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High Resolution Sequence Stratigraphy in the Eastern Styrian Basin (Miocene, Austria)

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Abstract

An improved sequence stratigraphic framework for the Styrian Basin is presented, based on the integration of twelve 2 D seismic sections and well-log data from the central and northern Fürstenfeld Subbasin and the Weichselbaum Graben. The Karpatian to Pannonian succession is subdivided into seven 3rd order sequences. Karpatian 3rd order sequence KAR-1 is poorly defined in the study area. The Karpatian/Badenian boundary ("Styrian Unconformity") is characterized by erosional features and a prominent angular unconformity.

The Badenian is subdivided into three 3rd order sequences (BAD-1 to BAD-3) attributed to the Lower, Middle and Upper Badenian. The assignment of BAD-1 and BAD-2 to global cycles TB 2.3 and TB 2.4 is problematic, but the stratigraphic position and duration of BAD-3 suggests a relation to TB 2.5. In the northern Fürstenfeld Subbasin, BAD-1 to BAD-3 include three prograding deltaic complexes. Marine sedimentation with deposition of mudstones and turbidites prevailed in the central Fürstenfeld Subbasin. Seismic facies of the HST of BAD-3 in the central Fürstenfeld Subbasin, confirmed by correlative outcrops, suggest the northward progradation of corallinacean limestones.

A major drop in relative sea level of at least 50 to 80 m is recorded at the Badenian/Sarmatian boundary in the northern Fürstenfeld Subbasin.

The 3rd order Sarmatian sequence SAR-1 is related to TB 2.6. Internally, five 4th order sequences can be defined. SAR-1.1 to SAR-1.3 represent the Lower Sarmatian Grafenberg Formation. The seismic facies suggests the presence of carbonate rocks in SAR-1.1 and SAR-1.2. A relation to bryozoan-serpulid limestones observed in outcrops of the Grafenberg Formation is likely. The HST of SAR-1.3 consists of the Carinthian Gravel. SAR-1.4 and SAR-1.5 represent the Upper Sarmatian Gleisdorf Formation. Erosional surfaces are recognized in several seismic sections at the top of SAR-1.4 and SAR-1.5. This indicates major drops in relative sea level during Late Sarmatian times and at the Sarmatian/Pannonian boundary. The depth of incised valleys indicates relative sea level falls of about 50 m during both events.

The Pannonian succession in the Styrian Basin includes 3rd order sequences PAN-1 and PAN-2. Following the Sarmatian/Pannonian boundary, an Early Pannonian transgression caused basin wide flooding. PAN-1 is formed by the Feldbach Formation and is separated from PAN-2 by a major erosional event. PAN-2 is subdivided into six 4th order sequences; the lowermost two correspond to the Paldau Formation. PAN-2.3 to PAN-2.5 represent the Beds of Loipersdorf and Unterlamm. PAN-2.6 is formed by the Beds of Jennersdorf. The MFS of PAN-2.6 is correlated with the MFS of PAN-2 (9.03 Ma according to Sacchi and Horváth, 2002).

Ein erweitertes sequenzstratigraphisches Modell wird für das zentrale und nördliche Fürstenfelder Becken sowie für die Senke von Weichselbaum präsentiert. Es basiert auf zwölf 2D-Seismiklinien und auf geophysikalischen Bohrlochmessdaten. Die Sedimente des Karpatiums bis Pannoniums werden in sieben Sequenzen 3. Ordnung eingeteilt.

Die Sequenz KAR-1 lässt sich im Untersuchungsgebiet nur eingeschränkt beschreiben. Die Grenze Karpatium-Badenium („Steirische Diskordanz") ist durch Erosionserscheinungen und eine deutliche Winkeldiskordanz am Nordrand der Südburgenländischen Schwelle charakterisiert.

Das Badenium wird in drei Sequenzen 3. Ordnung (BAD-1 bis BAD-3) eingeteilt, die dem Unter-, Mittel- und Oberbadenium zugeordnet werden. Eine Korrelation der Sequenzen BAD-1 und BAD-2 zu den globalen Sequenzen TB 2.3 bis TB 2.4 erscheint problematisch. Die stratigraphische Position und Dauer der Sequenz BAD-3 verspricht dagegen eine Korrelation zur globalen Sequenz TB 2.5. Im nördlichen Fürstenfelder Teilbecken beinhalten die Sequenzen BAD-1 bis BAD-3 drei progradierende deltaische Zyklen. Marine Sedimentation mit Turbiditen und Peliten dominiert im zentralen Fürstenfelder Teilbecken. Die seismische Fazies des HST der Sequenz BAD-3 lässt auf nordwärts progradierende Karbonate im zentralen Fürstenfelder Teilbecken schließen. Es ist nahe liegend diese mit Nulliporenkalken der Weißenegg-Formation zu korrelieren.

Im nördlichen Fürstenfelder Becken ist ein relativer Meeresspiegelabfall von mindestes 50 bis 80 m an der Badenium-Sarmatium Grenze zu beobachten.

Die sarmatische Sequenz 3. Ordnung SAR-1 besitzt ein ähnliches Alter wie die globale Sequenz TB 2.6. Sie wird in fünf Sequenzen 4. Ordnung eingeteilt. Die Sequenzen SAR-1.1 bis SAR-1.3 repräsentieren das Untersarmatium (Grafenberg-Formation). Aus der seismischen Fazies kann auf das Vorhandensein von Karbonaten in den Sequenzen SAR-1.1 und SAR-1.2 geschlossen werden. Eine Korrelation mit Bryozoen-Serpulidenkalken, welche in Aufschlüssen nahe Grafenberg beobachtet werden, ist wahrscheinlich. Der Carinthische Schotter befindet sich am Top des HST der Sequenz SAR-1.3. Die Sequenzen SAR-1.4 und SAR-1.5 repräsentieren die Gleisdorf-Formation des Obersarmatiums. Erosionserscheinungen an den Oberkanten der Sequenzen SAR-1.4 und SAR-1.5 deuten auf markante relative Meeresspiegelabfälle im Spätsarmatium und an der Grenze Sarmatium-Pannonium hin. Die Tiefen der eingeschnittenen Täler an der Sarmatium-Pannonium Grenze lassen auf einen Meeresspiegelabfall von mindestens 50 m schließen.

Das Pannonium des Steirischen Beckens wird in zwei Sequenzen 3. Ordnung (PAN-1 und PAN-2) unterteilt. Das Unterpannonium beginnt mit einem TST, der das Steirische Becken im Arbeitsgebiet vollständig flutete. Die Sequenz PAN-1 wird von der Feldbach-Formation aufgebaut und durch einen markanten Erosionshorizont von der Sequenz PAN-2 getrennt.

Die Sequenz PAN-2 wird in sechs Sequenzen 4. Ordnung untergliedert. Die untersten Sequenzen (PAN-2.1, PAN-2.2) werden von der Paldau-Formation aufgebaut. Die Sequenzen PAN-2.3 bis PAN-2.5 repräsentieren die Schichten von Loipersdorf und Unterlamm. Die Sequenz PAN-2.6 wird von den Schichten von Jennersdorf gebildet. Die MFS der Sequenz PAN-2.6 wird mit der MFS der Sequenz PAN-2 gleichgesetzt, die im Pannonischen Becken, mit 9.03 Ma datiert wurde (Sacchi und Horváth, 2002).

1. Introduction

The Neogene Styrian Basin is located at the eastern margin of the Alps and is the westernmost subbasin of the Pannonian Basin System (Horváth and Tari, 1999). It has an elongate shape of about 100 km in length and 50 km in width (Fig. 1). The Middle Styrian Swell separates the shallow Western Styrian Basin from the more than 4-km-deep Eastern Styrian Basin (Sachsenhofer et al., 1996). The Fürstenfeld and Gnas Subbasins are distinct depocentres within the Eastern Styrian Basin. The South Burgenland Swell separates the Styrian Basin from other Neogene basins of the Pannonian realm.

Many authors discussed the sequence stratigraphic evolution of different Miocene basins within the Pannonian Basin System (e.g., Pogácsás et al., 1988; Kovác et al., 1999; 2004; Sacchi and Horváth, 2002; Krézsek and Filipescu, 2005; Strauss et al., 2006). A sequence stratigraphic interpretation of Upper Sarmatian and Lower Pannonian horizons in a spatially limited area of the Fürstenfeld Subbasin has been provided by Kosi et al. (2003).

In recent years additional seismic sections from the northern and central part of the Fürstenfeld Subbasin, as wells as from the transition zone to the Pannonian realm became available. The aim of this paper, therefore, is to expand the sequence stratigraphic interpretation of Kosi et al. (2003) geographically and stratigraphically and to discuss the main controls on sediment accumulation in the Styrian Basin. Because the seismic resolution on Lower Miocene horizons is relatively poor, the paper concentrates on the Middle and Upper Miocene succession.

2. Geological Setting

The Styrian Basin is an extensional structure on top of a crus-

Figure 1: Geological map of the Styrian Basin (after Gross et al., 2007). Location of seismic sections and selected wells are indicated.

tal wedge, that was moving eastward during the final stages of the Alpine Orogeny (Ebner and Sachsenhofer, 1995). Eastward extrusion was a consequence of continental escape and extensional collapse within the Eastern Alps (Kázmér and Kovács, 1985; Ratschbacher et al., 1991).

As a simple model, the evolution of the Styrian Basin can be subdivided into an Early Miocene (Ottnangian, Karpatian) synrift phase and a subsequent postrift phase (Sachsenhofer et al., 1996). Thus, rifting in the Styrian Basin ended earlier than in other basins of the Pannonian Basin System (e.g., Horváth and Tari, 1999).

During the synrift phase more than 2000 m of sediments were deposited. Ottnangian rocks in the Fürstenfeld Subbasin were deposited in floodplain, lacustrine/swamp and coastal plain environments (Polesny, 2003; “Limnic Series”; Fig. 2). During Karpatian times subsidence rates up to 30 cm/100 a (Sachsenhofer et al., 1996) resulted in a facies differentiation into fluvial fans (Sinnersdorf Formation), deltaic systems (“Conglomerate-rich Group”) and deep marine settings (Kreuzkrumpel Formation; Polesny, 2003). Karpatian to Early Badenian magmatism commenced during the synrift stage and continued into the postrift stage. Huge volcanic complexes of acidic to intermediate composition were formed. Today, these volcanics are nearly totally buried by younger sediments.

Synrift sediments are separated from Badenian to Upper Pannonian postrift sediments by a major unconformity (Styrian Unconformity). A similar distinct hiatus is also observed in the Vienna Basin and the Molasse Zone (Rögl et al., 2002; 2007) and is linked with the interplay of block rotations and a global sea level fall at the Early/Middle Miocene boundary (Kovác et al., 2004).

Sedimentation during the postrift phase was controlled by marine ingressions during Badenian and Sarmatian times. Corallinacean limestones and associated shallow marine siliciclastics of Badenian age are integrated into the Weissenegg Formation (Friebe, 1990; 1991) which records three depositional sequences, controlled by sea-level fluctuations of at least 30 m (Friebe, 1993).

