

High Resolution Sequence Stratigraphy of Upper Sarmatian and Lower Pannonian Units in the Styrian Basin, Austria

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Abstract: By integrating seismic data, well logs, and detailed information from outcrops, a sequence stratigraphic framework for Upper Sarmatian and Lower Pannonian rocks in the Eastern Styrian Basin was established.

The Upper Sarmatian and Lower Pannonian succession is subdivided into four 3rd or 4th order unconformity-bounded sequences (USa-1; USa-2; LPa-1; LPa-2). The Upper Sarmatian Gleisdorf Formation comprises sequences USa-1 with progradational parasequences of a highstand systems tract (HST) and USa-2 formed by an aggradational parasequence set of a shelf margin systems tract (SMST).

A relative fall in sea level at the Sarmatian/Pannonian boundary caused the incision of valleys up to 60 m deep. Above this type 1 sequence boundary LPa-1 was deposited, which consists of lowstand systems tract (LST), transgressive systems tract (TST) and HST. The HST is subdivided into two parasequences. The Eisengraben Member (Feldbach Formation) forms the TST. The Sielegg Member (Feldbach Formation) forms the early HST. The Kapfenstein Member and the lowermost Mayerhanselberg Member (Paldau Formation) form the late HST.

LPa-2 consists of LST (lowstand prograding wedge), TST, and HST. The Münzengraben Bed is associated with the maximum flooding surface. The Kirchberg and Karnerberg Members represent coarse-clastic deposits at the top of prograding parasequences. The sequence stratigraphic interpretation of the “Beds of Loipersdorf and Unterlamm”, which overlie LPa-2, remains unclear.

A comparison with the Western Pannonian Basin and the Vienna Basin shows that the Sarmatian/Pannonian boundary is formed by a type 1 unconformity related to a major global sea level fall in all three areas. A good agreement exists between Lower Pannonian sequences in the Styrian Basin and in the Vienna Basin.

The seismic lines provide evidence for Sarmatian normal(?) faulting along the western margin of the South Burgenland Swell and post-Early Pannonian strike-slip faulting. Pannonian tilting of the Eastern Styrian Basin and Pliocene to Quaternary uplift of the Styrian Basin caused truncation of Middle Pannonian strata.

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Zusammenfassung: Auf Grundlage seismischer Daten, Bohrlochmessungen und detaillierter Aufschlussbeschreibungen, wird ein sequenzstratigraphischer Rahmen für die obersarmatischen und pannonischen Sedimente des Steirischen Beckens erstellt.

Die Sedimente des Obersarmatium und des Pannonium werden in vier Sequenzen dritter oder vierter Ordnung unterteilt (USa-1; USa-2; LPa-1; LPa-2). Innerhalb des Untersuchungsgebietes beinhaltet die obersarmatische Gleisdorf-Formation die Sequenzen USa-1 (progradierende Parasequenzen eines highstand systems tract; HST) und USa-2 (aggradierendes Parasequenzset eines shelf margin systems tract; SMST).

Ein relativer Meeresspiegelabfall an der Sarmatium/Pannonium-Grenze führte zur Bildung von bis zu 60 m tiefen Tälern. Über der Typ 1 Sequenzgrenze folgt die Sequenz LPa-1, die aus einem lowstand systems tract (LST), einem transgressive systems tract (TST) und einem HST besteht. Der HST wird in zwei Parasequenzen untergliedert. Die Eisengraben-Subformation (Feldbach-Formation) bildet den TST. Die Sieglegg-Subformation (Feldbach-Formation) bildet den frühen HST. Die Kapfenstein-Subformation und der unterste Teil der Mayerhanselberg-Subformation (Paldau-Formation) bilden den späten HST.

LPa-2 besteht aus einem LST (lowstand prograding wedge), TST und HST. Die Münzengraben-Bank repräsentiert den Horizont maximaler Überflutung. Die grobklastischen Kirchberg- und Karnerberg-Subformationen wurden am Top von progradierenden Parasequenzen abgelagert. Die sequenzstratigraphische Klassifizierung der „Schichten von Loipersdorf und Unterlamm“, die die Sequenz LPa-2 überlagern, bleibt unklar.

Ein Vergleich mit dem westlichen Pannonischen Becken und dem Wiener Becken zeigt, dass in allen untersuchten Gebieten die Grenze zwischen Sarmatium und Pannonium durch eine Typ 1 Sequenzgrenze gebildet wird, welche einen globalen Meeresspiegelrückgang repräsentiert. Zwischen unterpannonischen Sequenzen im Wiener und Steirischen Becken existiert eine gute Übereinstimmung.

Die seismischen Daten belegen sarmatische Aktivität von Abschiebungen entlang der Südburgenländischen Schwelle und post-unterpannonische Seitenverschiebungen. Eine Kippung des östlichen Steirischen Beckens im Pannonium und pliozäne bis quartäre Hebung des Steirischen Beckens führten zur Erosion mittelpannonischer Sedimente.

Keywords: Sequence Stratigraphy, Miocene, Pannonian, Sarmatian, Styrian Basin, Pannonian Basin

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1. INTRODUCTION

The Miocene Styrian Basin is located at the eastern margin of the Alps (Fig. 1). It is part of the Pannonian Basin System and is separated from other basins of the Pannonian realm by the South Burgenland Swell. The Middle Styrian Swell separates the shallow Western from the deeper Eastern Styrian Basin, which is filled with Ottnangian (Lower Miocene) to Pannonian (Upper Miocene) rocks more than 4 km thick (SACHSENHOFER et al., 1996). Sarmatian (Middle Miocene) and Pannonian deposits prevail at the surface (KOLLMANN, 1965). Exposures of these strata were studied recently in great detail (KRAINER, 1987a,b; FRIEBE, 1994; GROSS, 1997, 2000). Several high resolution seismic surveys were carried out during the last few years in the Eastern Styrian Basin in the frame of groundwater prospection.

In the present study the seismic data were used together with well log data (gamma ray, resistivity) and outcrop information to establish a sequence stratigraphic framework for Upper Sarmatian and Pannonian strata. Underlying deposits were not considered, because the acquisition parameters of the seismic lines were optimized for shallow levels and the resolution of the seismic lines rapidly decreases with depth. During Middle and Late Miocene times the study area was located in the transition zone between fluvial and marine or lacustrine environments. Therefore, this area is well suited for high resolution sequence stratigraphic studies, although time constraints for the rocks are poor.

2. GEOLOGICAL SETTING

The Neogene Styrian Basin represents an extensional structure on top of a crustal wedge, which was moving eastward during the final stages of the Alpine orogeny (EBNER & SACHSENHOFER, 1995). Eastward extrusion was a consequence of continental escape and extensional collapse within the Eastern Alps (RATSCHBACHER et al., 1991).

In a simple model the evolution of the Styrian Basin can be subdivided into an Ottnangian to Karpatian synrift and a subsequent postrift phase. During the synrift phase more than 2000 m of limnic and marine sediments were deposited. Karpatian to Early Badenian magmatism commenced during the synrift stage and continued into the postrift stage. Huge volcanic complexes with acidic to intermediate compositions were formed (Fig. 1). Today, the volcanoes are nearly totally buried by younger sediments.

