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„Structural re-evaluation of northern Burgenland and NW Hungary based on subsurface data"

verfasst von / submitted by

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1. Zusammenfassung

Ca. 90% des prä-Känozoischen Kristallins und ca. 60% der prä-Mittelmiozän Schichten des Pannonischen Beckens sind mit Sedimenten bedeckt. Daher lassen sich viele der historischen Probleme des Pannonischen Beckens durch Untersuchungen der Geologie des Untergrundes aufklären. Deshalb ist der Zweck dieser Masterarbeit, ein besseres Verständnis über die Geologie im Untergund des Pannonischen Beckens zu bekommen, wobei der Fokus auf NO Österreich und NW Ungarn liegt. Dies wird durch die Integration seismischer Daten Österreichs und Ungarns erreicht. Es wurden ungefähr 2500 km gescannte und georeferenzierte seismische Reflektionsdaten von Österreich und Ungarn und ca. 400 km single-channel und multi-channel seismische Profile aus dem Neusiedlersee verwendet. Weiters wurden drei regionale Profile (regional transects), die aus seismischen Segmenten beider Ländern zusammengestellt wurden, für ein besseres Verständnis des Untergrundes des Pannonischen Beckens erstellt. Die seismischen Linien wurden mit Bohrungsdaten integriert, die von OMV Austria für den österreichischen Teil und von Körössy (1987) und Tari (1994) für den ungarischen Teil, bereitgestellt wurden.

Drei strukturelle Phasen des Pannonischen Beckens wurden identifiziert. Zuerst wurde die pre-rift Schichtfolge beobachtet. Diese Schichtfolge ist aus prä-Känozoischen Gesteinen, wie z.B. Gneisen und Graniten, die ein paläozoisches und mesozoisches Alter aufweisen, zusammengesetzt. Außerdem wurde die syn-rift Schichtfolge erkannt. Diese Sedimentreihe wurde im Laufe des Riftings abgelagert und ist durch Mittelmiozäne (Karpat bis Baden) Gesteine charakterisiert. Die Hauptlithologien der syn-rift Phase sind Sande, Sandsteine, Tone und Ton-Mergel. Die seismischen Daten der syn-rift Phase stellen viele Abschiebungen dar, die durch Extension der Lithosphäre entstanden sind. Die Störungen weisen sowohl steile als auch flache Winkel auf. Im Falle der flachwinkeligen Störungen wurde eine Neigung der syn-rift (Karpat) Reflektoren beobachtet. Aufgrund der Neigung der Reflektoren kann ein Wachstum des Sedimentstapels, das während der Ablagerung stattfindet, (syn-depositional growth) angenommen werden. Dieses Wachstum ist auch ein Hinweis, dass Extension stattgefunden hat. Weiters ist weitverbreiteter Vulkanismus während der syn-rift (Baden) Phase in N Ungarn (Pasztori High) zu beobachten. Zum ersten Mal wurde die Expression des Vulkanismus in 2D Seismik interpretiert. Das Ende der syn-rift Phase wird durch eine mittel-badenische Diskordanz gekennzeichnet. Zuletzt wurde die post-rift Phase beobachtet, die durch eine weitverbreitete Subsidenz charakterisiert ist. Die Hauptlithologien der post-rift Phase haben ein sarmatisches bis quartäres Alter und sind aus Tonen, Ton-Mergeln und Konglomeraten zusammengesetzt. Zudem wurde eine pannonische Delta-Progradation in der post-rift Seismik erkannt. Diese Sequenz weist einen diachronen Charakter auf und wir schlagen vor, dass diese im ganzen Pannonischen Becken zu beobachten ist. Der starke diachrone Charakter der Progradation ist ein Hiweis auf die Seespiegelschwankungen des Pannonischen Sees. Die Gründe der Seespiegelschwankungen sind jedoch umstritten.

Schließlich wurde das Pannonische Becken während der post-rift Phase (spätes Pliozän bis Quartär) invertiert. Diese tektonische Reaktivierung ist durch Beckenrand-Hebung charakterisiert. Innerhalb der seismischen Daten ist die interpretierte der Hebung hauptsächlich im intra-pannonischen Reflektor manifestiert. Dieser seismische Reflektor wird nach NW zunehmend flacher und schließlich durch die Oberfläche abgeschnitten. Diese Termination des intra-pannonischen Markers ist

durch eine post-pannonische Erosion entstanden, die durch eine Beckenrand-Inversion und –Hebung verursacht wurde.

1.1 Abstract

In the Pannonian Basin, about 90% of the pre-Cenozoic basement, and ca. 60% of the pre-Middle-Miocene strata are covered by the sedimentary fill of the basin. Thus, many of the historical problems of the Pannonian Basin, can only be resolved using subsurface geological data. Therefore, the aim of this MSc thesis is to create a better understanding of the subsurface of the Pannonian Basin, focusing on NE Austria and NW Hungary, by integrating seismic segments with well data, for the first time, from both sides of the border. In order to achieve this, approximately 2500 km scanned and georeferenced legacy seismic reflection data from both Austria and Hungary, together with ca. 400 km single-channel and multi-channel seismic data from the Neusield Lake, were used. Furthermore, three regional transects, composed of seismic segments, were spliced together in order to have a better regional understanding of the Pannonian Basin subsurface. The seismic lines were integrated with well data, provided by OMV Austria for the Austrian pat and summarised from Körössy (1987) and Tari (1994) for the Hungarian part.

Three main structural stages of the Pannonian Basin were identified. Firstly, the pre-rift succession, deposited before rifting started, has been observed. This set of strata is composed of pre-Cenozoic rocks, such as gneisses and granites, belonging to the Palaeozoic and Mesozoic. Secondly, the syn-rift succession, deposited as rifting occurred, is characterized by Middle-Miocene strata (Karpatian to Badenian) and comprises of mainly sands, sandstones and clay-marls. During the syn-rift phase seismic data display several normal faults formed due to extension. These faults can be either steeply dipping or low-angle normal faults (LANF). In the case of the LANFs, the tilting of the syn-rift (Karpatian) strata against the low-angle fault plane can be observed. This suggests syn-depositional growth and is evidence for extension, thus corroborating the fact that extension due to rifting took place during this time. It was mainly during the syn-rift phase (Badenian) that widespread volcanism took place in N Hungary, mainly in the area of the Pasztori High. For the first time, the expression of this volcanism has bee interpreted in the 2D seismic, where scoria cones are displayed in the flank of a large strato volcano. The termination of the syn-rift phase is marked by an unconformity of mid-Badenian age. Thirdly, the post-rift succession has been observed, which is characterized by widespread subsidence. These strata are of Sarmatian to Quaternary age and are dominated by clay-marls and clastic sediments such as gravels and conglomerates. A Pannonian age delta progradation sequence has been observed in the post-rift seismic. This progradation is regional and we suggest that it is present basin-wide. Due to its strongly diachronous character, this delta progradation sequence marks the changes in lake-level of the Pannonian Lake. The causes for these lake-level changes, however, still remain disputed.

Finally, the Pannonian Basin underwent considerable inversion during the Late Pliocene to Quaternary times (post-rift). This tectonic reactivation was characterized by uplift at the basin margins. Within the seismic data, the interpreted manifestation of the uplift has been observed in the intra-Pannonian marker. This seismic reflector becomes progressively shallower towards the NW and gets truncated at the surface due to post-Pannonian erosion caused by basin margin inversion and uplift.

2. Introduction and area of study

The NW Pannonian Basin as the transitional zone between the Eastern Alps and the Western Carpathians is one of the classic regions of European geology. In fact, about 90% of the pre-Cenozoic basement and about 60% of the pre-Middle Miocene strata are covered by the sedimentary fill of the Pannonian Basin. This clearly shows the importance of subsurface geology. Many of the geological problems in the Pannonian Basin, debated for almost a century, may be resolved only by the systematic evaluation of all subsurface geologic information, most importantly from the interpretation of seismic data combined with well information.

The stratigraphy and structure of the broader area of the Neusiedlersee in northern Burgenland and its relation to the adjacent part of the Pannonian Basin in Hungary remains poorly understood. Existing geologic models of the area did not have the benefit to rely on industry subsurface data, i.e. reflection seismic and well data, and geological models have been not, or only marginally were, integrated across the border between Austria and Hungary.

Some 2000+ km scanned and georeferenced legacy seismic reflection data both from the Austrian and Hungarian sides of the area were merged with a circa 400 km single- and multi-channel seismic data set recently acquired on the Neusiedlersee. The aim of this study is to analyse deep hydrocarbon exploration and general purpose shallow wells drilled in the Austrian and Hungarian sides of the study area and integrate them with the vintage and modern reflection seismic data. Three regional transects, together with their corresponding reflection seismic profiles are presented from a large number of seismic data (Fig. 2.1), from both the Austrian and Hungarian sides of the study area in order to illustrate the subsurface geology of the area. The structural interpretation of the seismic data offers a better understanding of the Neogene tectonic evolution and stratigraphy of the area, as well as gives evidence on the evolution of the broader Pannonian Basin system.

The study area is located in the western part of the Pannonian Basin (Fig. 3.1) and comprises of areas in Northern Bugenland in the NE part of Austria and in NW Hungary. In a more specific geographical sense, the study area can be confined between Oberpullendorf and Frauenkirchen in N Burgenland and Köszeg and Györ in NW Hungary (Fig. 2.1). Furthermore, the area of study encompasses the Eisenstadt-Sopron Basin and Oberpullendorf Basin in Austria and parts of the Danube Basin in both Austria and Hungary (Fig. 2.1).

