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3D visualization of the sedimentary fill and subsidence evolution in the northern and central Vienna Basin (Miocene)

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Abstract

This study analyzes and visualizes data from 234 wells using a MATLAB-based program (BasinVis 1.0) for the sedimentary fill and subsidence evolution of the northern and central parts of the Vienna Basin. The sedimentary fills of seven selected horizons are shown in sediment distribution surfaces, thickness isopach maps, and cross-sections. The subsidence analysis from wells reaching the pre-Neogene basement results in subsidence depth and rate maps of basement and tectonic subsidence of the study area. The Vienna Basin has a complex history from a piggy-back basin phase (Early Miocene) to a pull-apart basin phase (Middle – Late Miocene). The 2D maps/3D surfaces generated in this study provide detailed insights into the polyphase basin evolution of the Vienna Basin, which is closely related to changes in the regional stress field and the paleoenvironmental setting. In the piggy-back basin phase, sedimentation and subsidence are slow, display E-W to NE-SW-trending troughs parallel to the strike of the orogen, and restricted to small depressions on top of the Alpine thrust. In the late Early Miocene, the Vienna Basin changes to a pull-apart basin system characterized by a wider sedimentation area and rapid subsidence along sinistral strike-slip faults and related normal faults. The depressions of the Early Miocene are filled with sediments supplied through deltaic systems entering from the south. After slow sedimentation and subsidence during the early Middle Miocene, the development of the Vienna Basin is controlled and accelerated by NE-SW trending synsedimentary normal faults, especially the Steinberg fault, until the Late Miocene. The Vienna Basin from the late Middle to Late Miocene is characterized by E-W extensional rift-type and decelerating subsidence, which corresponds to the E-W trending extension of the western parts of the neighboring Pannonian Basin system. During this time, enormous amounts of sediment are supplied mainly from the west by a broad paleo-Danube delta complex along the western flank of the Vienna Basin.

1. Introduction

The Vienna Basin is a Neogene basin of about 200 km length and 55 km width, situated between the Eastern Alps, the Western Carpathians, and the Pannonian Basin (Fig. 1). Along the NW flank the basin is separated by the thrust sheets of the Waschberg Zone from the Alpine Foreland Basin, which extends parallel to the Alpine-Carpathian units (Weissenbäck, 1996). The Vienna Basin has experienced a complex tectonic and depositional history (Fig. 2), ranging from piggy-back basins in the Early Miocene to a large pull-apart basin in the Middle to Late Miocene, and small pull-apart basins in the Quaternary (Arzmüller et al., 2006; Decker, 1996; Decker et al., 2005; Fodor, 1995; Royden, 1985; Salcher et al., 2012). Structurally, the Vienna Basin is dissected into numerous large and small fault blocks consisting of depressions, grabens, highs, and stable horsts (Fig. 1 and 3).

The Vienna Basin is one of the most extensively studied basins due to fundamental research and hydrocarbon exploration in the region over the last 150 years. The Neogene sedimentary succession is documented by numerous boreholes and a dense network of 2D and 3D seismic data. Various aspects of the structural and sedimentary setting of the basin have been analyzed in publications by Beidinger and Decker (2011), Brix and Schultz (1993), Čekan et al. (1990), Hinsch et al. (2005), Hölzel et al. (2010), Jiříček and Seifert (1990), Kováč et al. (2004), Lee and Wagreich (2016), Sauer et al. (1992), Seifert (1992), Strauss et al. (2006), Wagreich and Schmid (2002), Strauss et al. (2006), and Wessely et al. (1993).

The Vienna Basin is spreading over three countries in central Europe: Austria, Slovakia, and the Czech Republic (Fig. 1). However, a comprehensive detailed study on the basin evolution crossing the borders of the three countries is still missing. This study focuses on a transnational analysis of the northern and central parts of the basin to characterize and visualize the sedimentary fill and the subsidence evolution. This area is highly important to understand the overall stratigraphic and structural evolution of the basin, because it contains up to 6 km of the Miocene sedimentary rocks, several complex structures, and the Steinberg fault, one of the most prominent structural features of the basin (Fig. 1).

This study analyzes the sedimentary fill and subsidence evolution with 2D maps and 3D surfaces visualized from a number of data (i.e. a large number of wells, geophysical data, and seismic sections) covering an extensive region (Fig. 1b) of the northern and central Vienna Basin. The maps are 3D distribution surfaces, thickness isopach, and cross-sections for the sedimentary fill and 3D subsidence depth and rate maps for the basement and tectonic subsidence evolution of the Vienna Basin.

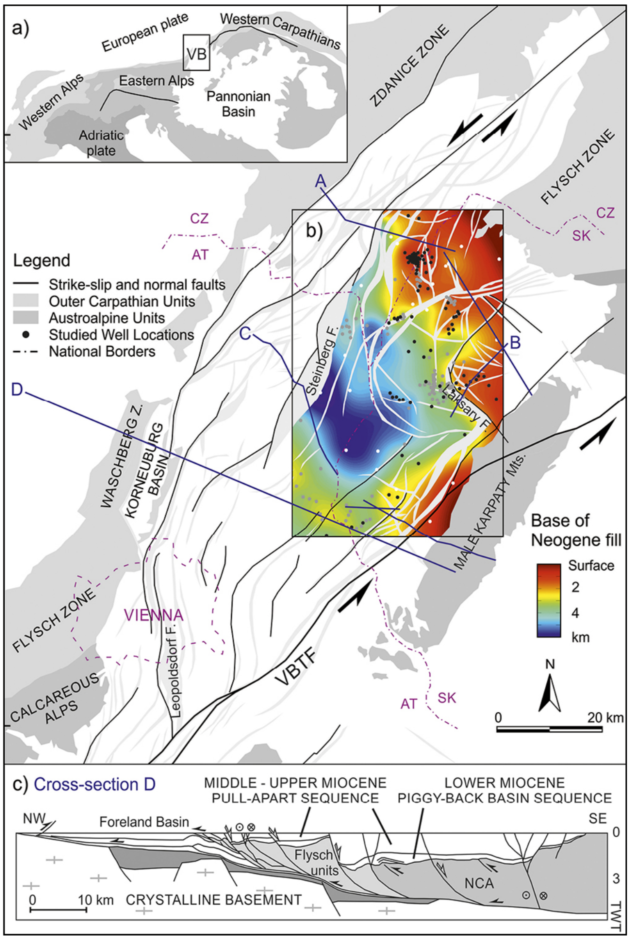

Figure 1: a) Tectonic sketch map of the Vienna Basin located at the junction between the Eastern Alps, the Western Carpathians, and the Pannonian Basin system (revised from Arzmüller et al., 2006; Wessely et al., 1993). b) Study area and depth map of the base Neogene, the latter being a result of this study. Locations of wells (black dots: wells reaching the pre-Neogene basement, gray dots: wells reaching the Miocene basin fill, and white dots: synthetic wells) and cross-sections (A - D) are shown. AT: Austria, SK: Slovakia, CZ: Czech Republic, and VBTF: Vienna Basin transfer fault system. c) Geologic cross-section through the Vienna Basin and the adjacent Alpine Foreland Basin (revised from Beidinger and Decker, 2014).