Synrift sediments are separated by a major unconformity from Badenian to Upper Pannonian postrift sediments. Sedimentation during the postrift phase was controlled by marine incursions during Early Badenian and Sarmatian times and a subsequent shift in water chemistry. Along the northern basin margin, marine environments interfingered with Sarmatian fluvial and lagoonal depositional settings (KRAINER, 1987a). Marine conditions continued until Late Sarmatian times and were only interrupted when up to 30 m

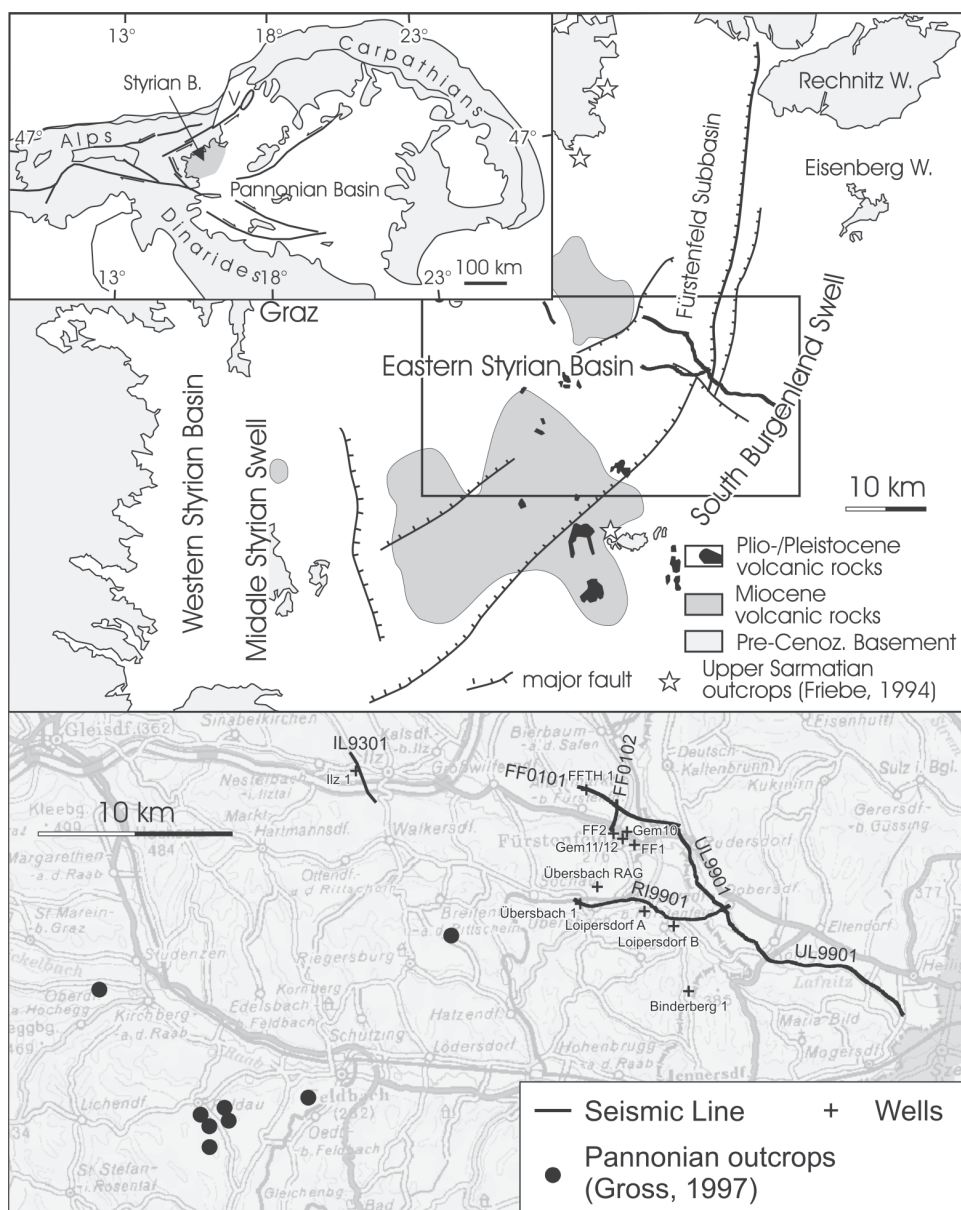


Fig. 1: Location map showing position of study area within the Pannonian Basin System and sketch maps of the Styrian Basin with position of seismic lines, wells, and outcrops used in this study. V – Vienna Basin.

thick fluvial gravels (Carinthian Gravel; KOLLMANN, 1965; SKALA 1967) were transported from a southwestern hinterland into the Eastern Styrian Basin.

Following a minor Sarmatian extension phase, subsidence rates slowed down during Pannonian times (SACHSENHOFER et al., 1997). Salinity decreased and marine conditions ended during the Early Pannonian (see also GEARY et al. 1989; MAGYAR et al., 1999). Afterwards alluvial fans developed along the northern margin of the Eastern Styrian Basin and continued to the south into an alluvial plain and deltaic environments. In Pliocene times subsidence was replaced by uplift, which resulted in the erosion of a few hundred meters of sediment. A second volcanic phase produced basalts in Plio-/Pleistocene times.

3. LITHOSTRATIGRAPHY OF UPPER SARMATIAN AND PANNONIAN UNITS

FRIEBE (1994) and GROSS (2000) studied Upper Sarmatian and Lower Pannonian sediments of the Styrian Basin. Fig. 2 shows the lithostratigraphic units distinguished by GROSS (2000, this volume).

The marine/brackish Upper Sarmatian Gleisdorf Formation overlies the fluvial "Carinthian Gravel". KOLLMANN (1965) distinguished an upper and a lower fossil-poor and a middle fossil-rich interval within the Upper Sarmatian deposits. FRIEBE (1994) described mixed siliciclastic-carbonate successions. The uppermost part of the Gleisdorf Formation in the Feldbach area is characterized by limnic-deltaic rocks with subordinate coaly layers (lignite of Feldbach).

Pannonian strata unconformably overlie Sarmatian rocks. Clays, silts and marls with fossils (*Congerina ornithopsis*, *Melanopsis* sp., *Lymnocardium* and ostracodes) form the Eisengraben Member representing the lowermost part of the Pannonian succession. The following Sieglegg Member is characterized by limnic-deltaic clays and sands. The Eisengraben Member and the Sieglegg Member form the Feldbach Formation (GROSS, 2000, this volume).

The overlying Paldau Formation comprises several members. The Kapfenstein Member with fluvial sandy gravels forms the base of the Paldau Formation and interfingers with the limnic-deltaic Mayerhanselberg Member. The Münzengraben Bed within the Mayerhanselberg Member forms a distinct horizon and is characterized by fossils indicating low energy oligohaline environments (see GROSS, this volume, for a list of fossils). Fluvial gravels in the middle and upper part of the Paldau Formation form the Kirchberg and Karnerberg Members, which are separated by interfingering clay-sand deposits.

Middle Pannonian sediments are represented by the "Beds of Loipersdorf and Unterlamm" with interbedded sands and clays and subordinate layers of gravel (KOLLMANN, 1965; GROSS, 2000, this volume).

4. DATA SET AND METHODS

The present study integrated seismic data, well logs and detailed outcrop information. Fig. 1 shows the location of the seismic lines, boreholes and outcrops. The seismic data were processed following standard procedures for land seismic data. Well log data

Paratethys stages	Bio-zonation	"Papp" zones	Lithostratigraphic units GROSS (2000, this volume)	Absolute ages Ma
Pannonian	<i>Congerina partschikovi</i> zone	D - E	Beds of Loipersdorf and Unterlamm	10.8
	<i>Congerina hoernesii</i> - zone	C	Karnerberg Member Kirchberg Member Mayerhanselberg Member Kapfenstein Member	
	<i>Congerina ornithopsis</i> / <i>Melanopsis impressa</i> - zone	A / B	Feldbach Formation Sieglegg Member Eisengraben Member	11.5
			Gleisdorf Formation	
Sarmatian				

Fig. 2: Lithostratigraphy of Upper Sarmatian and Pannonian strata after GROSS (2000, this volume). Biozones and absolute ages follow RÖGL & DAXNER-HÖCK (1996).
M – Münzengraben Bed.

(gamma ray and resistivity logs) and descriptions of cuttings were considered. Unfortunately, no cores were available. The interpretation of the seismic and well log data was greatly supported by excellent outcrop data (KOLLMANN, 1965; KRÄINER, 1987b; FRIEBE, 1994; GROSS, 2000, this volume).

The sequence stratigraphic concept relies on the methodology and terminology of MITCHUM et al. (1977 a,b), SANGREE & WIDIMIER (1977), VAIL et al. (1977 a,b), POSAMENTIER & VAIL (1988), POSAMENTIER et al. (1988), and VAN WAGONER et al. (1988, 1990).

