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Late miocene evolution of the Paleo-Danube Delta (Vienna Basin, Austria)

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ABSTRACT

The first deltas of the Paleo-Danube formed around 11.5 Ma ago along the northwestern margin of the Vienna Basin, during a lowstand of Lake Pannon. We present a detailed description of the depositional architecture of five individual lobes of these deltas in the Austrian part of the central Vienna Basin based on the integration of 3D seismic surveys and well-log data, covering an area of about 600 km^2. Based on geometry, steep clinoforms and the development of beach ridges, the delta is classified as mostly river-dominated with significant influence of wave-reworking processes. The development and shifts of individual lobes suggest a stepwise northward movement of the delta system, which is discussed in relation to a stepwise activity of regional fault systems. True vertical depth measurements between topset and bottomset deposits document a decrease of lake water depth from about 180 m during the early phase of delta formation at 11.5 Ma down to about 100 m during its mature phase. A major lake level rise of Lake Pannon around 11.3 Ma caused the flooding of the margins of the Vienna Basin, resulting in back stepping of fluvial deposits into the North Alpine Foreland Basin, which led to the termination of delta deposition in the study area. The Paleo-Danube delta of the Vienna Basin is comparable in many ways to the Holocene to modern Danube delta, located in the Black Sea. Size, sediment volume and speed of progradation of the lobes, however, indicate, that this primeval delta was distinctly smaller than its modern successor and had a much smaller sediment load.

1. Introduction

The Danube is the second largest river of Europe, flowing 2850 km from Germany through central and southeastern Europe before draining into the Black Sea. Like most of the modern deltas, the current Danube delta formed during the Holocene sea-level rise decrease and highstand phase. The chronology of the step-wise development of the three main lobes of the Chilia, Sulina and Sfântu Gheorghe branches have been depicted in detail by Panin et al. (2004, 2016), Giosan et al. (2005), Panin and Overmars (2012), Vespremeanu-Stroe et al. (2017) and Ţuţuianu (2021). The late Miocene and Pliocene development of the shelf margin of the Paleo-Danube delta is also well resolved. Based on core material, well-logs and seismic data, Magyar et al. (2012) and Sztanó et al. (2013) documented a progradation of the Paleo-Danube across the Pannonian Basin complex with about 67 km/Ma over the past 10 Ma, reflected by prograding shelf-margin clinoforms of up to 600 m height. Before the Paleo-Danube entered the western part of the Pannonian Basin complex, it drained into the Vienna Basin, which at that time was covered by Lake Pannon (Fig. 1). This lake had formed after a glacio-eustatic sea-level drop at 11.6 Ma, causing the final disintegration of the central and south–eastern European Paratethys Sea (Kováč et al., 1998, 2017; Magyar et al., 1999; Harzhauser et al., 2004; Piller et al., 2007; Harzhauser and Mandic, 2008). During the early phase of its formation, the delta of the Paleo-Danube started shedding its sediments into the central Vienna Basin, where the deposits are now deeply buried and only accessible by wells and seismic surveys (Wessely, 2006). The subsurface deltaic deposits can be linked to the Hollabrunn-Mistelbach Formation, which represents the coeval fluvial deposits of the Paleo-Danube in the eastern fluvial plains of the North Alpine Foreland Basin (Nehyba and Roetzel, 2004). Therefore, the late Miocene Paleo-Danube represents an extraordinary case in which coeval fluvial and deltaic deposits of a Miocene river are continuously preserved. The

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aim of the study is to investigate and map these upper Miocene subsurface deltaic sedimentary record using high resolution modern 3D seismic data and to trace their evolution through time.

2. Geographic and geological setting

The about 200 km long and 60 km wide Vienna Basin is a rhombohedral SSW-NNE oriented Neogene extensional basin that formed along sinistral fault systems during Miocene lateral extrusion of the Eastern Alps (Ratschbacher et al., 1991; Hinsch et al., 2005; Beidinger and Decker, 2016). Since the 1930s, the Vienna Basin, a highly prolific oil province in Central Europe, was systematically drilled and continuously explored for over 60 years, leading to a comprehensive knowledge of basin geometry, facies and tectonic architecture (Brix and Schultz, 1993; Wessely, 1988, 1993, 2006; Decker et al., 2005; Strauss et al., 2006; Siedl et al., 2020). The basin fill consists of lower to upper Miocene shallow marine to continental sediments reaching a thickness of up to 5500 m in the central part of the basin (Wessely, 2006). These deposits capture the influence of global climate and regional tectonics on the depositional environments of the Vienna Basin (Siedl et al., 2020; Harzhauser et al., 2020; Kranner et al., 2021a, 2021b). During the late Miocene (Pannonian), extensional tectonics prevailed (Royden, 1985; Decker, 1996; Decker et al., 2005) and rapid subsidence allowed the accumulation of up to 1200 m of lacustrine deposits (Harzhauser et al., 2004).

The studied 3D seismic covers an area located in the central part of the Vienna Basin in Austria (Fig. 2). The surface coverage of the study area extends from the Vienna city limits in the south-west to the Zistersdorf-area in the north-east, and from Großengersdorf in the north-west to Zwerndorf in the south-east. This area amounts to approximately 1125 km^2 with a maximum depth of Pannonian sediments of 2500 m.

2.1. Stratigraphy and age model

The upper Miocene (Pannonian) strata of the study area are represented by the Bzenec Formation (Čtyroký, 2000; Harzhauser et al., 2004) (Fig. 3). Its basal part comprises about 200 m of marls and sand including a 50-m-thick marker unit of green-grey marly clay ("schiefrige Tonmergel") (Fig. 3). This unit shows a clear shale-line appearance in geophysical logs and is used herein as correlation horizon (mfs 1). This unit is correlated with the *Mytilopsis ornithopsis* Zone and corresponds to zones A and B of Papp (1951) (Harzhauser et al., 2004) (Fig. 3). The deposits represent prodelta and basinal facies of a brackish lake (Kováč et al., 1998; Harzhauser et al., 2004). Above this layer, follows the deltaic facies of the "großer unterpannoner Sand" (= big lower Pannonian Sand), which represents a sandy succession with scattered gravels of up to 200 m thickness. This unit is correlated with the *Mytilopsis hoernesi* Zone and with Zone C of Papp (1951) (Harzhauser et al., 2004) and corresponds to the herein studied deltaic deposits of the Paleo-Danube. Above the "big lower Pannonian sands" a characteristic but thin shale-line pattern reflects a strong transgressional phase within the *Mytilopsis hoernesi* zone, which pushed back the deltaic system, flooding the basin margins and terminating deltaic deposition in the early Pannonian (Harzhauser et al., 2003; Harzhauser, 2009). The maximum flooding surface following this transgression is used herein as second marker horizon for correlation (mfs 2). Above these deposits follow lacustrine clay, silt, and sand of Lake Pannon, correlated with the *Lymnocardium conjungens* Zone and with Zones C and D (Papp, 1951; (Harzhauser et al., 2004), which are not discussed in this paper.