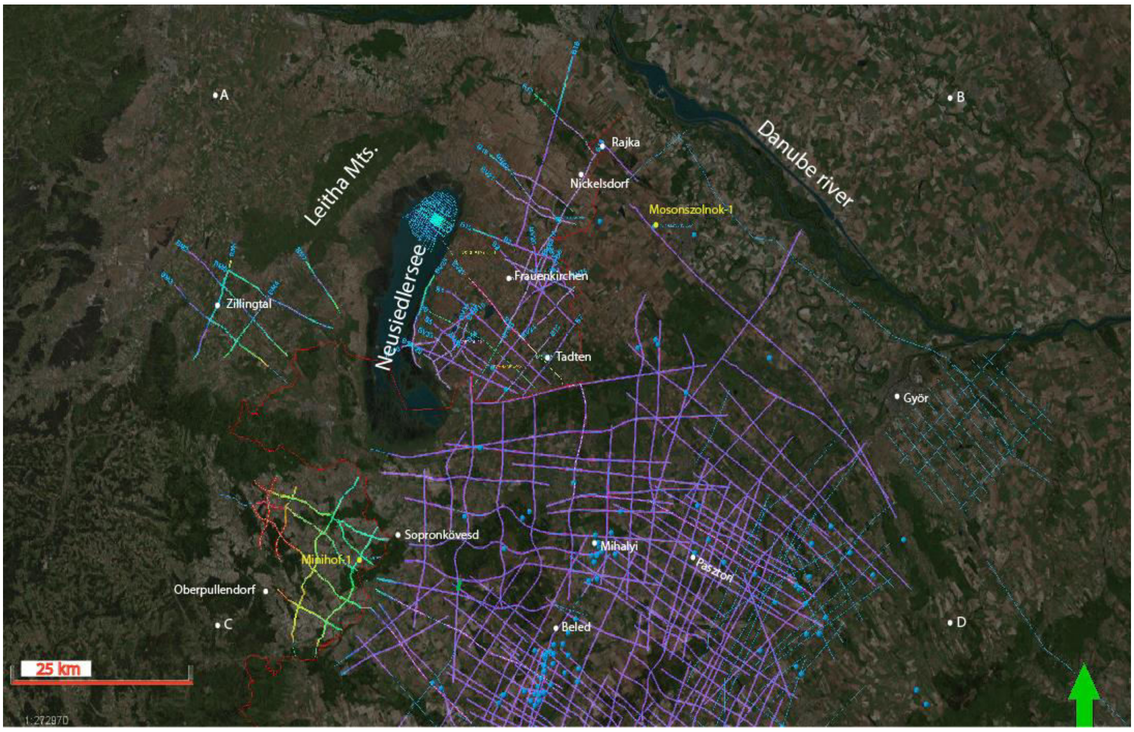

Figure 2.1 Google Maps image of study area in Austria and Hungary; note the position of the Leitha Mts., Neusiedl Lake and Danube River for reference. Showin in purple are the seismic lines interpreted for the project. The country boundary between Austria and Hungary is displayed in red.
GPS coordinates: **A**: N 48°4’50.52”, E 16°24’29.03”; **B**: N 48°0’35.611”, E 17°45’10.295”; **C**: N 47°27’1.926”, E 16°24’5.871”; **D**: N 47°27’5.267”, E 17°46’54.436”

3. Geologic and Regional Setting of the Study Area

The study area in northern Burgenland and in NW Hungary is regionally part of the Pannonian Basin system (Fig. 3.1). Burgenland is positioned in the transitional area between the eastern end of the Eastern Alps and the Danube Basin of the Pannonian Basin system. The study area in Burgenland includes seismic segments from the Eisenstadt-Sopron Basin, the Oberpullendorf Basin and the Austrian part of the Danube Basin. The Hungarian part of the study area is located completely in the Danube Basin, also known as Little Hungarian Plain. In this junction area there have also been important geologic events that have taken place, which have a strong influence in the Eastern Alps, the Western Carpathians and the Pannonian Basin (e.g. Hass, 2015). Therefore, the whole study area belongs regionally and geologically to the broader Pannonian Basin system (Fig. 3.1).

The southern and partially the northern parts of Burgenland are dominated by the Neogene and Quaternary deposits of the East-Styrian-West-Pannonian and southeastern Vienna and Eisenstadt Basins. Within these deposits, basalts and tuffs from the Miocene and Pliocene are sporadically found (Irene Zorn *in* Schönlaub et al., 2000).

The Pannonian Basin is a unique geologic structure, which is located in central Europe, and is part of the Alpine orogenic system (Horvath et al., 2006). This Neogene-Quaternary age basin is surrounded by the Alps, Carpathian mountains and Dinarides (e.g. Horvath and Tari, 1999; Horvath et al, 2014) (Fig. 3.1). The Alpine/Pannonian/Carpathian (AlCaPa) region contains most of the Central and Eastern European mountain belts which serve as a natural "laboratory" where many complex geologic processes have taken place (e.g. Cloetingh et al., 2005). The Pannonian Basin is superimposed on two distinct orogenic terranes, namely Alcapa and Tisza-Dacia (Horvath et al., 2014) (see section 3.2 for tectonic evolution). Furthermore, the Pannonian Basin consists of so called "inselbergs", which are isolated mountains and emerge from the well-defined plains of the Pannonian Basin (e.g. Horvath and Tari, 1999; Horvath et al., 2006).

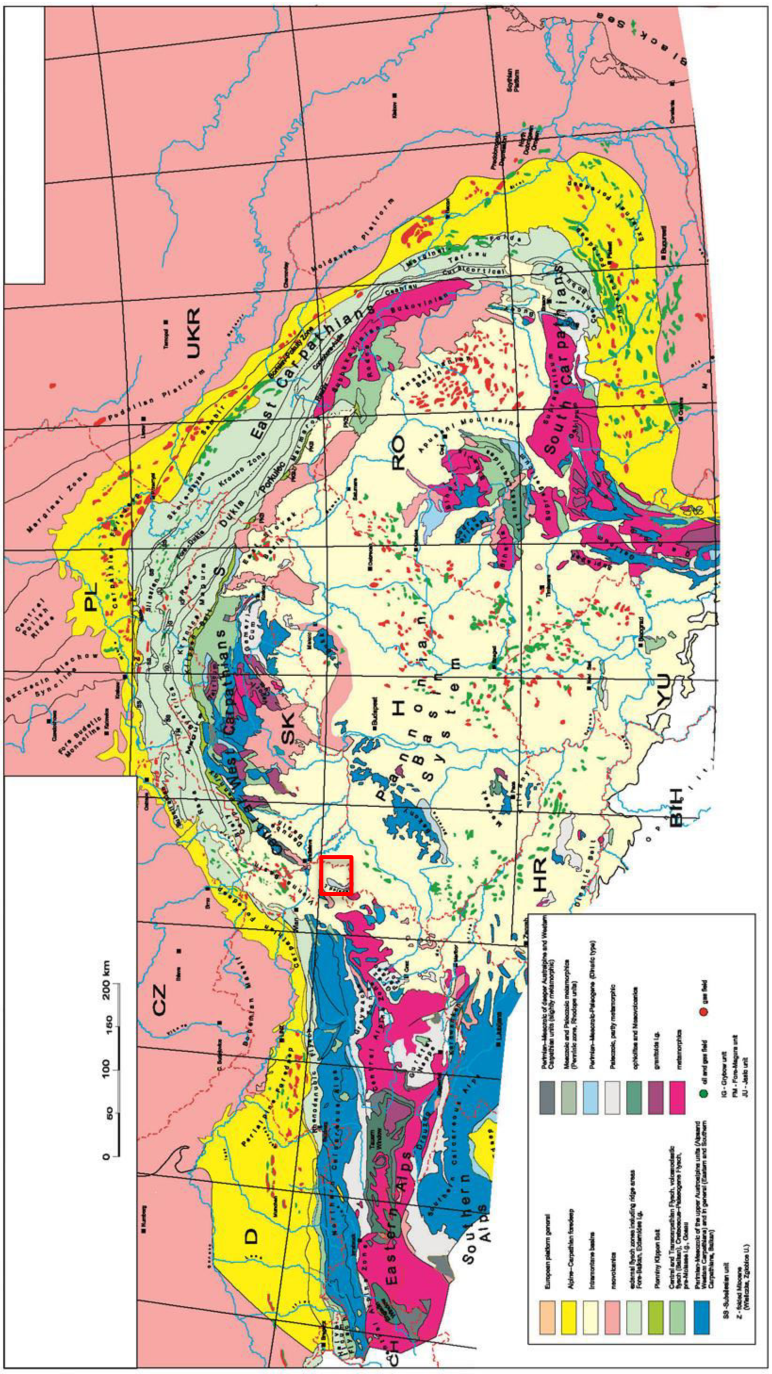

Figure 3.1. Regional geology and hydrocarbon fields of Central Europe with Pannonian basin shown in light yellow (Slaczka et al., 2006). The area of study is enclosed within the red square.