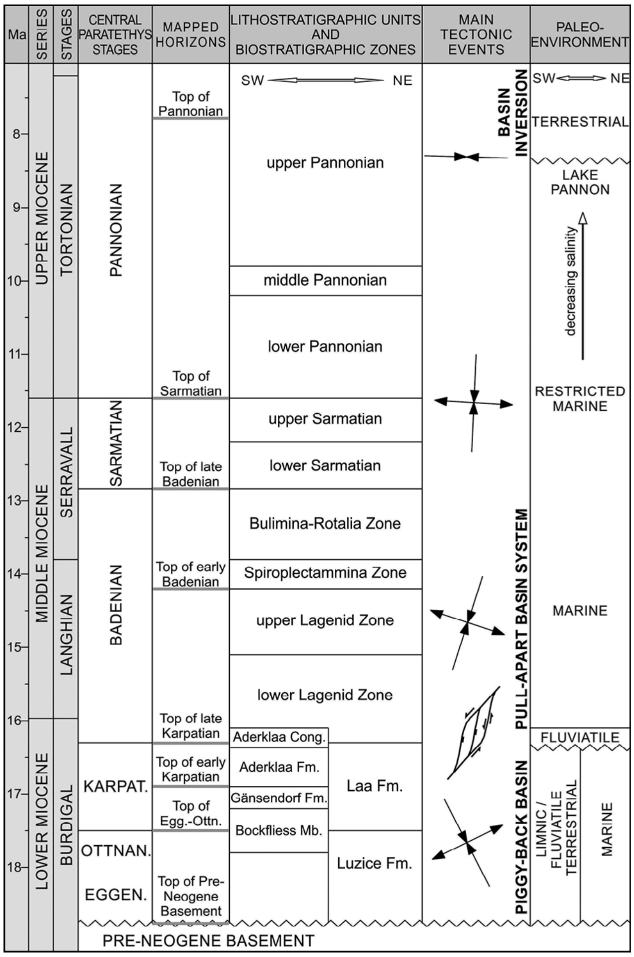

Figure 2: Stratigraphy and evolution of the Vienna Basin in the Miocene (Decker, 1996; Fodor, 1995; Hohenegger et al., 2014; Hölzel et al., 2010; Peresson and Decker, 1997a; Piller et al., 2007; Wagreich and Schmid, 2002). Horizons mapped in this study are; top of the Pre-Neogene Basement, top of the Eggenburgian-Ottnangian, top of the early Karpatian, top of the late Karpatian, top of the early Badenian, top of the late Badenian, top of the Sarmatian, and top of the Pannonian.

2. Geologic background

The Eastern Alpine - Western Carpathian - Pannonian Basin system was strongly influenced by the late Paleogene and Neogene lateral extrusion of the Eastern Alps towards the Pannonian area in the east (Ratschbacher et al., 1991a, 1991b). Extrusion caused complex and polyphase strike-slip faulting and back-arc-extension linked to the retreating Carpathian subduction zone, and further resulted in development of Miocene pull-apart basins such as the Vienna Basin and extensional rift basins (e.g. Pannonian Basin) (Csontos et al., 1992; Decker and Peresson, 1996; Horváth, 1993; Huismans et al., 2001; Royden, 1985, 1988). Thus, the Vienna Basin has a complex evolution (Fig. 2) due to its position between Eastern Alps in the west, the Western Carpathians in the northeast, and the Pannonian Basin system in the southeast (Fig. 1).

In the Early Miocene (Eggenburgian – early Karpatian; c. 20.4 – 16.9 Ma), several E-W trending small sub-basins (piggy-back basins; Ori and Friend, 1984) developed on the frontal parts of the N- to NW- propagating thrustbelt of the Eastern Alps (Decker, 1996; Fodor, 1995; Jiříček and Seifert, 1990). Although the Eggenburgian sediments were restricted to the northern part of the Vienna Basin, during the Ottnangian and the early Karpatian the sedimentation spread to the central part (Decker, 1996; Jiříček and Seifert, 1990; Kováč et al., 2004; Strauss et al., 2006).

At the end of the Early Miocene (late Karpatian; c. 16.9 – 16.3 Ma), the Vienna Basin became a pull-apart structure by the lateral extrusion of the Eastern Alps (Decker, 1996; Fodor, 1995). Structural styles within the pull-apart are dominated by NE-SW trending sinistral strike-slip duplexes and en-echelon listric normal faults (Fig. 3) with a left stepping geometry (Decker et al., 2005; Royden, 1985, 1988). Growth strata along normal faults (e.g. Steinberg fault, Leopoldsdorf fault) indicate that faulting occurred synsedimentary during the Middle Miocene (Decker, 1996). The Vienna pull-apart basin was filled mainly by Badenian deposits blanketed by Sarmatian and Pannonian successions without major depositional breaks (Arzmüller et al., 2006).

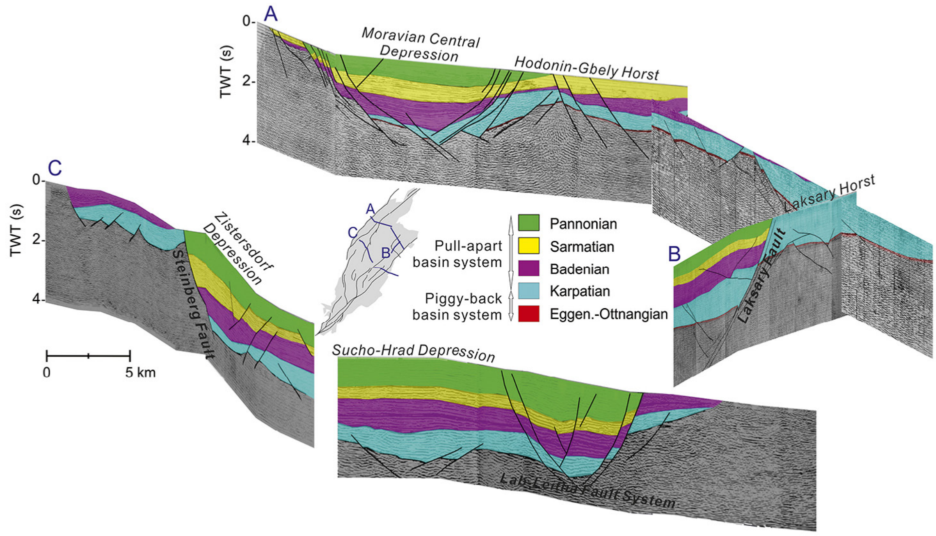

Figure 3: Seismic sections across the study area (see Figure 1 for location). Section A and C were revised from Čekan et al. (1990), and section B was acquired from the archives of the Dionyz Štur Institute, Slovakia. These sections were visualized by Blender which is an open-source 3D computer graphics software.

During the Late Miocene – Pliocene, the regional stress field switched from N(NW)-directed to E-W-directed compression (Decker and Peresson, 1996; Peresson and Decker, 1997a, 1997b). This compressional stress resulted in basin inversion, sediment deformation, and erosion (Decker, 1996; Strauss et al., 2006).