Three age models describe the duration of the delta formation based on well Eichhorn 1 (Harzhauser et al., 2004; Lirer et al., 2009; Paulissen et al., 2011). Harzhauser et al. (2004) placed the beginning of the delta formation at 11.3 Ma and its termination at 11.1 Ma, applying an integrated stratigraphy of the Pannonian basin fill of the Vienna Basin. Lirer et al. (2009) placed both horizons at 11.2 and 11.0 Ma based on

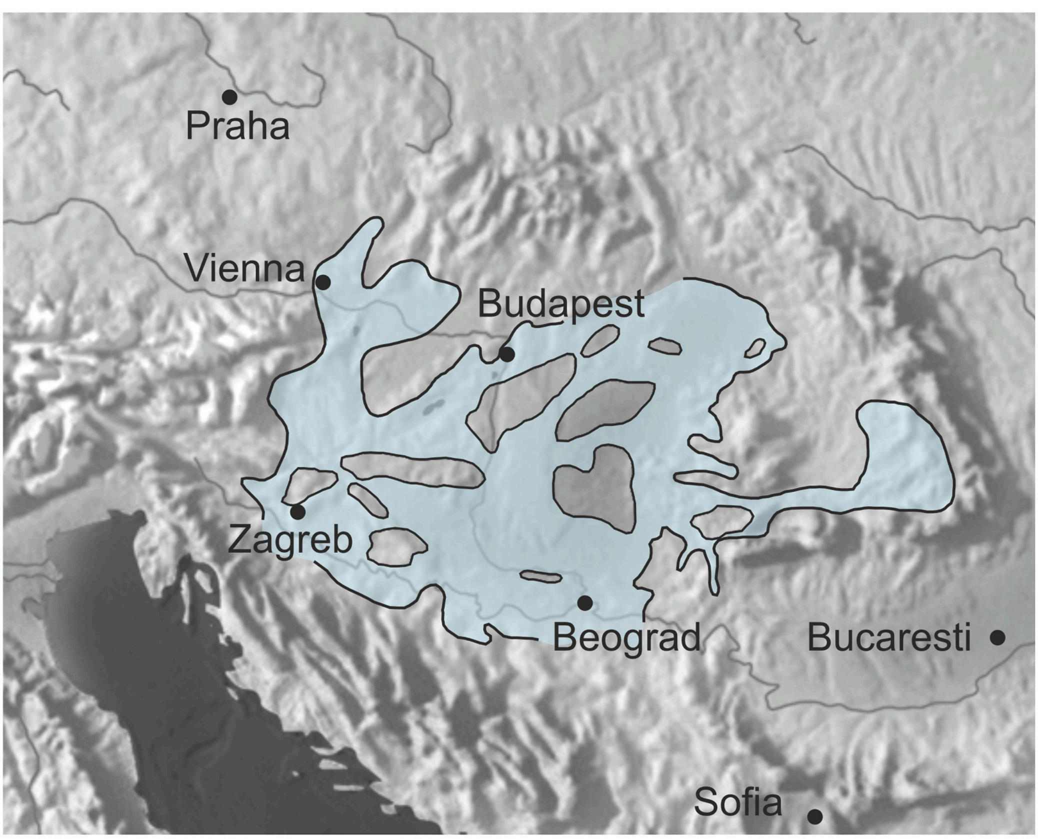

Fig. 1. Extent of Lake Pannon during the early Pannonian lowstand. The Paleo-Danube delta was established north of Vienna (modified after Magyar et al., 1999).

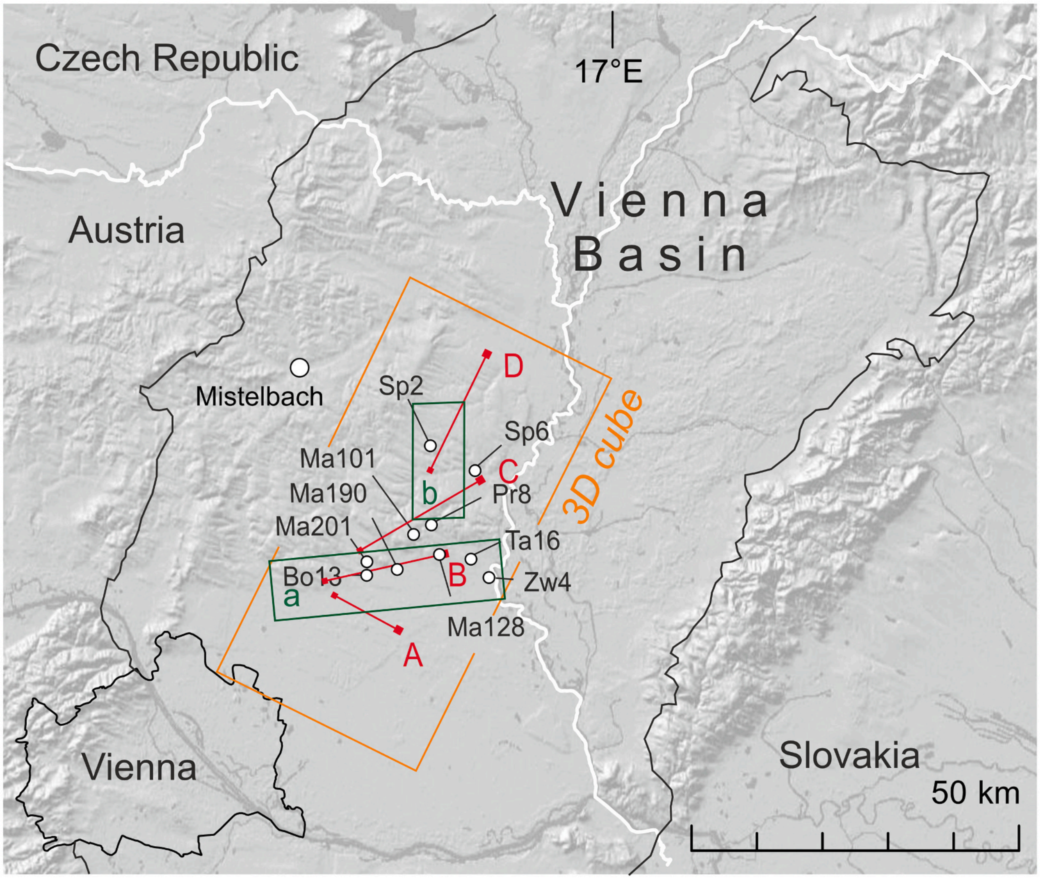

Fig. 2. Coverage of the seismic survey in the central part of the Vienna Basin (orange) and position of the investigated wells (white circles). Red lines correspond to seismic surveys in Figure 5. Green boxes correspond to the maps in Figure 7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

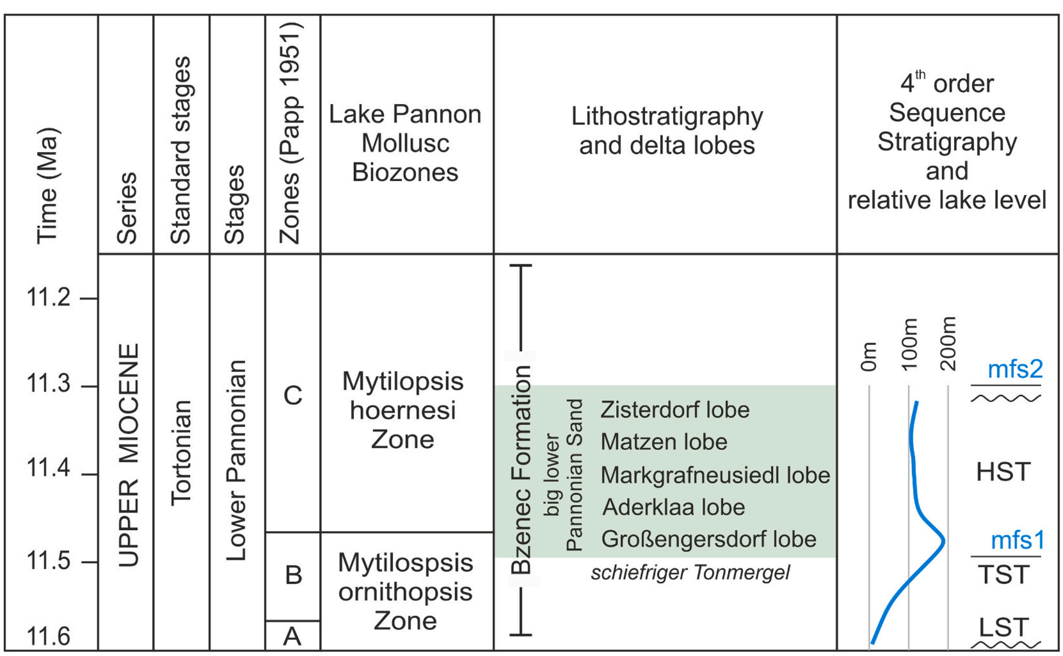

Fig. 3. Chronstratigraphy, biostratigraphy and lithostratigraphy of the lower Pannonian in the Vienna Basin (modified from Harzhauser et al., 2004). 4th order sequence stratigraphy modified after Kosi et al. (2003) and Harzhauser et al. (2004); terminology following Catuneanu (2017). Estimates of relative lake level are based on in-seismic true depth measurements. Green interval marks the duration of delta formation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

