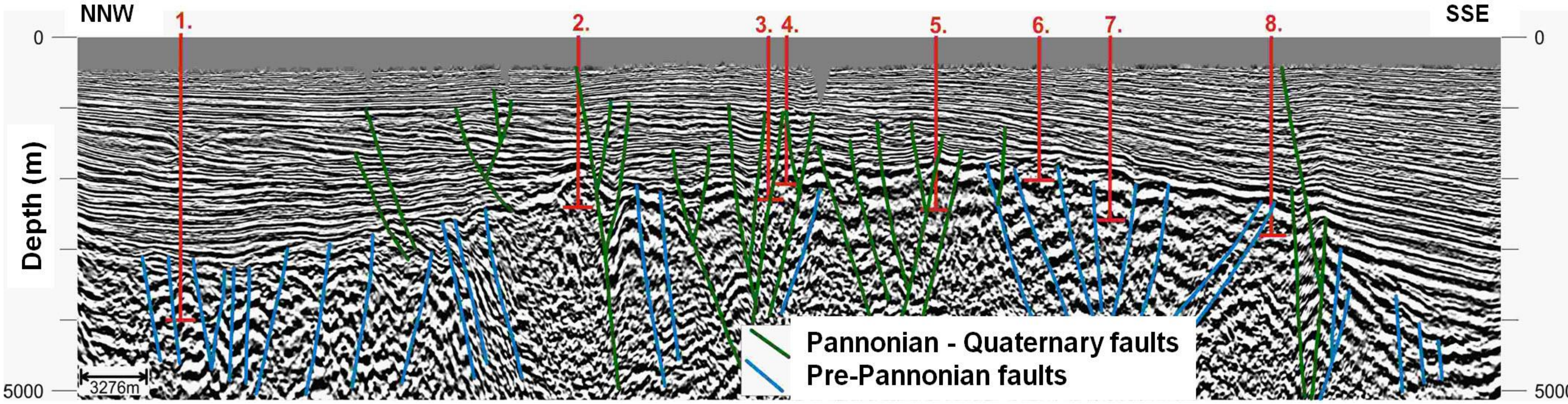

Figure 6. Identified faults and inferred activity timing.