3.1. Stratigraphy

The Pannonian Basin consists of a complex basement comprised of Proterozoic, Palaeozoic and Mesozoic rocks of sedimentary, metamorphic and igneous origin (Dolton, 2006). Overwhelmingly however, the Pannonian Basin consists of several kilometres-thick, young, loose sediments, which overlie the basement strata (e.g. Badics and Vetö, 2012). The basin fill of the Pannonian Basin is of Neogene to Quaternary age and overlies the pre-Cenozoic basement and the folds and thrusts of the Alpine-Carpathian fold and thrust belt. This Neogene basin fill is approximately 600 km from east to west and 500 km from north to south (Badics and Vetö, 2012).

Stratigraphic nomenclature is varied due to the large area involved, different depositional and lithological facies, political and language divisions, as well as local usage (Dolton, 2006).

Because of these differences in the stratigraphic nomenclature, this section has been divided into two parts to reflect the stratigraphy of both the Austrian and Hungarian part of the study area and of the Pannonian Basin in general.

3.1.1. Austrian Part

In the Austrian part of the study area, as it can be seen from the well summaries (see Appendices), the most dominant succession in the Pannonian Basin and study area by extension, are the Miocene strata. Overlying the Miocene succession is the Pannonian sequence, which is then in turn overlain by the Quaternary strata.

In the study area, the Neogene deposits belong tectonically to North Burgenland (geographically: Leitha Mountains, Neusiedl Lake area and Oberpullendorf Basin), to the side basin fill of the south-eastern Vienna Basin and to the Eisenstadt-Sopron Basin (together with the Mattersburg Cove). The Eisenstadt-Sopron Basin is a sub-basin of the pannonian Basin system and is located between the Rosalien and Leitha Mountains. This basin moreover, has a connection to the Vienna Basin. Overlying the Neogene succession, the Quaternary strata can be found (Irene Zorn *in* Schönlaub et al., 2000). This section, which describes the stratigraphy of the Austrian part of the study area has been adapted from the writings of Irene Zorn in the book "Burgenland, Geologie der österreichischen Bundesländer" from Schönlaub et al. (2000).

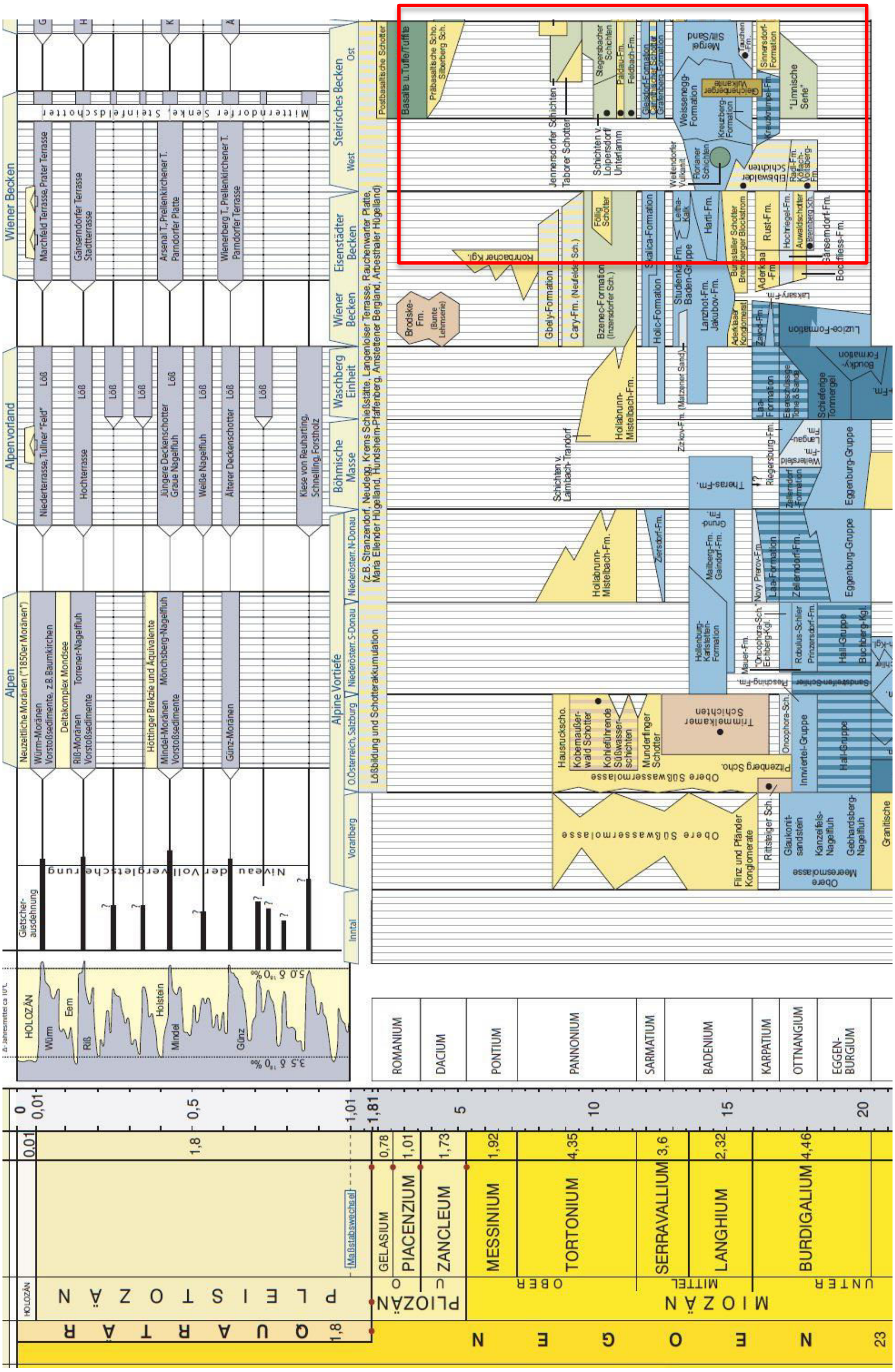

Figure 3.2. Stratigraphic table of Austria (Piller, 2004).

Pre-Cenozoic Basement

The pre-Cenozoic basement of the Pannonian Basin system consists of a complex of igneous, metamorphic, and sedimentary rocks of Precambrian, Paleozoic, and Mesozoic age that have been strongly folded, faulted, and assembled in nappes of the Inner Carpathian foldbelt (Dolton, 2006).

The basement of northern Burgenland is mainly comprised of crystalline rocks belonging to the Lower Austroalpine Units. The dominant lithologies are metamorphic Palaeozoic phyllites and marbles belonging to the basement in southern Burgenland and Styria (Hamilton et al., 1999).

The basin basement of the Mittelburgenland Basin has been predominantly formed by the Austroalpine crystalline. The Styrian Basin basement, is comprised by strata from the Penninic of Rechnitz, as well as different Upper Austroalpine Palaeozoic formations (Irene Zorn *in* Schönlaub et al., 2000). These Palaeozoic formations show similarities with the Grazer Palaezoic. The South Burgenland High on the other hand, is composed by Palaeozoic age rocks similar to the Palaeozoic of Remschnigg and Sausal. The lithologies that comprise these Palaeozoic formations are mainly gneiss and granite (Irene Zorn *in* Schönlaub et al., 2000).

In the Rust Range area, located west of the Neusiedl Lake, the crystalline basement is composed of metamorphic Palaeozoic rocks. The basement crops out in two small areas only, which are north of the Rust Range, northeast of Oslip and close to the Hungarian border in the south. Except for these areas, where the crystalline basement outrcops, the whole Rust Range is overlaid by Neogene deposits, of mainly Karpatian age (Häusler et al., 2014 and references cited therein).

Miocene Sediments

The Paleogene and Miocene sediment series are relicts of three main Cenozoic sedimentation cycles, which took place during a tectonic event in the Vienna Basin area. The Upper Eocene of Wimpassing represents the first cycle. The wide area covered by Upper Eocene sediments points towards a widespread transgression, which came from the east (Irene Zorn *in* Schönlaub et al., 2000).

The second sedimentation cycle is allocated to the Vienna, Eisenstadt and Oberpullendorf basins, from the Eggenburgian to the Lower Badenian. The Spannberg Ridge in the Vienna Basin was considered until the Lower Badenian as a separating high between the marine influenced northern Vienna Basin and the southern adjacent terrestrial zones (Irene Zorn *in* Schönlaub et al., 2000). From the Upper Lagenide Zone in the Lower Badenian, the first marine deposits started to show in the southern Vienna Basin and the Burgenland depositional zones. During the Ottnangian and Karpatian, terrestrial and fluviatile sediments were locally deposited. The marine Badenian sediments underlie the Sarmatian and Pannonian deposits, which because of their fossil content show an increasing desalinisation, which is characteristic for the central Paratethys (Irene Zorn *in* Schönlaub et al., 2000).

Ottnangian

The sediments belonging to the Ottnangian are mainly deposited in the eastern foot of the Rosalien Mountain. They are found near Sieggraben, west and south of the Ödenburg Crystalline as well as west of Kaiserdorf in the Oberpullendorf Basin. These deposits, called Auwaldschotter (gravel and conglomerates from Auwald) (Fig. 3.2) are more than 300 m thick (Irene Zorn *in* Schönlaub et al., 2000).