astronomical tuning of the Eichhorn-1-record. Paulissen et al. (2011) correlated the Eichhorn-1-record with the magnetostratigraphically dated well Spannberg 21. These authors placed the onset of delta formation at 11.5 Ma and its termination at 11.3 Ma. Thus, despite diverging interpretations of the absolute time frame, all three age models agree on the time interval (200 kyr) covered by the deltaic sedimentary record. Herein, we follow the age model of Paulissen et al. (2011).

3. Methods

All processed digital data were provided by OMV Exploration and Production GmbH and handled according to their data confidentiality policy. In total, one seismic volume, ten wells and an already mapped horizon were used in the seismic interpretation with the software Petrel. The investigated area is bound by a 3D seismic volume (Cropped_3D_VBSM_PSDM_Pannon) provided by OMV (Fig 2), depicting the Neogene basin fill in the central Vienna Basin. The outline of this seismic cube is 45 km long and 25 km wide, amounts to an area of 1125 km^2 and represents a part of the Vienna Basin Supermerge (VBSM), where seismic data of several seismic vintages (1994–2013) were merged to an approximately 1800 km^2 seismic survey (Siedl et al., 2020). *Z*-coordinates are expressed in TVD (true vertical depth) and show approximate true values, allowing seismic data derived quantitative measurements. Crosslines represent SW–NE oriented sections and inlines are oriented in NW–SE direction. OMV provided the surface grid "5UP_IG", which defines a stratigraphic horizon interpreted as the Sarmatian/Pannonian boundary and marks the lowermost part of the investigated sequence (red line in Fig. 4). Two time slices were created to flatten the seismic data, demonstrate the evolution of the deltaic bodies and to trace location, size, and depositional direction of delta lobes within the study area. The lower time slice corresponds to the flooding surface 1 (mfs 1 in Fig. 4), representing a first distinct flooding of the area. The onset of the evolution of the Paleo-Danube delta commences above that horizon. The second time slice corresponds to the flooding surface 2 (mfs 2 in Fig. 4) and marks the termination of the deltaic evolution. To depict the deltaic bodies as well as features, such as beach ridges and channels, amplitude extraction was used, where blue colors mark negative amplitudes and red colors positive amplitudes, respectively (Fig. 7). Stratal termination patterns were used to understand the relation between the distinct deltaic deposits and to delineate their spatial development over time.

General characteristic architectural and geometric features such as topset and foreset accommodations, clinoforms and stratal patterns were investigated to prove that the investigated sedimentary bodies are of deltaic nature. In-seismic measurements were carried out using true vertical-depth seismic data. These values have not been corrected for compaction, because no porosity data are available, which were used by Balázs et al. (2018) for backstripping of Lake Pannon deposits. Thus, the calculated vertical thickness is based on the in situ (gravitational compacted) thickness and do not represent the paleo-thickness. Cross-sections were not flattened to allow a visualization of the deposits without

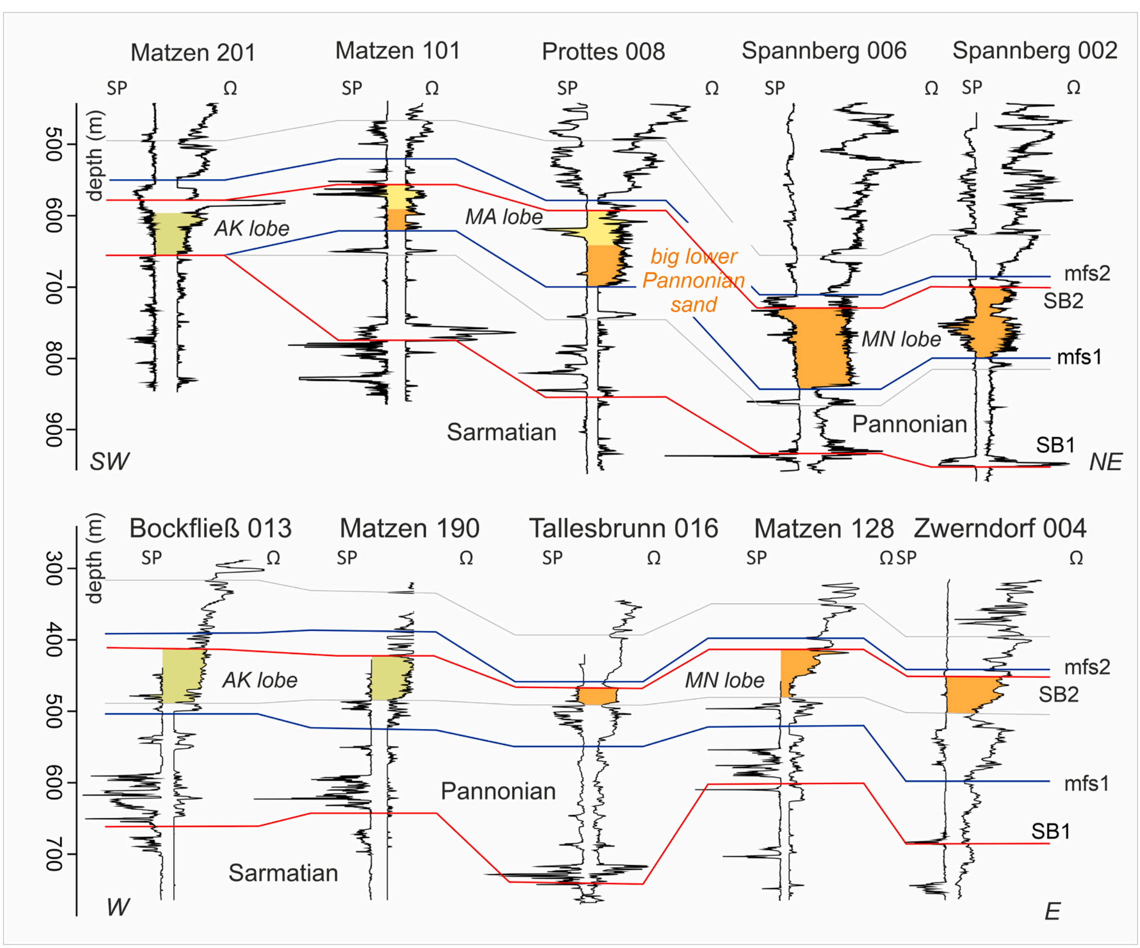

Fig. 4. Selected well-logs drilling the delta deposits of the Paleo-Danube (spontaneous potential [SP]. resistivity [Ω]). Red line marks unconformity between Sarmatian and Pannonian strata; grey lines represent correlative horizons (based on strong, continuous reflectors), blue lines correspond to flooding surfaces, which were used to correlate and flatten the seismic data; see Figure 2 for geographic position of wells (AK lobe: Aderklaa lobe, MA lobe: Matzen lobe, MN: Markgrafneusiedl lobe). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

any distortions, however, water depth and slope angles were calculated on flattened seismic horizons.