The Vienna Basin has been reactivated since c. 250 – 300 ka (Salcher et al., 2012) related to NE-SW extension at a releasing bend along slowly moving sinistral strike-slip faults (1 - 2 mm/a; Grenerczy et al., 2000; Decker et al., 2005). The Vienna Basin transfer fault system (VBTF) corresponds to a zone of moderate seismicity, proving the continued activity of the fault zone. Small Quaternary basins are filled mainly by up to 150 m fluvial sediments which are unconformably overlying Miocene sediments (Beidinger and Decker, 2011; Decker et al., 2005; Hinsch et al., 2005; Kullmann, 1966; Salcher et al., 2012).

3. Data and Methods

The visualized area covers an area of 40 x 60 km in the northern and central parts of the Vienna Basin (Fig. 1b). The sedimentary fill was analyzed using sediment thickness data of 201 wells of Slovakia and the Czech Republic and 9 wells from Austria. In addition, 24 synthetic wells were used to substitute for missing well-data in some areas, and the wells were mainly acquired from time-depth conversion of stratigraphic boundaries within seismic reflection data. Among them, well data reaching the pre-Neogene basement were selected for analyzing the basement and tectonic subsidence.

These data were evaluated and visualized with a MATLAB-based program, BasinVis 1.0 (Lee, 2015; Lee et al., 2016) for the sedimentary fill (3D sediment distribution, thickness isopach maps, cross-sections, and stratigraphic profiles) and the subsidence evolution (3D subsidence depth and rate for basement and tectonic subsidence). The smoothed and interpolated surfaces are reconstructed by the Thin-Plate Spline (TPS) method supported by the BasinVis 1.0. During the mapping and visualizing, the Male Karpaty Mts., the Flysch zone, and the Steinberg high (Mistelbach block) are not considered and subsequently removed by using the mask function of BasinVis 1.0.

In the BasinVis 1.0 software, the basement and tectonic subsidence analysis is calculated by the decompaction and backstripping techniques (e.g. Allen and Allen, 2013; Lee, 2015; Miall, 1999; Steckler and Watts, 1978; Van Hinte, 1978). For the subsidence analysis of the Vienna Basin, regional water-depth variations are taken from Sauer et al. (1992) and Seifert (1992) (Fig. 4). This study has not incorporated eustatic sea-level changes in the calculations, since the basin was separated from the world ocean around the early Late Miocene. Additionally, the regional sea-level changes in the Paratethys were only partially in accordance with global sea-level cycles, but superimposed by regional tectonic processes (Haq et al., 1987; Steininger and Wessely, 1999; Strauss et al., 2005; Hohenegger et al., 2014), and the known short-time sea-level fluctuations do not perturb the longer-term subsidence trends. This study uses initial porosity (Φ_0) and coefficient (c) of the porosity-depth relation evaluated from seismic velocity data of two wells (Zavod 76 and Lakšárska Nová Ves 7) in the Vienna Basin (Lee, 2015; Lee and Wagreich, 2016). The seismic velocity data were analyzed by recognizable correlations between seismic velocity-density and density-porosity (Fig. 5).

From the well data, this study arranges and visualizes the basin sedimentary fill and subsidence evolution in seven successive time steps based on stages of the regional Central Paratethys chronostratigraphy for the Miocene (e.g. Hohenegger et al., 2014; Piller et al., 2007) and regional and local zonations for the Vienna Basin (Fig. 2): 1) Eggenburgian-Ottnangian (c. 20.4 – 17.5 Ma), 2) early Karpatian (c. 17.5 – 16.9 Ma), 3) late Karpatian (c. 16.9 – 16.3 Ma), 4) early Badenian (c. 16.3 – 14.2 Ma), 5) late Badenian (c. 14.2 – 12.8 Ma), 6) Sarmatian (c. 12.8 – 11.6 Ma), and 7) Pannonian (c. 11.6 – 7.8 Ma).

4. Visualization of sedimentary fill

The sedimentary evolution of the study area is visualized in 2D maps and 3D surface reconstructions, where areas in which no sedimentation occurred are excluded. The isopach maps of sediment thickness are showing locations of the major faults (Steinberg fault, Laksary fault, and Leitha-Láb fault system) to

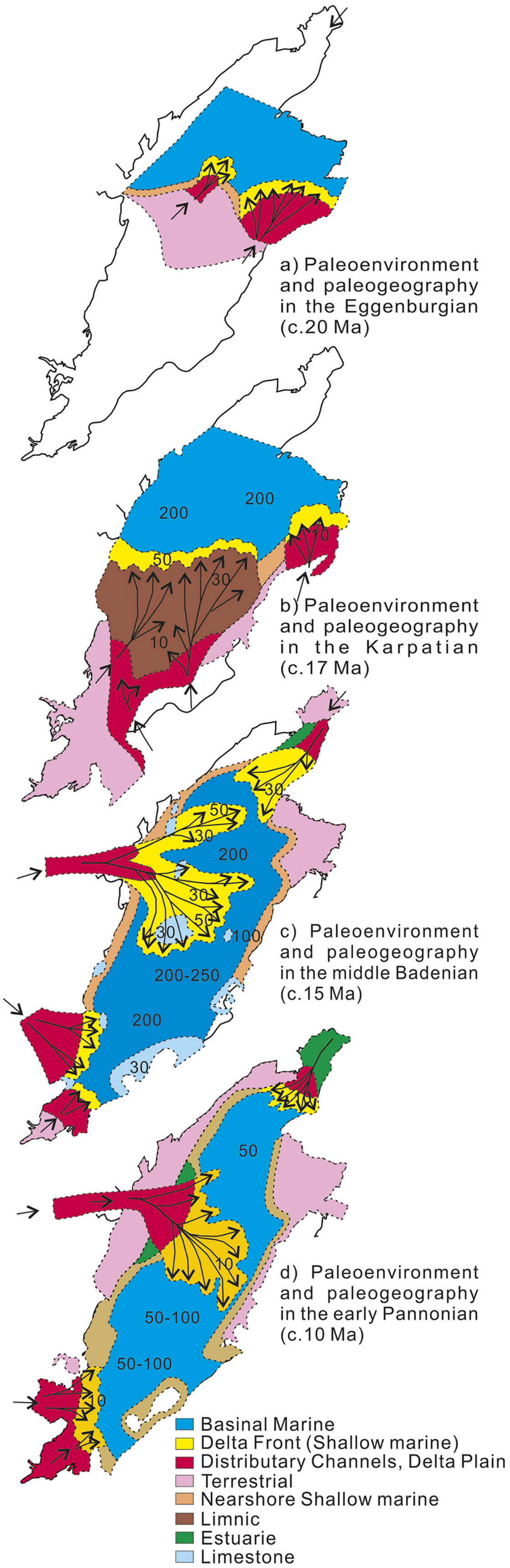

Figure 4: Paleoenvironment and paleogeographic models of the Vienna Basin (revised from Sauer et al., 1992); a) Eggenburgian (c. 20 Ma), b) Karpatian (c. 17 Ma), c) middle Badenian (c. 15 Ma), and d) early Pannonian (c. 10 Ma). Numbers are indicating the paleowaterdepth.

