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The Iváň Canyon, a large Miocene canyon in the Alpine-Carpathian Foredeep

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A B S T R A C T

During the latest Early Miocene a large drainage system developed in the Alpine-Carpathian Foreland transporting sediments through a prominent submarine canyon along the narrow corridor between the south-eastern Bohemian Massif and the Waschberg-Ždánice Unit. The canyon followed the Alpine-Carpathian Foredeep from Lower Austria towards the north and northeast into the Czech Republic. 3-D seismic data allow the mapping of this 600 m deep structure over a distance of 25 km and a width of 5 km. Despite its dimension, making it the largest submarine erosive and sedimentary structure of the Neogene Alpine-Carpathian Foredeep, this canyon has not been previously recognised. Herein, it is interpreted as shelf-indenting canyon that formed due to a combination of isostatic rebound along a terminating thrust front and sea-level change during the terminal Early Miocene.

The canyon fill comprises reworked littoral deposits with a typical Early Miocene, tropical micro- and macrofauna. The exact timing of this refilling remains unclear. Smaller channel structures in surface outcrops, representing potential tributaries of the canyon, suggest a more or less synsedimentary filling soon after indention. Finally, the top part of the canyon was eroded around the Early/Middle Miocene boundary, probably related to a global 3rd order sea level drop, and caped by marine marls during the subsequent early Middle Miocene transgression. With the sudden onset of the subsidence of the Northern Vienna Basin during that time, the drainage system abruptly moved southward shedding its sediments into the newly opening Vienna Basin. This explains the rather abrupt abandonment of the huge canyon feature, whose fan deposits are unknown so far.

1. Introduction

Large parts of south-central Europe were covered by the Paratethys Sea during the Early Miocene (Rögl, 1998; Popov et al., 2004). The western branch of this epicontinental sea formed in the North Alpine Foreland Basin (Grunert et al., 2010). Tectonic uplift of this foreland basin coupled with the northward movement of the Alpine nappes caused a step-wise shallowing of the sea and an eastward movement of the coast. Simultaneously, the deep depocenters moved from the North Alpine Foreland Basin (NAFB) into the Polish-Carpathian Foredeep (Meulenkamp et al., 1996; Pícha et al., 2006). With the onset of the Middle Miocene, the NAFB was continental, except for a few episodic ingressions in its easternmost part. At the same time, the Vienna Basin came into existence switching from an Early Miocene piggy-back basin into a Middle Miocene pull-apart basin (Strauss et al., 2006; Hölzel et al., 2010), terminating the strike slip tectonics by Middle Badenian times (Lankreijer et al., 1995; Kováč et al., 2004). The tectonic boundary between the Alpine-Carpathian Foredeep and the Vienna Basin was formed by the Waschberg-Ždánice thrust system (Fig. 1).

The subthrust of the Waschberg-Ždánice Unit (WZU) and its foreland basins are highly explored and prolific production areas for oil and gas (Hamilton et al., 1990, 2000; Pícha, 1996). To compensate for the production decline in this long known oil & gas province, extensive high-quality two and three-dimensional seismic surveys have been acquired over the past years by the Austrian international oil & gas company OMV AG (Hamilton et al., 2000). These modern seismic surveys not only lead to new discoveries in the geologically complex sub-thrust of the WZU, but have also revealed a challenging insight into the complex relationship between tectonics and sedimentation shedding new light onto the regional paleo-drainage pattern.

Although a major discordance in Lower Miocene deposits of the investigation area had been detected in 2-D seismic data on both the Austrian side (Aniwandter et al., 1990) and the Czech part (Jiříček, 1995) of the study area an interpretation of the important stratigraphic feature had not been possible. The new 3-D and 2-D

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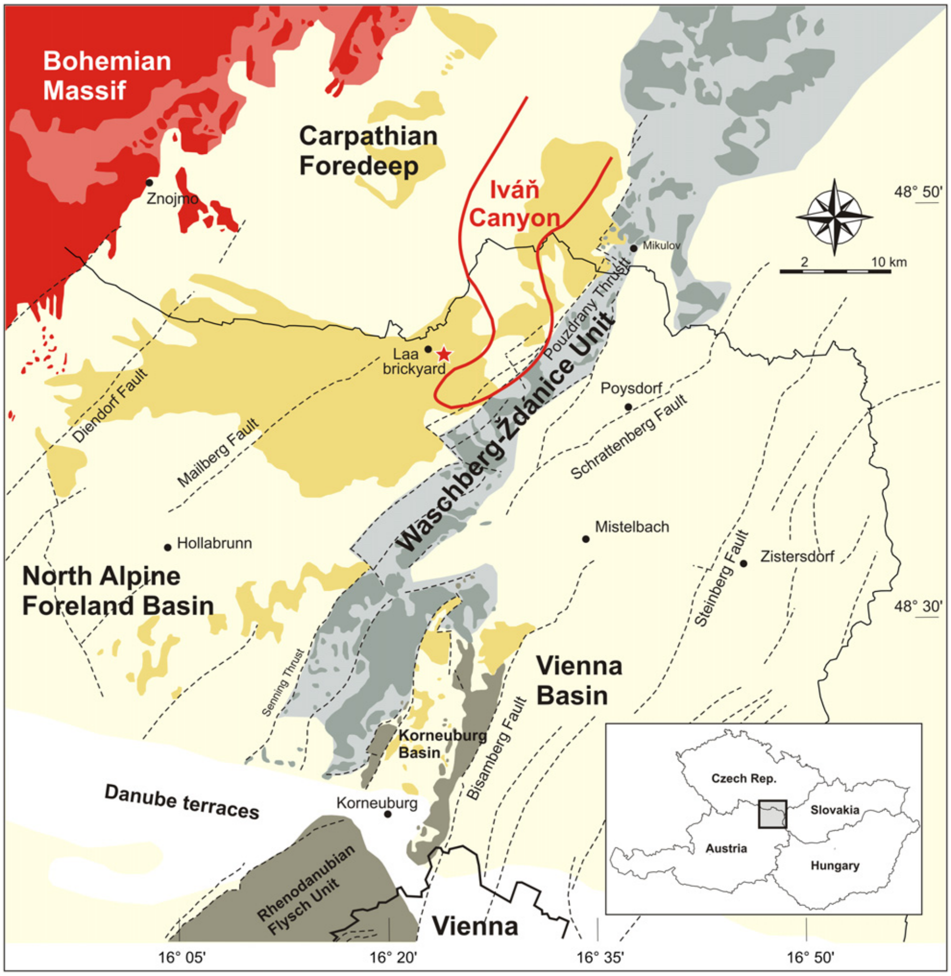

Figure 1. Geologic-tectonic map of the study area indicating the outline of the Iváň Canyon (map after Schnabel et al., 2002). The small geographic map shows the position of the geological map as insert. Red: Palaeozoic crystalline of the Bohemian Massif; green-grey: Jurassic–Lower Miocene deposits of the Waschberg-Ždánice Unit; ochre: Karpatian sediments, light orange: Neogene and Quaternary. Note that the eastern wall of the Iváň Canyon follows the frontal thrust of the WZU. The red star indicates the location of the outcrop study in the Laa brickyard. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

seismic data revealed this huge structure as a buried canyon that formed at a tectonic junction. This approximately 600-m-deep canyon, is termed herein the Iváň Canyon, with reference to the lithostratigraphic Iváň Fm. of Adámek et al. (2003).

The complex biotic and tectonic development of the Paratethys Sea is expressed in a system of regional stages (Piller et al., 2007). The regional Karpatian stage corresponds to the upper part of the international Burdigalian stage and ranges from c. 17.2 to 15.9 Ma (Grunert et al., 2010, 2012). The Middle Miocene comprises the Badenian and Sarmatian regional stages (Fig. 2). The Badenian spans the Langhian and Lower Serravallian, ranging from 15.9 to 12.7 Ma (Paulissen et al., 2011) [an alternative date is suggested by Hohenegger and Wagreich (2011), who propose a time span of 16.30–12.73 Ma].