Marine conditions continued during Sarmatian times (Piller and Harzhauser, 2005). Siliciclastic sediments interlayered with Hydroides-bryozoan bioconstructions form the Lower Sarmatian Grafenberg Formation. Up to 30 m of fluvial gra-

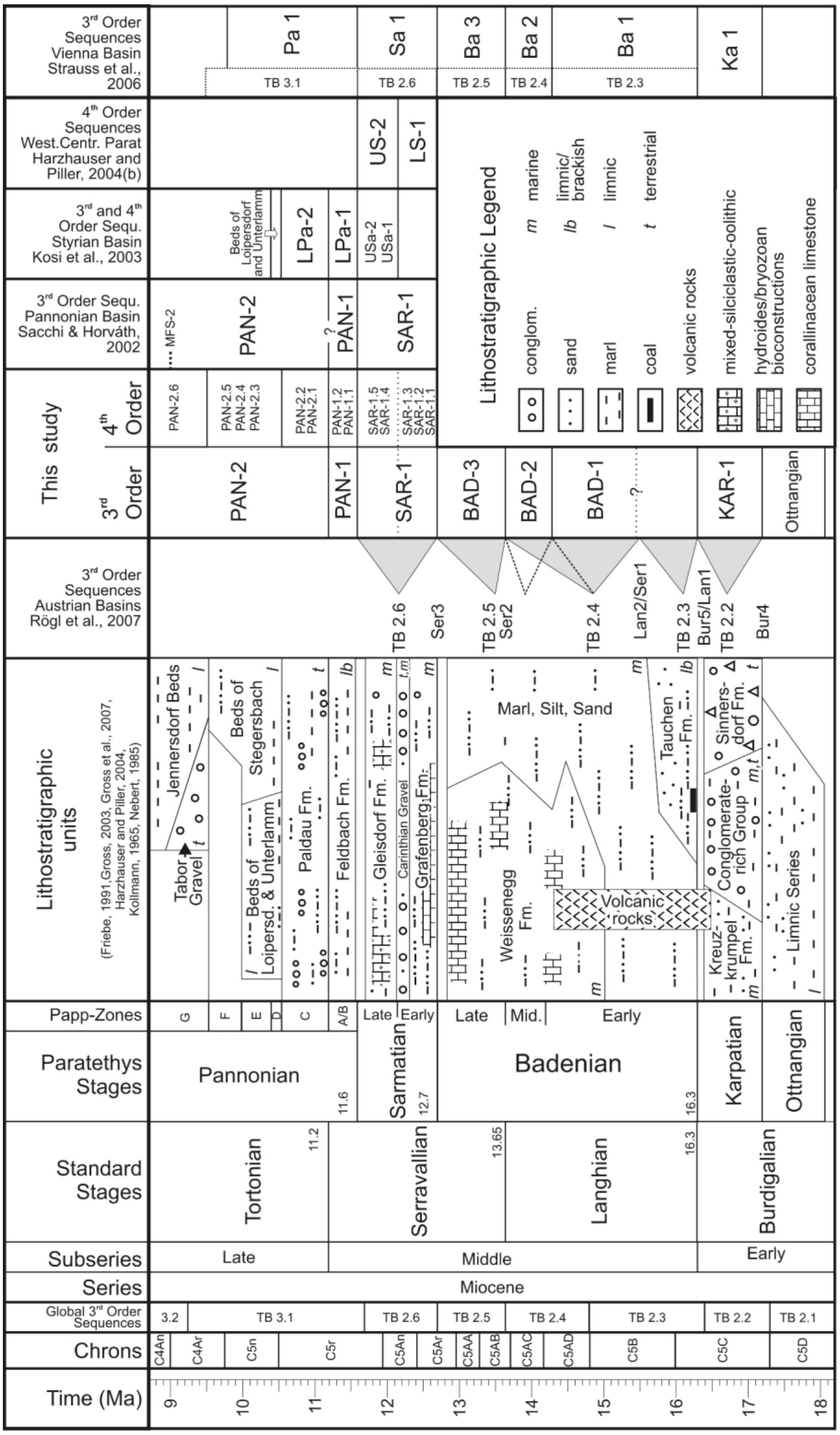

Figure 2: Stratigraphic frame and geologic time scale. Global 3rd order sequences after Hardenbol, et al. (1998). Correlation of regional zones of Papp (1951) follows Harzhauser, et al. (2004).

vels ("Carinthian Gravel") were transported from a southwestern hinterland into the Eastern Styrian Basin during late Early Sarmatian times (Kollmann, 1965; Skala, 1967). Upper Sarmatian sediments are characterized by mixed siliciclastic-oolithic alternations (Gleisdorf Formation). Frequent Sarmatian sea level fluctuations have been identified by Harzhauser and Piller (2004a). A minor Late Sarmatian extension phase (Krainer, 1984; 1987) resulted in increased Sarmatian subsidence rates (Sachsenhofer et al., 1997).

A relative fall in sea level at the Sarmatian/Pannonian boundary caused the isolation of the Central from the Eastern Paratethys and the formation of the brackish "Lake Pannon" (Magyar et al., 1999). Deep valleys incised at the Sarmatian/Pannonian boundary in the Eastern Styrian Basin were a consequence of this sea level fall (Kosi et al., 2003). Lower Pannonian sediments (Feldbach Formation, Paldau Formation) were deposited in limnic-brackish and fluvial environments (Gross, 2003) and represent two sequences (Kosi et al., 2003). Middle Pannonian Sediments ("Beds of Loipersdorf and Unterlamm", "Stegersbach Beds") and Upper(?) Pannonian sediments ("Tabor Gravel", "Beds of Jennersdorf") are restricted to the easternmost part of the Styrian Basin (c.f. Gross et al., 2007).

In Pliocene times subsidence was replaced by uplift, resulting in erosion of a few hundred metres of sediment. A second volcanic phase produced basalts in Plio-/Pleistocene time (Sachsenhofer, 1996).

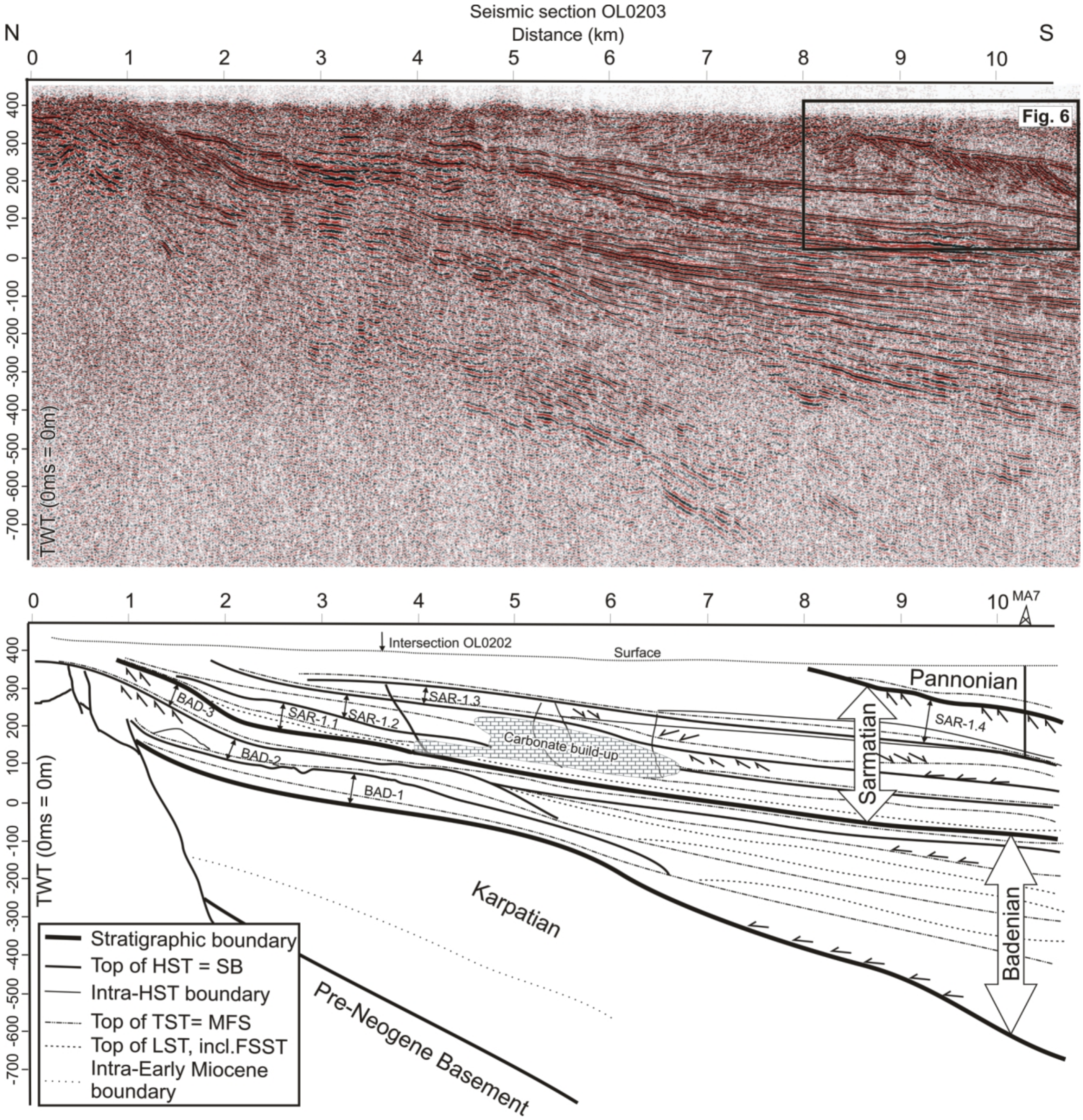

Figure 3: N-S seismic section OL0203 in the Upper Lafnitz Valley and its interpretation. See Figure 1 for location of seismic section.

3. Data and Methodology

This study is based on twelve seismic sections and data from several boreholes. Seismic sections are displayed in two way travel time (TWT), where 0 ms TWT corresponds to sea level. Seismic sections F205, F210 and information on deep wells Übersbach 1 (ÜB), Walkersdorf 1 (WA) and Binderberg 1 (BI) were kindly provided by Rohoel Aufsuchungsgesellschaft (RAG; Vienna). Joanneum Research reprocessed seismic line F205 in 2005. Ten additional seismic lines were acquired and processed during the last eight years by Joanneum

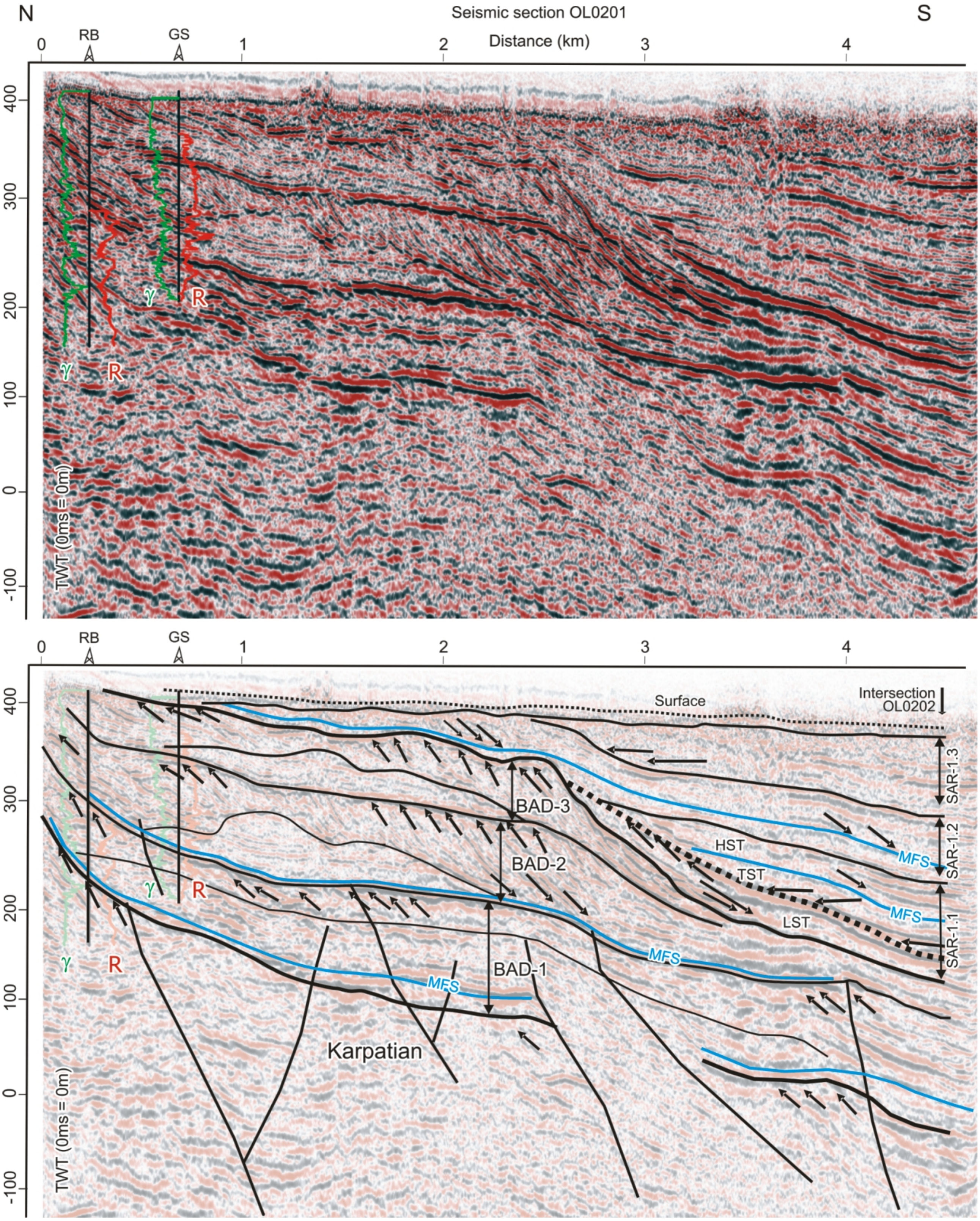

Figure 4: N-S seismic section OL0201 with gamma (γ) and resistivity (R) logs of wells RB and GS. See Figure 1 for location of seismic section.