5. SEISMIC AND SEQUENCE STRATIGRAPHY

5.1. Well cross section, seismic facies and log facies

The seismic lines studied are presented in Figs. 3–5. A well cross section displaying gamma ray and resistivity logs is shown in Fig. 6.

Different seismic facies have been recognized. The well log response, reflection characteristics, and palaeo-environmental interpretations are summarized in Fig. 7. Note, that well logs are not necessarily from the pictured zone of the seismic facies, but show a representative response of the logs to the lithologies corresponding to the seismic facies.

5.2. Sequence Stratigraphy

Both the Upper Sarmatian Gleisdorf Formation of Friebe (1994) and the Lower Pannonian rock column were subdivided into two sequences.

5.2.1. Upper Sarmatian Sequence 1 (USa-1)

Sequence USa-1 corresponds to the main part of the Gleisdorf Formation, which is 232 m thick in borehole Ilz 1 (SCHEIFINGER et al., 1999) and 325 m in borehole Übersbach RAG.

The base of USa-1 is formed by the Carinthian Gravel. These fluvial rocks cover major parts of the Styrian Basin and are genetically related to a Middle Sarmatian highstand systems tract (HST). On the seismic lines the top of the Carinthian Gravel can be recognized as a major continuous high amplitude reflection (Figs. 3, 5). Within borehole Ilz 1 block-shaped gamma ray motifs below 307 m depth indicate that the Carinthian Gravel is about 100 m thick (Fig. 8). Only in the eastern study area (UL9901; Fig. 4), is USa-1 underlain by a fault controlled slope apron along the South Burgenland Swell (Figs. 8, 9).

An Upper Sarmatian relative rise in sea level initiated deposition of rocks of USa-1 (Fig. 8). In the study area USa-1 is composed of a HST containing several prograding parasequences, which are separated by marine flooding surfaces. Clinoform geometries suggest sediment transport mainly from a western direction. Water depth during deposition of the uppermost parasequence was about 60 m (RI9901; stations 100–250) and increased eastward (Fig. 5). Due to poor data quality, a more detailed resolution of the internal architecture (e.g., subdivision into higher order sequences) is impossible.

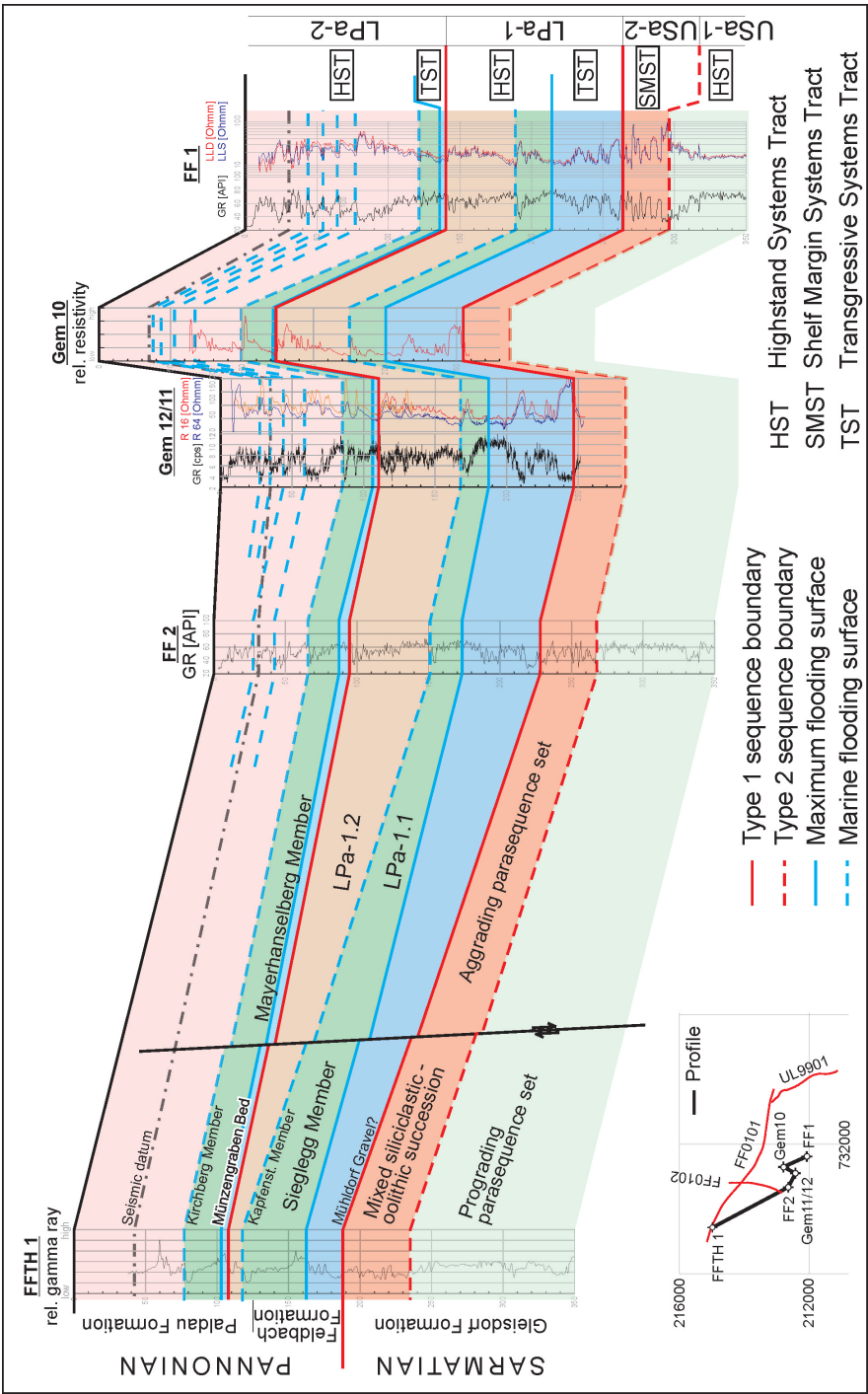


Fig. 6: Well log cross section.

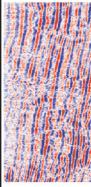
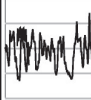
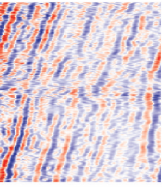
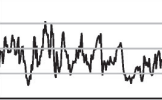
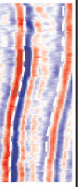
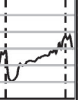
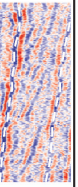
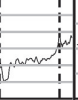
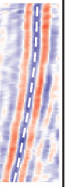
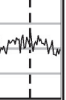
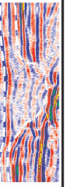
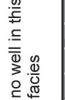
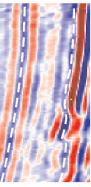
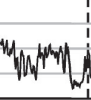
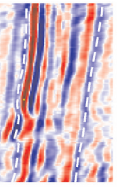
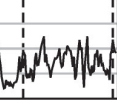
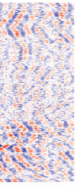
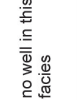
Seismic facies	Well log response	Reflection characteristics	Description and interpretation
	Laf 17 	Amplitude: moderate-high Frequency: low Continuity: high Configuration: parallel External form: sheet	Interbedded sand-shale Sand, shale and subordinate gravel layers; low amplitude reflections in the distal part may indicate an increase in shale contents; shallow lacustrine environment
	FF 2 	Amplitude: low-moderate Frequency: moderate Continuity: low Configuration: subparallel, sigmoidal External form: wedge	Prograding Parasequences Typically coarsening upward cycles with sharp lower boundary representing marine flooding surfaces; several prograding parasequences form a HST
	FFTH 1 	Amplitude: moderate Frequency: low-moderate Continuity: moderate Configuration: subparallel External form: sheet drape	Prograding delta systems Well logs indicate coarsening upward trends. Basal shaly prodelta deposits are characterised by low-amplitude reflections, whereas sandy deltafront-delta plain deposits show continuous reflections with high amplitudes;
	FFTH 1 	Amplitude: moderate Frequency: moderate Continuity: moderate Configuration: sigmoidal, oblique External form: wedge, bank, sheet	oblique or sigmoidal patterns suggest high or low energy environments
	FF 2 	Amplitude: high Frequency: low Continuity: high Configuration: parallel External form: sheet	Maximum Flooding Surface Fine-grained sediments deposited during maximum sea level rise
	no well in this facies 	Amplitude: moderate Frequency: low Continuity: low Configuration: hummocky External form: onlap fill	Incised valley fill Sandy and shaly fluvial or shallow marine sediments deposited during lowstand or early sea level rise
	FF 2 	Amplitude: moderate-high Frequency: moderate Continuity: low-moderate Configuration: subparallel External form: sheet, wedge	Transgressive Systems Tract Well logs indicate fining upward trends. Basal sands are interpreted as sediments reworked during transgression (e.g. Mühldorf Gravel). Beds rich in fossils may occur in upper portions
	FF 2 	Amplitude: high Frequency: variable Continuity: high Configuration: parallel External form: sheet	Shelf Margin Systems Tract Aggradational to slightly progradational parasequence set. Mixed siliciclastic-carbonate succession with oolites; This facies is restricted to the uppermost Gleisdorf Formation
	no well in this facies 	Amplitude: low Frequency: moderate Continuity: low Configuration: chaotic External form: rounded	Pre-Cenozoic Basement Upper Austroalpine Paleozoic (phyllite, carbonate) of the South Burgenland Swell