2. Geological setting

The study area represents the junction between the North Alpine Foreland Basin in the west and the Carpathian Foreland Basin in the northeast (Fig. 1), called Alpine-Carpathian Foredeep in this paper. It developed as peripheral foreland basin triggered by the tectonic loading during the Eocene to Miocene due to the advance of the Alpine-Carpathian thrust systems (Oszczypko, 2006). The major frontal thrust system between these units is the folded, thin-skinned Waschberg Unit which extends from north-east Austria to southeast Moravia (Krhovsky et al., 2001). Together with the Ždánice and Subsilesian Units, which continue via Moravia to Poland, it is considered as the lowermost element of the Outer Carpathian nappe stack (Pícha et al., 2006). This tectonically complex unit comprises Jurassic to Lower Miocene deposits. A compressional tectonic regime with A-type subduction prevailed in this critical area during most of the Early Miocene. The lateral extrusion of crustal blocks in the Eastern Alps and the oblique collision of the Alpine-Carpathian nappe systems with the European platform led to a change in tectonic regime to a transpressive-transtensional system during the latest Early Miocene and early Middle Miocene (Kováč, 2008). This also caused a major change in palaeogeography and is reflected in a distinct shallowing of the foreland basins and initiated the pull-apart mechanisms that formed the Middle Miocene Vienna Basin (Royden, 1985; Strauss et al., 2006; Hölzel et al., 2010).

The boundary between the foreland basins and the advancing thrust system is in general marked by the Pouzdřany Unit (sensu Stráník, 1999) (Fig. 1), which separates the nappe stacks of the Waschberg-Ždánice Unit from the autochthonous Molasse sediments (Poul and Melichar, 2010). A first compressive phase in the Waschberg-Ždánice Unit is represented by the reactivation of old Variscian strike-slip faults, such as the Diendorf fault and the

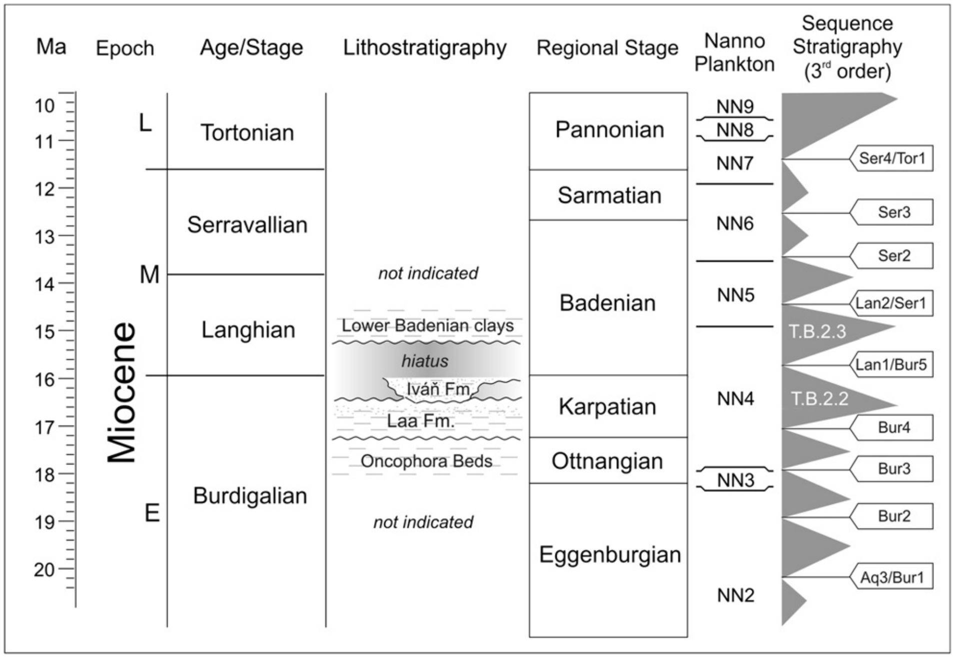

Figure 2. Miocene chronostratigraphy with regional Paratethys stages after Piller et al. (2007); sequence stratigraphy after Hardenbol et al. (1998). Lithostratigraphic terms for the WZU area as used in the text are indicated.

Mailberg fault during the Early Miocene (at. c. 20 Ma), while the main thrusting of the WZU took place during Early Karpatian times (at. c. 18–17 Ma) (Zámolyi et al., 2008). The front of the fold-thrust units (WZU) was oriented roughly parallel to the old inherited structural system. The thrusting ended during the late Early Miocene (Zámolyi et al., 2008, 2009).

3. Data base

3.1. Seismic and well data

Several merged 3-D surveys (Pottenhofen-Waschberg-Wildendürnbach-Hohenruppersdorf) and multiple vintage 2-D seismic have been acquired in this area over the past 30 years. The Seismic Reference Datum (SRD) used in this area of Austria is at 130 m above MSL. Average surface elevation of the area is around 200 m above MSL. The topography is characterized by a rolling plain with minor hills and is mainly farmland. It is the uplifted foreland of the thrusted and elevated WZU. The projection system used for the seismic project is WGS_1984_UTM_Zone_34N. The difference of the seismic velocities from the Laa Fm. to that of the canyon fill is negligible and no acoustic impedance contrast is observable; moreover the sediments of the canyon fill consist partly of reworked Laa Fm. Thus it is not surprising, that the nature of the canyon was not recognized by regional geologists for a long time. However, the canyon cut generated a remarkable erosional feature, which enabled it to be delineated on the modern seismic data.

Numerous wells have been drilled in the canyon area leading to the discovery of gas fields (Wildendürnbach, Altprerau, Pottenhofen). All these wells were targeting reservoirs deeper than the canyon, mainly sandstones of the so-called Oncophora Beds (Ottnangian Stage) [note that this is only an informal term used in the oil industry and does not imply a correlation with beds yielding the endemic bivalve *Oncophora*]. From two wells (WDK2 and WDK4) drilled within the limits of the canyon area core data from the canyon fill and the sediments below the canyon are available and have been studied.

Well WDK2 (Figs. 3 and 4) is located at the western margin of the canyon and penetrates the boundary between the Iváň Fm. and the Laa Fm. at c. 190 m depth below ground level. A core sample from well WDK2 (260–263 m, core 5) from the Laa Fm. contained sandy silt with a rich foraminiferal assemblage. Planktonic taxa such as *Globigerina ottnangiensis* Rögl, *Globigerina* cf. *lentiana* Rögl, *Tenuitella clemenciae* (Bermudez) and *Tenuitellinata selleyi* Li, Radford and Banner are dominant and represent a typical plankton assemblage of the lower and middle Karpatian stage. The benthos is dominated by *Sigmoilinita tenuis* (Czjzek), *Bolivina hebes* Macfadyen, *Bolivina dilatata* Reuss, *Bulimina elongata* d'Orbigny, *Uvigerina graciliformis* Papp and Turnovsky, *Myllostomella advena* (Cushman and Laiming), *Stilostomella adolphina* (d'Orbigny), *Siphonodosaria nuttalli gracillima* (Cushman and Jarvis) and *Caucasina schischkinskayae* (Samoylova). This assemblage corresponds fully to those assemblages described by Spezzaferri et al. (2002) and Petrová (2004) from other samples of the Laa Fm. and indicates deeper marine settings. This interpretation is further supported by the shells of pyramidellid gastropods, which are often found in deep sublittoral to bathyal environments.