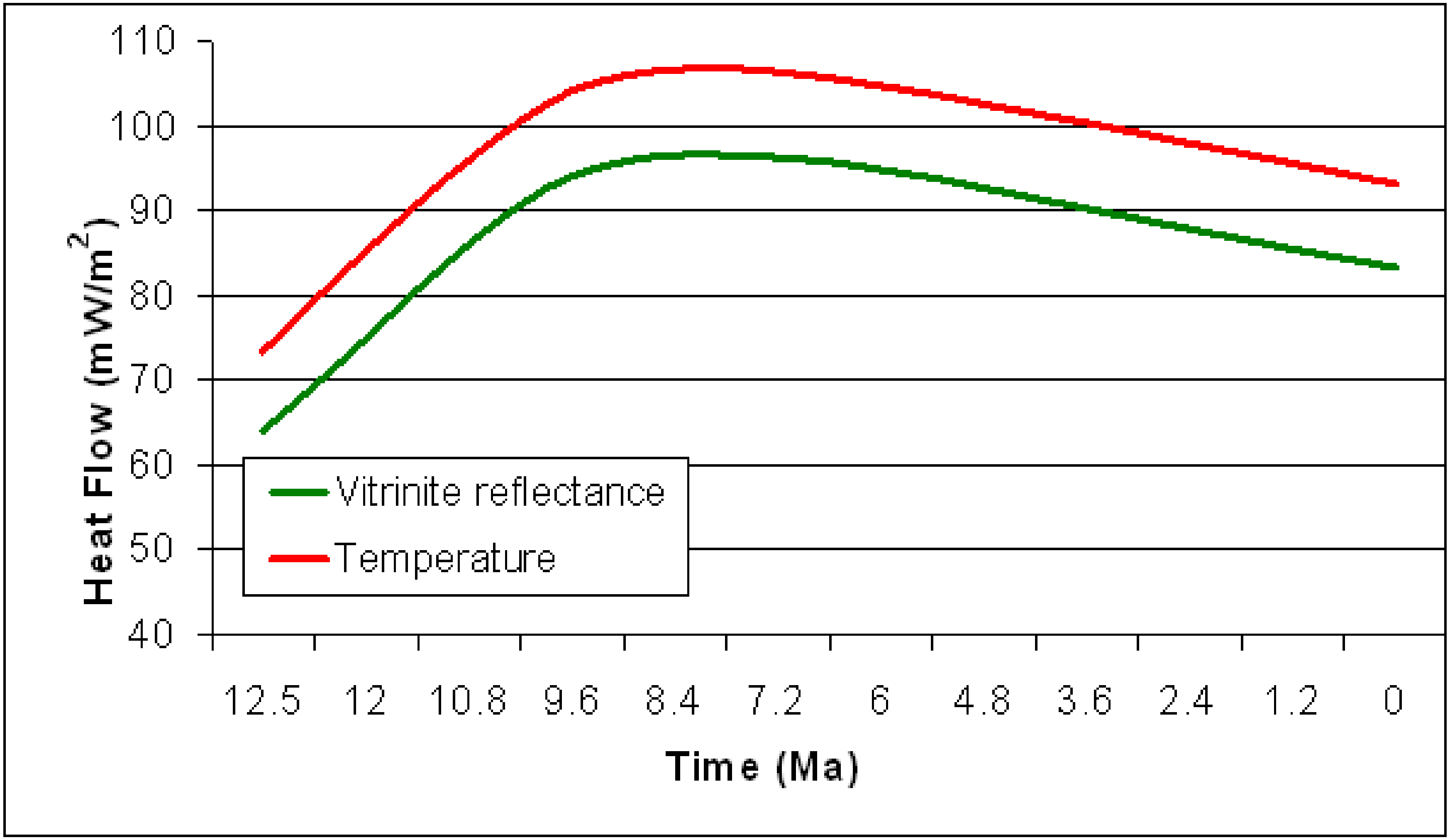

Figure 7. The two heat flow history, which were calibrated to the temperature and to the vitrinite reflectance.

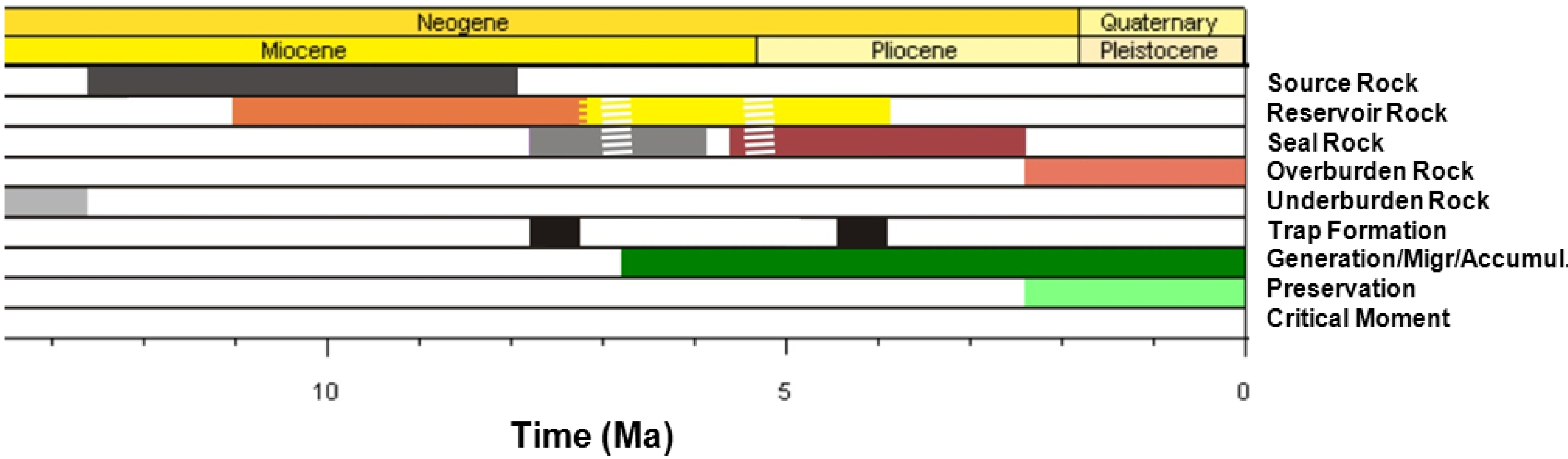

Figure 8. The event chart of the investigated Late Miocene – Quaternary petroleum system.