Research during exploration for drinking and geothermal water resources. Joanneum Research used dynamite as energy source and used small receiver group and source distances (mostly 5 m) to obtain high resolutions. Gamma ray and resistivity logs and descriptions of cuttings from drinking water wells Markt Allhau 7 (MA7), Königsdorf 1 (KD), and Römerbrücke 1 (RD) were also used. These wells are up to 300 m deep and were drilled along the seismic sections. Unfortunately, no cores are available from water wells or from the deep geothermal well Fürstenfeld Thermal 1 (FFTH1). The interpretation of seismic sections and well logs are supported by outcrop descriptions (Kollmann, 1965; Friebe, 1994; Harzhauser and Piller; 2004a).

The sequence stratigraphic concept is based on the methodology and terminology of Mitchum et al. (1977 a, b) Vail et al. (1977a,b) Posamentier and Vail (1988), Posamentier et al. (1988), Posamentier and Allen (1999), Cantuneanu (2002) and Coe (2003). The following abbreviations are used in this text: LST = Lowstand Systems Tract; FSST = Falling Stage Systems Tract; TST = Transgressive Systems Tract; HST = Highstand Systems Tract; MFS = Maximum flooding surface; TS = Transgressive Surface, SB = Sequence boundary.

3rd order sequences are termed designated an abbreviation of the stage name and a number (e.g. PAN-1 for the lowermost Pannonian 3rd order sequence). 4th order sequences are identified by an additional number (e.g., PAN-1.1 is the lowermost 4th order sequence of PAN-1).

4. Seismic and Sequence Stratigraphy

4.1 Northern Margin of the Fürstenfeld Subbasin

Three seismic sections were acquired in the Friedberg-Pinkafeld area (Fig. 1) to evaluate the hydrogeological regime and to locate wells for the regional water supply. Two sections are situated in the N-S trending upper Lafnitz and Stögersbach valleys (Fig. 3 and Fig. 4). The third section is a W-E trending connecting line (Fig. 5). Detail of the seismic section OL0203 is shown in Fig. 6.

4.1.1 Ottnangian/Karpatian

The Lower Miocene succession is characterized by disrupted subparallel reflectors. In contrast, the pre-Neogene basement (Austroalpine crystalline rocks, Kröll et al., 1988) is essentially free of reflections, so, the lowermost discontinuous high-amplitude reflector is taken as the base of the Lower Miocene succession (Fig. 3 to Fig. 5). In the northern part of seismic section OL0203, there is a southward dipping normal fault, which displaces the base of the Neogene at least 500 m (Fig. 3).

The upper boundary of the Lower Miocene in the southern

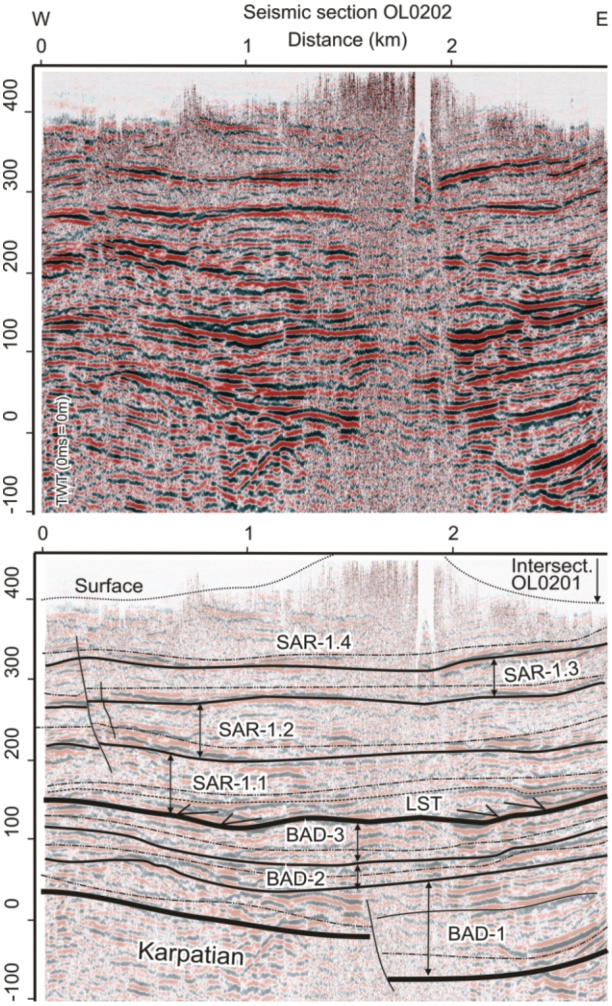

Figure 5: E-W seismic section OL0202 and its interpretation. See Figure 1 for location of seismic section and Figure 3 for legend.

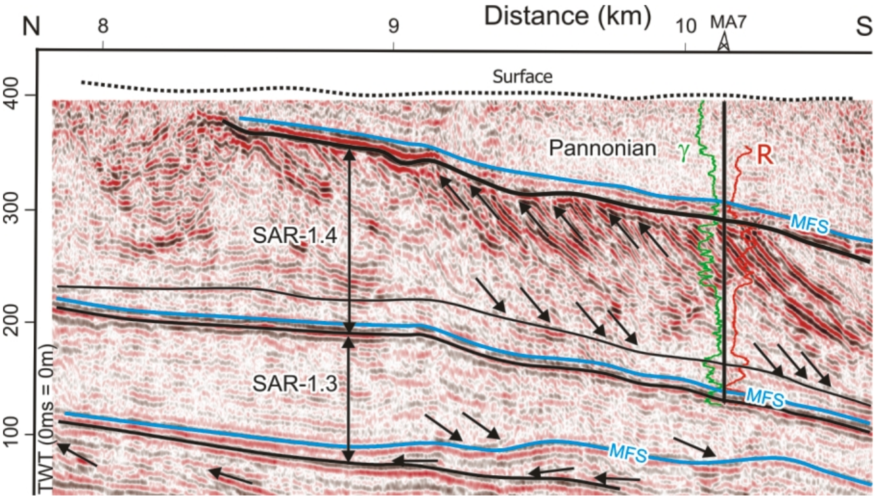

Figure 6: Detail of southern part of seismic section OL0203 showing southward progradation of an Upper Sarmatian (SAR-1.4) delta. Gamma (γ) and resistivity (R) logs of well MA7 are displayed. For position see Figure 3.

part of section OL0201 is characterized by toplaps (Fig. 4). Clinoforms near the top of the Lower Miocene interval represent a Karpatian southward prograding HST (Fig. 4). An intra-Early Miocene boundary separates a lower zone with low frequency reflections from an upper zone with higher frequencies (Fig. 3 to Fig. 5).

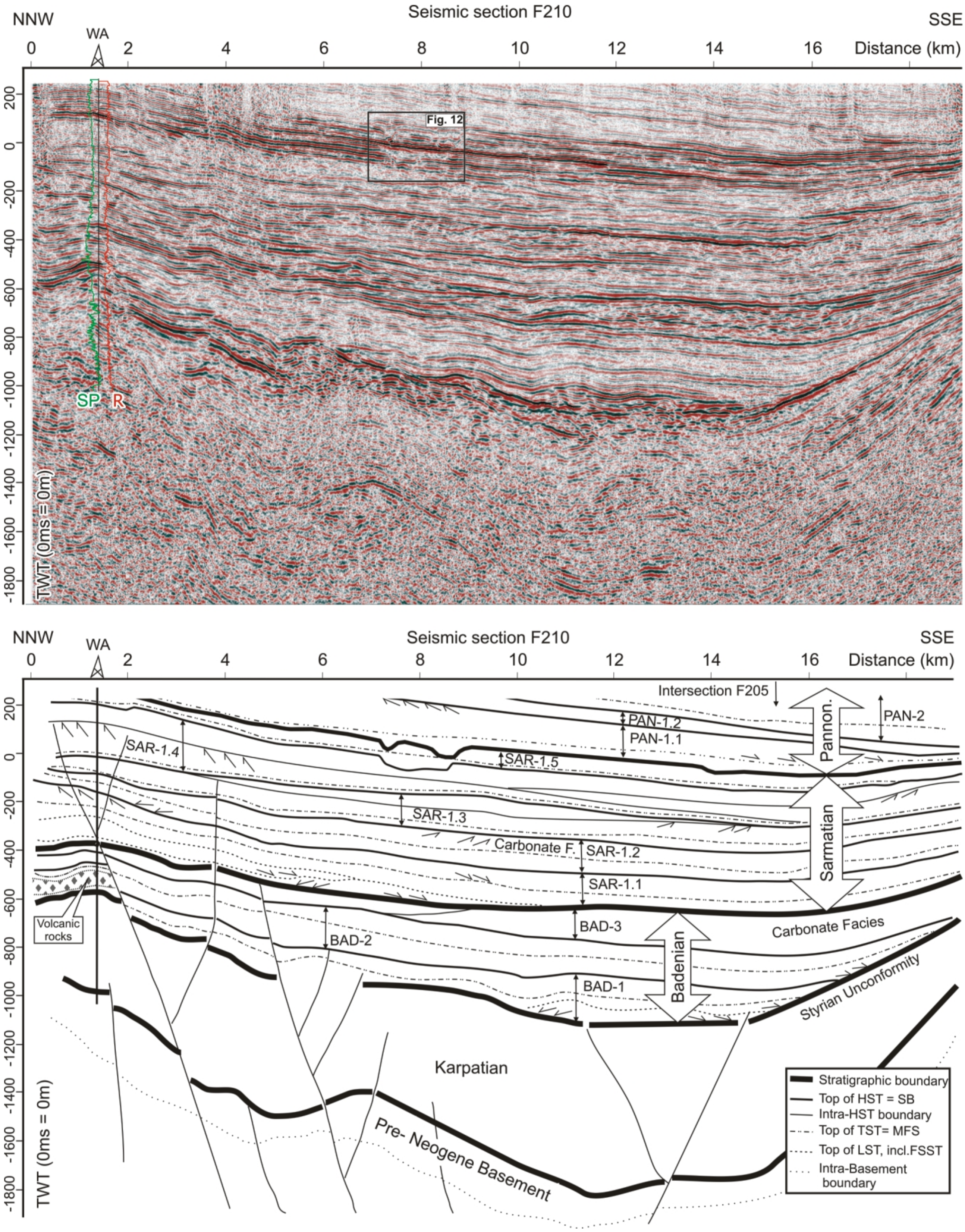

Figure 7: Seismic section F210 with Spontaneous Potential (SP) and resistivity (R) logs of well Walkersdorf 1 (WA) and its interpretation. See Figure 1 for position of seismic section.

According to Polesny (2003) the Karpatian sediments in the Pinkafeld area were deposited in fluvial environments. The presence of Ottnangian rocks is doubtful.

4.1.2 Badenian

The Badenian succession overlies the Lower Miocene succession with an onlap relation, as shown in Fig. 3. The Ba-