Samples from the Iváň Fm., taken at 50–55 m (core 1) and 100–105 m (core 2) depth comprise silty sand with benthic foraminfers (*Melonis pompilioides* (Fichtel and Moll), *Nonion* cf. *boueanum* d'Orbigny, *Ammonia viennensis* d'Orbigny, *Ammonia pseudobeccarii* (Putrja), *Aubignyna brixi* Rögl and rare plankton (*Globigerina praebulloides*) Blow). Some of the species seem to be reworked. The mollusc fauna consist of fragments of the neritid gastropod *Agapilia pachii* (Hörnes) and of the batillariid gastropod *Granulolabium bicinctum* (Brocchi). This assemblage is indicative of warm temperate to tropical littoral environments (Harzhauser, 2002).

Well WDK4 was drilled in the central part of the Iváň Canyon and penetrates the boundary between the Laa Fm. And the Iváň Fm. at c. 302 m depth (KB). The sample from the Laa Fm. was taken at 426–431 m (core 2, below the canyon fill) and comprises the planktonic foraminfers *Globigerina concinna* Reuss

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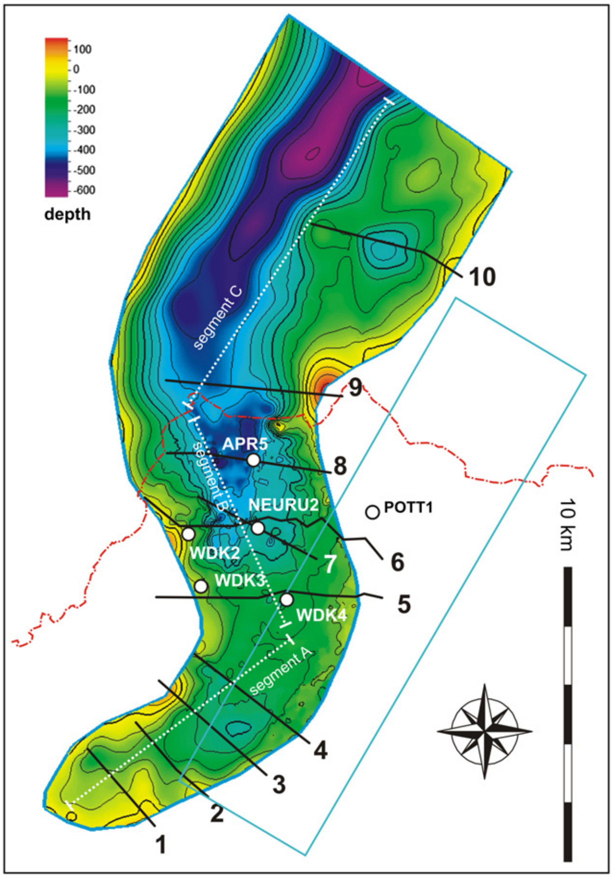

Figure 3. Location and data map of the study area in north-eastern Austria and parts of Czech Republic with depth contour map of the canyon base. The figure gives an overview of the outline of the 3-D survey Pottenhofen (cyan), the position of the wells mentioned in the text and a selection of important seismic lines used to delineate the geometry of the canyon. Note the sinuous canyon form and the gradual deepening along the thalweg towards the north and northeast; Colour depth scale annotated in m based on seismic reference datum (+130 m); contour interval 50 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and *G. ottnangiensis* Rögl and the benthic *C. schischkinskayae* (Samoylova) and *Virgulinella pertusa* (Reuss). Samples from the lowermost canyon fill were taken at 292–297 m (core 1) and yield opercula of the freshwater gastropod *Bithynia* sp. and rare planktonic foraminifers, which seem to be reworked from underlying strata (*G. ottnangiensis* Rögl, *Tenuitellinata angustiumbilicata* (Bolli), *T. selleyi* Li, Radford and Banner).

Both wells clearly indicate the abrupt facies change at the discordant boundary between the Laa and the Iváň Fm. The fully marine offshore fauna of the Laa Fm. is contrasted by the littoral fauna of the Iváň Fm.

3.2. Surface outcrops and potential tributaries

The fauna of the Iváň Canyon fill suggests a source from coastal mudflats and estuaries, which are widespread in the eastern NAFB and the Korneuburg Basin during the late Karpatian (Harzhauser, 2002). A close by surface outcrop which captures the discordant contact between the middle Karpatian Laa Fm. and the late Karpatian Iváň Fm. is situated at the abandoned brickyard Laa-Wienerberg Baustoffinustrie AG c. 2 km SE of Laa an der Thaya (N 48° 42′ 55″ E 16° 24′ 36″), some 5 km to the west of the Iváň Canyon (Fig. 1).

The underlying shales and siltstones of the Laa Fm. in this outcrop were exposed mainly in the SW and central parts of the pit. There, more than 10 m of dark grey–blue silty clay and clay form the base and the walls of the pit. The deposits are distinctly laminated in mm- to cm-scale. The laminae are often separated by drapes of silt and fine sand which may form distinct lenses and current ripples which point in NE direction towards the Iváň Canyon (Fig. 5). Bioturbation is completely absent, suggesting dysoxic bottom conditions during deposition. Consequently, macrofossils are very rare; benthic taxa are absent but shells of the pelagic pteropod *Vaginella austriaca* may form loose accumulations. Only in deeper parts of the former pit, bioturbated marly shales with microfauna were exposed. The foraminiferal assemblage of the pit, which is characterised by bolivinids and buliminids, was described in detail by Rögl (1969). The ecological analysis of the fauna by Spezzaferri and Ćorić (2001) points to a nutrient-rich, upwelling influenced shelf environment. These pelites are discordantly overlain by silt and sand of the Iváň Fm. which was exposed along a more than 300 m long W–E transect. The contact with the pelites of the Laa Fm. is a low relief erosive horizon, which may yield rare pebble-sized intraclasts. Above there is an alternation of bioturbated silt and fine sand layers which are overlain by a continuous unit of fine to medium sand of 2–4 m thickness. Plant debris, bioturbation and littoral molluscs are frequently found in huge concretions within this unit. The mollusc fauna, with infaunal venerid, donacid and lucinid bivalves suggests agitated shoreface conditions. There then follows a 4-m-thick unit of rapid alternation of bioturbated silt and sand layers with cross bedding and current ripples. Shallow channels, sand bars and lateral amalgamation of silt layers are typical. The mollusc fauna is dominated by mudflat dwellers such as the potamidid gastropod *Terebralia bidentata* and the giant oyster *Crassostrea gryphoides*.

These mudflat deposits become incised by a deep channel towards the NE part of the pit. This Laa Channel has a NE–SW orientation; its axis could be followed over 300 m. Its geometry is unclear due to the lack of outcrop but a width of more than 40 m is realistic. Based on the observations derived from the Iváň Canyon, it is possible to link up the Laa Channel with the time equivalent Iváň Canyon to the east of the studied outcrops.

The channel fill consists of intraclasts of up to 60 cm diameter. The size and morphology of the intraclasts is very variable ranging from spherical to elongate ellipsoid. These intraclasts are formed by silty sand, silt and silty clay. The latter may form armoured mudstone clasts with attached mollusc shells (Fig. 5, A3–A4). The intervening sediment is composed of silt and fine sand. Accumulations of mollusc shells are very frequent, forming stringers or dense nests. Relict silt layers separate at least three units of intraclasts. Each displays an indistinct fining upward trend. This documents that the channel fill was formed in multiple phases over a long period. The mollusc fauna was summarized by Harzhauser (2003) and consists of taxa which are typical inhabitants of coastal mudflats and mangroves (e.g. *Melongena cornuta*, *T. bidentata*, *Tympanotonos papaveraceus*). The abundance of the freshwater gastropod *Melanopsis impressa* documents increasing freshwater influx. Estuarine conditions are also indicated by teeth of the crocodilian *Gavialosuchus eggenburgensis*.

The entire succession reflects a step-wise but rapid shallowing from dysoxic shelf environments to foreshore conditions and the establishment of mudflats and finally to sediment bypass via the Laa Channel. This general development and the associated depositional environments may serve as surface counterparts for the coeval Iváň Canyon. Moreover, the Laa Channel formed only 2.5–2 km west of the upslope part of the Iváň Canyon and most likely represents a part of its tributary system.