Ten boreholes and their well-log shapes (Spontaneous Potential [SP], deep resistivity [Ω]) of the central Vienna Basin were investigated: Matzen 201, Matzen 101, Prottes 008, Spannberg 002, Spannberg 006, Zwerndorf 004, Matzen 128, Tallesbrunn 016, Matzen 190 and Bockfließ 013 (Fig. 4). Well-logs were chosen to follow a SW–NE and a W–E profile, following a proximal-distal trend. Well-log data were correlated to the existing age model of Harzhauser et al. (2004).

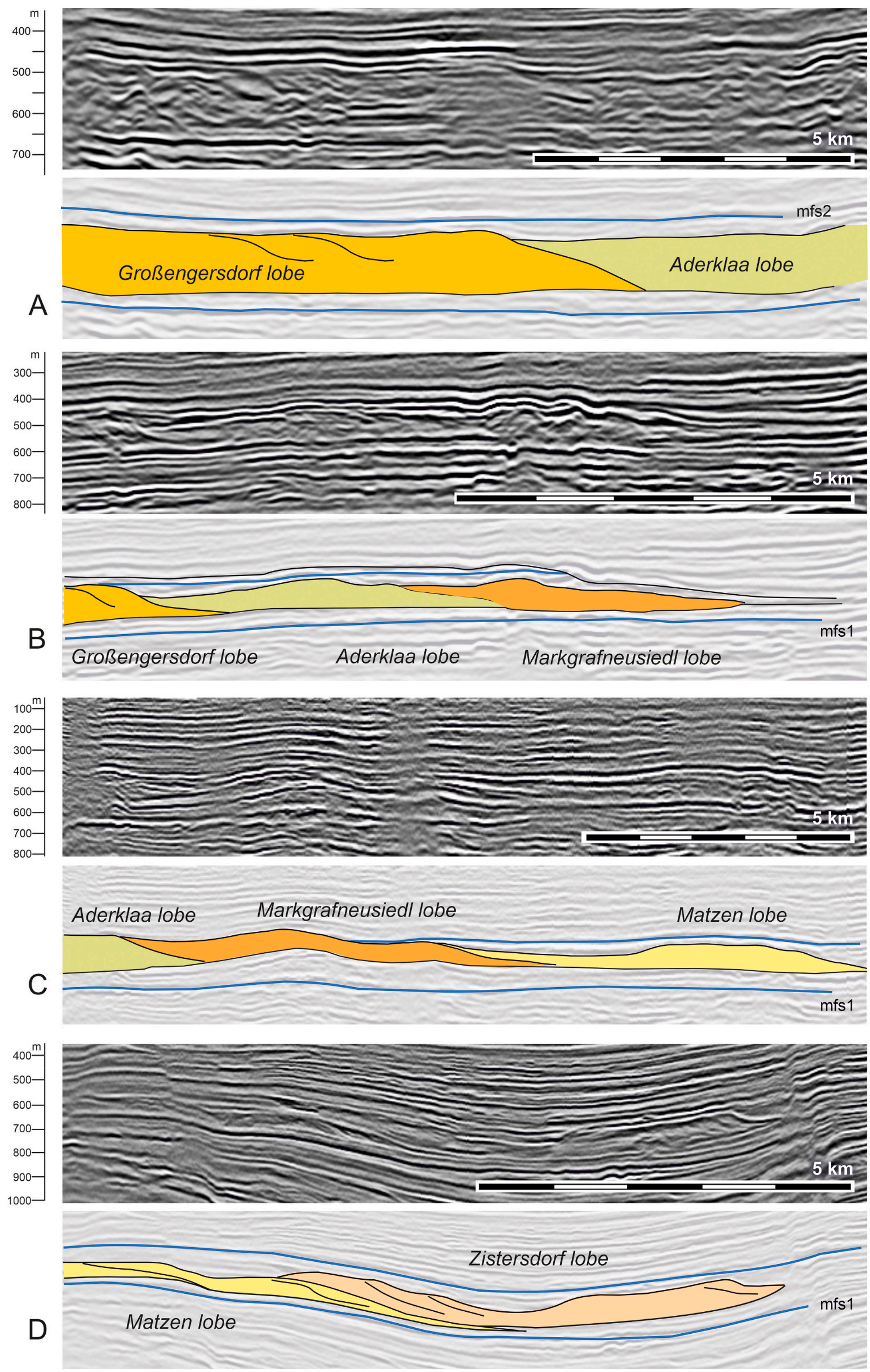

Fig. 5. Seismic panels illustrating the 2D architecture of individual delta lobes (raw data and interpretation). Blue lines represent flooding surfaces, bracketing the deltaic deposits; see Figure 2 for geographic position of seismic lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Results

Ten wells have been chosen, which are roughly arranged in SW–NE and E–W direction (Fig. 4) to illustrate correlative horizons. A distinct erosive discordance marks the Sarmatian/Pannonian boundary (red line). The basal Pannonian deposition is reflected by strongly serrated, high amplitude well log patterns. This unit is missing on topographic highs (Matzen 201); it ranges around few tens of meters thickness in distal wells (e.g., Zwerndorf 004, Spannberg, 002) and is most prominent in the Bockfließ and Matzen areas. This interval is followed by a low-amplitude to shale-line interval (Matzen 101, Tallesbrunn 016, Zwerndorf 004) with scattered high amplitude SP peaks (Prottes 008). The top of this interval is characterized by a short, strongly serrated, high amplitude intercalation (grey line in Fig. 4) slightly before the maximum flooding surface 1 (mfs1) is developed. This interval is followed by moderately serrated well log patterns and blocky, boxcar (Spannberg 006) or funnel shaped well logs (Matzen 201). Strongly serrated, irregular patterns, such as seen in Matzen 101 are rare. This unit corresponds to the "big Pannonian sand" and the delta lobes discussed in this paper. This development was terminated by a short bow trend, which is recognizable throughout all recorded wells, marked by a low amplitude interval, marking maximum flooding surface 2 (mfs2). Above follow distinctly funnel shapes successions, which are not part of the present study.