Fig. 7: Seismic facies recognized in this study, typical wire line logs and environmental interpretations. (Seismic images have different scales).

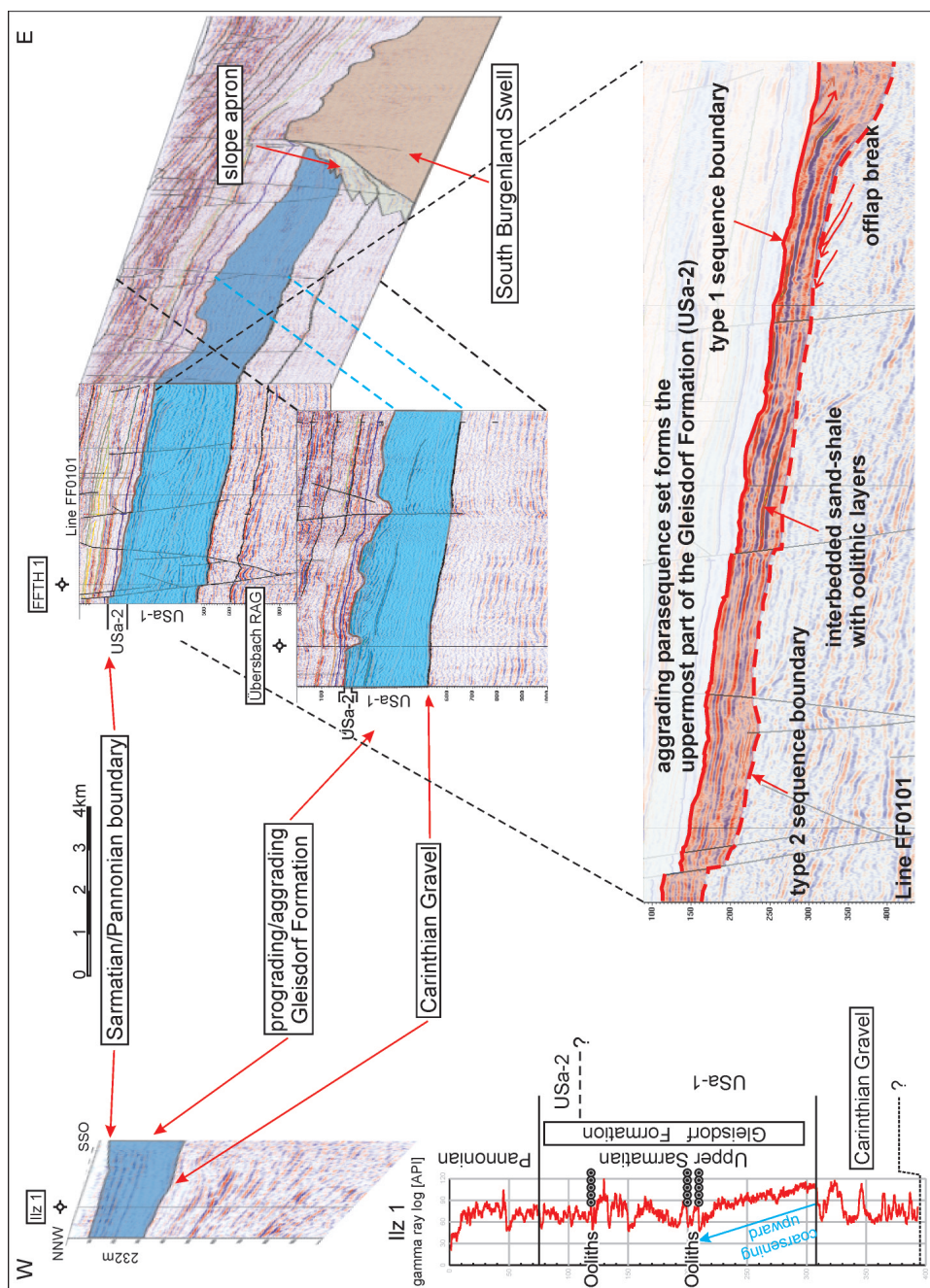


Fig. 8: Illustration of the distribution and seismic patterns of the Upper Sar­matian Gleisdorf Formation (USa-1; USa-2). Detail from seismic line FF0101 shows the aggrading uppermost part of the Gleisdorf Formation (USa-2). Position of oolitic layers in borehole Ilz 1 (SCHEIFINGER et al., 1999) is indicated.

At the upper boundary of USa-1 the prograding succession is replaced by an aggrading parasequence set. Based on our data, it is not completely clear whether the upper boundary of the prograding succession is a marine flooding surface (without subaerial erosion) or a type 2 sequence boundary (with minor erosion). However, questionable truncations (Fig. 5) and onlaps between stations 201 and 301 in FF0101 (Fig. 3) argue for a sequence boundary. Therefore, the uppermost part of the Gleisdorf Formation is considered as a separate sequence (USa-2).

5.2.2. Upper Sarmatian Sequence 2 (USa-2)

The uppermost part of the Gleisdorf Formation is formed by an aggrading mixed siliciclastic-oolithic succession with an average thickness of 50 m. The rock unit was interpreted as a shelf margin systems tract (SMST). Within the succession the offlap break separates an area with shallow water and ooid formation in the west from a deeper water area in the east (Fig. 8). Poor data quality complicates the tracing of the distal USa-2 along UL9901 (Fig. 4). It is also difficult to estimate the thickness of USa-2 in the Ilz area.

Within the Gleisdorf Formation flooding events caused the formation of oolites in different stratigraphic positions. In borehole Ilz 1 oolitic layers occur in a deep stratigraphic position (USa-1) and overlie coarsening upward siliciclastics about 100 m thick. In contrast, oolitic layers in the Fürstenfeld area are restricted to the aggrading parasequence set (SMST of USa-2). The sketch in Fig. 10 summarizes the depositional model of the Gleisdorf Formation. The figure illustrates the eastward movement of the shoreline and the related basinward shift of the site of the oolite formation during the HST of USa-1.