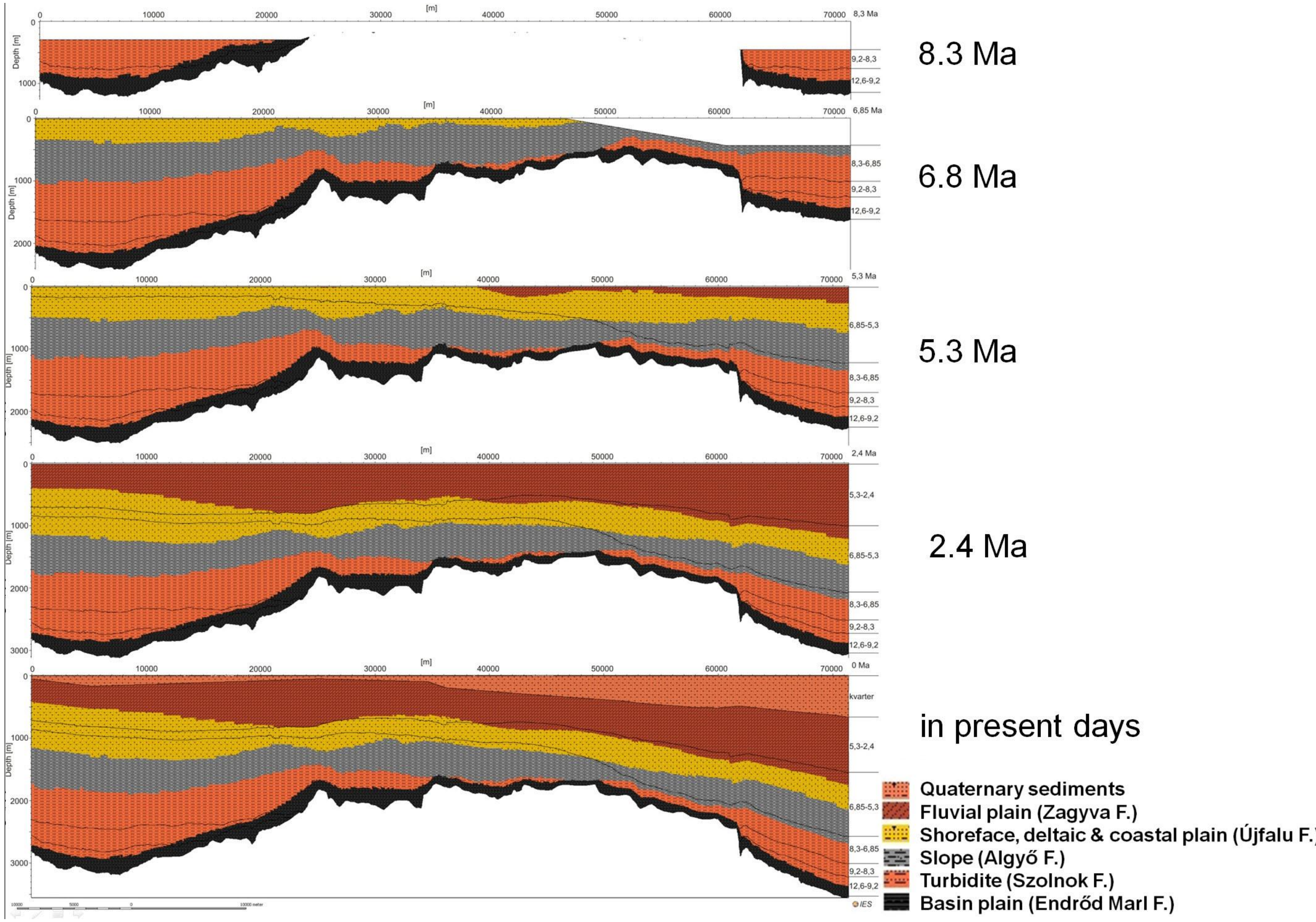

Figure 9. Subsidence history of the studied profile.