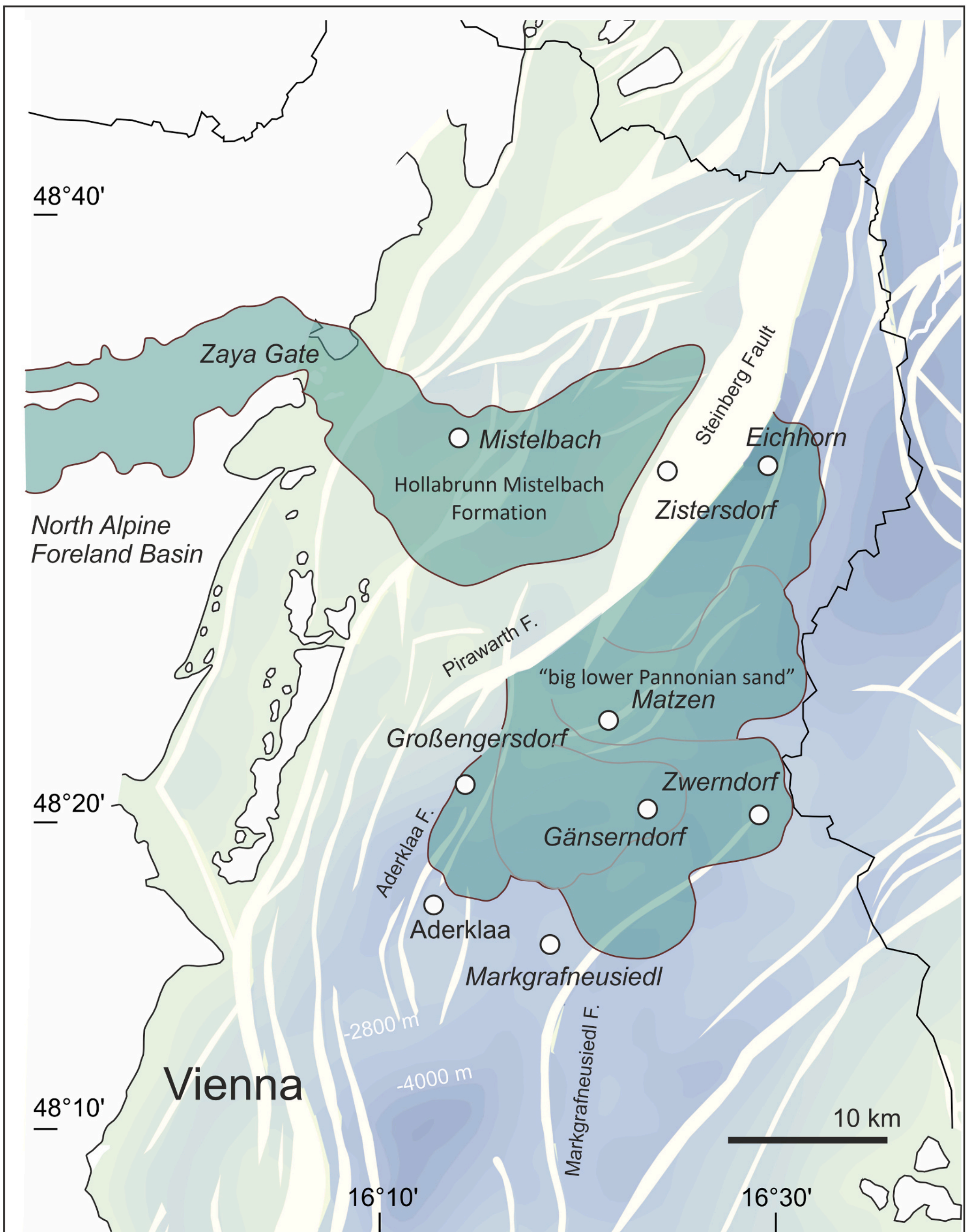

Fig. 6. Tectonic setting of the central Vienna Basin modified from Kröll and Wessely (1993) and Harzhauser et al. (2020) with distribution of the herein mapped delta lobes. The course of the Paleo-Danube in the North Alpine Foreland Basin and its fluvial plain in the Mistelbach area are reflected by the surface distribution of the Hollabrunn-Mistelbach Formation (Nehyba and Roetzel, 2004).

4.1. Delta lobes and clinoforms

The southernmost deposits of the delta complex are found in the Großengersdorf area (Figs 5a, 6) where a seismically wedge-shaped body of around 35 km^2 and a thickness of approximately 230 m is located (Großengersdorf lobe), representing the stratigraphically oldest Pannonian delta lobe in the study area. The base-reflector of this structure is situated at around 1000 m depth. The northwestern part of the structure is situated on the downthrown block of the Aderklaa fault, cutting through the seismic body with a vertical offset of around 400 m. Characteristic foreset deposits are easily recognizable (Fig. 5a) and mostly dip into southern direction. The next distinct sedimentary structures are mapped south-east of the Großengersdorf lobe close to Aderklaa (Figs 5a, 5b, 6). This structure can be subdivided into two distinct bodies, which are named herein Aderklaa lobe for the north-western part and Markgrafneusiedl lobe for the south-eastern part of the body (Figs 5b, 5c). The Markgrafneusiedl lobe is to a large extent stratigraphically overlapping the Aderklaa lobe, representing a thick amalgamated delta lobe with the latter. This lobe crosses the Markgrafneusiedl fault in the SE (Fig. 6). The Aderklaa lobe is found at a depth of around 600 m, has a size of roughly 35 km^2 and a thickness of 140 m. This structure is oriented towards a southeastern direction as indicated by the foreset. The Aderklaa lobe continues into southeastern direction into the Markgrafneusiedl lobe, which has a size of about 75 km^2, attains a thickness of 140 m and is also situated at a depth of c. 600 m. The Markgrafneusiedl lobe pinches out in southeastern direction. The largest sedimentary body was mapped in the Matzen area (Figs 5c, 5d, 6) with a size of around 170 km^2 and a thickness of 120 m. The base of this body is situated at around 750 m. The northernmost and stratigraphically youngest seismic body was mapped in the Zistersdorf area (Figs 5d, 6) and is named Zistersdorf lobe. This lobe covers an area of roughly 70 km^2, has a thickness of around 115 m and the base of this seismic body is situated at 730 m depth. Only a narrow overlap occurs between the Matzen and Zistersdorf lobes.

Stratal terminations show that deltaic evolution commenced with the Großengersdorf and Aderklaa lobes. The Aderklaa lobe terminated before the Matzen lobe was deposited (Fig. 5), which onlaps on the Aderklaa lobe. The Zistersdorf lobe onlaps onto the Matzen lobe, documenting it as the last deltaic body recognizable in the seismic survey.

The clinoforms are steeply inclined and represent typical delta-scale clinoforms as defined by Patruno and Helland-Hansen (2018). The Großengersdorf and Aderklaa lobes display inclinations of the clinoforms of up to 16–17°, the Matzen lobe reaches 14° and the Zistersdorf lobe has an inclination of up to 25°. Measurements of the true vertical