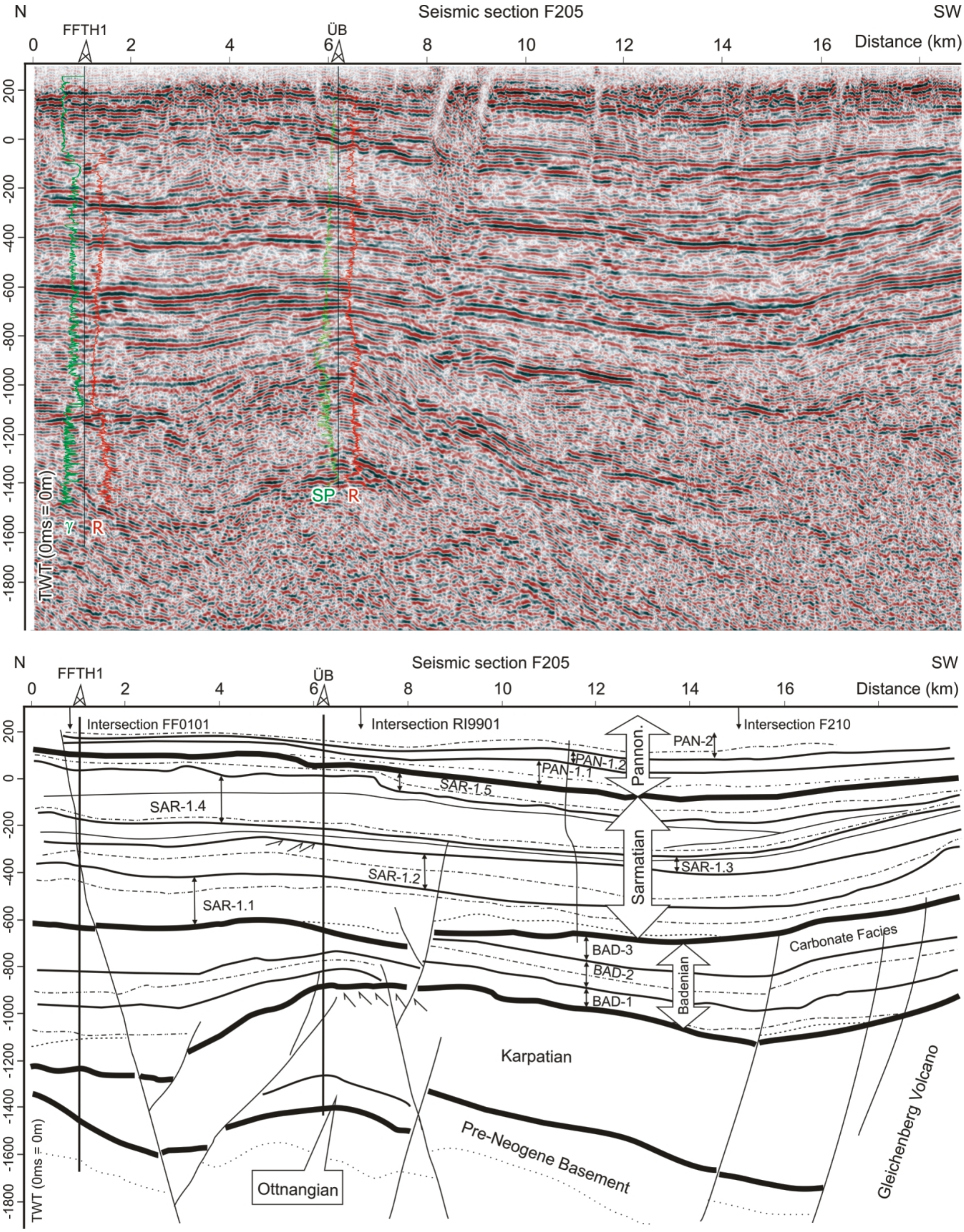

Figure 8: Seismic section F205 with gamma (γ) and resistivity (R) logs of wells FFTh1 and Spontaneous Potential (SP) and resistivity (R) logs of Übersbach 1 (ÜB) and its interpretation. See Figure 1 for position of seismic section and Figure 7 for legend.

denian sediments comprise thin TSTs and three prograding units (HSTs) which are separated by SBs. Undulating tops of the HSTs suggest erosion (Fig. 4). These are interpreted as three 3rd order Badenian sequences, BAD-1 to BAD-3.

Reflection configurations (Fig. 4) suggest a change in sediment transport direction during deposition of each HST. Subhorizontal reflectors and mounded structures indicate that the direction of sediment transport was oblique to the seismic lines during the early HSTs. In contrast, steeply inclined clinoforms overriding the mounded structures provide evidence for north-south progradation during the late HST. Probably this

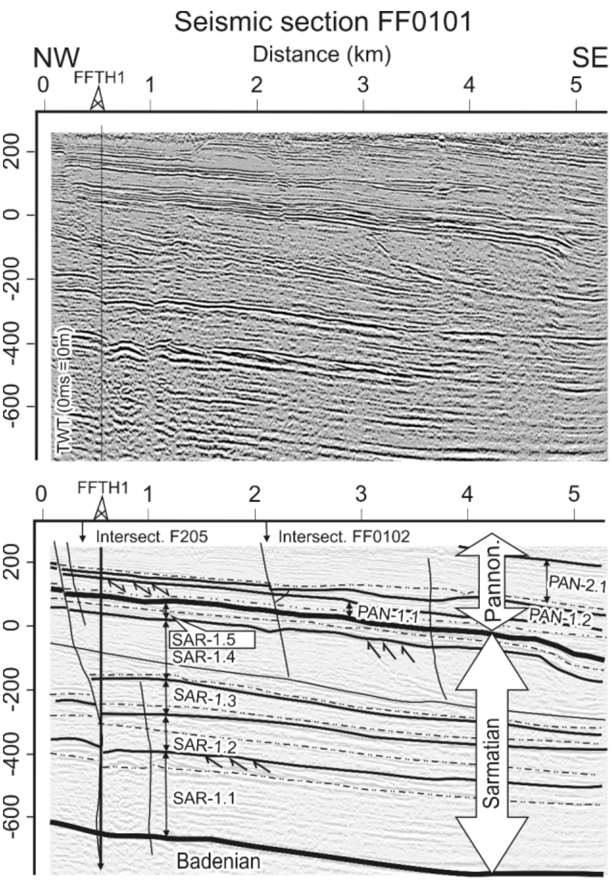

Figure 9: Seismic section FF0101 and its interpretation. Close-up of the shallow part is shown in Kosi, et al. (2003). See Figure 1 for position of seismic section and Figure 7 for legend.

results from the elongated funnel shape of the northern part of the Fürstenfeld Subbasin. There, local fans from the east and west reached the area of the seismic lines first, whereas prograding deltas from the north reached this area only during the late HSTs. Progradational HSTs are characterized by upward coarsening trends visible in the gamma (γ) and resistivity (R) logs of wells RB and GS (Fig. 4).

Paleowaterdepths can be estimated using the thickness of clinoforms (vertical distance between toplaps and downlaps). Using average seismic velocities for Badenian rocks (c. 2500 m/s), the waterdepths during deposition of the HSTs at the offlap break position was about 100 m for BAD-2 and 75 m for BAD-3. Because of the effect of sediment compaction, these are minimum estimates.

4.1.3 Sarmatian

The Badenian/Sarmatian boundary is marked by a significant drop in sea level resulting in erosion at the top of the HST of BAD-3 (Fig. 4). The distance between the offlap break of BAD-3 and the MFS of the overlying Sarmatian sequence suggests a sea level drop of at least 50 m to 80 m.

The Sarmatian succession is subdivided into four sequences. The average duration of the observed sequences argues for 4th order (SAR-1.1 to SAR-1.4; see chapter 5 for discussion). Probably, these sequences form part of a single 3rd order eustatic cycle (Harzhauser and Piller, 2004b).

The lowermost Sarmatian rocks were deposited during a time of falling sea level (forced regression package, FFST) forming the LST of SAR-1.1. The LST ("healing wedge" of Posamentier and Allen, 1999) is visible as N-S trending dip lines and can be observed on a W-E strike-line (OL0202; Fig. 5) as a mounded structure with bi-directional downlap. A downward shift in the top level of the HST of SAR-1.1 relative to the HST of BAD-3 indicates that during the deposition of SAR-1.1 sea level remained below the offlap break of BAD-3. Consequently, SAR-1.1 is missing along the northern margin of the Fürstenfeld Subbasin north of the position of the offlap break of BAD 3.

LSTs of Sarmatian sequences SAR-1.2 to SAR-1.4 are not observed. This is either because they are located in a distal (southern) position not covered by the seismic sections, or because they are too thin to be resolved seismically.

The MFS of SAR-1.2 is characterized as a downlap surface and overlaps the HST of BAD-3, which remained emergent during deposition of SAR-1.1 (Fig. 4). SAR-1.2 has a significantly wider northward extent indicating a general transgressive trend. The 4th order sequences SAR-1.1 and SAR-1.2, therefore, form part of a TST of a 3rd order sequence.

Sarmatian horizons are often characterized by continuous high-amplitude reflectors, but chaotic low-amplitude reflectors prevail on seismic line OL0203 between 4 km and 7 km in SAR-1.1 and SAR-1.2 (Fig. 3). This reflection geometry suggests the presence of a carbonate build-up within sequences SAR-1.1 and SAR-1.2 (Fig. 3). This build-up may be the equivalent of Lower Sarmatian bryozoan-serpulid bioconstructions exposed near Grafenberg north of Hartberg (Friebe, 1994; compare Fig. 2).

The overlying sequence SAR-1.3 consists of a TST and a HST. The HST is separated into two units indicating delta lobe switching. Bi-directional downlap indicates prevailing sediment transport oblique to the N-S seismic section during deposition of the lower unit. The upper unit is characterized by southward progradation (Fig. 3).

Southward prograding delta sediments are about 90 m thick and form oblique tangential clinoforms along the southernmost part of line OL0203 (Fig. 6). They represent the HST of the 4th order sequence SAR-1.4. These deltaic sediments were the target of water-well MA7. Logs from this well highlight the upward coarsening character of the prograding succession. Between the MFS of SAR-1.4 and the southward prograding succession, coarsening-upward deposits of an earlier stage of the HST can be observed in the logs. Because clinoforms are not visible in the seismic section, we conclude that the sediment-transport direction was oblique to the seismic section. This, together with chaotic clinoform patterns in the proximal part of the main delta complex (to the north of 8.5 km in Fig. 3 and Fig. 6) probably result from delta switching.

An erosional surface at the top of the deltaic sediments marks the Sarmatian/Pannonian boundary. The uppermost Sarmatian 4th order sequence SAR 1.5, present in the central Fürstenfeld Subbasin (see below), is missing along the northern margin of the subbasin, probably as a result of erosion.

4.1.4 Pannonian

Lower Pannonian rocks are widely exposed on the surface of the northern Fürstenfeld Subbasin, where they unconformably overlie older Neogene and even basement rocks (Fig. 2). Pannonian sediments cannot be subdivided along seismic section OL0203 (Fig. 6). However, logs of well MA7 clearly show the position of the MFS, which represents the top of a TST (Fig. 6). The overlying HST is characterized by a coarsening-upward trend and is attributed to the sequence PAN-1.1. Downlaps are not visible, because sediment transport was oblique to the section.

4.2 Central Fürstenfeld Subbasin and its southern margin

The interpretation of the Neogene deposits in the central Fürstenfeld Subbasin is based on the five seismic sections F205, F210, FF 0101, UL9901 and RI9901 shown in Fig. 7 to Fig. 11. The locations of the sections are shown on Fig. 1. Close-ups of the shallow part of sections FF0101, UL9901, and RI 9901 are presented by Kosi et al. (2003).

4.2.1 Ottnangian/Karpatian

The top of the pre-Neogene basement can be identified as a discontinuous reflector with high amplitudes (Fig. 7 and Fig. 8). The maximum depth of the pre-Neogene basement in the study area occurs along section F2 10 at distance marker 11 km. Here, the Neogene basin fill is more than 3 km thick and includes at least 1000 m of Karpatian rocks (Fig. 8).

The top of the Lower Miocene section along the southern part of line F210 is an angular unconformity (the "Styrian Unconformity"), which appears as exceptionally high amplitude reflector (Fig. 7). The Lower Miocene sediments are repre-

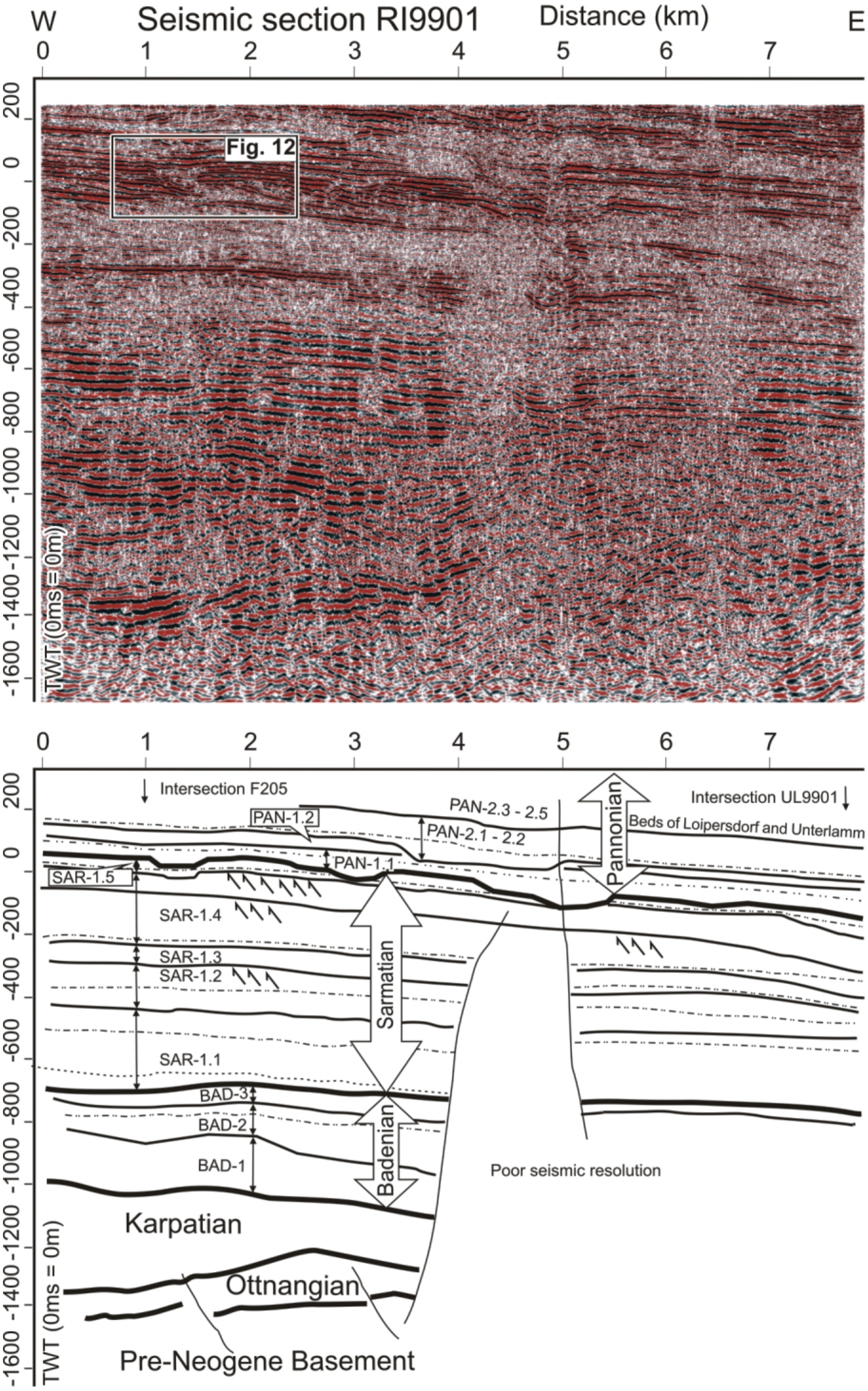

Figure 10: Seismic section RI9901 and its interpretation. Close-up of the shallow part is shown in Kosi, et al. (2003). See Figure 1 for position of seismic section and Figure 7 for legend.