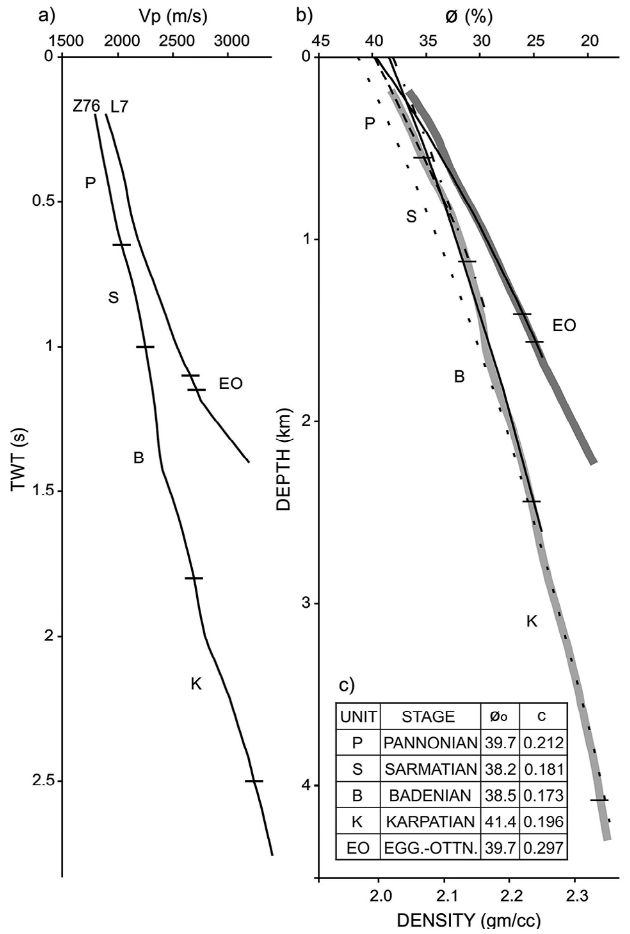

Figure 5: Porosity-depth relation evaluated for the Vienna Basin. a) Seismic velocity-Two Way Time (TWT) curves from locations of two wells (Zavod 76 and Lakšárska Nová Ves 7), b) Porosity and Density-Depth curves with exponential trend lines of each stage, and c) evaluated initial porosity (Φ_0) and coefficient (c) of each stage.

help understanding the transport systems and geometrical trends of each successive stage. 2D cross-section profiles are images exported from the visualized sedimentary fill, which document important structural elements of the Vienna Basin.

4.1 Sedimentary fill of the Piggy-back basin system (Early Miocene)

The Early Miocene sedimentation is related to the opening of piggy-back basins mainly in the northern part of the Vienna Basin. According to Kováč et al. (2004) and Sauer et al. (1992), during the Early Miocene, the northern part of the Vienna Basin comprised a fully marine environment, while the central part was characterized by the deposition of huge lacustrine-deltaic formations, and the southern part was fully continental (Fig. 4a).

The Eggenburgian–Ottnangian sediments are distributed in small, shallow, and E-W trending depressions with an overall thickness of less than 500 m (Fig. 6A and 8). Thicker depositional packages (up to 800 m) are recorded in the southwestern part of the study area, which correlate to the Bockfliess Formation (Fig. 2) which is a deltaic-brackish stratal complex deposited from the Ottnangian to the early Karpartian.

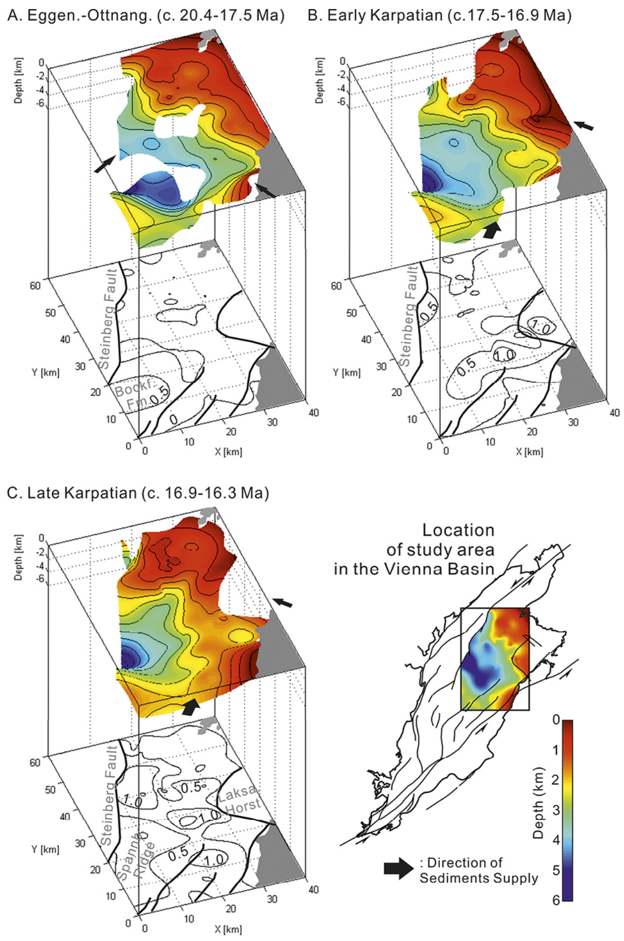

Figure 6: 3D sediment distribution surfaces (above) and sediment thickness isopach maps (below) of the Early Miocene visualized in the study area; A: Eggenburgian-Ottnangian (c. 20.4 – 17.5 Ma), B: early Karpatian (c. 17.5 – 16.9 Ma), and C: late Karpatian (c. 16.9 – 16.3 Ma). The major faults and contour lines (0.5 km) are shown with black solid lines in the maps. Direction of sediment supply is from Sauer et al. (1992).