At the base of the Auwaldschotter, the freshwater layers of Brennberg were developed (Fig. 3.2). These layers consist of approximately 50 meters thick sandy crags and crystalline basal Brennberg coal beds, which can reach a thickness of 1.5 to 16 meters (Irene Zorn *in* Schönlaub et al., 2000). The Brennberg sequence's main development area is located in the Hungarian zone. Until now, very few plant rests have been found in the hanging wall of the coal beds. The few finds indicate a former swamp forest (Tauber, 1952). Occasionally, thin anthracite beds can be located within the Auwaldschotter. It is considered that the formation of the Auwaldschotter is fluviatile in origin (Irene Zorn *in* Schönlaub et al., 2000). Within the Podersdorf-1 well (Appendix F), at approximately 280 m depth, some lignite has been found. Due to its relative close proximity to the Auwaldschotter, this well serves as evidence for the coal occurrence within the Auwaldschotter and Brennberg series.

Karpatian

Karpatian times (17.5–16.5 Ma) in the Pannonian Basin, are generally characterised by dominantly fluviatile/deltaic deposits (e.g. Strauss et al., 2006).

Karpatian - Rust Formation

Within the study area (Fig. 2.1), the Karpatian deposits are mainly found within the Austrian area, especially in the Eisenstadt-Sopron and Oberpullendorf basins (Irene Zorn *in* Schönlaub et al., 2000). Karpatian lithologies are dominated by clays, sands and gravels (Irene Zorn *in* Schönlaub et al., 2000). The first stratigraphic member deposited during the Karpatian in the Eisenstadt-Sopron Basin was the Rust formation, also known as Rust Gravel (Häusler et al., 2014; Kapounek, 1939). This stratigraphic member spreads itself from the northern foot of the Mörbisch crystalline block to the northern end of the Rust mountain range in Schützen (Irene Zorn *in* Schönlaub et al., 2000). The lithologies of the Rust formation are quite diverse, consisting mainly of matrix-supported gravelly sand. It reaches a maximum thickness, which is estimated to be 100 m, although deep wells and seismic exploration in the Rust Range are lacking (Häusler et al., 2014).

Badenian

The Badenian was divided by Tollman (1955) into three main zones, namely the Upper Lagenide zone, the Sandschaler zone and the *Bulimine-Bolivine* zone. The Leithakalk itself comprises of *Corallinacea*-limestone and coral-limestone. Other types of fossils found in it are bivalves, gastropods, echinoderms and fish remains (Irene Zorn *in* Schönlaub et al., 2000).

In the Leitha Mountain area, except for the Leitha limestone one may find Badenian gravel, sands, sandstone and clay-marl (Irene Zorn *in* Schönlaub et al., 2000). Furthermore, basisconglomerate (Basiskonglomerat) containing white quartz components can also be found in the Leitha Mountains area. North of Eisenstadt the so called Terebratel sands can be found. They consist of limestone-quartz sands which are rich in fossils such as brachiopods and bryozoa. These fossils indicate shallow water development (Irene Zorn *in* Schönlaub et al., 2000).

Because of the greater Badenian water depths in the Mattersburg High, located in the southern part of the Eisenstadt Basin, the main deposits in that area are clay-marls. In the Upper Lagenide Zone the sedimentation of sands and clay marls took place, mainly in the central part of the basin (Irene Zorn *in* Schönlaub et al., 2000). The gravel deposits have an approximate thickness of about 500 meters and the finer grained sediments a thickness of 700 meters (Küpper, 1957). Other lithologies belonging to this zone are mainly clay-marls, limestone-sands and quartz-sands. Through various findings of foraminifera in the clay rubble, the biostratigraphic classification could be pinpointed and these deposits were defined as marine conglomerates (Irene Zorn *in* Schönlaub et al., 2000).

The sediments of the Sandschaler zone appear as blackish-gray, plastic looking, silty marls and sandy, light grey to brown clay-marls, where the latter dominate the area (Irene Zorn *in* Schönlaub et al., 2000). In the area of Walbersdorf the sediments of the *Buliminen-Bolivinen* zone and the Lower Sarmatian are also present therefore, the name Walbersdorf Schlier includes both the deposits of the Sandschaler zone and *Bulimine-Bolivine* zone. The main fossil groups observed in the Sandschaler zone are foraminifera, ostracodes, molluscs and echinoderms (Irene Zorn *in* Schönlaub et al., 2000).

The *Bulimine-Bolivine* zone could only be determined in south-west Ritzing where it appeared as grey-green, sandy clay-marls rich in microfauna (Mostafavi, 1978).

Badenian - Leithakalk

The sediments of the Badenian are predominantly found in the northernmost parts of Burgenland, mainly deposited as the so-called Leithakalk (Leitha limestone) (Fig. 3.2) of the Leitha Mountain (Irene Zorn *in* Schönlaub et al., 2000). The Leitha Mountain represents the boundary facies of the Badenian Sea and shows generally a large lithological range. This lithology developed, like the entire marine sequence in Burgenland, during the early until the late phases of the Badenian. Its main development phase however, occurred during the Mid- until Late Badenian. The main fossils found in the Leithakalk are various mollusc fauna, which developed during the Mid-Badenian (Irene Zorn *in* Schönlaub et al., 2000).

Sarmatian

The clastic sediments of the Sarmatian can be found in the study area spread around the Leitha Mountain area, north-west to south-east of Mattersburg and on the western and especially on the southern Oberpullendorf Basin (Irene Zorn *in* Schönlaub et al., 2000). They mainly consist of clays and clay-marls, sands and gravel (Irene Zorn *in* Schönlaub et al., 2000).

According to Strauss et al. (2006) at least three sea-level drops have been identified in the Lower Sarmatian deposits of the Vienna Basin and of the Eisenstadt-Sopron Basin. The main regression caused the exposure of the Leitha Mountains during the *Elphidium hauerinium* zone and the lowermost *Porosononion granosum* zone, which can be found in the eastern Leitha Mountain area (Strauss et al., 2006). Other Sarmatian fossils include molluscs and ostracodes, with the former being very prominent (Strauss et al., 2006).

In the southern Oberpullendorf Basin the Sarmatian deposits have a thickness of approximately 60 meters (Irene Zorn *in* Schönlaub et al., 2000). Both the southern and western parts of the Oberpullendorf Basin are dominated by Sarmatian deposits which are cahracterised by white and yellow sands and are fossil-poor. Only in some parts a few fossils were found, mainly molluscs belonging to the Lower and Middle Sarmatian (Irene Zorn *in* Schönlaub et al., 2000).

Pannonian

A significant relative sea-level drop occurred at the Sarmatian-Pannonian boundary, approximately 16 million years ago. During the lowstand, which took place in the Early Pannonian, the deposition of the Hollabrunn formation occurred. This formaiton was deposited in the central Vienna Basin (Harzhauser et al., 2003; 2004). In the Eisenstadt-Sopron Basin on the other hand, fluvial gravel with *Melanopsis impressa,* overlying the marine sediments of the Sarmatian, was deposited (Strauss et al., 2006).

Neufeld Formation

In the Wiener Neustädter Pforte area, the limnic Neufeld formation was deposited during the Upper Pannonian. This formation spreads out as a thin strip from east of Neufeld an der Leitha until the Wiener Neustadt High and has an approximate thickness of 700 m (Irene Zorn *in* Schönlaub et al., 2000).

The Neufeld formation is separated into two distinct units; the sandy-marly Upper Neufeld layers and the lignite-rich Lower Neufeld layers. The Lower Neufeld layers contain clay, sands and gravel and the lignite developement has reached thicknesses of approximately 90 m (Irene Zorn *in* Schönlaub et al., 2000). On the other hand, the Upper Nefeld layers are made of sand and sandstone with alternating layers of clay and caly-marls. These layers, in contrast with the Lower Nefeld layers, contain only very low amounts of lignite (Irene Zorn *in* Schönlaub et al., 2000).

Undifferentiated Pannonian Sediments

Generally the sediments of the Pannonian are mainly found in the Ödenburg Mountain (Sopron Mountains) area. Furthermore, they have been observed around the Leitha Mountains, in the Eisenstadt Basin and in the eastern part of the Oberpullendorf Basin in South Burgenland. The Pannonian sediments in this area have been described as sandy- and clay-marls, where the sand content increases from the Lower to the Upper Pannonian (Irene Zorn *in* Schönlaub et al., 2000).

Within the Eisenstadt Basin, the Pannonian deposits are mainly composed of clay-marls together with sands, sandstones, gravel and conglomerates. In the meantime, in the Oberpullendorf Basin, the Pannonian deposits contain fine to coarse, white quartz-sands, where partially gravel and clay can be found. The thickness of these deposits increases from west to east (Irene Zorn *in* Schönlaub et al., 2000).

The thickness of the Pannonian deposits in the Styrian Basin has been estimated to be more than 600 meters. In the Lower Pannonian of the eastern Styrian Basin there is a strong dominance of clay-marls and sands. Furthermore, well rounded gravels have also been found, which point to a fluviatile development (Irene Zorn *in* Schönlaub et al., 2000).

The Mid-Pannonian deposits comprise of fossil-poor to fossil-rich clays and sands with gravel layers. The main documented fossil faunas are molluscs and ostracodes (Irene Zorn *in* Schönlaub et al., 2000).

The Upper Pannonian is confined in Burgenland to the area of the South Burgenland High and contains sands, clays, freshwater limestones and gravel. The freshwater limestones contained mainly gastropode faunas (Irene Zorn *in* Schönlaub et al., 2000).

Quaternary

The sedimentation in the Austrian part of the Pannonian Basin started in the uppermost Pliocene and continued its development in the Pleistocene. The most widespread and important sediments were deposited from rivers, which have their source in the Alpine area where basin gravels and partially finer sediments were deposited. Alongside these lithologies, further Quaternary deposits have aeolian, limnic, diluvial and anthropogenic origin (Paul Herrmann *in* Schönlaub et al., 2000).