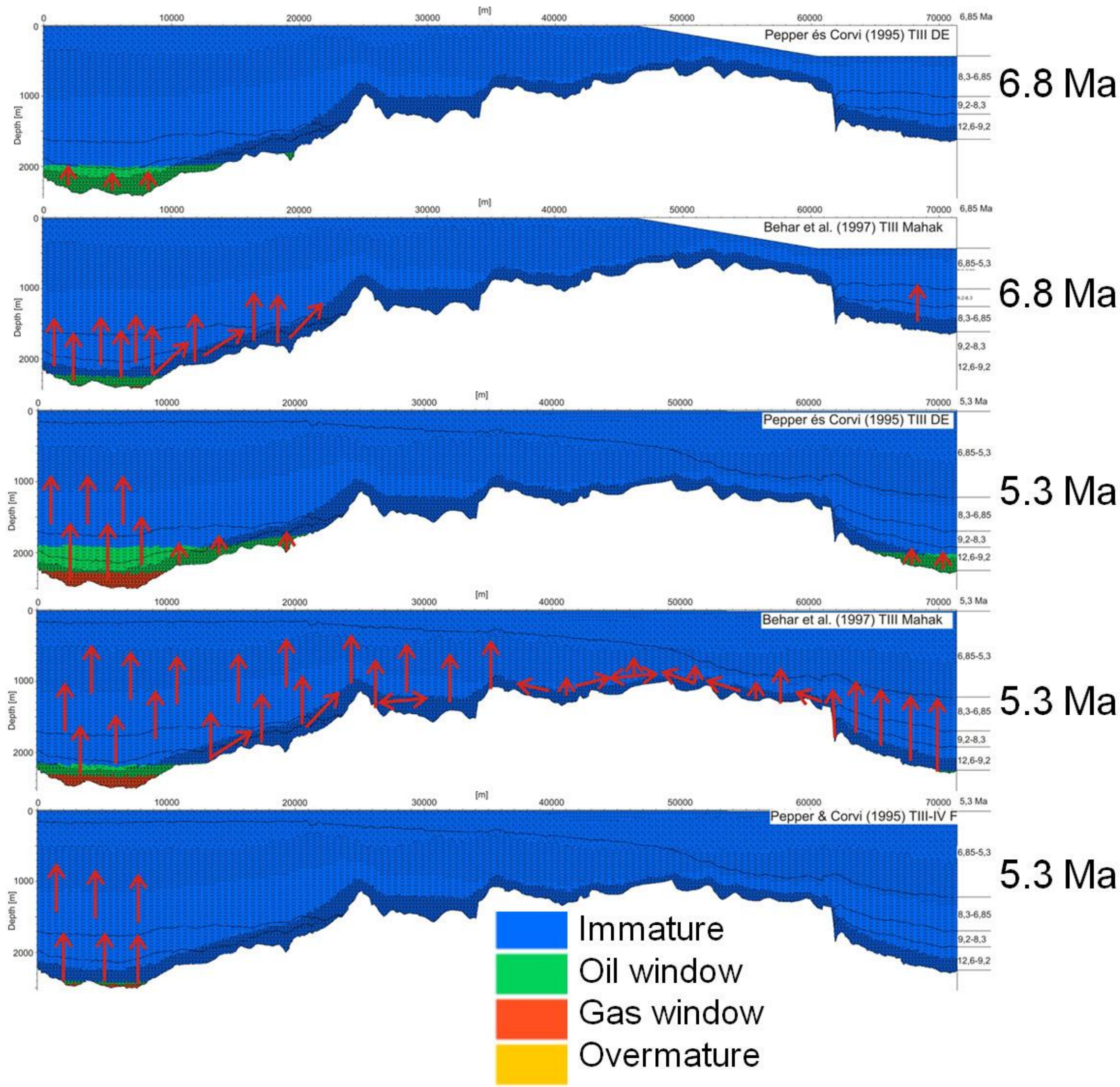

Figure 10. Maturity and migration according to the higher (temperature calibrated) heat flow model 6.8 and 5.3 Ma ago. The maturity zones are according to the kinetic models (right corner of the sections). The red arrows show the direction and the intensity of the migration, not effected by the quantities.