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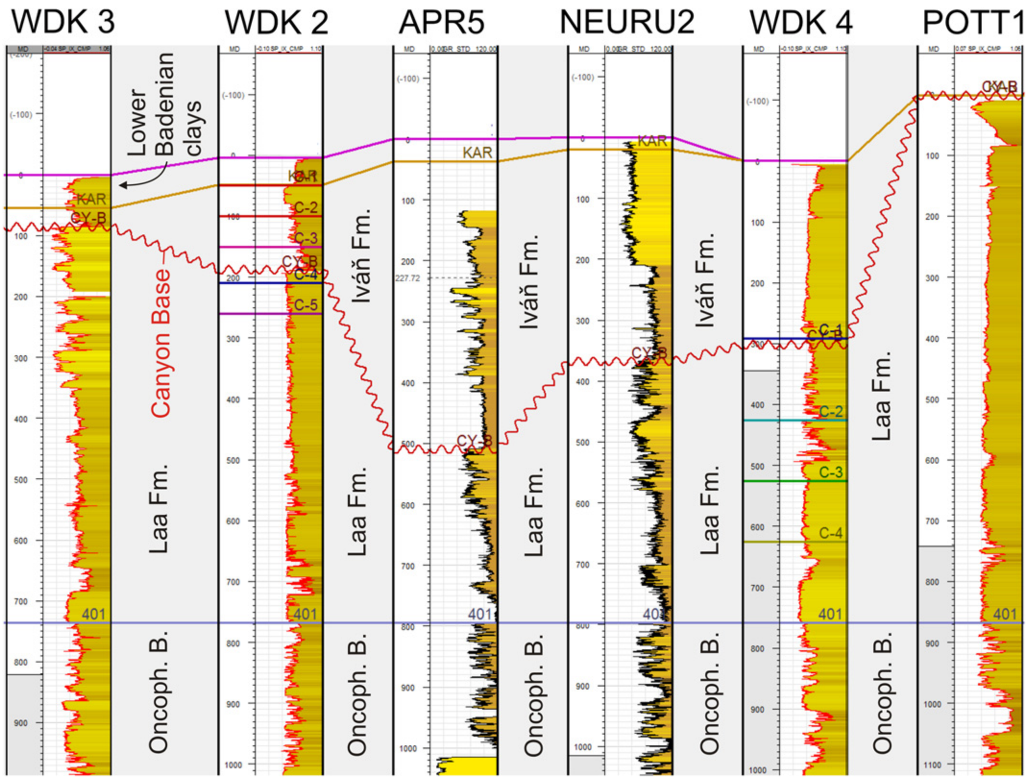

Figure 4. SP IX-CMP & GR logs (from left to right: WDK3, WDK2, APR5, NEURU2, WDK4, POTT1) showing the Upper Karpatian canyon fill and underlying Karpatian (= Laa Fm.) and Ottnangian (= Oncophora Beds) formations; logs flattened on Top Ottnangian (horizon 401); the log character over the section of the canyon fill shows a very heterogeneous fill of shales, silt and sandstones and differs from the Laa Fm. below; the deepest part on this section is on well APR5 at 500 m MD (measured depth) below KB (kelly bushing) = near ground level (GL); KAR (= Top Karpatian), CY-B (= Canyon Base, red unconformity); vertical increments along axes: 100 m; reference depth in MD below KB. Cores C-1 to C-3 in well WDK2 are within the canyon fill and C-4 is already from the underlying undisturbed Laa Fm.; cores (C-2 to C-3) in well WDK4 are all located below the canyon base in the undisturbed Laa Fm., while core C-1 is from the lowermost canyon fill. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Iváň Canyon: geomporphology, biostratigraphy and paleo-environment

The recognition and genetic interpretation of the Iváň Canyon as a Late Karpatian SW–NE oriented submarine canyon system depended on the combined evidence and conclusions from seismic data analysis, well logs, cutting and core analysis, sedimentological and biostratigraphic studies from nearby surface outcrops as well as paleo-environment and tectonic considerations relating the Late Karpatian to Early Badenian geological evolution of the North Alpine-Carpathian system to the opening of the Vienna Basin.

4.1. The Iváň Canyon geomorphology

The Iváň Canyon geomorphology is clearly recognized on seismic images by a significant angular unconformity throughout its distribution area (Figs. 4, 6 and 7). The surrounding shales and siltstones of the Laa Fm. are characterised by strong, continuous and planar high frequency reflectors whilst the canyon-fill appears as chaotic and relatively isotropic seismic facies without noticeable internal reflections. The log character of the canyon fill shows significant lateral and vertical facies inhomogeneity. This is confirmed by the core description and the isotropic seismic character of the fill where no layering, as is typical for the Laa Fm. on the either side of the canyon, can be recognized (Fig. 6). In certain wells (APR5 (Altprerau-005) and NEURU2 (Neuruppersdorf-002)) the canyon-fill starts with a c. 200 m thick shale section, while in the logs from wells WDK2 and WDK4 this package is absent (Fig. 4). Seismic observations further support canyon wall failure and slumping from both sides of the steep cut canyon walls. Three distinct steps of incision can be differentiated based on the formation of large terraces formed at the eastern cut bank side (cliff-face) of the canyon (orographic right side) (Fig. 7).

Following Smith et al. (2007), the deepest part of a canyon cross section is the *axial channel*. The *channel floor* comprises the axial channel and its adjacent terraces. The flanks are formed by the *canyon walls* and the *canyon rim* which marks the transition into the shelf. The Iváň Canyon geometry was largely delineated by seismic data (about 90% 2-D and 10% 3-D). Only the northern and the north-western part, where no seismic data was available to the authors, has been reconstructed using information derived from the data published by Šikula and Nehyba (2004). The most prominent features of the canyon are the cascaded depth profile, with three distinct plateaus, and the abrupt pathway changes from a SW–NE oriented system into a S–N and return again into a SW–NE trending one (Fig. 3). Due to the subsequent Middle Miocene erosion, no data are available on the canyon head and hypothetical tributaries.

The seismically mapped part of the canyon can be subdivided into three segments (Fig. 3):

- Segment A: starting from the canyon apex, in the very SW, to the first knickpoint of the canyon near to well WDK4.
- Segment B: from the well WDK4 to the second knickpoint close to the Austrian/Czech border.
- Segment C: from the Austrian/Czech border to the north-eastern end of the mapped canyon in South Moravia (Czech Republic).