Terrace Sediments

In North Burgenland the Quaternary deposits are dominated by so called terrace sediments. In the northern part of the Neusiedl district a terrace-staircase has been formed which leads from the Parndorf plate of Günz age to the Lower terrace of Würm age (Paul Herrmann *in* Schönlaub et al., 2000). These terraces consist of gravel from the Danube out of which only local, weathering-prone components are subsequently eliminated (Paul Herrmann *in* Schönlaub et al., 2000). Finer sediments do not play a very large role in this area. South of the Gols-Halbturn Line, the Seewinkel gravel can be found, which traditionally is regarded as part of the Danube gravels (Frasl, 1961). These have been described as fine to medium-grained, very well rounded to sometimes angular roundness quartz-gravels with relatively high carbonate and crystalline component content. In the hanging wall of the gravels there is a local occurrence of low thickness fine sands which partially have an aeolian origin but can also show an aquatic sedimentation (Paul Herrmann *in* Schönlaub et al., 2000).

Loess

The sediments that belong to this category are sediments that have a loess-like texture. Furthermore, other sediments which are included are those which have been aquatically reworked; evidence for this can be found in South Burgenland where limnic fossils have been found within these sediments (Paul Herrmann *in* Schönlaub et al., 2000). In North Burgenland however, mammoth rests have been found which indicate that these sediments have developed during a warm interval (Paul Herrmann *in* Schönlaub et al., 2000).

Weathering Loam

In the Leitha Mountain area, where thick weathering layers envelop the in-situ rocks, the so called weathering loam has been located. This lithology has a brown colour and a fine-grained matrix where single, very angular components, which come from the neighbouring rocks, swim (Paul Herrmann *in* Schönlaub et al., 2000). The age of this complex has not yet been determined; it is however believed that its development may have already begun during Neogene times (Paul Herrmann *in* Schönlaub et al., 2000).

3.1.2. Hungarian Part

The Hungarian part of the study area stretches from Köszeg to Györ in NW Hungary and is mainly characterised by a thick Neogene-Quaternary sedimentary fill (Tari et al., 1992). Underlying it, the crystalline basement is located, which is composed of rocks of Proterozoic, Palaeozoic and Mesozoic age (Dolton, 2006).

Pre-Cenozoic Basement

The pre-Cenozoic basement of the Hungarian part, similarly to the Austrian part, consists of igneous, metamorphic, and sedimentary rocks of Precambrian, Paleozoic, and Mesozoic age (e.g. van Balen et al., 1999). The basement of the Pannonian Basin in Hungary is divided into two parts by the so called Mid-Hungarian Lineament (Csontos and Nagymarosy, 1998). This lineament has a ESW-ENE strike and is located more or less in the area south of Lake Balaton and the Bükk Mountains. This line is a major boundary between two main units in the Pannonian Basin system, namely Alcapa to the NW and Tisza-Dacia to the SE (Csontos and Nagymarosy, 1998).

The study area in Hungary is located in the NW and therefore, it belongs to the Alcapa unit. Thus, only the basement lithologies of the Alcapa unit will be described in this section. In the Alcapa unit, north of Lake Balaton and of the Bükk Mountains, Palaeozoic to Mesozoic basement successions can be found (Csontos and Nagymarosy, 1998). The Palaeozoic and Mesozoic sequences of NW Hungary are similar to those of the Southern Alps. However, a weak regional metamorphism, which took place during the Late Jurassic, Early and Late Cretaceous, affected some of the rocks of this area. Crystalline basement rocks are not very common (Csontos and Nagymarosy, 1998). Accoridng to the well summaries of the wells from the Hungarian part of the study area, the main Palaeozoic lithologies are scists and mica-schists (Appendices A and D). The main Mesozoic lithologies on the other hand, can be found within the Györ Basin where the Mososnzolnok-1 (Appendix B) well is located. These lithologies comprise of reddish Triassic sandstones.

Miocene Sediments

The first Miocene sediements, which overlie the Palaeozoic-Mesozoic basement in Hugary, are Ottnangian to Karpatian age (syn-rift) terrestrial deposits. This set of strata is mainly composed of conglomerates, sandstones and coal-bearing clay, of lacustrine and alluvial origin. These sediments are interbedded with the so called Lower Rhyolite Tuff, which contributed largely to the infilling of the Pannonian Basin (Horvath et al., 2014).

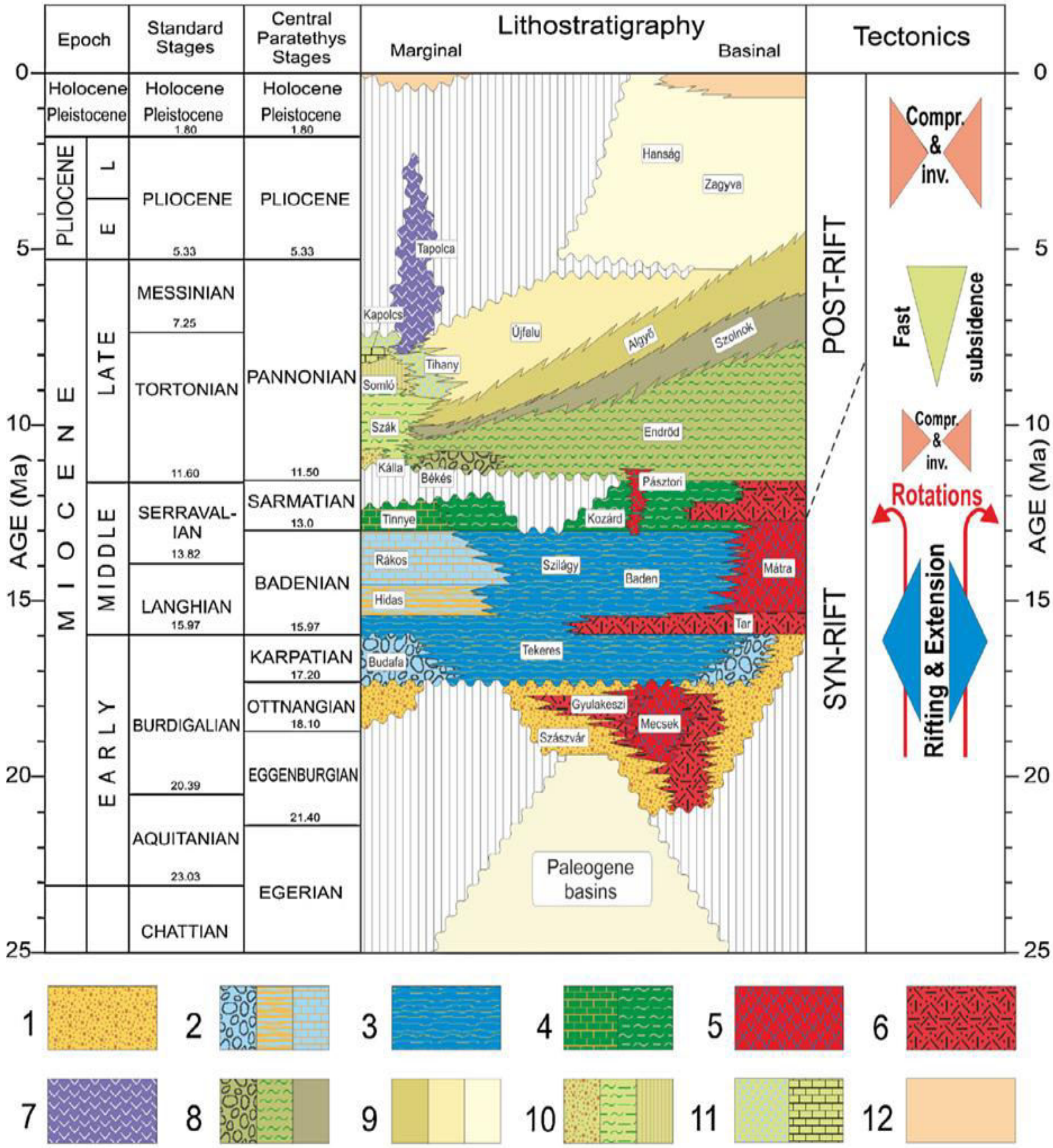

Figure 3.3. Stratigraphic table of Pannonian Basin in Hungary (Horvath et al., 2014)

Central Paratethys megasequence: 1-Fluvial and lacustrine; 2-Marine basin margin formations; Brackish; 3-Marine pelagic; 4-Brackish basin margin; 5-Volcanics, mostly andesites; 6-Volcanics, mostly rhyolithic ignimbrites and tuffs;

Lake Pannon megasequence: 7-Volcanites, alkali basalts; 8-Lacustrine, deep basin; 9-Lakustrine, shelf slope to plain; 10-Lake margin; 11-Alluvial plain; 12-Fluvial and aeolian

Ottnangian

The Ottnangian period is generally defined as the time when the initiation of rifting took place (eg. Horvath et al., 2006). The sedimentary rocks, which are related to the initiation of rifting and thus make up the vast majority of Ottnanigan lithologies are continental deposits. These strata consist mainly of coarse clastics, fluvial sands, marsh and lagoonal muds and lignite seems (Horvath et al., 2014). A representative of this set of strata is the Szaszvar Formation (Fig. 3.3), which is mostly composed of conglomerates and gravels, sandstones, clays, marshy siltstones, lignites and carbonaceous clay. These lithologies were deposited in a fluvial and shallow lacustrine environment (Horvath et al., 2014).