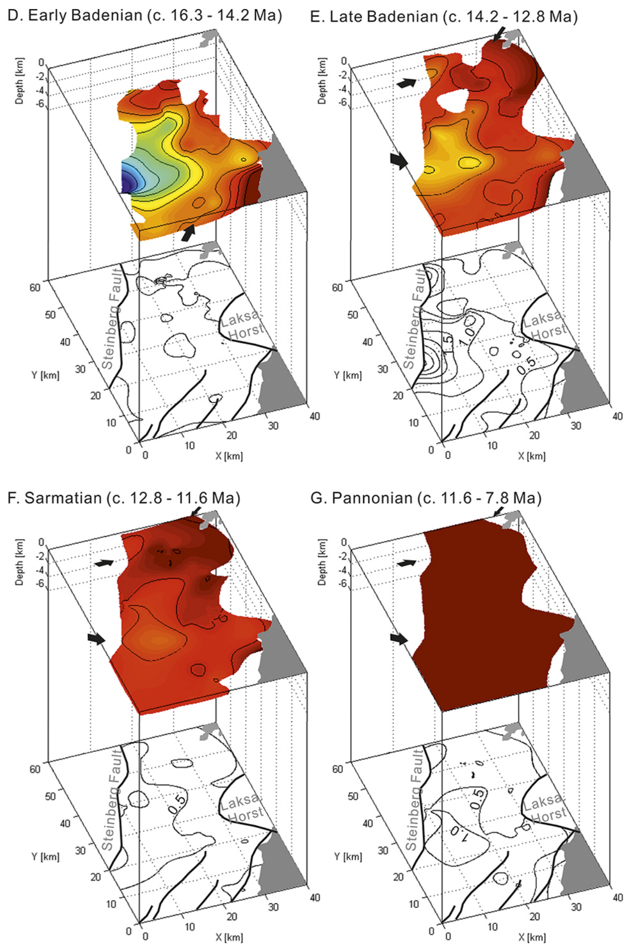

Figure 7: 3D sediment distribution surfaces (above) and sediment thickness isopach maps (below) of the Middle - Late Miocene visualized in the study area; D: early Badenian (c. 16.3 – 14.2 Ma), E: late Badenian (c. 14.2 – 12.8 Ma), F: Sarmatian (c. 12.8 – 11.6 Ma), and G: Pannonian (c. 11.6 – 7.8 Ma). The major faults and contour lines (0.5 km) are shown with black solid lines in the maps. Direction of sediment supply is from Sauer et al. (1992). The top depth of the Pannonian unit is assumed as 0 km.

In the early Karpatian infill phase, the overall sediments are thicker (up to 1,000 m) compared to the former ones, and accumulated mainly in NE-SW trending depressions of the central part (Fig. 6B).

4.2 Sedimentary fill of the Pull-apart basin system (Middle – Late Miocene)

At the end of the Early Miocene (late Karpatian), the Vienna Basin changed to a pull-apart basin system controlled by transtension. Due to the tectonic regime change, the sedimentation is bound by synsedimentary fault blocks and structural ridges (e.g. Spannberg ridge and Laksary horst) (Fig. 8). The area of the late Karpatian sedimentation widens to the south and covers nearly the whole study area except the northernmost part and the Laksary horst (Fig. 6C). Especially, on the Laksary horst, no sediments have been deposited since the late Karpatian. The major depocenters are located along the Leitha-Láb fault system which consists of strike-slip faults and negative flower structures activated along the southeastern margin of the basin, and also between the Steinberg fault and the Laksary fault. The depocenters are filled with voluminous masses of sediments eroded from the Alps which are supplied due to the development of a deltaic system entering the Vienna Basin from the south (Fig. 4b).

The early to middle Badenian deposits are of minor thickness (0 - 500 m) and confined to the central part of the Vienna Basin (Fig. 7D). The lower Badenian sediments transgress unconformably on various stratal units of the Lower Miocene (Fig. 8) and onlap the northern slope of the Spannberg ridge that was uplifted during the late Karpatian (Hölzel et al., 2010). According to Kováč et al. (2004), the Lower Badenian sediment extent in the Slovak part of the Vienna Basin is approximately identical with the paleo-shoreline.

During the late Badenian, the sedimentation area widens and a thicker pile of sediments is deposited (Fig. 7E), forming westward thickening wedges which are bound to the west by synsedimentary faults (Fig. 8). The configuration of the Vienna Basin is mainly influenced by NE-SW and NNE-SSW oriented normal faults, and growth strata develop along the normal faults. The highest thickness areas are known from the Zisterdorf depression and the Moravian-Central depression along the Steinberg fault. The thick sedimentary units are related mainly to a new 40 x 50 km broad paleo-Danube delta complex on the western flank of the basin (Fig. 4c). The delta complex was developed by paleogeographic changes around the middle Badenian and carried massive sediments from the Alpine Foreland Basin area into the Vienna Basin (Sauer et al., 1992; Seifert, 1992).

The Sarmatian sediments cover a large part of the study area and extends further northward than the Badenian ones (Fig. 7F). The sediments attain a varying thickness between 200 – 600 m with a depocenter along the Steinberg fault (Fig. 8). The sedimentation continues without major depositional break across the Sarmatian/Pannonian boundary in the central part of the basin (Fig. 3), despite of the regression and salinity decrease by the separation of the Paratethys (Jiricek and Seifert, 1990; Kováč et al., 2004; Sauer et al., 1992).

Compared to the Sarmatian sedimentary fill, the Pannonian sedimentation phase shows a deepening depocenter along the Steinberg fault, which shifts to the southwest of the study area (Fig. 7G). The main delta system that developed around the middle Badenian continuously transported sediments from the Alpine Foreland Basin area into the shallowing basin (Fig. 4d). However, considering the uplift and erosion during the latest Pannonian and Pliocene (e.g. Peresson and Decker, 1997a), the Pannonian sediments were originally thicker than the present-day preserved thickness.

5. Visualization of the subsidence evolution

To help understanding the Miocene subsidence evolution trends of the Vienna Basin, our visualization of the basement subsidence and tectonic subsidence presents 3D subsidence depth and rate maps at the seven successive time steps. The subsidence rate maps are showing locations of the Alpine-Carpathian nappe front for the piggy-back basin system (Fig. 9) and the position of major faults (Steinberg fault, Lak-

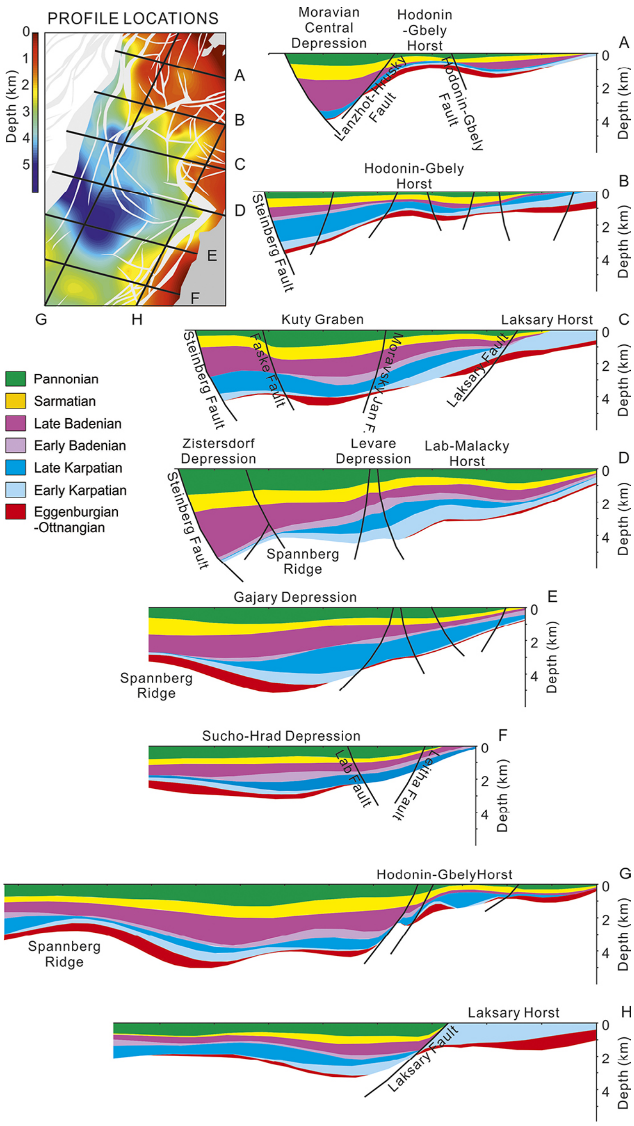

Figure 8: Cross-section profiles across the study area, exported from the cross-section function of BasinVis 1.0. Important structural elements are labeled.