sented by discontinuous and subparallel to divergent reflectors that dip steeply to the north (Fig. 7). The high dip angles are the result of block rotations at the Karpatian/Badenian boundary (Sachsenhofer et al., 1996).

In other parts of the central Fürstenfeld Subbasin, the Lower/Middle Miocene boundary is a paraconformity, often characterized by a high amplitude reflector (e.g., between WA and the basin center in F210 (Fig. 7) and around FFTH1 and south of well ÜB (Fig. 8)).

Although the seismic resolution in the Lower Miocene section is generally poor, some information is provided by the deep boreholes (Polesny, 2003). ÜB is located in a structural high along seismic line F205 and penetrated 290 m Ottnangian age rocks (Fig. 8). The non-marine sediments are overlain by 765 m of marine Karpatian rocks that include a high proportion of conglomerates. Well WA drilled 703 m of Karpatian conglomerate-rich rocks near the NNW end of the seismic section F210 (Fig. 7).

Toplaps and southward dipping clinoforms can be observed in the uppermost part of the Karpatian succession along seismic line F205 south of well ÜB (Fig. 8) indicating southward progradation toward the south.

4.2.2 Badenian

The Badenian succession is subdivided into three sequences. It commences in the deepest part of the basin (F210; Fig. 7) with a mounded sediment package having bi-directional downlap that is interpreted as the LST of BAD 1. The overlying TST is characterized by onlaps onto the deeper parts of the Styrian Unconformity. A HST completes the sequence BAD-1 with a coarsening-upward trend in FFTH1 Fig. 8). Well WA penetrates a volcanic unit within BAD-1 (Fig. 7).

The TST of BAD-2 produces onlaps onto the Styrian Unconformity at the southern end of F210 and overlaps the volcanic rocks in the Walkersdorf area (Fig. 7). A HST completes the sequence BAD-2. The top of the HST is formed by a continuous high-amplitude reflector (F205, F210).

LST and TST of the overlying sequence BAD-3 are not visible in the seismic sections. The configuration of reflections of the HST suggests two different facies zone. In southern part of seismic sections F205 and F210 the HST is dominated by hummocky clinoform patterns (Fig. 7 and Fig. 8). The overall thickness of this facies decreases towards the north. This seismic facies is interpreted as carbonate rocks that are prograding northward from the South Burgenland Swell into the central Fürstenfeld Subbasin. Most probably, these rocks are the equivalents of Upper Badenian corallinacean limestones that form the base of Klapping outcrop (Harzhauser and Piller, 2004a; Gross et al., 2007).

In the northern part of seismic sections F205 and F210, the HST of BAD-3 is characterized by continuous subparallel reflectors that are typical for siliciclastic sediments as confirmed

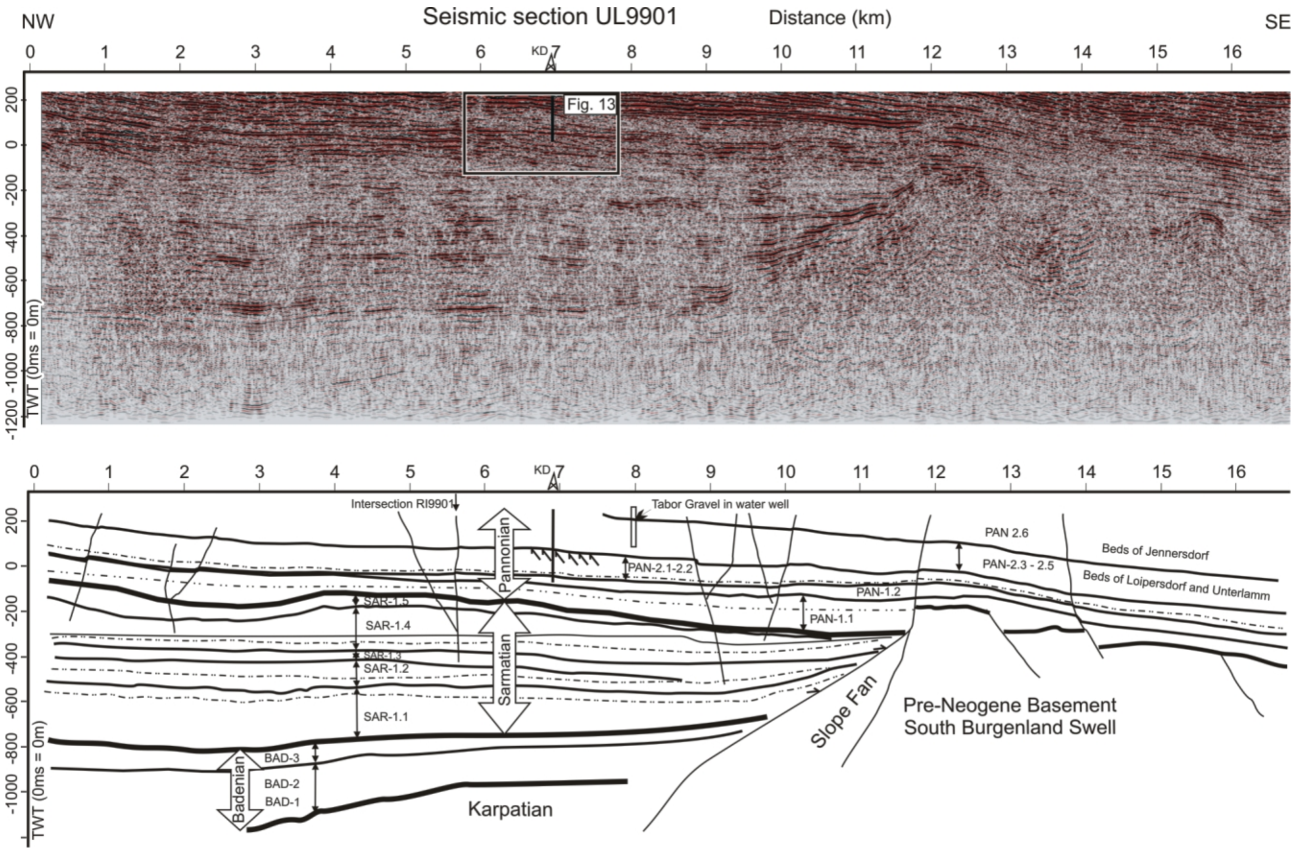

Figure 11: Seismic section UL9901 and its interpretation. Close-up of the shallow part is shown in Kosi, et al. (2003). See Figure 1 for position of seismic section and Figure 7 for legend.

by boreholes FFTH1, ÜB, and WA.

A wavy-shaped reflector with high amplitude forms the top of the carbonate facies of BAD-3 (Fig. 7). The geometry of the upper boundary suggests an erosional event marking the Badenian/Sarmatian boundary.

4.2.3 Sarmatian

The Sarmatian succession in the central Fürstenfeld Subbasin is subdivided into five 4th order sequences. The lowermost preserved Sarmatian rocks occur along section F210 (Fig. 7). They are marked by a mounded structure and bi-directional downlap and are interpreted as a lowstand fan. The overlying unit shows southward progradation and is assigned to the lowstand wedge (Fig. 7). Lowstand fan and lowstand wedge deposits form the LST of SAR-1.1, which is covered by a thick TST. Along UL9901 the TST onlaps a slope fan developed along the northwestern margin of the South Burgenland Swell (Fig. 11). The HST of SAR-1.1 is relatively thin. In wells WA and ÜB the HST is represented by sediments that coarsen-upwards. NW-SE progradational patterns are visible in section FF0101 (Fig. 9) and the northern part of section F210 (Fig. 7). At distance marker 1-3 km the top of the HST dips relatively steeply to south.

The TST of SAR-1.2 overlies the top of the steeply dipping HST of SAR-1.1 near WA with an onlap relation. The HST of SAR-1.2 shows patterns of progradation to the north along sections F210 and F205. The seismic facies along section F210 is characterized by hummocky clinoforms indicating the presence of carbonate rocks extending into the central Fürstenfeld Subbasin. The high amplitude of the top reflector of the HST (Fig. 7) supports this interpretation. We speculate that the carbonate rocks along F210 are the equivalents of Lower Sarmatian Hydroides/bryozoan bioconstructions exposed in the Klapping outcrop (Harzhauser and Piller, 2004a; Gross et al., 2007). Apparent eastward progradation and a seismic facies consisting of oblique clinoforms in the HST of SAR-1.2 are seen along RI9901 (Fig. 10). Well ÜB, located in this section, shows that this facies coincides with the absence of carbonate rocks.

The TST of SAR-1.3 is relatively thin. The MFS is expressed as a low resistivity layer in WA. The HST consists of two units. The lower unit shows an apparent northward progradation along F210 (e.g., near the intersection with F205). The fluvial Carinthian Gravel forms the top of the HST.

The HST of SAR-1.4 consists of three parasequence sets. The lower parasequence set shows toplaps at the NNW-part of F210 near WA (Fig. 7). The middle parasequence set shows toplaps at the SSE-part of F210 and overlies the previous one south of distance marker 10 km. The upper parasequence set shows aggradation with parallel reflectors in F210 (Fig. 7). Along RI9901, the upper parasequence set progrades eastwards (Fig. 10). In the present paper, we include the parasequence set into SAR-1.4. However, it cannot be excluded that it forms a separate 4th order sequence. The upper boundary of SAR-1.4 is an erosional surface. Erosion is clearly visible in F210 (Fig. 7 and Fig. 12) at the distance marker 8 km and in seismic section F205 (Fig. 8) at the distance marker 7 km. Erosion at the top of SAR-1.4 is also observed along RI9901 (distance marker 1.3 km, Fig. 10 and Fig. 12). Kosi et al. (2003) observed the same incised valley but interpreted it as resulting from erosion at the Sarmatian/Pannonian boundary. However, the additional information from F210 provides clear evidence for erosion at the top of SAR-1.4. The incised valley observed at F210 is 40-50 m deep (e.g., Fig. 10).