During Ottnagian times, approximately during the 21-17 Ma time interval, a felsic calc-alkaline volcanic eruption was recorded. This time was characterised by the deposition of rhyolithic ignimbrites and tuff layers (Gyulakeszi Formation) (Horvath et al., 2014) (Fig. 3.3).

Karpatian

The early syn-rift Karpatian succession is characterised by siltstones, sandstones and conglomerate beds, mainly belonging to the Budafa Formation (Fig. 3.3) (Horvath et al., 2014). This formation can reach a thickness of up to 800 m. During Karpatian times, due to the transgression of the Paratethys sea, the marine Tekeres Schlier was formed (Fig. 3.3) (Horvath et al., 2014). This lithology is composed of sandy clay and clay-marl and is very rich in marine fossils (Horvath et al., 2014).

The Karpatian was also a time when similarly intensive eruptions to the one recorded in the Ottnangian, took place. These eruptions were mainly composed of ignimbrites, tuffs and outflows of rhyolites and dacites, which continued from the Early Karpatian into Late Sarmatian times (Horvath et al., 2014). Thick intrusions of dacite tuffs, during the 15.3-17.4 Ma time period, mark the Karpatian/Badenian boundary (Saftic et al., 2003).

Badenian

Further transgression of the Paratethys sea resulted in open marine conditions (Horvath et al., 2014), thus making the Badenian the last fully marine period in the life of the Paratethys (Saftic et al., 2003). The transition from Karpatian environments to Badenian fully marine conditions is characterised by fish-bearing lacustrine clay-marls and sands containing *Congeria* (Saftic et al., 2003). On top of these strata lie coarse clastics, such as sands, sandstones and conglomerates, which were deposited from foreshore to nearshore areas (Saftic et al., 2003). Furthermore, the Baden Formation (Fig. 3.3) also overlies the fossil-rich sands mentioned above. This formation is composed of grey clay and clay-marls, which can reach a thickness of approximately 1000 m in deep basins (Horvath et al., 2014).

The Late Badenian is represented by Szilagy Clay-Marl Formation (Fig. 3.3), which is characterised by *Turritella*-bearing clay-marls that can reach up to 300-450 m thickness and indicate open marine conditions (Saftic et al., 2003; Horvath et al., 2014). The clay-marl is interbedded with *Lithothamnion*-containing Leitha Limestone, formed in the nearshore-littoral zone (Saftic et al., 2003).

The Badenian period is also characterised by widespread volcanism. During this time the Matra formation was deposited, which is mainly composed of andesites (Horvath et al., 2014). During the Badenian the volcanism of the Pasztori High in NW Hungary also took place. This volcanism is represented by scoria/cinder cones (Schleder, 2001) and can be seen quite well in seismic sections displayed in this study.

Sarmatian

Sarmatian sediments often consist of laminated to thinly bedded marls of the Kozard Formation, (Fig. 3.3) (Horvath et al., 2014), which then alternate with minor amounts of poorly consolidated sandy layers. Close to the Sarmatian/Pannonian boundary, the presence of diatomites has been recorded. The microfauna of the Sarmatian is dominated by benthic foraminifera and ostracods (ter Borgh et al., 2013). This fossil record indicates shallow marine water depths (ter Borgh et al., 2013), thus disproving the theory that brackish environmental conditions prevailed in the Sarmatian (Piller and Harzhauser, 2005).

Due to the uplift and exhumation of mountain belts around the Pannonian Basin, which involved the central part of the basin system too, an unconformity was formed (Horvath et al., 2014). However, in the few deep basins where no erosion occurred, the Sarmatian and the overlying Pannonian succession are very similar. Therefore, the base Pannonian unconformity cannot be identified in seismic sections and well logs (Horvath et al., 2014). Apart from these depocentres however, the Sarmatian strata is completely missing or present as layers, which are only a few metres thick. As an example of this are the central parts of the Pannonian Basin, which in the study area correspond to the Danube Basin in Hungary, where the Sarmatian succession is very thin. In the basin margins however, corresponding in the study area to the Styrian Basin, Oberpullendorf Basin and Eisenstadt-Sopron Basin, the Sarmatian strata are very thick and can reach a thickness of up to 1200 m (Horvath et al., 2014).

Pannonian

The sediments of the Pannonian form the so called Lake Pannon megasequence in the Pannonian Basin (Horvath et al., 2014). Lake Pannon sediments, depending on their palaeostratigraphic position, either conformably overlie Sarmatian layers or unconformably lie over older sediments, which occasionally belong to the crystalline basement (Saftic et al., 2003).

The relatively low sediment influx in Lake Pannon, until ca. 10 Ma, caused the formation of calcareous marls and clay-marls (Endröd Formation, Fig. 3.3) (Horvath et al., 2014). Turbidity currents, which originated from the slopes, caused a gradual transition of the marls of the Endröd Formation into the turbiditic Szolnok Formation (Fig. 3.3). This formation mainly consists of alternating fine-grained sandstone and pelitic layers (Horvath et al., 2014).

The base of Pannonian deposits generally consists of transgressive sandstones and conglomerates. These are then succeeded by deposits which are composed of grey to light-coloured marls. In the lowermost part of the unit cm- to dm-scale layers of well-rounded conglomerates, which display a marly matrix, have been recorded (ter Borgh et al., 2013). These lithologies are representative for the deeper parts of the Pannonian

Basin and therefore it can be concluded that water depths must have been considerably larger than during the Sarmatian (ter Borgh et al., 2013).

Quaternary

During Quaternary times, the coastal plain environment of the Pannonina Basin, experienced during the Neogene time period, was replaced by an alluvial plain across a larger area (Horvath et al., 2014). During this time the sediments of the Zagyva and Hansag Formation, which are fairly similar to each other from a litho- and biostratiraphical point of view, were deposited. These successions were characterised by channel fills, floodplain and marsh deposits and paleosols (Horvath et al., 2014).

In the 8-2 Ma time interval alkaline magmatism took place. This volcanic activity caused the formation of small monogenetic fields, which were sporadically distributed in the Pannonian Basin (Horvath et al., 2014).

3.2. Tectonic Evolution

The Alpine-Mediterranean region was a large convergence zone between the European and Nubian plates during Late Cretaceous and Cenozoic (Horvath et al., 2014). Since the Oligocene, extensional basins have developed in this mainly compressional setting (Horvath et al., 2014). The Pannonian Basin, located in eastern Central Europe, is one such basin. This basin has a Neogene to Quaternary age and is superimposed on two orogenic terranes, namely Alcapa and Tisza-Dacia (Horvath et al., 2014).

The formation of the Pannonian-Carpathian system occurred during the Triassic to pre-Cenozoic evolution of four continental blocks: Tisza to the south-west, Dacia to the south-east, Alcapa to the north and the external East European/Scythian/Moesian platforms to the south, east and north (Jarosinski et al., 2011 and citations therein).

According to Horvath et al. (2014) two different oceanic domains existed between the converging European and Adriatic plates, namely the Neothethys and the younger Alpine Tethys. The Neotethys is located east of Adria and started its development during the Late Palaeozoic, due to rifting with the northern margin of Gondwana. Two further branches of the Neotethys can be recognised in the Alpine-Mediterranean area: the Western and Eastern Vardar oceans (Horvath et al., 2014). The Western Vardar ocean was fully consumed during the Early Eocene as it subducted below Tisza and Dacia (Horvath et al., 2014). The East Vardar ocean (Transylvanides) however, closed during Cretaceous to Early Paleogene times, and caused the formation of the Tisza-Dacia block, which acted as one of the most important tectonic blocks during the evolution of the Pannonian Basin system (Jarosinski et al., 2011). During this time, shortening and continental collision also took place, which has been recorded in the Austroalpine units in the Alps and their lateral equivalent, the West Carpathians and the northern part of the East Carpathians. Due to this Cretaceous-Paleogene shortening and continental collision, the Alcapa block was formed (Jarosinski et al., 2011).

The Tethys (also called Alpine Tethys) was formed to the north and west of Adria and was created as part of the rifting process that caused the formation of the Central Atlantic Ocean. The closure of the Tethys started in the Early Cretaceous (Barremian to Aptian) (Horvath et al., 2014) and continued during Late Mesozoic and Cenozoic times. This process was accompanied by the collision of the European plate with fragments of the African plate, together with the separation of the North American plate from the Eurasian plate (Smith et al. (1994) *in* Faupl, 2000).

This continental collision produced the Paratethys (Fig. 3.4), an enclosed sea, which existed during Oligocene to Middle Miocene times consisting of a series of basins of various tectonic origin and the fold belts of the Alpine orogene. The Pannonian Basin system is located on top of these fold belts (Saftic et al., 2003). In the beginning of the Late Miocene, the Paratethys became isolated from other seas and a large lake was formed, namely Lake Pannon (e.g. Magyar et al., 1999; Saftic et al., 2003; Hohenegger et al., 2009).

Figure 3.4. Central Paratethys: palaeogeographic reconstruction of the Early Badenian main transgression within nannoplankton zone NN5 (Hohenegger et al, 2009).

By the Late Oligocene to Early Miocene, the present Pannonian crustal fragment was assembled. This process was accompanied by large-scale lateral displacement, namely continental extrusion, particularly of the Tisza block. Furthermore, rotation of the internal blocks took place, which caused the disintegration of the Alpine fold thrust belt and also strongly dismembered the Palaeogene basins (Horvath and Tari, 1999).