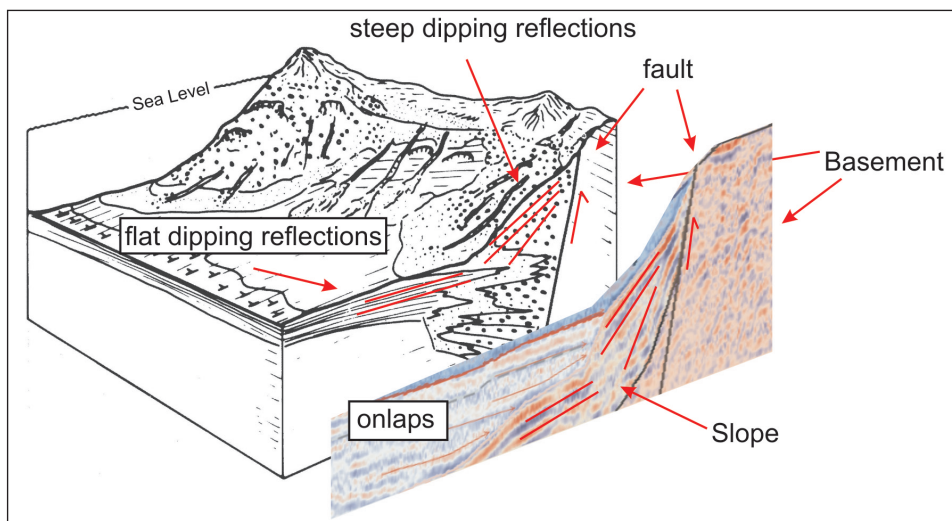


Fig. 9: Seismic patterns at the western margin of the South Burgenland Swell. Scheme of a fault controlled slope apron after STOW (1985) is shown for comparison.

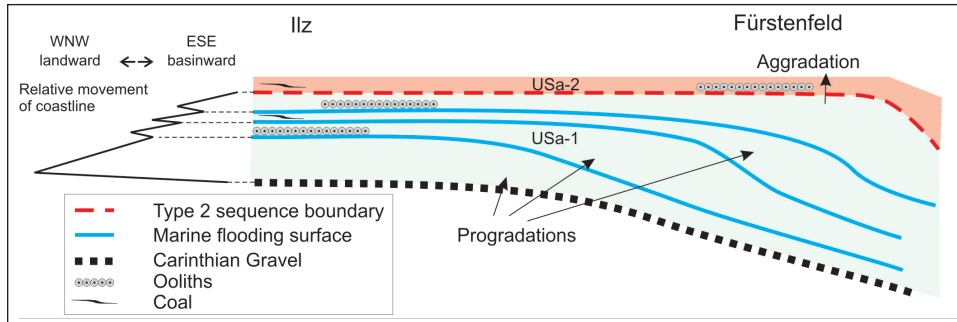


Fig. 10: Sketch demonstrating the depositional model for the Upper Sarmatian Gleisdorf Formation between Ilz and Fürstenfeld.

5.2.3. Sarmatian/Pannonian Boundary

A relative fall in sea level at the Sarmatian/Pannonian boundary caused the incision of valleys up to 60 m deep and more than 300 m wide along line RI9901 (Figs. 5, 11). Locally the entire USA-2 is eroded. No deep paleovalleys are visible in the northern lines FF0101 and FF0102 (Fig. 3). The exact delimitation of erosional features in UL9901 is difficult (see Fig. 4). Obviously, the 2D data do not allow the course of the incised valleys to be mapped.

The paleovalleys classify the erosional surface as a type 1 sequence boundary formed during subaerial exposure. Because of the poor quality of the seismic line, an exact definition of the Sarmatian/Pannonian boundary in the eastern part of line RI9901 was impossible. Alternatives are shown in Fig. 11.

5.2.4. Lower Pannonian Sequence 1 (LPa-1)

Sequence LPa-1 consists of a lowstand systems tract (LST), a transgressive systems tract (TST), and a HST.

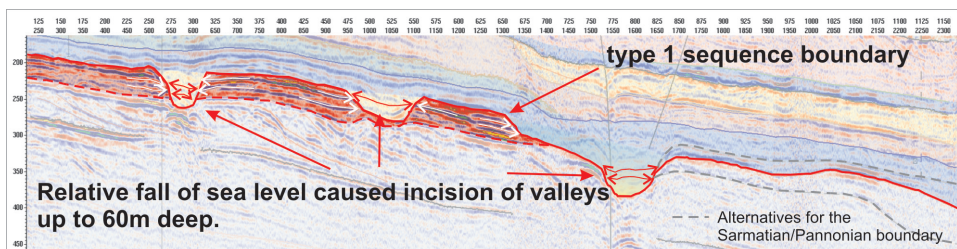


Fig. 11: Detail from seismic line RI9901 illustrating incised valleys at the Sarmatian/Pannonian boundary.

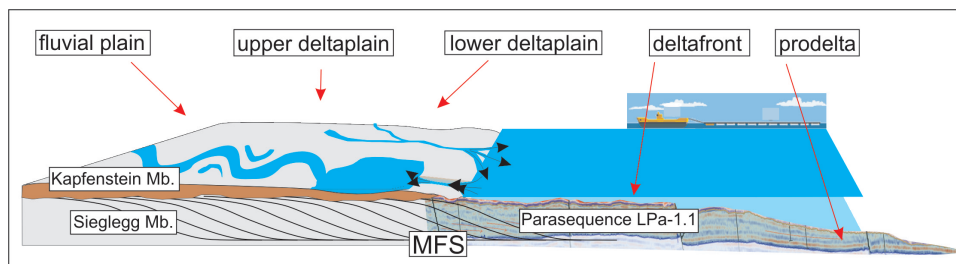


Fig. 12: Cartoon showing the relation between fluvial environments in the Paldau area (GROSS, 1997) and deltaic environments in the Fürstenfeld area.

Onlap channel-fills (Fig. 7) above the type 1 sequence boundary in RI9901 and UL9901 were interpreted as LST deposits. The top of the LST is a transgressive surface (TS). Subsequently a major rise in relative sea level resulted in an extensive transgression, flooding most of the Styrian Basin. Coarse clastic rocks above the TS may represent the Mühldorf Gravel (GROSS, 2000) and are interpreted as reworked older deposits. The TST is formed by the Eisengraben Member (GROSS, 2000, this volume). A *Congerina* bed in the upper part of the TST (KOLLMANN, 1965) indicates brackish low energy environments. The top of the TST is formed by a maximum flooding surface (MFS). The pelites of the MFS were recognized in the seismic lines as continuous high amplitude reflections and in the wireline logs as intervals with high gamma intensity on top of a fining upward sequence (Figs. 6, 7).

The HST of sequence LPa-1 is composed of two parasequences labelled LPa-1.1 and LPa-1.2. Clinoform geometries and coarsening upward trends (Figs. 5, 6) in LPa-1.1 indicate a delta complex prograding towards the southeast. Along the seismic lines fine-grained prodelta clays are overlain by sediments of the deltafront/deltaplain. GROSS (1997) studied this parasequence in a more proximal position (outcrops near Paldau; see Fig. 1) with fluvial deposits (Kapfenstein Member of the Paldau Formation) overlying a coarsening upward cycle (Sieglegg Member of the Feldbach Formation). These fluvial deposits are characteristic of the late HST (POSAMENTIER & VAIL, 1988). The resulting depositional model is illustrated in Fig. 12. A relative rise in sea level interrupted the further progradation of LPa-1.1. Chaotic reflections and onlaps at the distal clinoforms (line FF0101; stations 751–1051; Fig. 3) suggest slumping and deposition of distal delta sediments. The sea level rise resulted in a landward shift of the coastline.

The thickness of the second parasequence LPa-1.2 varies between 55 m (boreholes FF 2, Übersbach 1) and 10 m (FFTH 1; Fig. 6). The observed thickness variations are related to a shift of the point of sediment entry and/or the local topography (delta lobe switching). Rocks of LPa-1.2 are missing in outcrops (GROSS, 1997) suggesting that the westward shift of the coastline due to the rise in sea level did not reach the Paldau area.

During deposition of LPa-1.2, the South Burgenland Swell along line UL9901 became submerged and was covered by sediments.

5.2.5. Lower Pannonian Sequence 2 (LPa-2)

Another relative fall in sea level formed a type 1 sequence boundary and caused minor erosion (Fig. 3) and the deposition of a lowstand prograding wedge (LPW; Figs. 4, 5). Along line UL9901 the LPW exhibits oblique clinoforms suggesting southeastward sediment transport (Fig. 4).