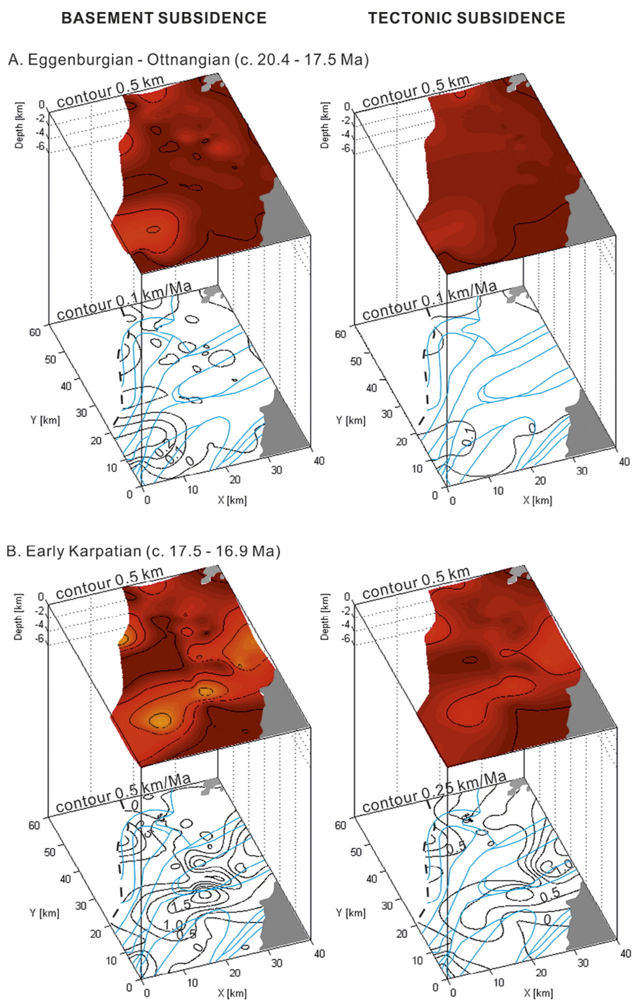

Figure 9: 3D subsidence depth (above) and subsidence rate (below) maps of the basement subsidence (left) and tectonic subsidence (right) visualized in the study area; A: Eggenburgian–Ottnangian (c. 20.4 – 17.5 Ma) and B: early Karpatian (17.5 – 16.9 Ma). The Alpine-Carpathian thrust nappe borders are shown with blue solid lines and the location of the Steinberg fault with black broken lines.

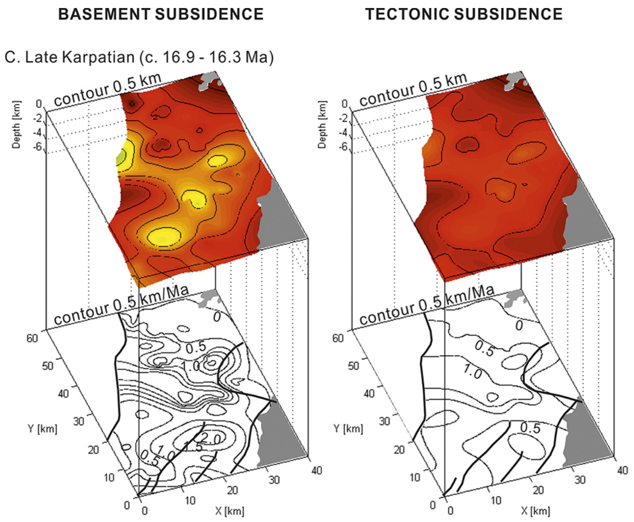

Figure 10: 3D subsidence depth (above) and subsidence rate (below) maps of the basement subsidence (left) and tectonic subsidence (right) visualized in the study area; C: late Karpatian (c. 16.9 – 16.3 Ma). The major faults are shown with black solid lines in the rate map.

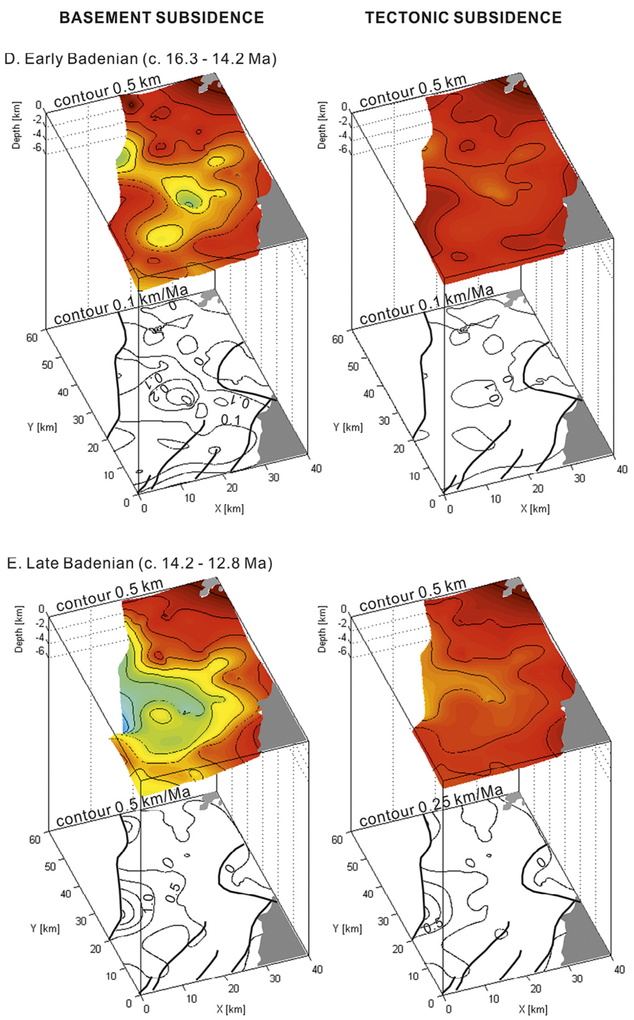

Figure 11: 3D subsidence depth (above) and subsidence rate (below) maps of the basement subsidence (left) and tectonic subsidence (right) visualized in the study area; D: early Badenian (c. 16.3 – 14.2 Ma) and E: late Badenian (c. 14.2 – 12.8 Ma). The major faults are shown with black solid lines in the rate map.