Continued convergence between the European and African plates, caused the formation of fold thrust belts (e.g. Horvath and Tari, 1999). These events occurred during the Mid-Miocene, which was also the period when widespread continental rifting took place in the Pannonian Basin area. Generally, a rift is formed at points where the crust is pulled apart by and the basin formed is an elongate crustal depression (Withjack et al., 2002). Rift systems, such as the Pannonian Basin system, are collections of stepping, intersecting and/or parallel rift basins (e.g. Withjack et al., 2002). Generally, two main models of rifting are identified, known as active and passive rifting (Fossen, 2010 and citations within). In the active rifting model, the rift is generated by rising hot mantle material or plumes in the asthenosphere causing doming and adding tensile stress to the domed area (Fossen, 2010 and citations therein). Therefore, the subsequently formed rift is mainly characterised by magmatism and not so much by extension. In the passive rifting model however, the rift forms due to stresses related to plate tectonics (Fossen, 2010 and citations therein). These types of rifts tend to form along zones of weakness in the lithosphere, such as reactivated contractional structures along former orogenic zones. During passive rifting, rifting takes place first and doming may follow it however, it may never precede it (Allen, P. and Allen, J., 2005).

In the case of the Pannonian Basin, the passive rifting model is more appropriate however, in many cases both models can be applied. Traditionally the evolution of the Pannonian Basin is subdivided into a syn-rift (Early to Mid-Miocene) and a post-rift (Late Miocene to Quaternary) phase (Fig. 3.5), which is reflected in the sedimentary architecture and therefore also visible in seismic imaging (Horvath et al., 2006).

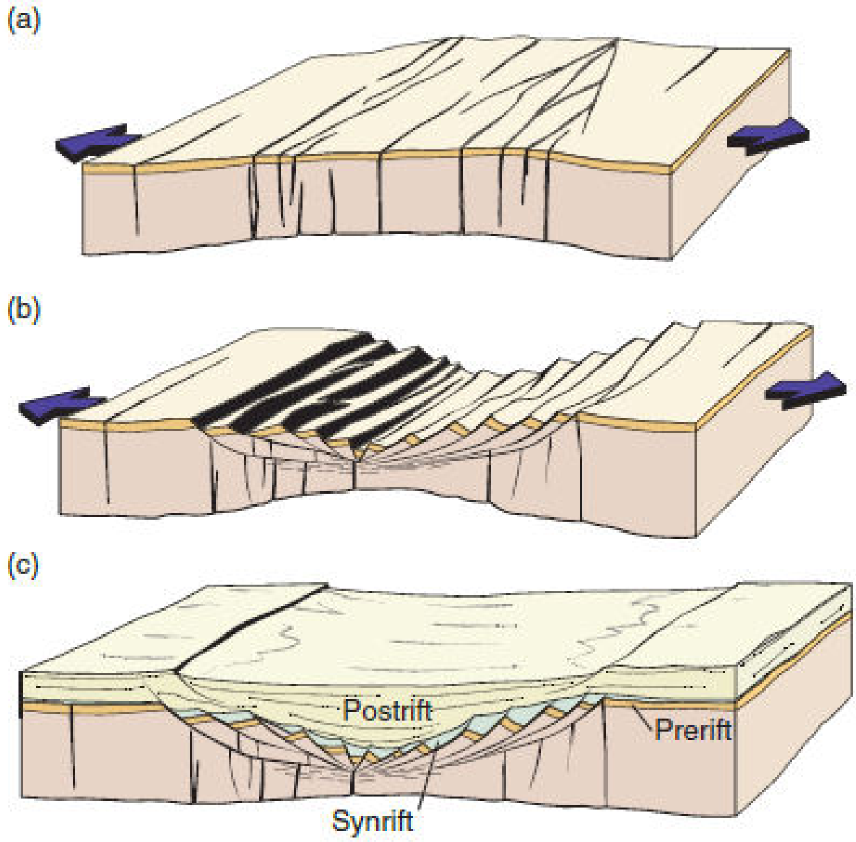

Figure 3.5. Three major stages of rift development (general case) according to Fossen (2010): a) Early extension creating or reactivating deep fractures. b) Stretching phase, during this time major faults are formed, syn-rift period. c) Post-rift (thermal) subsidence and sedimentation.

The syn-rift phase started during Early Miocene times, as early as Eggenburgian or Ottnangian times, characterised by non-marine to shallow marine sediments (Horvath, 1995 in Huismans et al., 2002). It is however, more often placed during Karpatian times, i.e. around 17.5-16.5 Ma, which was the time when rapid transgression occurred and when there was a large influx of terrigenous sediments derived from the syn-sedimentary faulting and uplifted blocks into the sub-basins of the Pannonian Basin system (e.g. Horvath and Cloetingh 1996, Horvath et al., 2006). This process continued until the end of the Badenian, which was the time when pure extension occurred (Huismans et al., 2002 and citations therein). Further evidence that the syn-rift phase starting during Karpatian times can be had from Sachsenhofer et al. (1997) who postulate that the peak of tectonic activity occurred during the Karpatian, when the tectonic movements caused tilting and uplift in the Styrian Basin, which is a so called “satellite” basin of the Pannonian Basin system (Sachsenhofer et al., 1997). The syn-rift phase is characterised by a regional unconformity between the pre-rift strata and the Early Miocene (Ottnangian to Badenian) sediments. The boundary between the pre-rift and syn-rift successions has been placed by Tari (1994) at 15.8 Ma, between the Early and Lower Badenian. This 15.8 Ma boundary has been considered a good local approximation however, the pre-rift/syn-rift boundary is not synchronous across the whole Pannonian Basin system (Tari et al., 1999).

Late Middle Miocene (ca. 12 Ma) marks the onset of the post-rift phase, which is documented by a regional unconformity, sealing most of the rift related faults by the Upper Miocene strata (e.g. Horvath and Cloetingh, 1996). Typically for a rift basin such as the Pannonian Basin, the post-rift sequence was controlled by the geometry of fault blocks and thermal subsidence (Fossen, 2010 and citations therein). According to Ebner and Sachsenhofer (1995), during this period, due to the cooling of the lithosphere, fault-controlled syn-rift subsidence was replaced by regional subsidence. Thermal cooling caused a rapid, thermal subsidence. During Late Miocene times, due to its broadening, the Pannonian area became a large single depression with uneven bottom morphology (Tari et al., 1992). When the Paratethys became separated from other seas in the beginning of the Late Miocene, the Pannonian Sea was separated from it and became the so called Lake Pannon with decreasing salinity. This large lake was then filled with sediments, mainly from the north and south (e.g. Saftic et al., 2003). Using seismic data together with well-log interpretation, it has been shown that the Pannonian Basin area has been filled up by a fluvial-dominated delta system (see sub-chapter 8.3.1 for further details on the delta progradation sequence), which prograded into the basin (e.g. Vakarcs et al., 1994; Sacchi et al., 1999; Sztano et al., 2013).

Since the cooling of the lithosphere took place during the post-rift phase, this period is often believed to be a tectonically quiet period (Tari et al., 1999). However, according to Tari et al. (1999) this was not the case. It is believed that during the post-rift period two events of compression were recognisable. Both of these phases are associated with fault reactivation and structural inversion on a regional scale. The earlier compressional event occurred a few million years after the termination of the syn-rift phase (ca. 11-8 Ma). The next event started sometime during the Late Pliocene and has continued until Recent (ca. 3.0 Ma) (e.g. Tari et al., 1999) (see sub-chapter 8.4 for further details on basin inversion).

During Late Miocene to Early Pliocene times, the evolution of the Pannonian Basin was characterised by general uplift, erosion and young, neotectonic faulting. Therefore, during this time, the Pannonian Basin experienced a tectonic inversion (e.g. Csillag et al., 2004; Horvath et al., 2006). The latest inversion phase took place during Pliocene to Quaternary times and is responsible for the partial exhumation and erosion of the Miocene Pannonian Basin fill (Tari et al., 1999; Horvath et al., 2006). This late evolution of the Pannonian Basin is closely connected to the continuous indentation and counterclockwise rotation of the Adriatic plate (e.g. Dombradi et al., 2009; Jarosinski et al., 2011).

The present tectonic setting of the Pannonian Basin is characterized by a system of Cenozoic basins (Dolton, 2006), such as the Styrian, Oberpullendorf and Eisenstadt-Sopron basins in Austria and the Danube Basin in Hungary, overlying a pre-rift basement of mainly Palaeozoic and Mesozoic age.

3.3. Styrian Basin

The Styrian Basin of Neogene age, is located at the eastern margin of the Eastern Alps and it is the westernmost sub-basin of the Pannonian Basin system (Ebner and Sachsenhofer, 1995; Sachsenhofer et al, 1997). It is separated from the other Neogene sub-basins of the Pannonian Basin system by the South Burgenland High (Südburgenländische Schwelle) (Ebner and Sachsenhofer, 1995). The Styrian Basin displays an elongate shape and is approximately 100 km length and 50 km width (e.g. Sachsenhofer et al., 1997). The Middle Styrian High separates the shallower Western

Styrian Basin from the deeper (ca. 4-km-deep) Eastern Styrian Basin (e.g. Sachsenhofer et al., 1997).