Subsequently, an extensive transgression initiated the deposition of a TST forming part of the Mayerhanselberg Member of the Paldau Formation (GROSS, 1997). The Münzengraben Bed within the Mayerhanselberg Member represents the MFS of LPa-2 (Fig. 13). The coals of Ilz and the coals of the Carolinen- and Emma mine south of Paldau (GROSS, 1998) are associated with this transgression. Sulfur contents ranging from 3 to 9 % (NEBERT, 1988) indicate a brackish environment during coal formation.

The HST is characterized by rapid lateral changes in sediment architecture (Fig. 13). Along line FF0101 the HST comprises several parasequences with coarsening upward sediments (Fig. 13). These short timed cycles can also be recognized in boreholes FF 1, FF 2 and Gem 10/11/12 (Fig. 6). However, the cycles could also be a result of autocyclic processes (delta lobe switching). In borehole Übersbach 1 only one prograding system can be identified.

5.2.6. Middle Pannonian Strata

The sediments above another type 1 sequence boundary are interbedded sands and clays with subordinate layers of gravel. These rocks represent the “Beds of Loipersdorf and Unterlamm” of zone D/E according to PAPP (1951). It was not possible to determine the position of these sediments within the sequence stratigraphic framework from the data.

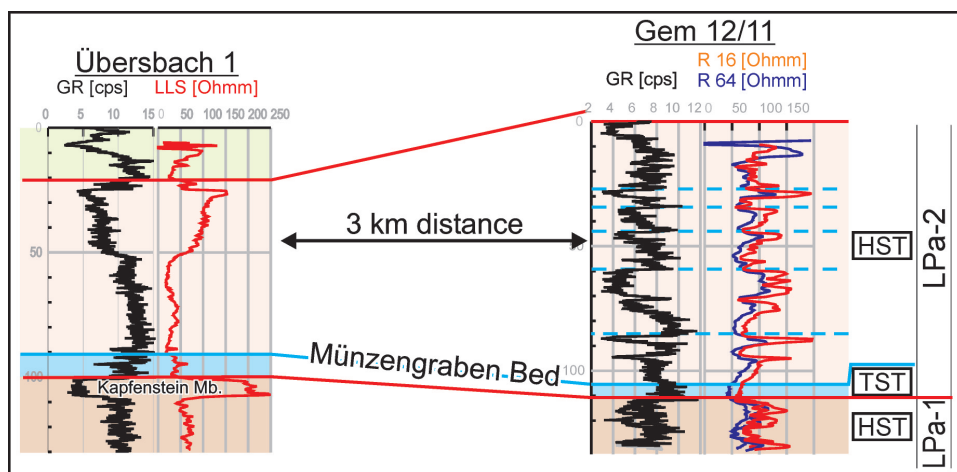


Fig. 13: Detail of wireline logs of Übersbach 1 and Gem 12/11, showing a dramatic lateral change in stratal patterns of the HST of LPa-2.

6. DISCUSSION

6.1. Lithostratigraphy vs. sequence stratigraphy

In general there is a good agreement between the units defined by lithostratigraphy (FRIEBE, 1994; GROSS, 2000, this volume) and the systems tracts of sequence stratigraphy. The Gleisdorf Formation corresponds to USa-1 and USa-2, and the bulk of the Feldbach and Paldau Formations can be correlated with LPa-1 and LPa-2, respectively (Fig. 14). The Eisengraben Member forms the TST of LPa-1, the coarsening upward Sielegg Member forms the lower part of its HST. The Münzengraben Bed represents the maximum flooding horizon of LPa-2 and the fluvial Kapfenstein, Kirchberg, and Karnerberg Members occur at the top of prograding parasequences of LPa-1 and LPa-2.

However, there are some differences in detail. In the proximal study area of GROSS (2000, this volume), the HST of LPa-1 is formed by the Sielegg and Kapfenstein Members. The seismic lines show that the distal part of this HST comprises two parasequences, which cannot be distinguished within the proximal part of the prograding system.

According to GROSS (2000), the boundary between the Feldbach and Paldau Formations is the base of the fluvial Kapfenstein Member, whereas the boundary between LPa-1 and LPa-2 is defined as a type 1 sequence boundary at the top of the Kapfenstein Member (proximal area) or at the top of LPa-1.2 (distal area).

In well logs coarse grained rocks were observed above the type 1 unconformity, which marks the Sarmatian/Pannonian boundary. These rocks are therefore Pannonian in age and perhaps represent the "Sarmatian" Mühldorf Gravel (WINKLER-HERMADEN, 1957 cum lit.). Additional biostratigraphic investigations are necessary to prove the age of these sediments.

According to the time-scale of RÖGL & DAXNER-HÖCK (1996), the Feldbach and Paldau Formations (LPa-1/2) cover a time-span of c. 0.7 Ma (see also Fig. 2). Because erosion occurred at the base of LPa-1, the time-interval is probably even shorter. Therefore the Pannonian sequences are classified as 4th order. Because the absolute age of the Carinthian Gravel is unknown, it was not possible to decide whether USa-1 and USa-2 are 3rd or 4th order sequences.

6.2. Relative changes in sea level and paleogeography

Because of the limited extent of the seismic lines and the poor time constraint, the curve of relative sea level could neither be drawn from coastal onlaps nor be related to an absolute time-scale. Instead, the curve of the relative sea level was correlated to borehole FFTH 1 (Fig. 15).

The relative changes in sea level had a major influence on the paleogeographic evolution of the study area. Despite the limited data base, paleogeographic sketches for the Eastern Styrian Basin during Late Sarmatian and Early Pannonian times are displayed in Fig. 16.

Fig. 16a illustrates the facies distribution during latest Sarmatian times (SMST of USa-2). An offlap break separates an aggrading shelf platform with mixed siliciclastic-carbonate deposition in the west from an area of deeper water in the east. A fault controlled slope