SAR-1.5 starts with incised valley-fills interpreted as LST deposits. The main part of SAR-1.5 is formed by an aggrading mixed siliciclastic-oolithic succession with an average thickness of 50 m (Kosi et al., 2003). The rock unit was interpreted as a shelf margin systems tract (SMST). Within the succession the offlap break, visible in FF0101 (Fig. 9), separates an area of shallow water and ooid formation in the west from a deeper-water area in the east (see also Kosi et al., 2003). The top of SAR-1.5 is formed by another erosional surface (e.g. Fig. 12), which forms the Sarmatian/Pannonian boundary. Incised val-

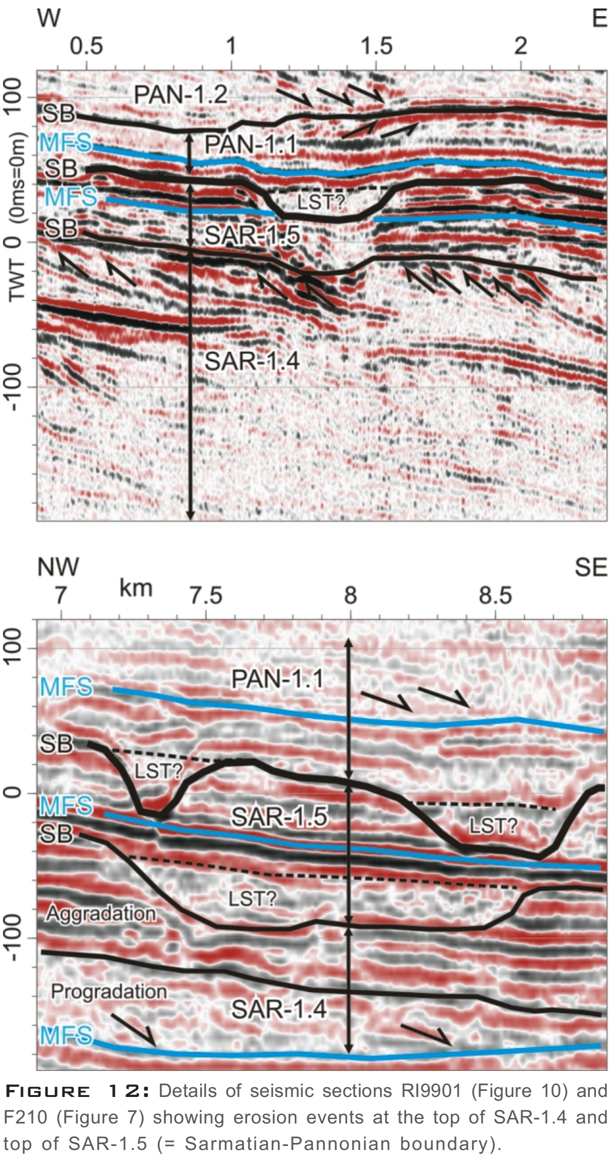

Figure 12: Details of seismic sections RI9901 (Figure 10) and F210 (Figure 7) showing erosion events at the top of SAR-1.4 and top of SAR-1.5 (= Sarmatian-Pannonian boundary).

leys, up to 50 m deep, formed at Sarmatian/Pannonian boundary are observed along F210, UL9901 and RI9901.

4.2.4 Pannonian

The Pannonian in the central Fürstenfeld Subbasin is subdivided into 3rd order sequences PAN-1 and PAN-2.

PAN-1 starts with a 4th order sequence PAN-1.1 consisting of LST, TST and HST. Onlap incised valley-fills above the Sarmatian/Pannonian boundary (Fig. 12) are interpreted as LST deposits. The TST covers the entire study area and indicates a major rise in relative lake level. The HST of PAN-1.1 is characterized by clinoform geometries and log patterns, which indicate south(east)ward progradation of delta complexes along F210 (Fig. 7 and Fig. 12) and FF0101 (Fig. 9), but westward progradation along RI9901 (Fig. 10 and Fig. 12). In the Weichselbaum Graben the top of PAN-1.1 is formed by an erosional surface (see below).

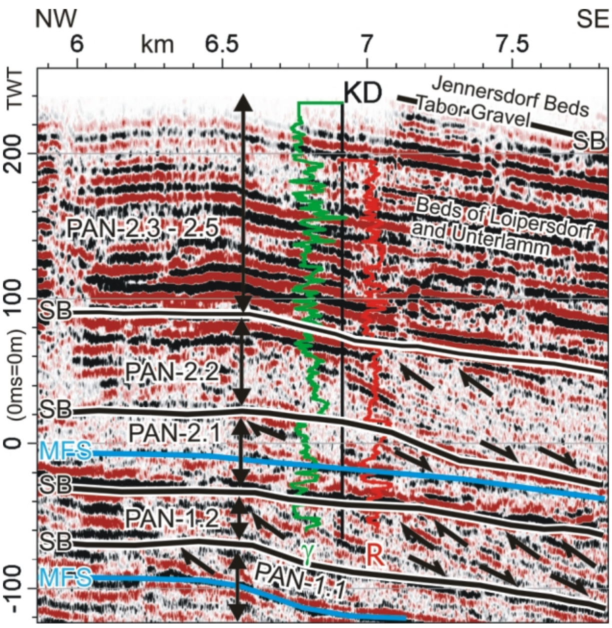

Figure 13: Detail of seismic section UL9901(Figure 11) with gamma (γ) and resitivity (R) logs of well KD.

The HST of the 4th order sequence PAN-1.2 progrades towards the southeast. The top of the HST is formed by an erosional surface representing the boundary between 3rd order sequences PAN-1 and PAN-2. Up to 45 m deep valleys are observed in the seismic section RI9901 between distance markers 3.5 and 5 km (Fig. 10).

4th order sequences PAN-2.1 and PAN-2.2 form the base of PAN-2. The subdivision of both sequences is mainly a result of the study in the Weichselbaum Graben (see below). At the southern margin of the central Fürstenfeld Subbasin, PAN-2.1 consists of a TST and a HST. The MFS is clearly visible as a low-resistivity, high gamma-ray marker on well logs (e.g. KD; Fig. 13, see also Fig. 9 in Kosi et al., 2003). Both the HST of PAN-2.1 and PAN-2.2 show coarsening-upward trends (Fig. 13) and southeastward progradation.

PAN-2.3 to PAN-2.5 are restricted to the FF0101, RI9901 and UL9901 located in the eastern part of the study area. A subdivision will be provided in the chapter on the Weichselbaum Graben.

The fluvial Tabor Gravel (Gross, 2003) overlies PAN-2.5. Its position along section UL9901 is known because it has been drilled near the well KD (Goldbrunner, 1994; Fig. 11). The sequence stratigraphic position of the Tabor Gravel remains unclear. Tentatively, we attribute it to the LST of PAN-2.6.

4.3 Weichselbaum Graben – South Burgenland Swell

Four seismic lines were acquired north of the city of Jennersdorf (Fig. 15 to Fig. 17 see Fig. 1 for position of sections). The well Grieselstein Thermal 1 (GST) was drilled in 2003. Biostratigraphic data are not available, so the stratigraphy of the well has been determined from log correlations with the Binderberg 1 well (BI) (see Fig. 14).

4.3.1 Ottnangian/Karpatian

The top of the pre-Neogene basement is identified as a discontinuous southward dipping high-amplitude reflector in seismic section JE0103 near the well GST (Fig. 17). This well drilled phyllitic basement rocks at a depth of 1714 m. Ottnangian rocks probably are missing or cannot be distinguished from Karpatian ones. The Karpatian succession onlaps the pre-Neogene basement (Fig. 17). The top of the Karpatian is represented by a high-amplitude reflector with high continuity. Erosion is indicated along section JE0103 between distance markers 2 and 2.5 km.

4.3.2 Badenian

The Badenian succession along the Jennersdorf sections is very thin and it is only 136 m thick in well BI. Note that the Badenian succession in the OMV well Jennersdorf 1 located a few kilometres south of the study area is 624 m thick (Ebner and Sachsenhofer, 1991). Only a few reflectors correspond to the Badenian precluding a sequence stratigraphic interpretation.

4.3.3 Sarmatian

The subdivision of the Sarmatian succession along sections JE0101-04 is aided by the correlation of wells located in the central Fürstenfeld Subbasin (ÜB) and in the Jennersdorf area (BI, GST; Fig. 14).

The HSTs of SAR-1.1 to SAR-1.3 are characterized by coarsening-upward trends in the wells. Sections JE0101 and JE 0102 provide evidence for a general southeastward direction of progradation.

The HST of SAR-1.4 in the Jennersdorf area is composed of two parasequence sets. The top of the HST is an erosive surface. Along the seismic section JE0103 an incised valley approximately 750 m wide and at least 60 m deep can be seen near distance marker 2 km. Another valley containing a progradational channel fill is observed along JE0102 (distance marker 0.5 km; Fig. 16).

The erosive valleys were filled during the LST/TST of SAR-1.5. The MFS is characterized by a continous reflector. The HST of SAR-1.5 is formed by an aggrading succession with continuous high-amplitude reflectors. The top of the SAR-1.5 (Sarmatian/Pannonian boundary) is another erosive surface. A minor valley is visible in section JE0104 (Fig. 17).

4.3.4 Pannonian

The Pannonian succession in the area of the Weichselbaum Graben is subdivided into 3rd order sequences PAN-1 and PAN-2.

PAN-1 includes the 4th order sequences PAN-1.1 and PAN-1.2. The TST of PAN-1.1 onlaps the Sarmatian/Pannonian boundary (e.g., Fig. 16). The HST of PAN-1.1 shows N-S progradation. The top of the HST is partly eroded, there is a 10-15 m deep incised valley with onlap fill between distance markers 1.5-1.8 km on section JE0102 (Fig. 16). The valley was filled during the TST of PAN-1.2. The HST of PAN-1.2 shows a general southward progradation similar to that of PAN-1.1 (Fig. 15 to Fig. 17).

PAN-2 comprises 4th order sequences PAN-2.1 to PAN-2.6. The HST of PAN-2.1 progrades northwards on all seismic sections in the Jennersdorf area. This indicates a significant change in sediment transport direction, because from all other Pannonian 4th order sequences, which are characterized by southward progradation. The succession overlying PAN-2.1 is characterized by continuous high amplitude high frequency reflectors. This succession can be subdivided into 4th order sequences labelled PAN-2.2 to PAN-2.6 based on erosional surfaces, (shingled) clinoforms and log data from wells Jennersdorf 1 (JE1), JD, and GST (Fig. 18). The HSTs of PAN-2.2 and PAN-2.5 prograde south(east)ward and the HSTs of PAN-2.3 and PAN-2.4 are aggrading. The most prominent erosion surface forms the boundary between PAN-2.4 and PAN-2.5 (see JE0103; Fig. 17). The most prominent MFS on the well logs is MFS-2.6 (Fig. 18).

5. Discussion

5.1 Ottnangian/Karpatian

From the data of the present study, no final conclusion can be drawn about Ottnangian sequences. Onlaps formed by Karpatian rocks in the Jennersdorf area (JE0103; Fig. 17) represent a Karpatian TST. In the northern (OL0201; Fig. 4) and central Fürstenfeld Subbasin (F205; Fig. 8), Karpatian rocks form south dipping clinoforms below the Karpatian/Badenian boundary indicating southward progradation of fluvial fans (Sinnersdorf Fm.) and deltaic systems (Conglomerate-rich group). Similar southward progradation of upper Karpatian delta sequences have been observed on seismic lines in the Gnas Subbasin and have been attributed to a Late Karpatian HST (Sachsenhofer et al., 1996). We speculate that the TST and the HST form part of a 3rd order sequence (KAR-1),

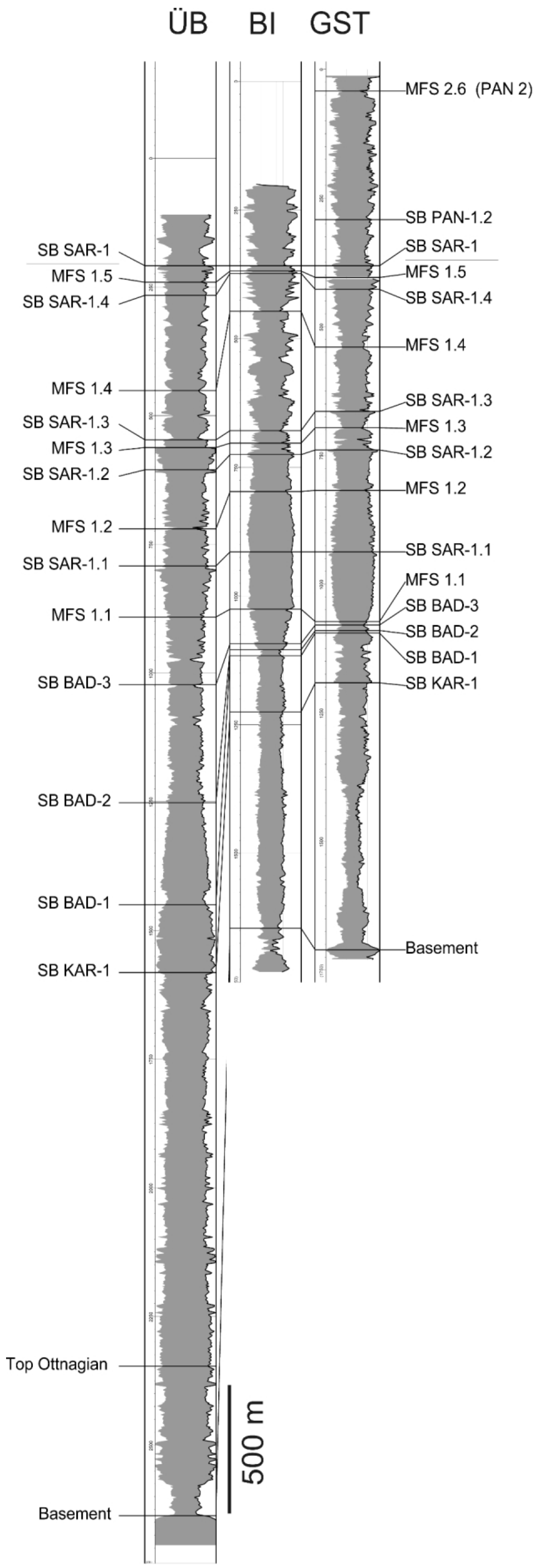

Figure 14: Cross section based on mirrored resistivity logs of wells Übersbach 1 (ÜB), Binderberg 1 (BI) and Grieselstein Thermal 1 (GST). Datum is the Sarmatian/Pannonian boundary (SAR-1).

which is roughly coeval with the global 3rd order sequence TB 2.2. However, it is likely that during Ottnangian and Karpatian times synrift tectonic subsidence rates overruled any eustatic signature.