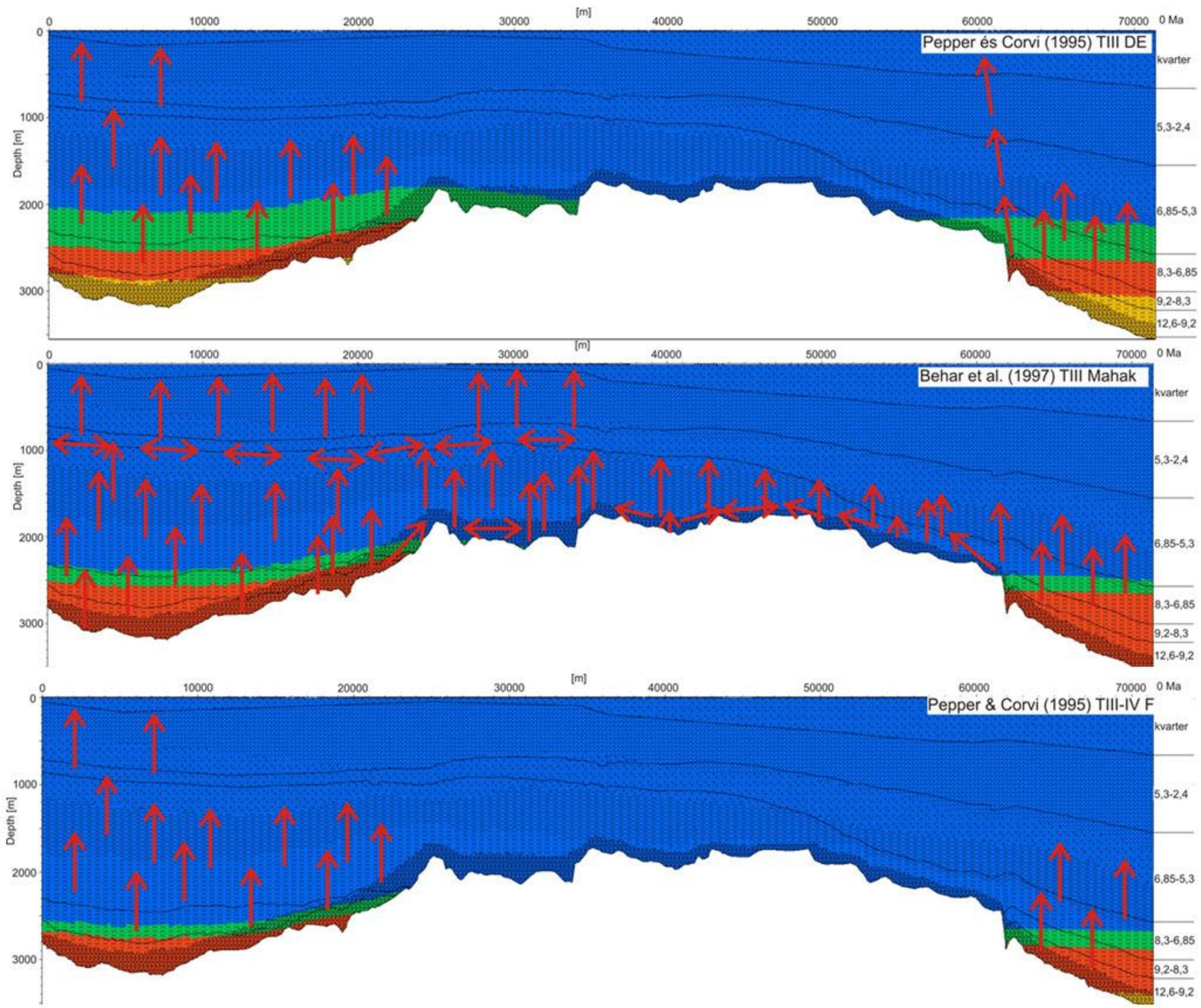

Figure 11. Recent maturity and migration according to the higher (temperature calibrated) heat flow model. The maturity zones are according to the kinetic models (right corner of the sections). The red arrows show the direction and the intensity of the migration, not effected by the quantities.