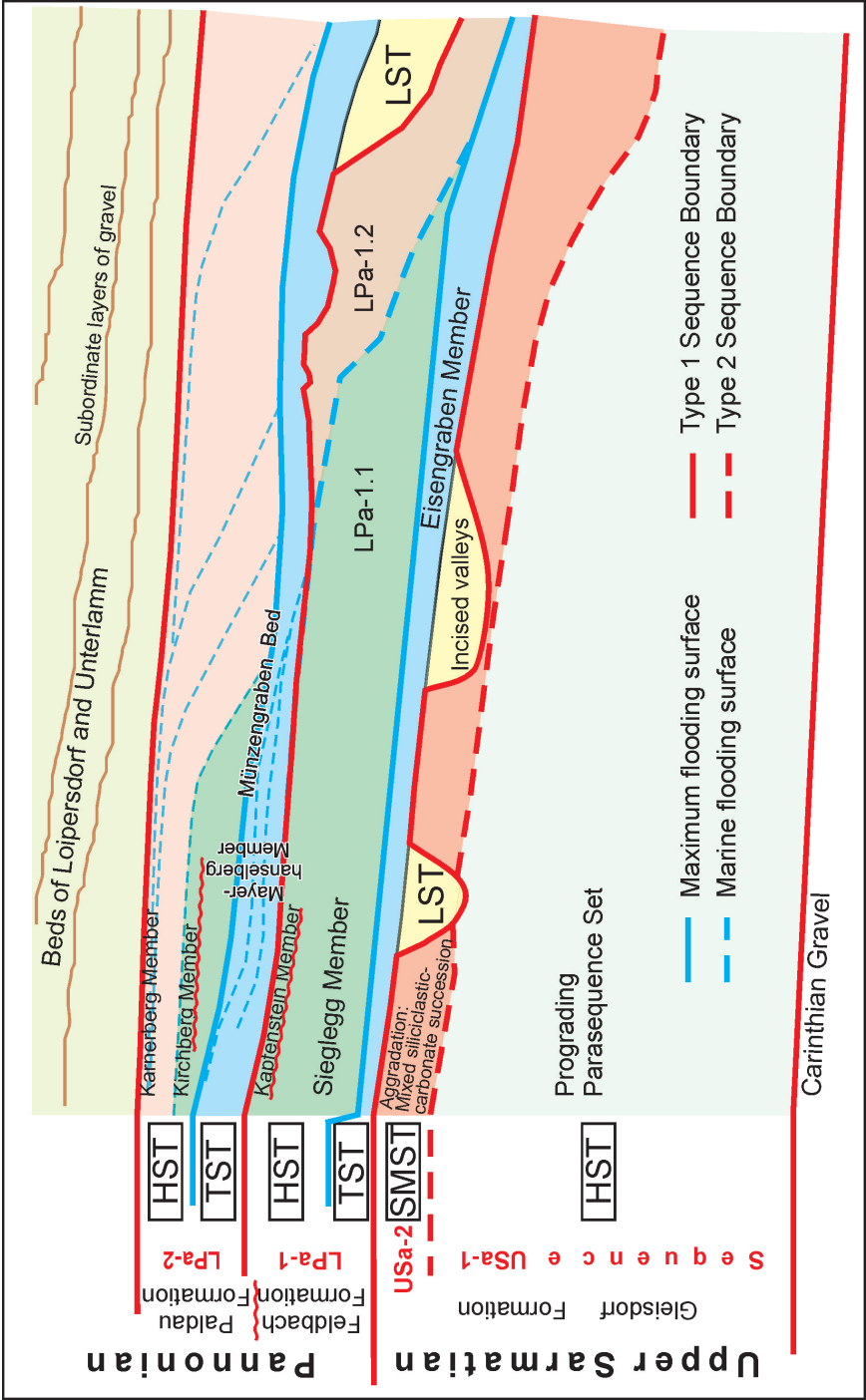


Fig. 14: Sequence stratigraphic framework for Upper Sarmatian and Lower Pannonian sediments in the Eastern Styrian Basin.

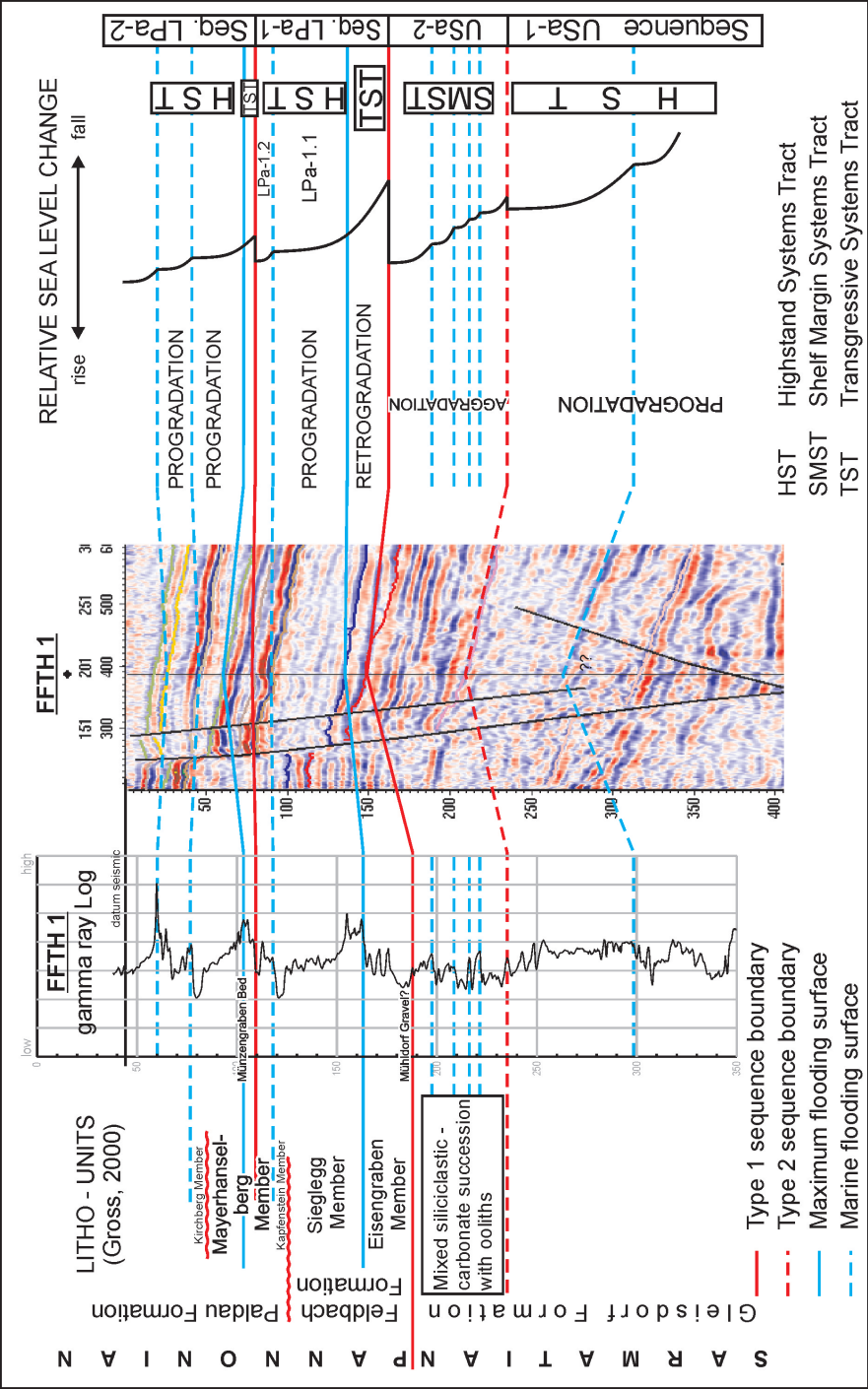


Fig. 15: Detail of seismic line FF0101, well log of FFTH1, lithostratigraphic units after Gross (2000, this volume), and a curve of relative sea level changes.

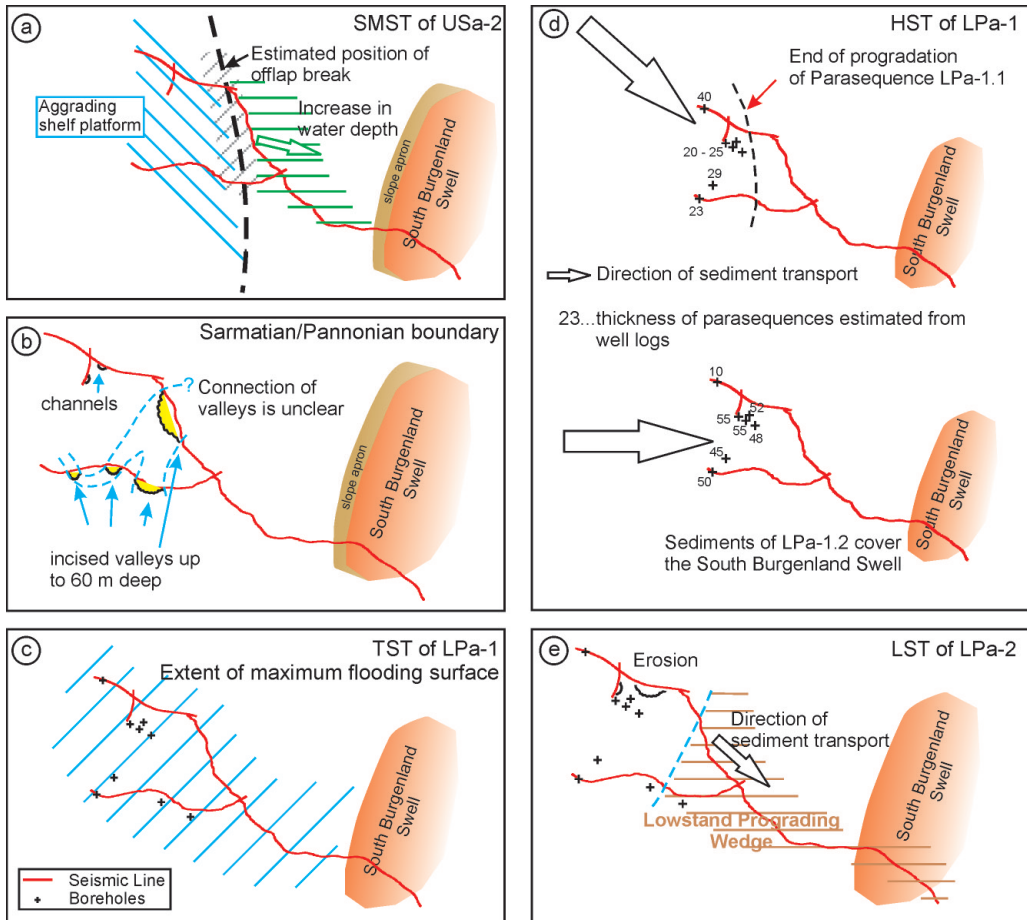


Fig. 16: Paleogeographic sketches of the Eastern Styrian Basin. See text for explanations.

apron occurred along the western margin of the South Burgenland Swell. The lowstand at the Sarmatian/Pannonian boundary caused the incision of deep valleys. Their position is shown in Fig. 16b. Because of the wide spacing of the seismic lines, the regional distribution of the valleys remains unclear.