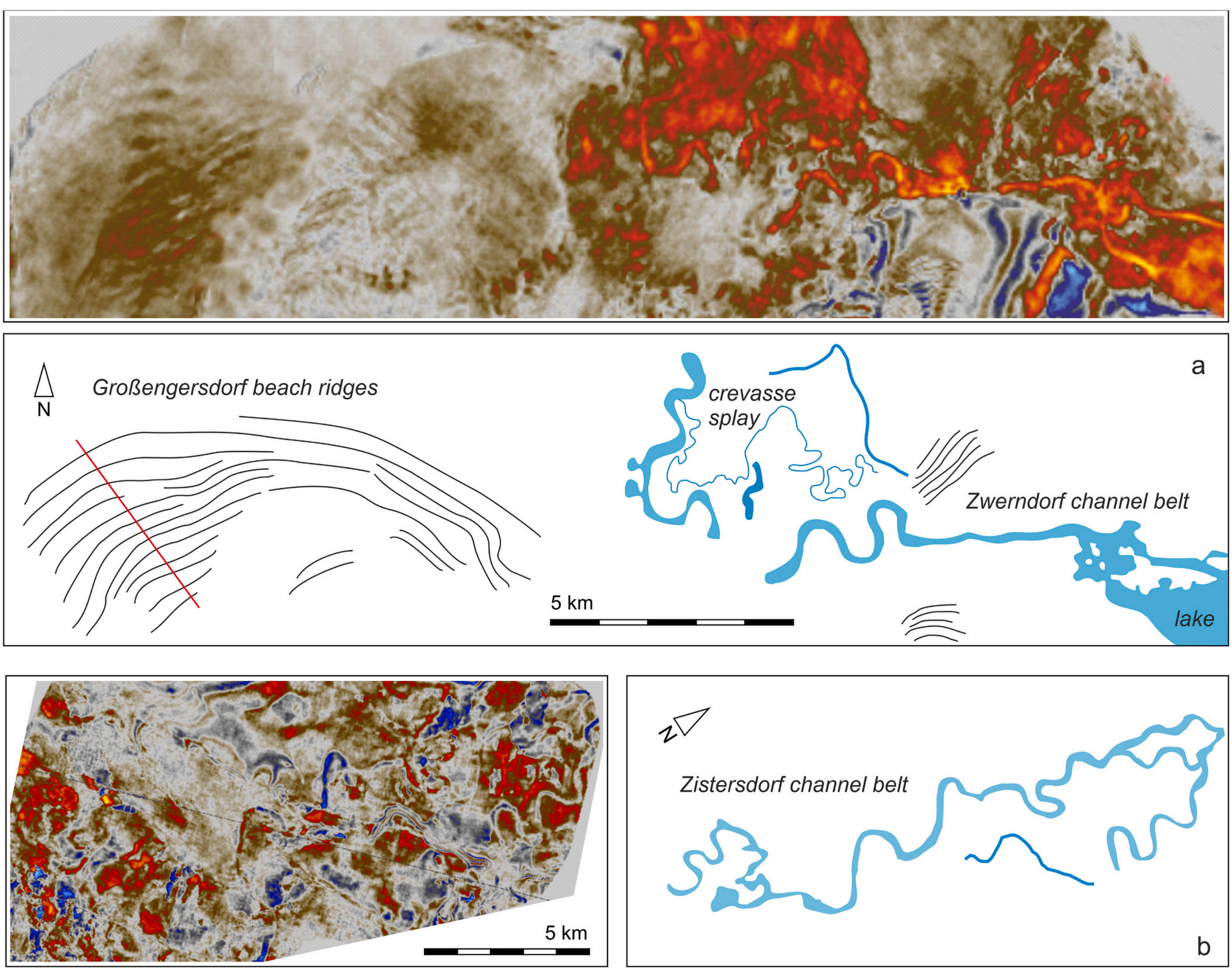

Fig. 7. Horizontal seismic panel depicting single time horizons. **a.** Beach ridges and the channels of the Zwerndorf channel dominate the area between Großengersdorf and Zwerndorf during the early stage of delta evolution. Red line indicates position where crest spaces were calculated. **b.** Floodplain during the late stage of delta evolution in the Zistersdorf area showing the meandering Zistersdorf channel; see Figure 2 for geographic position of maps. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

depth between the topset deposits of the delta and the base of the bottomset deposits reveal a difference of 180 m for the Großengersdorf lobe. 110 m for the Aderklaa lobe, 100 m for the Matzen lobe and 120 m for the Zistersdorf lobe.

4.2. Channels and beach ridges

Numerous channels were detected within the investigation area in various time slices. Of these, two larger channel belts can be mapped reliably along several kilometers and are described herein. The older channel belt is recorded in the southeastern part of the seismic survey and is termed herein Zwerndorf channel belt (Fig. 7a). The channel belt formed during the early stage of delta evolution above mfs 1. The observable part of the channel belt is strongly meandering over about 12 km and is about 200 m wide. The channel belt enters from the north, bends into eastern direction, and shows sinuosity with large crevasse splays in the westernmost part. Towards the east, the channel belt passes via a mostly straight course into a small delta-plain lake in the easternmost part. This channel has a sinuosity index of 1.73, which classifies it as meandering river.

The second channel belt was mapped between Matzen and Zistersdorf (Fig. 7b) and is termed herein Zistersdorf channel belt. It is situated below mfs 2 and developed on the delta plain during a late stage of delta evolution. The measurable part of the channel is 22 km long (as straight line), about 240 m wide and can be subdivided into three segments. The northernmost part comprises a multiple channel system. The middle segment shows a clear meandering pattern, and the southernmost part represents a highly sinuous meandering part, that splits into two branches of which the eastern branch might represent a crevasse splay. This channel has a sinuosity index of 1.70, which classifies it as meandering river as well. Morphologically both channels are highly reminiscent of the meandering course of the Sfântu Gheorghe branch of the modern Danube, although the Miocene pendants are clearly smaller (Fig. 8). Like for the Sfântu Gheorghe branch, local subsidence might have fostered the development of meanders on the delta plain of the Paleo-Danube (Giosan et al., 2005).

Throughout the seismic survey, large scale longitudinal to crest shaped structures of up to 11 km length and more than 20 m height are recorded. The reflectors are interpreted as successions of prograding beach ridges. This seismic feature is best preserved in the southwestern part of the survey in the Großengersdorf area (Fig. 7a) where we have analyzed the crest spacings for 12 individual ridges (red line in Fig. 7). The mean crest spacing is 280 m (min. = 220 m, max. = 410 m, $\sigma = 53$ m).

Thus, these beach ridges are comparable in size, density and shape to the Holocene beach ridges in the Danube delta, as described by Giosan et al. (2005) and Vespremeanu-Stroe et al. (2016, 2017) (Fig. 8).

5. Discussion

The subsurface deltaic deposits of the 3D-cube can be linked to the surface sands and gravels of the Hollabrunn-Mistelbach Formation in the North-Alpine Foreland Basin (NAFB) as mapped by Nehyba and Roetzel (2004) (Fig. 6). This formation can be followed along 85 km from Krems in the west to the Mistelbach region in the east and represents fluvial deposits of the Paleo-Danube. A broad spectrum of architectural elements has been recognized by Nehyba and Roetzel (2004) within this formation, comprising gravel-bed river deposits, gravelly channel fills, sandy channel fills and various overbank deposits. The Paleo-Danube was a braided river with vertical and lateral transitions into a gravelly wandering river (Nehyba and Roetzel, 2004). Two major paleotopographic players influenced the prevailing fluvial regime of the Paleo-Danube. The first was the Zaya Gate (Fig. 6), through which the gravel-bed river entered the Mistelbach Basin and developed into a braid-delta system. The second element are the Steinberg and Pirawarth faults, active at the time of deposition, which separated the uplifted

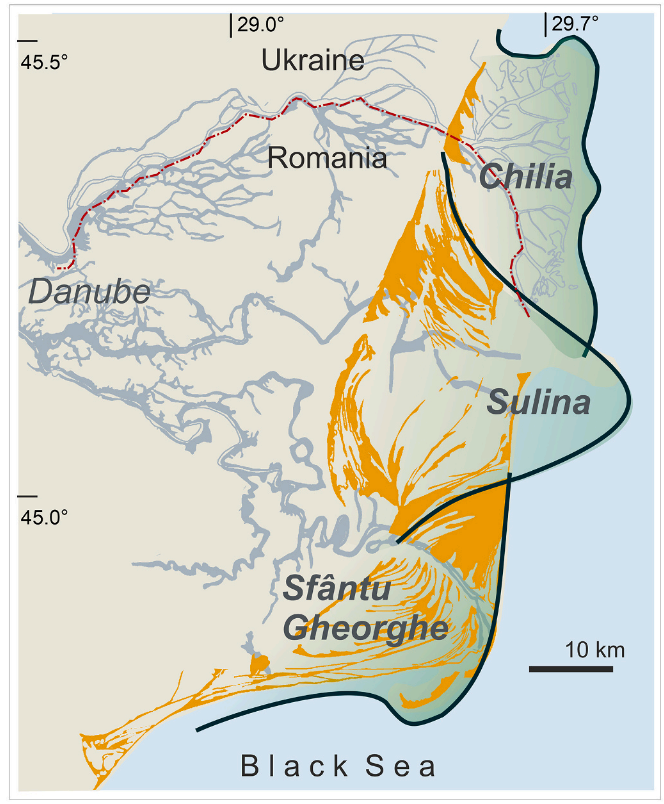

Fig. 8. Channels and channel levees of the modern Danube delta (grey), Holocene beach ridges and dune fields (yellow) and the three modern lobes of the Danube delta after Giosan et al. (2005) and Vespremeanu-Stroe et al. (2017). Note the similarity between the modern Sfântu Gheorghe branch and the Miocene Zwerndorf channel (Fig. 7a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

block of the Mistelbach Basin from the deeper parts of the Vienna Basin (Harzhauser et al., 2019). Today, the Steinberg fault marks the boundary between the surface outcrops of the Hollabrunn-Mistelbach Fm. from the subsurface equivalents of the Bzenec Fm. The western part of the delta, preserved in surface outcrops of the Mistelbach Basin, covers about 250 km^2, whereas the eastern, subsurface part, extends over 600 km^2.