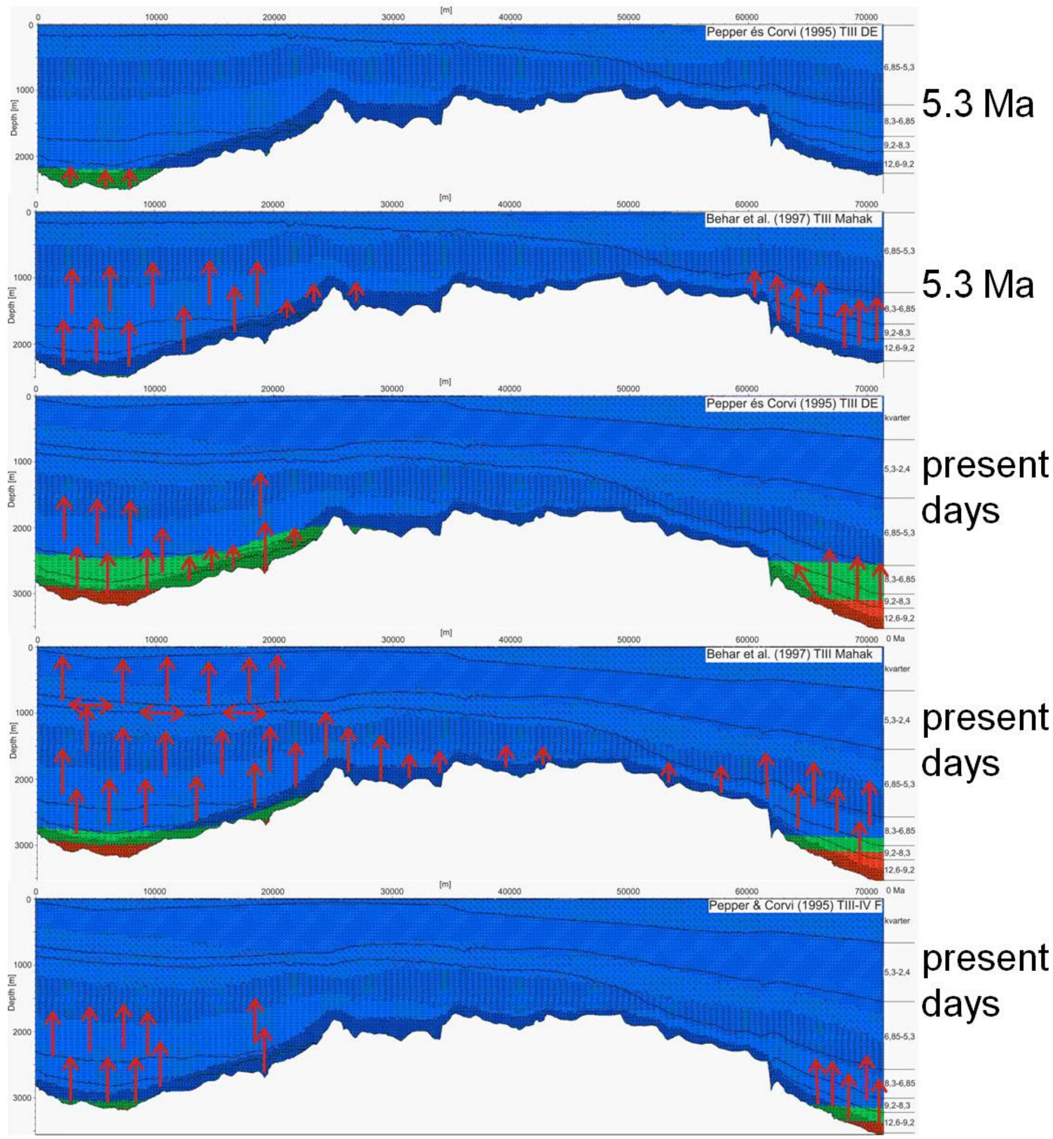

Figure 12. Maturity and migration according to the lower vitrinite reflectance calibrated heat flow model 5.3 Ma ago and in present days. The maturity zones are according to the kinetic models (right corner of the sections). The red arrows show the direction and the intensity of the migration, not effected by the quantities.