The Early Pannonian transgression caused basinwide flooding of the Styrian Basin (TST of LPa-1). Sediments of the TST onlap the slope apron at the South Burgenland Swell. The extent of the MFS at the top of the TST is shown in Fig. 16c. The HST of LPa-1 is subdivided into two parasequences (LPa-1.1; LPa-1.2). Thicknesses of parasequences estimated from well logs and transport directions are summarized in Fig. 16d. Clinoform geometries indicate water depths up to 60 m. While LPa-1.1 shales out within the study area, sediments of LPa-1.2 cover the South Burgenland Swell along line UL9901.

Another fall in sea level caused erosion in the western study area and the formation of a LPW (LST of LPa-2). The position of erosional features and the distribution of the LPW are shown in Fig. 16e.

6.3. Correlation with global eustatic curves, the Western Pannonian Basin, and the Vienna Basin

Fig. 17 displays a part of the Cenozoic sea level curve after SEN et al. (1999) and sequence stratigraphic frameworks for the Styrian Basin, the Vienna Basin (KOVÁČ et al., 1998), and the Western Pannonian Basin (SACCHI et al., 1999).

SEN et al. (1999) updated the sea level cycle chart of HAQ et al. (1987) for the Neogene with absolute ages provided by BERGGREN et al. (1995; Fig. 17). According to this updated chart, a major eustatic sea level fall (> 100 m) occurred 11.3 Ma before present, separating 3rd order sequences TB 2.6 (12.5–11.3 Ma) and TB 3.1 (11.3–8.92 Ma).

KOVÁČ et al. (1998) studied the seismic stratigraphy of Late Miocene rocks in the northern Vienna Basin. According to these authors, rocks deposited during Pannonian A/B biozones represent a 4th order sedimentary cycle, with a possible further subdivision into two higher-order cycles (PS 1/2). These cycles are regarded as parasequences within the late stage of a 3rd order sequence, which continued from the Sarmatian. The erosive base of PS 1 is correlated with the Sarmatian/Pannonian boundary. In the Pannonian C-H biozones, a further subdivision into four sequences was determined.

SACCHI et al. (1999) presented a sequence stratigraphic framework for the Late Miocene non-marine strata of the Western Pannonian Basin. They distinguished five 3rd order sequences (Sarmatian-1 and Pannonian-1 to Pannonian-4; SAR-1, PAN-1 to PAN-4). The Sarmatian/Pannonian boundary (~11.5 Ma) is defined as a sequence boundary. PAN-1 is thin and often eroded. The maximum flooding surface of PAN-2 was dated as 9.0 Ma.

There is little doubt that the type 1 unconformity at the Sarmatian/Pannonian boundary in the Styrian Basin, the Vienna Basin (see also POGÁCSÁS & SEIFERT, 1991), and the Western Pannonian Basin is related to the major eustatic sea level fall separating TB 2.6 and TB 3.1 (Fig. 17). Therefore, on a global scale, USa-1 and USa-2 in the Styrian Basin might be higher order sequences within TB 2.6. The age of the Carinthian Gravel underlying USa-1 is unknown. We speculate that the fluvial rocks are related to the pronounced sea level fall at the boundary between TB 2.5 and TB 2.6 (12.5 Ma; Fig. 17).

The Pannonian rocks in the Styrian Basin are significantly older than 9 Ma (RÖGL et al., 1993; RÖGL & DAXNER-HÖCK, 1996). Thus, the entire Pannonian succession in the Styrian Basin is an equivalent to the early TB 3.1 and was deposited simultaneously to PAN-1 and the lower part of PAN-2 in the Western Pannonian Basin. The Lower Pannonian 4th order sequence LPa-1 comprising two parasequences fits well with the 4th order cycle PS 1/2 in the Vienna Basin (KOVÁČ et al., 1998). LPa-2 correlates with a 4th order sequence in the Vienna Basin representing Pannonian zone C and the lower part of zone D.

6.4. Tectonic aspects

A detailed tectonic investigation was beyond the scope of the present paper. However, some observations should be mentioned.

The fault controlled sediments along the western margin of the South Burgenland Swell (Fig. 9) indicate Sarmatian faulting. This fault activity is probably related to Sarmatian extension (SACHSENHOFER et al., 1997). KRAINER (1984) recognized vertical displacements of more than 300 m along faults at the northern basin margin. Evidence for Late Sarmatian faulting along the seismic lines in the central study area is missing.

Steeply dipping faults displace the Sarmatian and Pannonian sequence and reach the surface. Upward branching of the near-vertical faults indicates positive and negative flower structures, suggesting that strike-slip faults were active after Middle Pannonian deposition of the "Beds of Loipersdorf and Unterlamm".

Eastward dip of sediments along line UL9901 (Fig. 4) results from Pannonian tilting of the Eastern Styrian Basin towards the Pannonian realm and a Pliocene to Quaternary uplift of the Styrian Basin (SACHSENHOFER et al., 1997). The latter also caused truncation of Middle Pannonian strata (Fig. 4).

7. CONCLUSION

(1) The Upper Sarmatian and Pannonian deposits in the Eastern Styrian Basin are subdivided into four sequences (USa-1; USa-2; LPa-1; LPa-2) and the overlying "Beds of Loipersdorf and Unterlamm" (Fig. 14). USa-1 is a 3rd or 4th order sequence, whereas USa-2, LPa-1, and LPa-2 are 4th order sequences.

- USa-1 comprises the lower part of the Gleisdorf Formation. It is bottomed by the Carinthian Gravel and consists of a prograding parasequence set (HST).
- USa-2 represents the uppermost Gleisdorf Formation and is formed by a SMST. The mixed siliciclastic-carbonate succession exhibits aggradational stacking patterns.
- The Sarmatian/Pannonian boundary is a type 1 sequence boundary characterized by deep valley incisions (Fig. 16b).
- LPa-1 consists of LST, TST, and HST. The HST is subdivided into two parasequences. The Eisengraben Member (Feldbach Formation) forms the TST. The Sieglegg Member (Feldbach Formation) forms the early HST. The Kapfenstein Member and the lowermost Mayerhanselberg Member (Paldau Formation) form the late HST.
- LPa-2 consists of LST (lowstand prograding wedge), TST, and HST. The Münzengraben Bed is associated with the maximum flooding horizon. The Kirchberg and Karnerberg Members represent coarse-clastic deposits at the top of prograding parasequences.
- The sequence stratigraphic classification of the "Beds of Loipersdorf and Unterlamm" remains unclear.

(2) A comparison with the Western Pannonian Basin and the Vienna Basin shows that the Sarmatian/Pannonian boundary is formed by a type 1 unconformity in all three areas. It is related to a major global sea level fall (11.3 Ma). Perhaps, the Carinthian Gravel was deposited during a sea level fall 12.5 Ma before present. A good agreement

exists between Lower Pannonian sequences in the Vienna Basin and in the Styrian Basin.

(3) Sarmatian faulting is indicated by slope aprons at the western margin of the South Burgenland Swell. Steeply dipping strike-slip faults were active after Early Pannonian times. A Pannonian tilting of the Eastern Styrian Basin towards the Pannonian realm and Pliocene to Quaternary uplift of the Styrian Basin caused truncation of Middle Pannonian strata (Fig. 4).

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