5.1. Delta type

Deltas comprise the subaerial delta plain, dominated by river processes, the delta front, representing the area of interaction between river and basinal processes, and the prodelta, which marks the most sea/lakeward section of a delta and receives fluvial sediment. In seismic stratigraphy, these environments are represented by the topset, foreset and bottomset strata of a delta (Bhattacharya, 2006). Many different approaches have been proposed in the literature to classify alluvial deltas (Coleman and Wright, 1975; Galloway, 1975; Ethridge and Wescott, 1984; Orton, 1988; Nemec, 1990; Postma, 1990). The most common classification, which is applied herein, is the classification after Galloway (1975), which describes deltas as either fluvial, wave, or tide dominated endmembers with a wide range of mixed type varieties. These endmembers produce typical sedimentological patterns, which are recognizable also in seismic surveys in which resolution usually is rather low and only larger scale structures can be observed. Geometry and shape of the Paleo-Danube delta correspond to the geometry of a lobate, river dominated delta with influence of wave reworking processes (Galloway, 1975; Postma, 1990; Galloway and Hobday, 1996;

Bhattacharya and Giosan, 2003). The clinoforms of the Paleo-Danube delta in the Vienna Basin are distinctly steeper compared to the slightly younger clinoforms in the Pannonian Basin, which range around 5° (Magyar et al., 2012) and represent lacustrine equivalents of a marine continental slope. Steep inclination angles, in contrast, are typical for strongly river-dominated settings (Postma, 1990) and the observed values in the Paleo-Danube delta agree with measurements from modern river-dominated deltas described by Adams et al. (2001). Overall, the elongate Großengersdorf lobe is closest to the river-dominated end-member of Galloway (1975), whereas the more lobate and expanding Aderklaa, Markgrafneusiedl, Matzen and Zistersdorf lobes indicate increasing wave influence. The onset of significant accretions of beach ridges after the deposition of the Großengersdorf lobe points also to an increased influence of wave reworking (Otvos, 2000; Mcmanus, 2002; Tamura, 2012; Vespremeanu-Stroe et al., 2016). Due to this predominantly lobate geometry with beach ridges, the upper Miocene delta is morphologically very close to that of the Holocene Danube delta, which is also a river dominated delta with wave reworking (Galloway, 1975; Postma, 1990).

5.2. Delta evolution

Our data allow for tracing the evolution of the complex of delta lobes of the Paleo-Danube in five steps. In terms of sequence stratigraphy, the lower Pannonian deposits are interpreted as lowstand systems tract of a 3rd order cycle (Kováč et al., 1998, 2004; Kosi et al., 2003; Harzhauser et al., 2004; Nehyba and Roetzel, 2004), whereas the lake level oscillations observed herein are expressions of a single 4th order cycle (Kosi et al., 2003; Harzhauser et al., 2004) (Fig. 3). The basal deposits, detected in the well logs as strongly serrated high amplitude patterns, represent lowstand wedge deposits (Harzhauser et al., 2004). The first transgression culminated in the mfs 1 surface (4th order). The subsequent boxcar log patterns and the subordinate funnel shaped patterns, document a predominately aggradational system grading laterally in propagational areas during this lowstand. This phase corresponds to the 4th order HST (Fig. 3). Delta evolution was terminated by a minor lake level drop associated with a sequence boundary, which is difficult to trace in seismics and wire logs due to the succession of HST gravel and subsequent LST gravel (SB 2 in Fig. 4). Therefore, we used the better defined maximum flooding surface (mfs 2) as correlation horizon. Thus, the observed delta progradation is linked to a 4th order HST within a 3rd order LST of Lake Pannon rather than to a certain tectonic event. Tectonic control, in contrast, seems to be reflected by switching directions of the delta lobe progradation.

The initial delta formation commenced with the Großengersdorf lobe (Fig. 8.1), which was a comparatively narrow lobe prograding into southern direction. The course of the lobe follows the Aderklaa fault system. The fault-related subsidence seems to have provided space for the prograding lobe (Fig. 6). In addition, due to the rising lake level the Paleo-Danube did not form lobate lobes but developed a narrow,

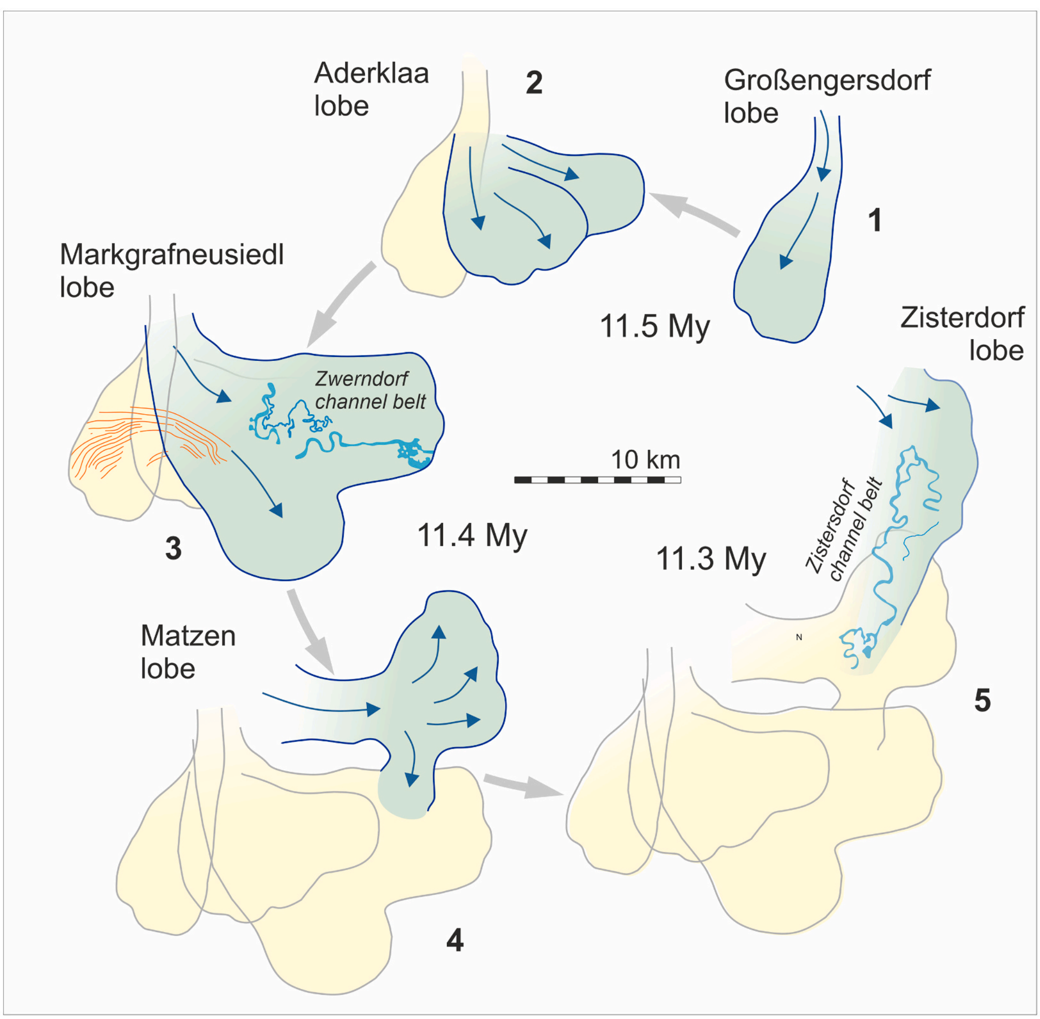

Fig. 9. Evolution of the Paleo-Danube delta and its individual delta lobes during 200 kyr. Note the shifts in progradation directions and the marked northward migration of the main channel feeding the Matzen and Zistersdorf lobes; see Figure 6 for geographic position; orange lines represent beach ridges.

aggregational body. At that time, the Paleo-Danube passed the Mistelbach Basin and entered the Vienna Basin. The boundary between these two basins is defined by the Pirawarth Fault, which is a southwestern branch of the Steinberg Fault (Fig. 6). The next step was the evolution of the Aderklaa lobe (Fig. 9.2), which followed the course of the Großengersdorf lobe but started to direct sediment deposition into southeastern and eastern directions. The ceasing accommodation in the south might have forced the deflection of the shedding direction. This depositional system developed into the Markgrafneusiedl lobe (Fig. 9.3), for which the Zwerndorf channel belt represents one of the main branches. Extensive beach ridge plains started to develop along the western margin of this lobe. The morphology of these crests of up to 20 m height, suggests sub-parallel foredune ridge formation (Hesp, 2002, 2012), which represents a subtype of beach ridge morphology (Tamura, 2012).