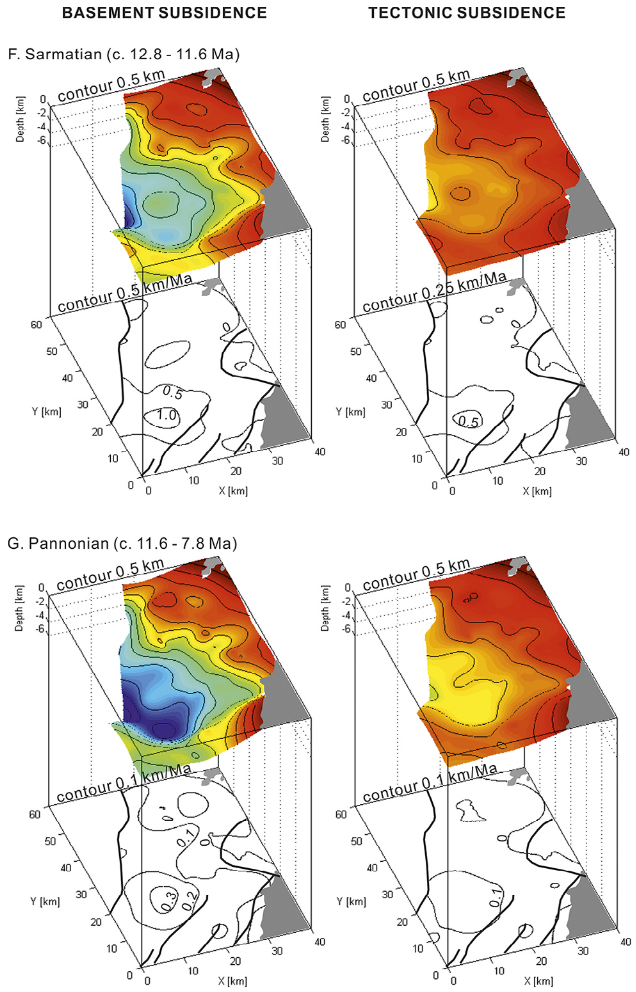

Figure 12: 3D subsidence depth (above) and subsidence rate (below) maps of the basement subsidence (left) and tectonic subsidence (right) visualized in the study area; F: Sarmatian (c. 12.8 – 11.6 Ma) and G: Pannonian (c. 11.6 – 7.8 Ma). The major faults are shown with black solid lines in the rate map.

sary fault, and Leitha-Láb fault system) for the pull-apart basin system (Fig. 10, 11, and 12).

5.1 Subsidence evolution of the Piggy-back basin system (Early Miocene)

During the Eggenburgian–Ottnangian, the subsidence is slow showing small basement subsidence rates of up to 0.3 km/Ma and up to 0.1 km/Ma in the tectonic subsidence (Fig. 9A). Subsidence spreads over the main study area, but is localized in E-W trending small areas. The southwestern corner of the study area subsides relatively fast and is correlated with the location of the deltaic-brackish depositional system (Bockfliess Formation) as reported from visualization of the Eggenburgian–Ottnangian sedimentary fill.

In the early Karpatian, the study area shows increasing basement subsidence (up to 1.5 km deep) and tectonic subsidence (up to 0.5 km deep), and subsidence takes place in a more NE-SW trending structural confinement (Fig. 9B). In this stage, high tectonic subsidence rates (0.5 – 1.0 km/Ma) are found in a NE-SW trending area continuing from the Laksary

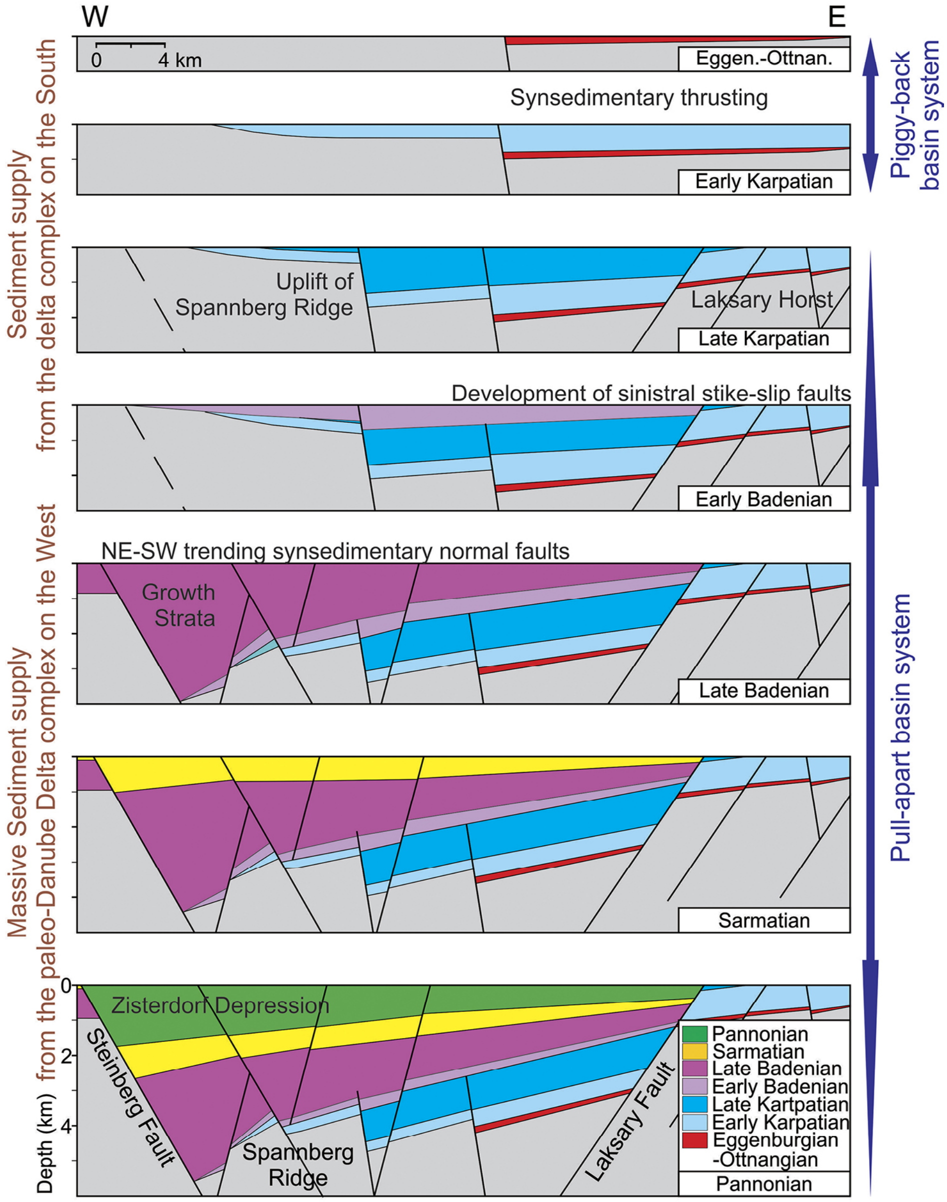

Figure 13: Schematic evolutionary model for sedimentary fill and subsidence evolution of the central Vienna Basin from the Early to Late Miocene in successive cross-sections.

horst to the Leváre depression and the Gajary depression of the central part and an area near the proto-Steinberg fault in the northern part.