5.2 Karpatian/Badenian Boundary

In seismic sections the Karpatian/Badenian boundary is typically formed by the lowermost continuous high-amplitude reflector. This reflector is generally more prominent than the basement reflector. Erosional features are observed in section JE0103 (Fig. 17). Along the southern part of F210 (Fig. 7) the Karpatian/Badenian boundary is an angular unconformity ("Styrian Unconformity") resulting from block rotations. Thus, it is obvious that the sequence boundary is tectonically determined. The additional influence of a global sea level fall at the Karpatian/Badenian boundary cannot be appraised from our data.

5.3 Badenian

The Badenian succession in the Fürstenfeld Subbasin is subdivided into three 3rd order sequences (BAD-1 to BAD-3). These correspond to those described in seismic studies of the Vienna Basin (Strauss et al., 2006) and the Transylvanian Basin (Krézsek and Filipescu, 2005), which traditionally are correlated with the global 3rd order cycles (TB 2.3 to TB 2.5) of Haq et al. (1988). New biostratigraphic data of Rögl et al. (2007), however, suggest that this correlation should be treated with caution (Fig. 2).

In the northern Fürstenfeld Subbasin BAD-1 to BAD-3 include three prograding deltaic complexes. BAD-1 is the equivalent of Lower Badenian rocks (Tauchen Formation) exposed in the Pinkafeld area (Nebert, 1985). A coal seam up to 25 m thick occurs near the base of the Tauchen Formation. Most probably, the stratigraphic position of the seam coincides with the TST of BAD-1. The Tauchen Formation has been dated as late Early Badenian (Upper Lagenidae Zone) to early Middle Badenian. Younger Badenian rocks (equivalent to BAD-2 and BAD-3) are missing in outcrops, but reworked Upper Badenian foraminifera occur in Sarmatian sediments near Pinkafeld (Hermann, 1984). This indicates there was a wide northward extension of BAD-2 and BAD-3 reworked by an erosional event at the Badenian/Sarmatian boundary in the Friedberg-Pinkafeld Embayment. The relative sea level fall between sequences BAD-2 and BAD-3 cannot be quantified in the Friedberg-Pinkafeld Embayment. However, outcrop studies along the Middle Styrian Swell suggest a drop in the order of 30 to 50 m (Friebe, 1993).

Marine sedimentation with mudstones and turbiditic rocks prevailed in the central Fürstenfeld Subbasin. The HST of Upper Badenian sequence BAD-3 probably includes northward prograding corallinacean limestone (F210, Fig. 7). These are equivalent to Badenian limestones of the Weissenegg Formation exposed in the Klapping outcrop (Harzhauser and Piller, 2004a).

Báldi et al. (2002) distinguished three Badenian cycles in the southwestern part of the Pannonian Basin and concluded that the first two were tectonically controlled, whereas the third one was primarily controlled by global sea level variations. According to these authors, the unconformities between the sedimentary cycles formed by uplift triggered by compression. No evidence for compression and uplift events can be found in the Styrian Basin.

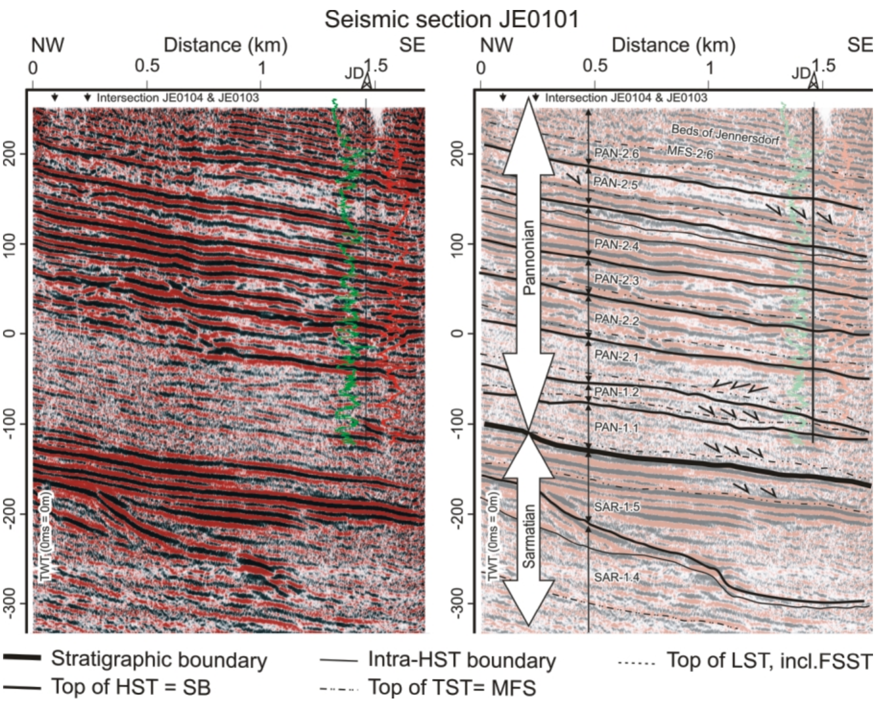

Figure 15: Seismic section JE0101 with gamma (γ) and resistivity (R) logs of well JD and its interpretation. See Figure 1 for position of seismic section.

5.4 Sarmatian

The Badenian/Sarmatian boundary is characterized by a drop in relative sea level of at least 50 to 80 m, resulting in major erosion along the northern margin of the Fürstenfeld Subbasin (Fig. 4), at the Klapping outcrop on the South Burgenland Swell (Harzhauser and Piller, 2004a) and in the southern part of the central Fürstenfeld Subbasin (F210; Fig. 7). Major erosion also occurred in the Vienna Basin (Strauss et al., 2006). Because evidence for tectonic events is missing, a eustatic cause for the sea level fall seems most likely.

Harzhauser and Piller (2004b) divided the Sarmatian into two 4th order sequences (LS-1, US-2, Fig. 2). In this paper, the Sarmatian succession is subdivided into five 4th order sequences. In contrast, Schreilechner and Sachsenhofer (2007) classified the subdivision as 5th order. However, the duration of the sequences argues for 4th order. The entire Sarmatian stage covers roughly 1 Ma resulting in an average duration of each sequence of about 0.2 Ma. The good sequence resolution is probably a result of moderate subsidence rates and high sediment supply (e.g., Vakarcs et al., 1994). According to Schäfer (2005), 4th order cycles may be explained by the influence of Milankovich cyclicity. However, in the present case the limited age control does not allow an attribution of the observed 4th order cycles to orbital cycles.

SAR-1.1 to SAR-1.3 represent the Lower Sarmatian succession. The general transgressive character of SAR-1.1 and SAR-1.2 in the northern Fürstenfeld Subbasin suggests that these sequences form part of the LST and TST of the 3rd order sequence SAR-1. Based on similar ages, the Sarmatian 3rd order sequence has been correlated with the global cycle TB 2.6 (e.g., Harzhauser and Piller, 2004b; Strauss et al., 2006).

The seismic facies in both, SAR-1.1 (northern Fürstenfeld Subbasin) and SAR-1.2 (northern and central Fürstenfeld Subbasin) suggest the presence of carbonates. Outcrop equivalents (Grafenberg, Klapping) suggest these are bryozoanserpulid limestones of the Grafenberg Formation, which prograde to the center of the Fürstenfeld Subbasin. The HST of SAR-1.3 is composed of the Carinthian Gravel.

SAR-1.4 and SAR-1.5 represent the Upper Sarmatian succession (US-2 of Harzhauser and Piller, 2004b) and are equal to 4th order sequences USa-1 and USa-2 of Kosi et al. (2003). They correspond to the Gleisdorf Formation. Only SAR-1.4 is present at the northern margin of the Fürstenfeld Subbasin, whereas SAR-1.5 is missing, probably because of erosion at the Sarmatian/Pannonian boundary. Erosional events on top of both, SAR-1.4 and SAR-1.5 are clearly visible in F210 (Fig. 12). These indicate that drops in relative sea level of about 50 m were not restricted to the Sarmatian/Pannonian boundary (top of SAR-1.5), but also occurred during the Late Sarmatian. The overall picture confirms frequent sea level fluctuations during Sarmatian times, as postulated by Harzhauser and Piller (2004a). Both, tectonic (Horváth, 1995) and eustatic causes (Vakarcs et al., 1999) for Late Sarmatian fluctuations in relative sea level have been argued (Magyar et al., 1999).

5.5 Pannonian

Based on a major erosional event indicated by a 45 m deep incised valley (RI9901; Fig. 10), the Pannonian succession in the Styrian Basin is subdivided into sequences PAN-1 and PAN-2. These are correlated with 3rd order sequences PAN-1 and PAN-2 defined by Sacchi et al. (1999) and Sacchi and Horváth (2002; see Fig. 2).

Following the Sarmatian/Pannonian boundary, an Early Pannonian transgression caused basinwide flooding of the Styrian Basin (TST of PAN-1). The flooding is related to a significant expansion of Lake Pannon (Magyar et al., 1999). An erosional event in the Weichselbaum Graben (JE0102, Fig. 16), located at the transition between the Styrian and Pannonian basins, provides evidence for a subdivision of PAN-1 (LPa-1 according to Kosi et al., 2003) into two 4th oder sequences (PAN-1.1, PAN-1.2). The subdivision is less clear in the central Fürstenfeld Subbasin, where Kosi et al. (2003) split the HST of PAN-1 (=LPa-1) into two parasequences. These authors correlated the Eisengraben Member of the Feldbach Formation with the TST and the Sieglegg Member of the Feldbach Formation with the early HST. The Kapfenstein Member and the lowermost Mayerhanslberg Member of the Paldau Formation form the late HST.

PAN-2 is separated in the Weichselbaum Graben into six 4th order sequences. The lowermost 4th order sequences PAN-2.1 and PAN-2.2 correspond to LPa-2 of Kosi et al. (2003). PAN-2.1 and PAN-2.2 (=LPa-2) can be distinguished only in the Jennersdorf area. Kosi et al. (2003) associate the MFS of LPa-2 with the Münzgraben Bed (Mayerhanslberg Member of

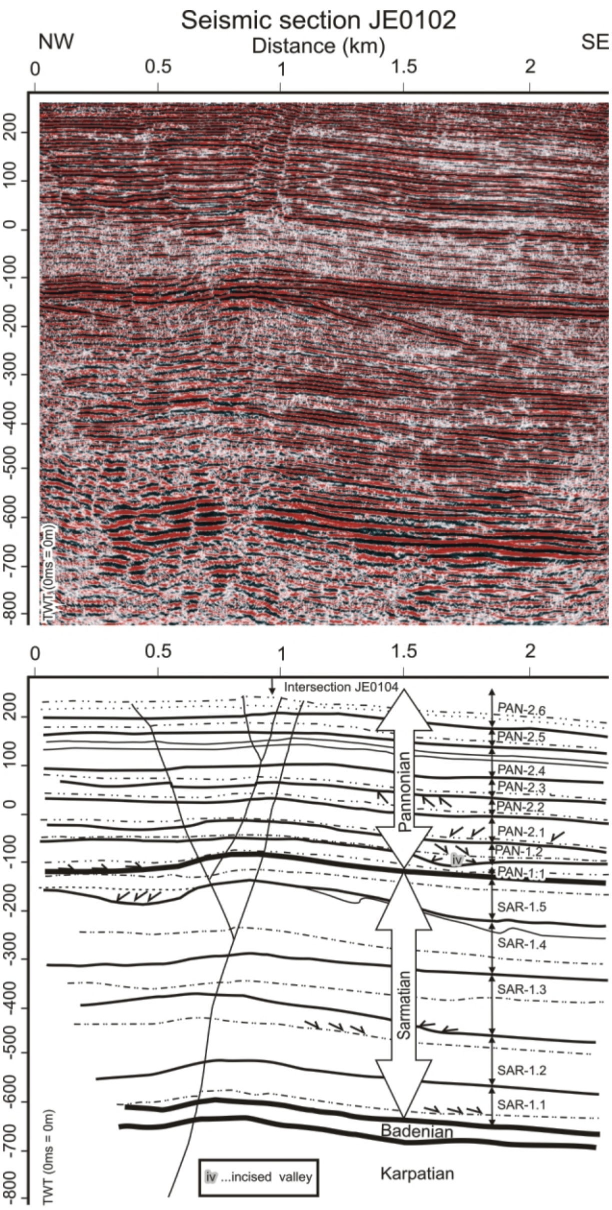

Figure 16: Seismic section JE0102 and its interpretation. See Figure 1 for position of seismic section and Figure 15 for legend.

the Paldau Formation). Because the Jennersdorf sections are not connected with sections in the central Fürstenfeld Subbasin, it remains unclear whether the Münzgraben Bed belongs to PAN-2.1 or PAN-2.2. PAN-2.1 in the Weichselbaum Graben is unique in including a HST having northward progradation.