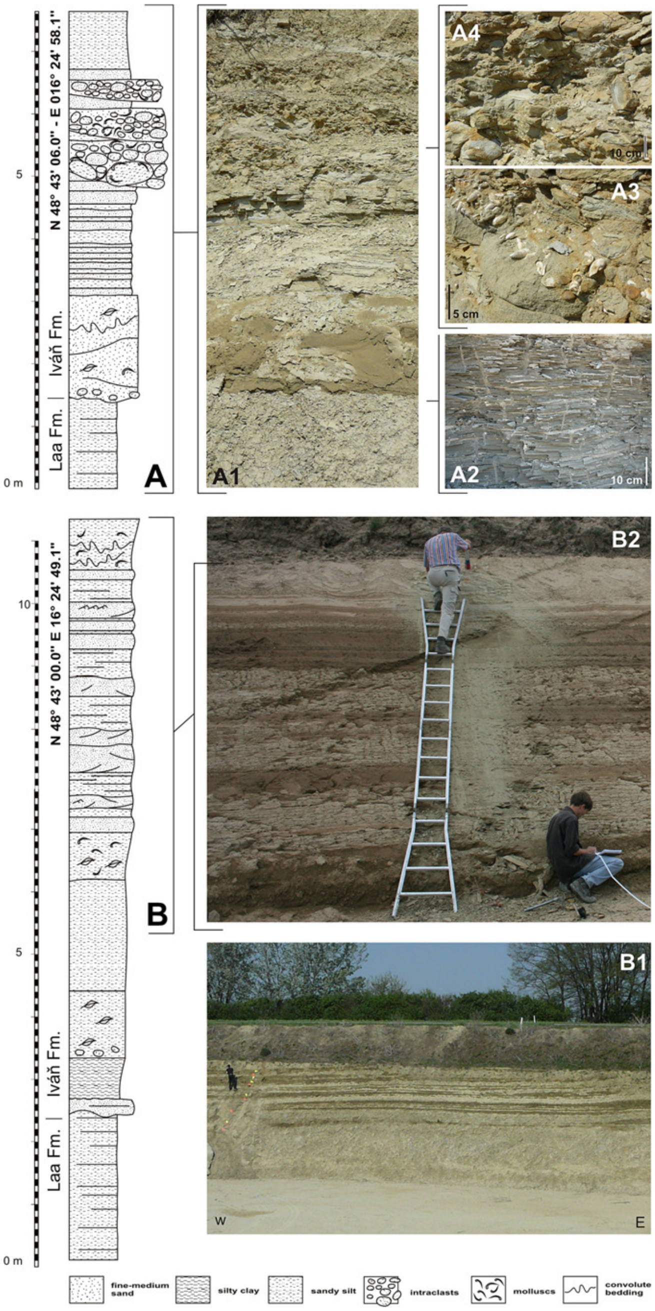

Figure 5. Surface outcrop in the abandoned clay pit Laa. A: section showing the contact between the Laa Fm. (A2) and the infill of the Laa Channel (A3, A4). This channel might have represented a tributary of the Iváň Canyon. Its fill comprises sand, silt and clay of reworked mudflat deposits with rich littoral mollusc fauna (A3, A4). Laterally, the channel is replaced by autochthonous mudflats (B). B1–B2: panoramic views of the mudflat deposits as given in log *B*.

4.1.1. Segment A

The Segment A represents the south-western end of the canyon and is interpreted as the erosional preserved near-canyon-mouth. In terms of present day tectonic setting it is located in the easternmost North Alpine Foreland Basin. This canyon segment forms a SW–NE oriented relatively shallow (preserved) axial channel of c. 3 km width and 9 km thalweg length, before it starts abruptly deepening and changing direction in the area of well WDK3 and WDK4 from a SW–NE to a S–N orientation (first knickpoint, transition to Segment B). To the south of well WDK4, a tectonic induced local low of 250 m depth was generated by the partial overriding of the Pouzdřany thrust, causing a post sedimentary push down (Fig. 6, Section 3).

4.1.2. Segment B

From the first knickpoint onwards, the thalweg forms a 7 km long N–S oriented narrower valley-like channel floor and the canyon deepens from a preserved 280 m depth (WDK4) down to 360 m (GL) between wells WDK2 and NEURU2 (Fig. 3). The change in pathway is also accompanied by a change in canyon walls morphology. The initial part of the canyon (Segment A) is bordered by symmetric, wide and shallow concave walls. At the beginning of the first knickpoint, however, the western wall forms a moderately steep slip-off slope whilst the eastern wall becomes steep and terraced between the first knickpoint and the second knickpoint (Fig. 6, seismic Sections 5–8). In this area, the Iváň Canyon deepens down to 400–450 m forming a deep valley-like channel floor with steep walls and wide terraces of ca. 0.5 km width.

The section of the well-developed terraces ends as a hanging valley at a shoulder, which leads to the deepest part of the canyon. This area forms a S–N oriented 7 km long and 1–3 km wide channel, which is bordered by a moderately steep concave western wall and a comparatively steep and straight eastern slope. A slight embayment (near well WDK2) forms a terrace in the western margin and could indicate the existence of a tributary channel embayment (probably the connection to the Laa Channel), which is however outside the available seismic coverage area. The canyon becomes slightly shallower again in northern direction with a more than 6 km wide canyon floor.

4.1.3. Segment C

From the second knickpoint onwards the thalweg switches to a SSW–NNE direction and forms a 12 km long and 6–7 km wide axial channel. The channel is widening and the floor becomes shallower along the eastern wall. The canyon wall remains steep only in its upper part close to the rim, but shallow concave on its lower slope, forming an asymmetric profile, the deeper part on the western side and shallower part on the eastern side.

A local deep is developed in this segment of the canyon, however this is not caused by tectonic influence like the one in the segment A. Close to an undercut slope in the area of the Austrian border, this low reaches a depth of approximately 500 m (GL) (Fig. 6, seismic Sections 9 and 10). This local low is also shown on a published isopach map from the Upper Karpatian in South Moravia (Jiříček, 1995, Fig. 18). There the canyon floor reaches a general base at c. 450 m from the top of the eroded canyon wall, gradually deepening along the thalweg towards the NE up to ca. 600 m (GL) at the edge of the study area (Fig. 3). This northeasternmost part of the described geobody of the Iváň Canyon, does not represent the final canyon mouth, but just the limit of the seismic data used to delineate the geometry and the direction of flow. The published data (Jiříček, 1995) shows the canyon to extend further to the northeast following the Carpathian foredeep. The detailed description of the canyon in this paper however, is limited to the area for which seismic data have been available to the authors. The northern part of the studied canyon has low seismic coverage and the western rim has been partly reconstructed using data from well logs and isopach maps published by Šikula and Nehyba (2004) as well as seismic data published by Jiříček (1995). The isopach map of the log facies "L" (Upper Karpatian – Lower Badenian, Šikula and Nehyba, 2004) coincides with the canyon fill, showing the trend of the canyon as mapped in the seismic data.

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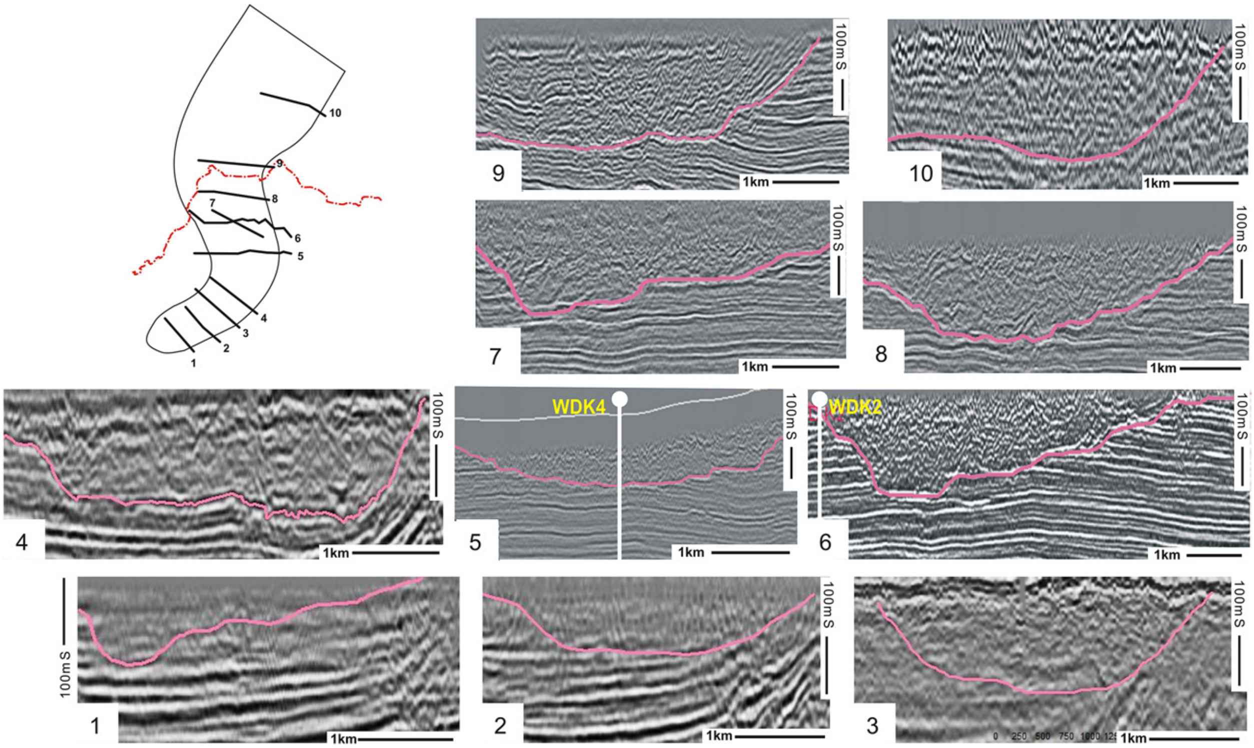