5.2 Subsidence evolution of the Pull-apart basin system (Middle – Late Miocene)

Basement and tectonic subsidence are considerably higher in the late Karpatian, especially in the areas between the Steinberg fault and the Laksary fault and along the Leitha-Láb fault system (Fig. 10C). The areas with high subsidence rates are bound by synsedimentary faults of the en-echelon fault system and by structural ridges. This subsidence trends reflect the onset of transtensional tectonic movements between two convergent left-lateral strike-slip fault segments (Decker, 1996; Fodor, 1995; Royden, 1985; Sauer et al., 1992). In the northern basement high and the Laksary horst, however, the tectonic subsidence rate is relatively low or decreasing. It is supposed that these areas were not affected by the transtensional tectonic subsidence, in contrast to most parts of the basin. According to Fodor (1995) and Jiříček and Tomek (1981), a significant angular unconformity in the northern part indicates a basin inversion caused by local transpression where sinistral-slip was transferred toward the northeast.

After the fast subsidence event of the late Karpatian, both the basement subsidence and the tectonic subsidence decrease markedly during the early Badenian (Fig. 11D). Relatively high rates of the basement subsidence are indicated in the Kuty graben and the Leváre depression, while the tectonic subsidence almost stops in this stage (0 – 0.1 km/Ma).

From the late Badenian onwards, high basement and tectonic subsidence commence along the Steinberg fault (Fig. 11E). The Steinberg fault is synsedimentary subsiding with large displacement of 5–6 km, especially near the Zistersdorf depression (more than 1.0 km/Ma in the basement subsidence rate). The Spannberg ridge, uplifted during the late Karpatian (Hölzel et al., 2010), also subsides from this time onwards. However, the subsidence of the pre-Neogene basement is much higher than the calculated tectonic subsidence, therefore this study interprets that the high basement subsidence resulted mainly from sediment (and water) loading.

During the Sarmatian, the basement subsides significantly in the hanging wall region of the Steinberg fault (Fig. 12F). The highest rates (0.5 – 1.0 km/Ma) of the basement subsidence are restricted to the Zisterdorf, the Gajary, and the Sucho-Hrad depressions. Compared to the late Badenian subsidence, the area of Sarmatian subsidence shifts slightly to the south. The subsidence evolution during the Pannonian shows similarities to the Sarmatian one (Fig. 12G) being restricted mainly to the hanging wall of the Steinberg fault, however the Pannonian subsidence rate is much lower (~ 0.3 km/Ma in the basement subsidence, ~ 0.1 km/Ma in the tectonic subsidence).

Due to the basin inversion resulting from the latest Pannonian and Pliocene E-W compressional event(s), it is possible that the overall Pannonian subsidence has been underestimated and biased. In addition, this study found that Quaternary deposits have not been separated consistently from the Pannonian sediments in well data, thus the Pannonian subsidence, especially along the Vienna Basin transfer fault system (VBTF), includes partly Quaternary vertical fault displacement and subsidence. The Quaternary tectonic subsidence rate is ~ 0.3 km/Ma in the central Vienna Basin (Lee, 2015; Lee and Wagreich, 2016).

6. Discussion and conclusions

This study presents the Early to Late Miocene basin evolution of the Vienna Basin and visualizes the sedimentary fill and the basement and tectonic subsidence. The results demonstrate that the basin evolution of the Vienna Basin is closely coupled with changes of the basin structural setting, the regional stress field, and the regional sediment supply (Fig. 13).

During the Early Miocene piggy-back basin system (c. 20.4 – 16.9 Ma), the sedimentation and subsidence are slow and restricted in small depressions (Fig. 13). The depressions were filled with sediments supplied from small deltaic systems entering from the south (Fig. 4a). While slowly subsiding areas of the Eggenburgian-Ottnangian predominate in the E-W trending depressions of the northern and central parts, the early Karpatian basin setting was deeper, wider, and more NE-SW trending. The NE-SW trending structural features strike sub-parallel to the Leitha-Láb fault system, which, however, is not genetically related to the strike-slip faults. The Early Miocene kinematic of the Vienna Basin is characterized by the combination of synsedimentary thrusting and wrench faulting (Decker, 1996). According to Fodor (1995), the Eggenburgian depocenters concentrated at the junction area of the Eastern Alps and the Western Carpathians. Successively, the Ottnangian – the early Karpatian depocenters migrated southward along sinistral strike-slip or oblique thrusts, therefore the early Karpatian depressions spread more to south and show a NE-SW trend. It can be also related to an apparent counterclockwise rotation of the Alpine thrust front between the Eggenburgian and the Karpatian (Beidinger and Decker, 2014).

During the late Karpatian (c. 16.9 – 16.3 Ma), the area of sedimentation and subsidence widens and deepens with depressions developed by synsedimentary faulting, which is related to development of a rhomb-shaped pull-apart basin between two left-stepping segments. The deep subsiding areas are activated mainly by the Leitha-Láb fault system, the Steinberg fault, and Laksary fault, while the northern part is relatively stationary regarding subsidence due to the transpressional regime. The voluminous accommodation space was filled with sediments eroded from the Alps with a system of large deltas entering from the south (Fig. 4b).

In the study area, the early-middle Badenian (c. 16.3 – 14.2 Ma) subsidence is slow and confined to a narrow area due to the nearly stopped tectonic subsidence. In contrast, high tectonic subsidence rates of the early Badenian are observed in the southern part of the basin (Hölzel et al., 2008). There are three suggestions trying to explain this regional difference of the early Badenian subsidence. (1) According to Weissenbäck (1996), towards the end of the Karpatian, subsidence slowed down with the cessation of fault movements and a short-lived inversion period took place with producing noticeable tectonic uplift of the Matzen/Spannberg ridges in the central Vienna Basin. Although in the early Badenian the subsidence increased again, the subsidence was not accompanied by large fault activity. (2) Hölzel et al. (2008) explain the different subsidence pattern mainly with a paleoenvironmental effect caused by the Spannberg ridge which uplifted during the late Karpatian (Hölzel et al., 2010). The ridge largely restricted sedimentation to the southern part during the early Badenian. (3) Lee and Wagreich (2016) suggest that the regional difference of the Badenian tectonic subsidence was influenced by a regional Badenian paleostress change, considering a change of the major tensional regime shifting from transtension to E-W directed extension toward the late Middle Miocene.

The NE-SW trending normal faults, especially the Steinberg fault in the central Vienna Basin, seem to govern the basin development from the late Badenian to the Pannonian (c. 14.2 – 7.8 Ma) in the Vienna Basin (Fig. 13). These faults accompanying growth strata induce high subsidence in the Zisterdorf depression and the Moravian-Central depression, while the sinistral strike-slip faults along the southeastern border zone play a minor role. This time is characterized by E-W extensional rift-type subsidence, reaching up to 5.6 km of the basement subsidence along the Steinberg fault. The extensional subsidence is also reported in the Styrian Basin, the Danube Basin, and the western parts of the Pannonian Basin system for the Sarmatian - Pannonian (e.g. Fodor, 1995; Huisman et al., 2001; Kováč et al., 1999; Sachsenhofer et al., 1997; Vass et al., 1990). Also, the deposition of the late Badenian–Pannonian strata is strongly related to a large paleo-Danube delta complex on the western flank and smaller deltas in the SW and the NE corners of the Vienna Basin (Fig. 4c) which are continuously carrying sediments from areas of the Alpine Foreland, the Eastern Alps, and the Western Carpathians into the basin until Pannonian times.

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