PAN-2.3 to PAN-2.5 represent the Beds of Loipersdorf and Unterlamm.

The Tabor Gravel is located at the base of the Jennersdorf Beds (Pannonian G). The depth of the Tabor Gravel in a borehole located at section UL9901 (distance marker 8 km) is shown in Fig. 11 according to Goldbrunner et al. (1994). The position indicates that the Tabor Gravel forms the base of PAN-2.6. In surface outcrops the Tabor Gravel cuts unconformably into the Beds of Loipersdorf and Unterlamm and even into the Paldau Formation (Gross, 2003). Therefore, the Tabor Gravel is attributed to the LST of PAN-2.6. According to Harzhauser et al. (2004) the Pannonian G (Papp, 1951) spans the period from 9.55 to 8.55 Ma and includes the boundary between chrons C4Ar and C4An (9.03 Ma), which, according to Sacchi et al. (1999) and Sacchi and Horváth (2002), defines the MFS of 3rd order sequence PAN-2 (=MFS-2). The maximum flooding also caused the maximum extension of Lake Pannon (c. 9.5 Ma; Magyar et al., 1999). Therefore, we correlate the MFS of PAN-2.6 with the MFS of PAN-2.

Mattick et al. (1994) attribute the origin of unconformities in the Pannonian succession of the Békés Basin to delta lobe switching. Pogácsás et al. (1994) argue that some of the unconformities are related to lake-level changes, caused by fluctuations in eustatic sea level, whereas Juhász et al. (1999) emphasize climatic control. It is impossible to decide, which of these factors controlled the observed Pannonian sequences in the study area.

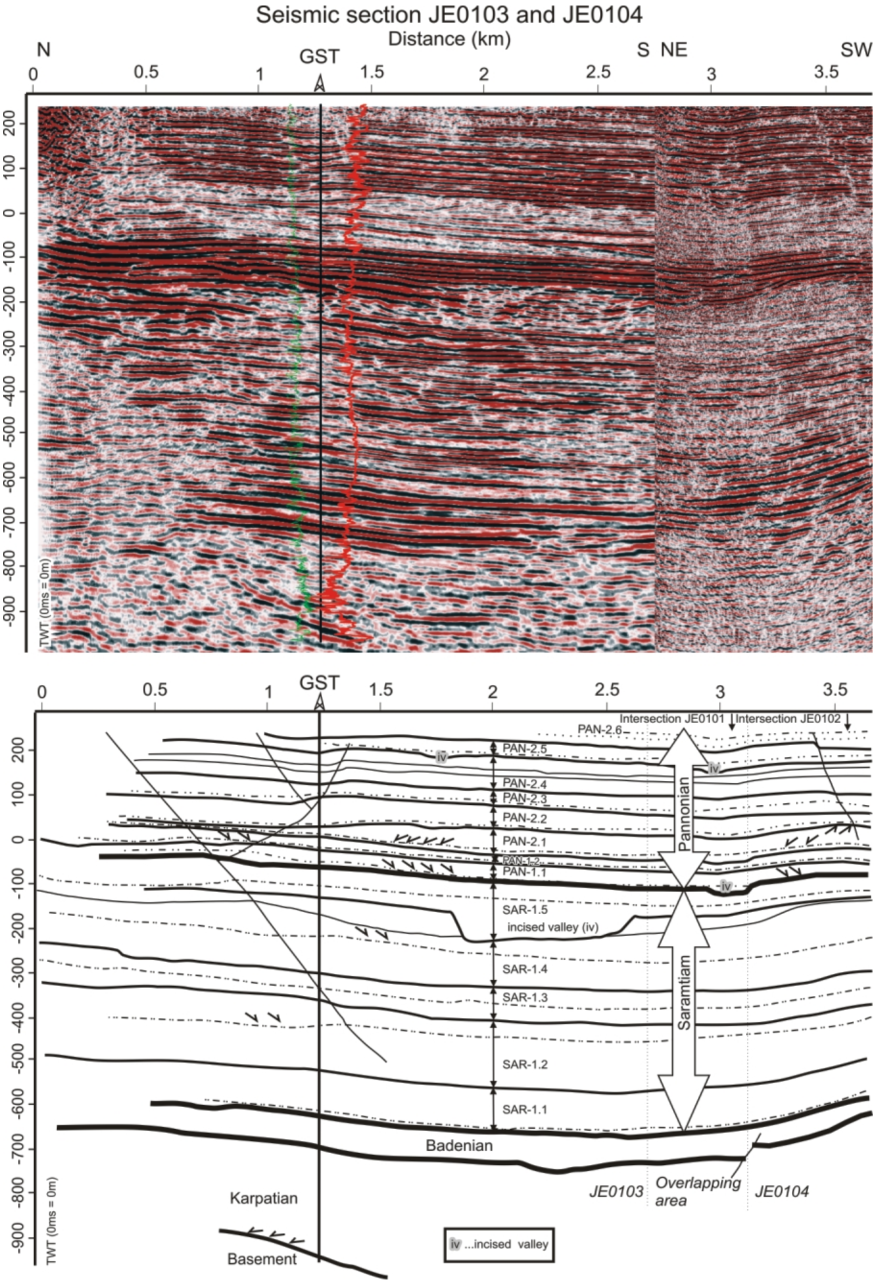

Figure 17: Seismic sections JE0103/JE0104 with gamma (γ) and resistivity (R) logs of well GST and there interpretation. See Figure 1 for position of seismic sections and Figure 15 for legend.

6. Conclusions

A high resolution sequence stratigraphic framework for the Styrian Basin is presented. The Badenian to Pannonian succession is subdivided into six 3rd order sequences.

- The Karpatian/Badenian boundary ("Styrian Unconformity") is a sequence boundary, which is obviously tectonically determined. A possible influence of a coeval global sea level fall cannot be evaluated.
- The Badenian is subdivided into three 3rd order sequences (BAD-1 to BAD-3) attributed to the Lower, Middle and Upper Badenian. The assignment to global cycles TB 2.3 to TB 2.5 is problematic given the lack of reliable age data. In the northern Fürstenfeld Subbasin BAD-1 to BAD-3 include three prograding deltaic complexes. Marine sedimentation with mudstones and turbiditic rocks prevailed in the central Fürstenfeld Subbasin. The HST of Upper Badenian sequence BAD-3 probably includes northward prograding corallinacean limestone in the central

Fürstenfeld Subbasin.

- A major fall in seal level, probably caused by eustatic seal level variations, occurred at the Badenian/Sarmatian boundary between BAD-3 and SAR-1. In the northern Fürstenfeld Subbasin the relative sea level dropped at least 50-80 m.
- The 3rd order Sarmatian sequence SAR-1 is correlated with the global cycle TB 2.6. In the Styrian Basin, SAR-1 is subdivided into five 4th order sequences. SAR-1.1 to SAR-1.3 represent the Lower Sarmatian succession (Grafenberg Formation). SAR-1.1 correlates with the LST of SAR-1. SAR-1.2 forms part of the TST of SAR-1. Seismic facies suggest the presence of bryozoan-serpulid limestones in SAR-1.1 and SAR-1.2. The HST of SAR-1.3 consists of the Carinthian Gravel.

  SAR-1.4 and SAR-1.5 represent the Upper Sarmatian succession (Gleisdorf Formation). Erosional events on top of SAR-1.4 and SAR-1.5 indicate major drops in relative sea level during Late Sarmatian times and at the Sarmatian/Pannonian boundary.
- The depths of incised valleys at the Sarmatian/Pannonian boundary indicate a relative sea level fall of at least 50 m.
- The Pannonian succession in the Styrian Basin is subdivided into 3rd order sequences PAN-1 and PAN-2. Following the Sarmatian/Pannonian boundary, an Early Pannonian transgression caused basin wide flooding. An erosional event in the Weichselbaum Graben provides evidence for a subdivision of PAN-1 into 4th order sequences PAN-1.1 and PAN-1.2. PAN-1 is formed by the Feldbach Formation. PAN-2 is separated from PAN-1 by an erosional event caused by a drop in relative sea level of at least 45 m. PAN-2 is subdivided into six 4th order sequences. The lowermost 4th order sequences PAN-2.1 and PAN-2.2 correspond to the Paldau Formation. PAN-2.3 to PAN-2.5 represent the Beds of Loipersdorf and Unterlamm. The Tabor Gravel forms the LST of PAN-2.6. The TST and HST are formed by the Beds of Jennersdorf. The MFS of PAN-2.6 is correlated with the MFS of PAN-2, dated as 9.03 Ma by Sacchi and Horváth (2002).

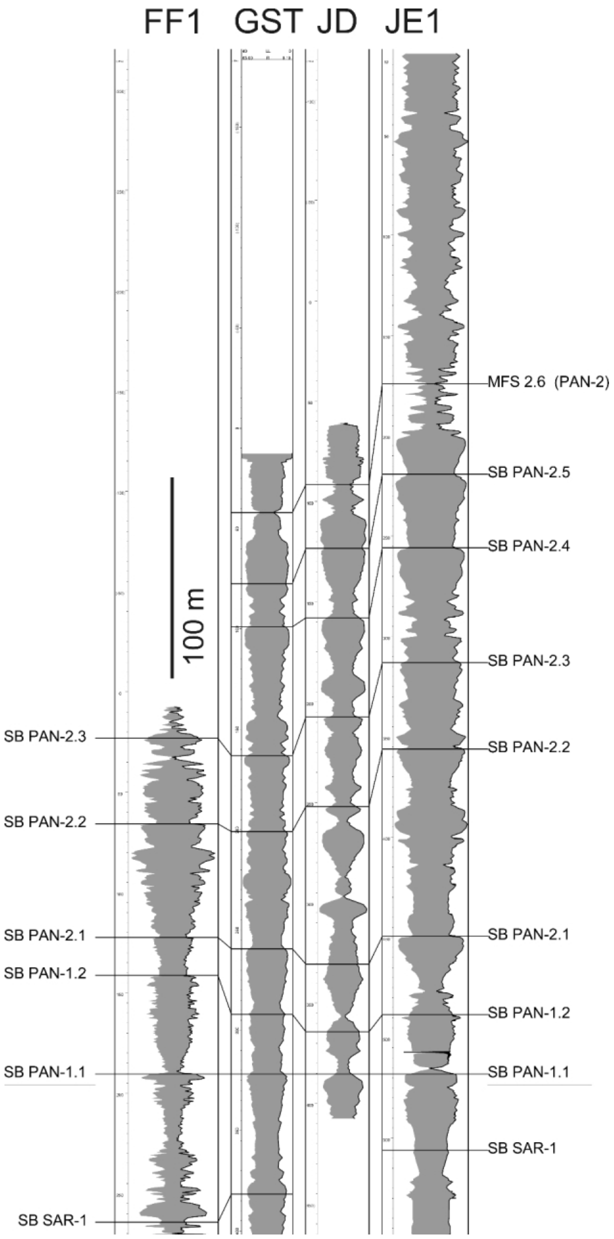

Figure 18: Cross section based on mirrored resistivity logs of wells Fürstenfeld 1 (FF1), Grieselstein Thermal1 (GST), Jennersdorf (JD) and Jennersdorf1 (JE1) showing the subdivision of the Pannonian succession into 4th order sequences. The MFS-2.6 corresponds to the MFS-2 of PAN-2 after Sacchi and Horváth (2002). Datum is SB PAN-1.1.

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