Figure 6. Series of 10 seismic lines as indicated in Figure 3 showing West (left) – East dip sections through the canyon; the lines are starting on bottom left with seismic section 1 in the very southwest of the canyon and finish with line 10 in the top right. Line 6 illustrates very clearly the exceptional change in seismic facies between base and canyon fill.

4.2. Biostratigraphy and depositional environment of the eroded canyon wall, the Iváň Canyon fill and the Badenian truncation of the canyon system

4.2.1. Canyon wall deposits

Two lithostratigraphic units of the Laa Fm. dominate the area in which the canyon developed. The base and walls of the canyon and large parts of the surrounding surface geology, are formed by the Lower Miocene Laa Fm. (Roetzel and Schnabel, 2002), which comprises up to 1000 m of marine calcareous silty shales with thin fine sand intercalations (Roetzel, 2003, 2009). The laminated greenish to brownish grey micaceous silty shales display an overall coarsening upward trend (Nehyba and Petrová, 2000). Within the NAFB, the deposits are limited in the south and the east by Cretaceous sediments of the WZU. Towards the west, single surface outcrops occur as far as the Diendorf-fault at the eastern margin of the Bohemian Massif in the area of Gaindorf (Schnabel et al., 2002).

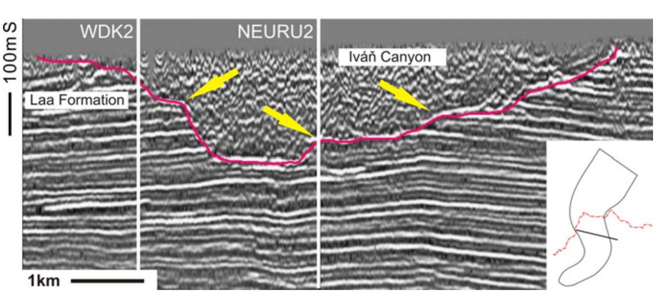

Figure 7. W (left) to E seismic profile through central part of the canyon illustrating flat canyon bottom and three pronounced terraces (arrows); the stepwise canyon incision into the low angle bedded Laa Fm. forming several stages of terraces. Location of seismic line is indicated in the insert. Chaotic internal seismic pattern accounts for rapid lateral facies change.

The upper part of the Laa Fm. was defined as the Nový Přerov Member by Adámek et al. (2003). This, up to 550 m thick member, differs from the underlying parts of the Laa Fm. in its higher proportion of silt and thick sand intercalation within the grey to whitish grey micaceous siltstones.

The Laa Fm. was deposited during the Late Burdigalian and corresponds to the early and middle Karpatian of the regional stratigraphy, suggesting an absolute age of c. 17.2–16.5 Ma (Grunert et al., 2010) [the total range of the Karpatian is 17.2–15.9 Ma]. The foraminiferal assemblage is correlated with the Foraminifera Zone M4 (Rögl et al., 2003) and the nannoplankton assemblages indicate a correlation with the nannoplankton Zone NN4 (Fig. 2). The depositional environment of the Laa Fm. was outer shelf to upper bathyal of the NAFB and the Carpathian Foredeep. Cool, nutrient-rich, upwelling influenced surface waters (Spezzaferri and Ćorić, 2001), and these caused, dysoxic bottom conditions with reducing environments, supporting the formation of pyritized levels (Spezzaferri et al., 2002). The foraminiferal fauna consists of calcareous benthic and planktonic taxa with *U. graciliformis*, *Pappina primiformis* and *Globigerinoides bisphericus* as typical taxa (Spezzaferri et al., 2002; Petrová, 2004). *G. bisphericus* has been described by Jiříček (1995) as a frequent species in the strata of the "Terminal Karpatian" from the Carpathian foredeep in Moravia (Iváň Canyon fill equivalent), and also from the Karpatian and lowermost Badenian of the NAFB and the Vienna Basin (Papp, 1963).

Only in the northernmost section (Segment C), the canyon cuts down into stratigraphically older formations (Egerian and Eggenburgian of Early Miocene age). Egerian and Eggenburgian sediments are comprised of an alternation of sandy, silty and shaly sediments and will not be described further in this paper.

4.2.2. Iváň Canyon fill deposits

The canyon-fill is represented by the Iváň Fm., which was originally introduced as member of the Laa Fm. by Adámek et al.

(2003). It overlies the Nový Přerov Member with a marked angular unconformity throughout its distribution area. In cores and cuttings from wells it comprises fine-grained calcareous sandstones and up to 200 m of grey calcareous claystones. In outcrops sand-silt interbeds with channel structures and a rich intertidal mollusc fauna are typical (e.g. Laa brickyard). The Iváň Fm. is restricted to the northeasternmost part of the NAFB (North Alpine Foreland Basin) and a small area of the southwestern part of the Carpathian Foredeep (well log facies K in Šikula and Nehyba, 2004) and pinches out quickly in all directions, supporting the canyon fill interpretation.

The Iváň Fm. was deposited during the latest Burdigalian and represents the late Karpatian of the regional stratigraphic scheme (Piller et al., 2007), roughly spanning from 16.5 to 16.3 Ma, when *Praeorbulina* first appears. Its nannoplankton assemblage is indicative for zone NN4. The overlaying marls contain *Praeorbulina* and *Orbulina* and are of Langhian age (Adámek et al., 2003). The cool water conditions of the early and middle Karpatian, contrast with the tropical conditions that became established during the latest Burdigalian. Its mollusc fauna is indicative of subtropical tidal flats, mangrove coasts and shallow marine settings and the vegetation points to high mean annual temperatures of c. 15.7–20.8 °C (Harzhauser, 2002; Kern et al., 2010). The depositional environment of the Iváň Fm. canyon fill displays many similarities with the fill of the Paleogene canyons in South Moravia which were also filled partly by reworked sediments from estuaries (Pícha, 1974, 1979).

4.2.3. Badenian truncation of the Iváň Canyon system

The Iváň Canyon and the laterally adjacent canyon wall sediments of the Laa Fm. have been eroded before the deposition of Lower Badenian sediments. Evidence for this stratigraphic relationship is the seismic data studied as well as the formation tops dated based on micro- and nannoplankton fossils (Rögl, 1969; Rögl et al., 2002) from wells in the area (WDK2, WDK3, APR5, NEURU2, Fig. 4). Log and outcrop studies of the Lower Badenian sediments in the area of the Iváň Canyon reveal a thin cover (less than 50 m) of marine plankton rich clays of Badenian age covered partially by Quaternary sediments (Roetzel and Schnabel, 2002).