The Matzen lobe (Fig. 9.4) marks a major switch in depositional direction from southeast to east and northeast. This pattern suggests an eastward shift of the course of the channel belt of the Paleo-Danube, which was splitting into smaller branches. At that time, the influence of the Pirawarth Fault ceased, and the southern branch of the Steinberg Fault started to shape the course of the river. A second distinct northern shift of the main channel belt is indicated by the Zistersdorf lobe (Fig. 9.5), which directs sediment into southern and southeastern directions. The feeder of the Matzen lobe was abandoned and instead the main feeder of the Zistersdorf lobe established about 15 km in the northeast. This marked shift suggests that the central part of the Steinberg Fault started to shape the topography and guided the direction of delta lobe migration.

The in-seismic measurements of the clinoforms of the delta lobes indicate that water depth decreased significantly during the evolution of the delta. Between the deposition of the Großengersdorf lobe and the Aderklaa lobe, the relative lake water depth decreased with 70 m, starting from a lake level of about 180 m. A further decline of 10 m occurred between the formation of the Aderklaa lobe and the Matzen lobe, followed by a slight rise of the lake level to about 120 m during the formation of the Zistersdorf lobe (Fig. 3). Thus, the declining water depth of Lake Pannon might have been an additional factor explaining the switch of drainage direction between the Großengersdorf and Aderklaa lobes. As we do not observe major changes in water depth in the seismic data after this phase, lake level changes cannot fully explain the subsequent shifts of the course of the river. Thus, local tectonics predominantly influenced formation of accommodation space and switching of delta lobes.

5.3. Paleo-Danube delta versus modern Danube delta

The Miocene Paleo-Danube delta and the modern (or Holocene) Danube river represent the same river-dominated delta type. A main difference between both, however, is the considerable smaller size of the Miocene delta, which covers about 850 km^2 whereas the Holocene and modern Danube delta extends over about 5000 km^2 (based on the polygon function of Google Earth). Thus, the Holocene and modern delta is roughly 6 times larger compared to its Miocene ancestor. The individual lobes of the Paleo-Danube attain about 15 to 20 km in lengths. The time frame for the evolution of these lobes spans about 200 kyr. As the five lobes developed successively in time, each lobe formation occurred within about 40 kyr. These estimates suggest a progradation of the delta lobes by about 0.5 m/year. Holocene beach ridge progradation rates in Danube Delta, in contrast, range around 3.5 to 12 m/yr (Vespremeanu-Stroe et al., 2016).

Based on the mean length of the delta (35 km), its mean width (16 km) and its average thickness of 0.12 km, a rough estimate of the sediment volume stored in the lower Pannonian deltas can be calculated, resulting in a volume of about 67 km^3. Balancing this value against the available time of sedimentation results in a sediment accumulation of roughly 0.3 km^3/kyr (note that we did not correct for compaction).

The formation of the modern Danube delta started approximately 7500–5500 ^{14}C years ago (Giosan et al., 2005; Vespremeanu-Stroe et al., 2017) and the deltaic deposits attain about 30–50 m in thickness on average (Giosan et al., 2005; Vespremeanu-Stroe et al., 2016). This results in a total volume of the Holocene Danube delta of at least 160 km^3 and an accumulation rate of at least 20 km^3/kyr during the Holocene. Thus, the accumulation rate of the Holocene Danube delta is about 70 times higher compared to that of the Miocene Paleo-Danube delta. This strong discrepancy could be explained by two hypotheses: either the Paleo-Danube built its delta in a shorter time interval than proposed herein (significantly shorter than 200 ka) or the Paleo-Danube built several distinct deltas during this time span and the five delta lobes identified herein are only a part of the paleo-Danube activity. The first hypothesis is unlikely given the good stratigraphic control by paleomagnetics (Paulissen et al., 2011). The second hypothesis is not supported by geological data. No additional major Pannonian delta complexes are known along the western margin of the Vienna Basin except for the delta of the Paleo-Triesting south of Vienna (Wessely, 2006). The source of this delta was an Alpine river, which was not connected to the Paleo-Danube drainage. Therefore, the Paleo-Danube, being about six times shorter than the modern Danube, had a much lower sediment load compared to the Holocene and modern Danube.

6. Conclusions

For the first time, the earliest delta of the Paleo-Danube is described based on seismic data. The delta formed between c. 11.5–11.3 Ma (following the age model of Paulissen et al., 2011) as part of a 3rd order lowstand of Lake Pannon. The delta deposits are framed within two 4th order flooding surfaces, used as correlation horizons in the seismic interpretations. Morphologically, the delta is divided into a western part with a braided river delta plain (Nehyba and Roetzel, 2004) and an eastern and southeastern part consisting of five distinct delta lobes, which are defined herein as Großengersdorf, Aderklaa, Markgrafneusiedl, Matzen and Zistersdorf lobes. Seismic architecture reveals consecutive onlaps of theses lobes, documenting that the lobes developed successively through time. The initial delta progradation was oriented in southern direction, roughly coinciding with the Aderklaa fault system. Subsequent lobes switched into eastern and northeastern directions and finally switched back into southern direction. Simultaneously, the point of origination of the lobes switched towards the northeast with the most prominent shift of 15 km occurring between the Markgrafneusiedl and the Matzen lobes. This channel migration was probably governed by a stepwise activity of the Pirawarth-Steinberg fault system.

In total, the delta complex spreads over about 850 km^2. The geometry of the lobes, the steeply inclined clinoforms and the development of large beach ridge fields classify the delta as a river-dominated delta with strong influence of wave reworking, comparable to the modern Danube delta. The switch in geometry, from narrowly elongate of the initial lobe to broad lobate of subsequent lobes, suggests increasing influence of wave activity and a decrease in accommodation space. In-seismic measurements of clinoforms illustrate a drop of the relative lake level of about 80 m during deposition of the lobes. The shallow lake depth of about 180 m during the early phase of delta formation supports data of Magyar et al. (1999), who reported that no deeper water environments have been established during that stage of Lake Pannon.

The size of the Paleo-Danube delta was about six times smaller than the Holocene to recent Danube delta in the Black Sea. The pace of delta progradation was distinctly slower and the rate of sediment accumulation was about 70 times smaller, indicating a considerably lower sediment load compared to that of the modern Danube. This observation is in line with the distinctly shorter and substantially smaller drainage system of the Paleo-Danube as compared to the extent of the modern Danube river drainage basin (Giosan et al., 2005, Fig 1A).

After about 200 kyr, the Paleo-Danube delta was pushed back into the North Alpine Foreland Basin at around 11.3 Ma due to the strong 3rd order lake level rise of Lake Pannon, which culminated in the maximum extent of Lake Pannon during the middle Pannonian (Magyar et al., 1999; Neubauer et al., 2016).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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