5. Discussion of submarine canyons in general and canyons in the Alpine-Carpathian setting in particular

Canyons and incised valleys are being studied worldwide not only for scientific reasons but also because they funnel potential clastic reservoir sediments into the marine setting (deltaic and fan systems) and are therefore of high interest for explorationists. As pointed out by Pícha et al. (2006) canyons, paleovalleys and channels are not uncommon sedimentary features in the Carpathian Foredeep. Several canyons and incised valleys of Late Cretaceous to Paleogene age up to 1500 m deep and 12 km wide, developed during the uplift in the Laramide orogenic phase in Moravia. The two most prominent ones are the Nesvacilka and Vranovice Canyons described by Pícha (1974, 1979) and Pícha et al. (1978, 2006). Further Paleogene canyons were detected in Moravia by Jiříček (1987, 1994). Most of the Paleogene canyons were originally interpreted as tectonic grabens (Homola et al., 1961). Similarly, the Iváň Canyon was misinterpreted in older literature. Even though the canyon fill reveals a different sedimentary environment to the Laa Fm., which forms the canyon walls, poor surface outcrops and a thin cover by younger sediments (Schnabel et al., 2002) mask the canyon feature, making it difficult to be identified by field geology. Only seismic data and a subsequent tie-in of well data allowed the final identification and mapping of the canyon morphology. Earlier studies interpreted the canyon feature as a stratigraphic interfingering (Aniwandter et al., 1990) and as a listric fault (Tomek, 1999). Jiříček (1995) interpreted the structure as a regional successive transgression of the "Terminal Karpatian" onlapping onto the eroded Laa Beds. Indeed, figure 13 of Jiříček (1995) displays the same seismic line as shown herein in Figure 6, section 9. On this seismic line of Jiříček (1995), reflections within the canyon fill resemble bedding planes parallel to the unconformity. A closer look however reveals the nature of these reflections as multiples of the canyon base reflector. No transgressive features are thus deducible from the seismic lines. Instead, the seismic sections in Jiříček (1995), indicate that the northwestern part of the Iváň Canyon is further deepening, cutting locally down to the Eggenburgian (Early Miocene) and even Jurassic rocks (Jiříček, 1995, Figs. 14–16; seismic lines 317/84, 286/84 and 287/84), eroding the entire package of over 1000 m of Karpatian sediments Jiříček and Seifert (1990). An alternative interpretation as a fluvial deltaic body prograding from the NE can be excluded for several reasons. On the one hand, the palaeogeography of the region as presented by Kováč et al. (2004) clearly documents the presence of open marine deep sea conditions in the adjacent Carpathian Foredeep at that time. On the other hand, the deposits of the canyon fill lack any fluvial gravel or sand, its fauna is marine (though mostly reworked) and the seismic does not show the presence of deltaic foresets.

5.1. Triggering the Iváň Canyon formation

Submarine canyons are typical physiogeographic features on many continental margins worldwide (Canals et al., 2004) and are important conduits for sediment transport into the deep oceanic basins. Especially, the shelf-indenting canyons are often closely related to a fluvial system (Liu and Lin, 2004). Based on the palaeontological data, the investigation area in the Alpine-Carpathian Foredeep represented a shallow shelf setting. The shelf-indenting submarine canyon can be mapped over a length of 25 km and width of over 5 km and deepens gradually towards the northeast to over 600 m. This deepening is also indicated by the isopach maps of Šikula and Nehyba (2004). This structure is the largest and deepest Neogene canyon that has been detected in the Alpine-Carpathian Foredeep. The canyon fill is sandwiched between the Lower Miocene deposits of the Laa Fm., with an approximate youngest age of 16.5 Ma, and Middle Miocene Badenian clays, with an age of about 15.1 Ma, based on the occurrence of the marker species *Praeorbulina circularis* (Ćorić et al., 2004). This creates a time window of 1.4 m.y. available for canyon incision and burial. The initial formation of the canyon coincides with the terminal phase of thrusting of the Waschberg-Ždánice Unit along the Pouzdřany thrust (Zámolyi et al., 2008, 2009). The influence of the WZU on the course of the canyon is obvious as the upslope part of the canyon follows the Pouzdřany thrust over a distance of 7 km before the canyon turns to northerly direction following the axes of the Carpathian foredeep towards the NE (Fig. 1). No deformation of the canyon wall or the canyon fill sediments is observable. Only in the southeastern part of the canyon, immediately to the south of the well WDK4, the Pouzdřany thrust partly overrides the eastern canyon wall, pushing down the channel and generating the local low about 5 km SW of WDK4 (Fig. 3).

This coincidence points to a forced redirection of the paleodrainage systems. For the first time, the Waschberg-Ždánice Unit formed a topographic barrier, which disconnected the Alpine-Carpathian Foredeep from the early Vienna Basin. The drainage systems, entering the foredeep from the Alps and the Bohemian Massif, were deflected in NE direction, resulting in sediment transport into the Carpathian Foredeep. In addition, the isostatic rebound of the foreland, during and after the late stage of thrusting,

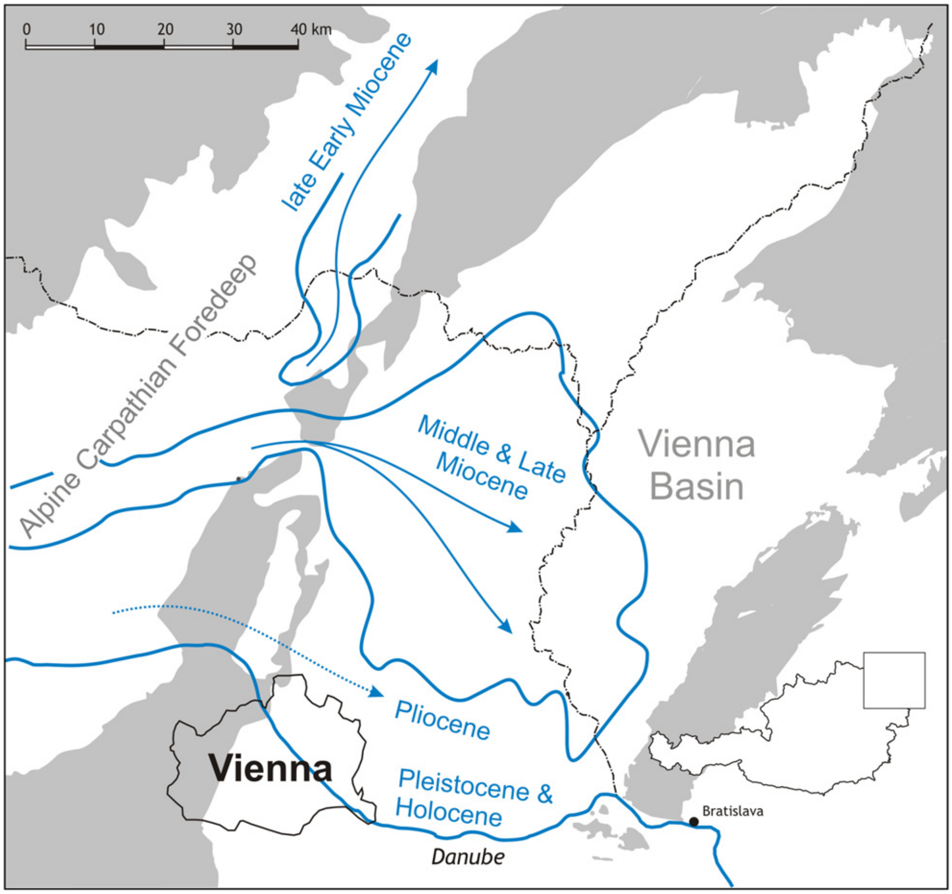

Figure 8. Sketch map showing the modern Alpine-Carpathian Foredeep and the Vienna Basin and the switch of the predominant Neogene drainage system of the area. The late Early Miocene drainage is reflected in the deep incision of the Iváň Canyon. Starting with the early Middle Miocene, first delta lobes develop along the western margin of the Vienna Basin (the outline represents the maximum extension of the Late Miocene paleo-Danube delta modified from Harzhauser et al., 2004). The modern Danube drainage course established during the Pleistocene (Wessely, 2006).

caused uplift, supporting the incision of the canyon. Later, this mechanism resulted also in erosion and therefore, the southernmost termination of the seismically identifiable canyon, is an erosional relict. It remains unclear how far the canyon had originally extended towards the WSW and where the transition into the fluvial system charging the canyon was located. Finally, the global 3rd order sea-level drop at the Burdigalian-Langhian boundary (Bur-5/Lan-1 sensu Hardenbol et al., 1998) coincides in the Paratethyan basins with a major unconformity and erosion (Rögl et al., 2002; Strauss et al., 2006; Kováč et al., 2007).

A problematic issue, is the timing of the re-filling of the canyon. Well data clearly document a Karpatian age of the reworked, littoral deposits. Thus, they have been deposited already during the latest Karpatian, being roughly synsedimentarily deposited immediately after the canyon formation. This interpretation would explain the well preserved topography of the canyon and the rare occurrence of canyon-wall collapse structures. Above an erosional unconformity, the canyon fill is draped by marine sediments of the Badenian (Langhian). These lower Badenian clays were formed during the transgression, which is related to the global 3rd order sea-level cycle T.B.2.3 of Haq et al. (1988) (Rögl, 1998; Kováč et al., 2007; Piller et al., 2007). Therefore, the canyon fill could also represent low-stand deposits of the LST of that cycle. Tentatively, we prefer the first interpretation (Upper Karpatian age) as the Laa Channel might serve as coeval analogue. According to this interpretation, the infill of the channel represents synsedimentary reworking of littoral deposits during the latest Karpatian.

Our model, which requires a combination of tectonics with a change of the relative sea level, can be compared with several Pleistocene–Holocene submarine canyons as well as with the assumed genesis of the Paleogene canyons in South Moravia (Pícha et al., 2006). Ridente et al. (2007) describe a combination of regional uplift and shelf progradation as initial trigger for the formation of the Pleistocene–Holocene Bari Canyon in the Adriatic Sea. The same combination caused the formation of the Dohrn Canyon in the Tyrrhenian Sea (Milia, 2000). A comparable process is also discussed by Popescu et al. (2004) for the development of the Danube Canyon in the modern Black Sea. The Danube Canyon developed due to down cutting and headward erosion by hyperpycnal currents, initiated by the Pleistocene sea level low.

5.2. The deep-sea fans and the hypothetical limits of the Iváň Canyon system

The limited seismic data exclude mapping the course of the canyon further into the Carpathian Foredeep. Isopach maps of Šikula and Nehyba (2004) and Jiříček (1995) suggest a potential continuation of another 20 km into north and north-eastern direction. The canyon-associated deep-sea fans and/or channel–levee complexes, however, are completely unknown. Observations of frequent alternations of sandy intercalations in shales (Nehyba and Petrová, 2000) and the fluctuation of palaeoecological conditions from dysoxic to oxic in these deposits (Petrová, 2004) might be hints to unrecognised distal parts of the canyon or its fan deposits. Unfortunately, these studies were based largely on well-data and very little 2-D seismic data from the area have been published. Therefore, the 3-D geometry of the distal part of the Iváň Canyon remains largely unknown to the authors. An even more northward continuation of the Iváň Canyon into the Polish part of the Carpathian Foredeep can be excluded. Already in the area of Brno in the Czech Republic the foredeep was strongly narrowed by the Vyškov Gate (Dvořák, 1994), which resulted in a distinctly different lithostratigraphic development north of that gate (Adámek et al., 2003). This would limit the hypothetic length of the canyon system to c. 60 km, which is very close to the calculated entire length of the well documented and in size comparable Paleogene canyon/fan system of South Moravia, traced in a NW–SE orientation so far of over 40 km length (Pícha et al., 2006).

Due to the tectonic setting of the Iváň Canyon even the distal parts of the canyon system might be preserved, given that required seismic data are available over that area. While the more distal parts of channel/fan systems are often structurally incorporated and thus deformed or even totally cannibalized in front of tectonically active shelf/slope areas (e.g. the distal parts of the Paleogene Moravian canyons, Pícha, 1974), the Iváň Canyon was oriented parallel to the active frontal thrust of the foldbelt and has been therefore structurally almost entirely unaffected. This does very likely apply also to the yet un-described and unidentified distal parts of the Iváň Canyon.

5.3. Iváň Canyon abandonment and switching drainage systems

The thickness of the overlying Badenian sediments in the area is very restricted, with a maximum thickness of 49 m documented in well WDK2, comprising only Lower Badenian clays. The sedimentology and microfossils of these clays suggest open marine conditions and shelf settings (Petrová, 2004). The Iváň Canyon was already completely sealed and abandoned at the time of the deposition of the Lower Badenian sediments. Obviously, the drainage pattern has changed drastically. This was initiated by the formation of the rapidly deepening and widening Vienna Basin some 20 km to the southeast of the canyon area. There, a new depocenter was created, catching the sediments previously transported through the canyon towards the northeast into the Carpathian Foredeep (Fig. 8). Now, tectonic breaching along a sinistral fault system in the central part of the Waschberg-Ždánice Unit allowed the drainage system to switch from its northeast bound direction towards the east and to enter via the uplifted foldbelt into the subsiding Vienna Basin. This caused an immediate abandonment of the Iváň Canyon and a southward migration of the major drainage system (Paleo-Danube) originating from the North Alpine Foreland Basin (NAFB). The same gate allowed timely very limited marine ingressions into the NAFB during phases of high sea level (Grill, 1953; Mandic et al., 2002).

Consequently, large deltaic complexes developed during Middle to Late Miocene times along the north-western margin of the Vienna Basin (Strauss et al., 2006; Kováč et al., 2003, 2004, Fig. 8). These deltaic complexes represent a rich reservoir for many oil and gas discoveries (Wessely and Liebl, 1996; Hamilton et al., 2000). The Vienna Basin remained the depocenter for this drainage system until it moved further eastwards to the next depocenter (Pannonian Basin) during the Late Miocene. From the Badenian onwards the drainage system moved in steps further southward, breaking its new way through the foldbelt north of the city of Korneuburg (Grill, 1953) before it finally reached its most recent pathway through the Pleistocene breakthrough ("Wiener Pforte") in the south of the Bisamberg (Grill, 1953; Wessely, 2006).

6. Conclusions

In this paper the largest submarine Neogene canyon that is known so far from the Alpine-Carpathian Foredeep has been described. The structure of the canyon could be mapped over a distance of c. 25 km and attains a depth of c. 600 m. The canyon formation started within the latest Early Miocene coinciding with the terminal phase of the thrusting of the neighbouring Waschberg-Ždánice Unit (WZU). Morphologically, the canyon suggests a development in three phases, expressed by a cascade-like canyon floor topography and a switch in direction. The trigger for the development might have been a coincidence of at least three factors. The main cause seems to be the tectonic setting at the margin of a thrust belt and the initial isostatic rebound of the foreland which initiated canyon incision. The same mechanism caused the emergence of parts of the WZU, which then blocked the drainage into eastern direction. The onset of a sea-level drop at the Early/Middle Miocene boundary might have additionally accelerated the canyon formation. Around this boundary, tectonic breaching in the WZU re-established a connection between the Alpine Foredeep and the subsiding Vienna Basin, where new accommodation space was generated during the early Middle Miocene. Consequently, the canyon was abandoned and sediments redirected into the opening Vienna Basin where huge deltaic bodies started to form along the north-western margin of the Vienna Basin. The sealing of the canyon happened quite rapidly by deposition of eroded and reworked sediments from Karpatian mudflats. The exact timing of this refilling remains unclear and might have occurred also during the Badenian as lowstand deposit of the 3rd order cycle TB2.3.

The restricted seismic data do not allow to identify the bathyal fan deposits related to the canyon incision. These deposits, however, are expected to be potential hydrocarbon plays in the Czech part of the Carpathian Foredeep.

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