The Styrian Basin basement comprises high-grade metamorphic crystalline, anchimetamorphic and phyllites of Palaeozoic age together with carbonates, belonging to the Upper Austroalpine nappe system (e.g. Ebner and Sachsenhofer, 1995; Hamilton et al., 1999). During Early Miocene times, probably during the Ottnangian, the subsidence of the basin started and caused the formation of plain and swamp shale, sands and breccias with coal rich and bituminous layers (e.g. Hamilton et al., 1999; Hohenegger et al., 2009). During Mid-Miocene times (Karpatian to Early Badenian) andesitic shield-volcanoes developed. During Plio-Pleistocene times a second magmatic phase took place, which produced numerous tuff pipes and local basaltic lava flows (Ebner and Sachsenhofer, 1995).

The formation of the Styrian Basin was connected with the lateral extrusions of the crustal wedges along the strike-slip faults towards the Pannonian Basin (Ebner and Sachsenhofer, 1991; 1995; Sachsenhofer et al., 1997). A combination of block rotation, subsidence and uplift caused the formation of the various sub-basins of the Pannonian Basin system (e.g. Sachsenhofer et al., 1997).

Extrusion tectonics were caused by the interplay of extensional collapse of the overthickened and therefore unstable crust of the Eastern Alps and tectonic escape (e.g. Ebner and Sachsenhofer, 1991; 1995; Ratschbacher et al., 1991). These movements occurred along sets of sinistral strike-slip faults, which bordered the wedge in the north and northwest (e.g., Noric Depression) (Ebner and sachsenhofer, 1995). Furthermore, they occurred along the dextral Periadriatic Lineament and its associated strike-slip zones (e.g., Lavant Line), which border the wedge in the south and southwest (Ebner and Sachsenhofer, 1995). The structure of the crust beneath the Styrian Basin, serves as evidence for the position of the basin in the transitional zone between the Alpine and the Pannonian areas. Crustal thickness at the western part of the basin is ca. 35 km and decreases up to 25 km at the border between Austria and Hungary (Ebner and Sachsenhofer, 1995 and citations within).

In general, the evolution of the Styrian Basin, as compared to the evolution of the Pannonian Basin system as a whole, is subdivided into a syn-rift phase, which took place during the Early to Mid-Miocene (Ottnangian to Badenian) and a following Sarmatian to Quaternary post-rift phase. Sedimentation started during the Ottnangian, where it was dominated by non-marine to shallow marine sediments (Ebner and Sachsenhofer, 1991; 1995). Extended lignite formation took place in the Western Styrian Basin during Early and early Middle Miocene times, which overlaid coarse-grained fan deposits (Hohenegger et al., 2009). During Karpatian times, the Paratethys transgressed across the Eastern Styrian Basin (Hohenegger et al., 2009). The highest subsidence rates were recorded during the Karpatian, which were caused by the significant syn-sedimentary faulting (Ebner and Sachsenhofer, 1991; 1995). During this time the basin was comprised of swamp and floodplain deposits, formed due to basin subsidence (Hohenegger et al., 2009). The Karpatian/Badenian boundary is marked by sedimentation gaps and angular unconformities, such as the so-called Styrian Unconformity. These unconformities were formed through a series of marine transgressions of the Badenian Sea, which were deposited on top of the Karpatian deep-water sediments (Steirischer Schlier) (Hohenegger et al., 2009). The transgressions in the Styrian Basin reached their greatest extent during the Early Badenian, which was the time when the centre of the basin was filled with marine turbiditic conglomerates, shales and sandstones (Hamilton et al., 1999; Hohenegger et al., 2009). During the Sarmatian and Pannonian, a continuous shrinking of the relict Paratethys Sea has been documented and during this time the Styrian Basin was separated from the Pannonian Basin, taking its place as a "satellite" basin of the Pannonian Basin system (Hamilton et al., 1999; Hohenegger et al., 2009).

The Karpatian was also the time when tectonic activity reached its peak (Ebner and Sachsenhofer, 1991; 1995). These tectonic movements caused the uplift of the western hinterland and the uplift of the Sausal Mountains (Middle Styrian High) (Ebner and Sachsenhofer, 1995). The pronounced uplift, together with tilting and erosional truncation, also caused the asymmetry which is observed in the strata of the Styrian Basin (Ebner and Sachsenhofer, 1991; 1995). From its uplift on the Middle Styrian High formed a structural high separating the Western Styrian Basin from the Eastern Styrian Basin. Furthermore, major normal faults define the western border of the South Burgenland High and the internal structure of the Eastern Styrian Basin

(Ebner and Sachsenhofer, 1991; 1995). Thus, the South Burgenland High formed a stable block until Pontian times and also acted a barrier between the Styrian Basin and the Pannonian Basin (Ebner and Sachsenhofer, 1995).

3.4. Leitha Mountains and Burgenland High

This section will focus on the Leitha Mountains and the South Burgenland High, which are both integral parts of the Pannonina Basin system.

3.4.1. Leitha Mountains

The Leitha Mountains are a mountain range located northwest of Lake Neusiedl (Neusiedlersee) (Földvari, 1988 and citations therein). The Leitha Mountains are an important part of the Pannonian Basin system. The Eisenstadt-Sopron Basin is bound by this mountain range in its northern part where the Leitha Mountains act as a barrier between the Eisenstadt-Sopron Basin and the Pannonian Basin as a whole (McCann, 2008 and citations therein).

This mountain range, displays a relatively simple geological composition with mainly mica schists, which have the same strike direction (NE-SW) as that of the long axis of the range itself (Földvari, 1988 and citations therein). The ridge of the Leitha Mountain rises approximately 150-250 m above the level of the Lajta river, dipping steeply towards the east. It has an average height of 400 m (Földvari, 1988 and citations therein). Its highest point is the Sonnenberg, with a height of 483 m and is characterised by coarse-grained gneisses (Földvari, 1988 and citations therein). Its slopes are mainly composed of sedimentary sequences such as small relics of Mesozoic (mainly Triassic) limestones, quartzites, and predominantly Miocene deposits. The Miocene deposits are dominated by the Leitha limestone of Tortonian (Badenian-Late Miocene) age, which formed approximately 10 Ma (Földvari, 1988 and citations therein).

The Eisenstadt-Sopron Basin in N Burgenland, is bound by the Leitha Mountains in the N. The oldest Neogene deposits in the present Eisenstadt-Sopron Basin belong to the Early Miocene (McCann, 2008 and citations therein). They consist of terrestrial, fluvial and lacustrine deposits, which are considered to be genetically related to the fluvial system of the southern Vienna Basin. This fact suggests that the Leitha Mountains did not exist as a barrier between the Eisenstadt-Sopron Basin and the larger Pannonian Basin at that time, and that the basin development only started during the Middle Miocene and not before it (McCann, 2008 and citations therein). As subsidene started, during Early Badenian times, it caused an initial marine ingression, which led to the Leitha Mountains becoming a peninsula connected with the Alpine mainland in the east (McCann, 2008 and citations therein). The nearshore deposits of this marine transgression are expressed along the SE margin of the Leitha Mountains by the Hartl Formation. This formation ranges from reworked gravel, to marine sandwaves and finally into corallinacean debris (McCann, 2008 and citations therein). During Middle and Late Badenian times, periods of high sea level occurred. This was the time when the Leitha Mountains were completely submerged. This flooding of the Leitha Mountains allowed the growth of thick corallinacean limestones and coral carpets (McCann, 2008 and citations therein).

This shallow sea was also the depositional environment for the Leitha limestone (Leithakalk), which contains large amounts of fossils such as red algae and molluscs (Földvari, 1988 and citations therein). Furthermore, it often consists almost entirely of bryozoan and *Lithothamnium* skeletal remains (Földvari, 1988 and citations therein). Near the northern part of the Leitha Mountains, the Kaiserststeinbruch is located, which is famous for its fossil-rich limestone quarries and plays an important role in construction (Földvari, 1988 and citations therein). Leitha limestone is a prominent deposit in the Leitha Mountains area. This fossil-rich limestone belongs to the Badenian and presents evidence for the fully marine character of that time period. The strata overlying the Leitha limestone are dominated by Late Miocene deposits such as clays, clay-marls and sands. On top of the Miocene layers, Quaternary deposits such as loess and weathering loam can be found (Irene Zorn *in* Schönlaub et al., 2000).

After a sea-level fall at the Badenian/Sarmatian boundary, the Leitha Mountains together with their Badenian sedimetary cover became exposed thus, causing the mountain range to become an island until the Late Miocene when Lake Pannon withdrew (McCann, 2008 and citations therein). Therefore, incised valleys developed, which then eroded the platforms formed during Middle Miocene times. Lake Pannon covered the Eisenstadt-Sopron Basin during Late Miocene times. The main evidence for this are the clay-marls and sands present in the basin (McCann, 2008 and citations therein). During Middle Pannonian times, a small river formed on the Leitha Mountains, which supplied reworked Lower Miocene gravels into the Eisenstadt-Sopron Basin. Similarly to the Vienna Basin, the withdrawal of Lake Pannon allowed the formatin of flood-plains and swamps in the Eisenstadt-Sopron Basin during the latest Pannonian times (McCann, 2008 and citations therein).

3.4.2. South Burgenland High

The South Burgenland High also known as South Burgenland Swell is a ridge of the pre-Cenozoic, Palaeozoic, cristalline basal complex (Nebert, 1979) This high fulfills the role of a barrier, which separates the Styrian Basin from the so called Small Hungarian lowlands (western Pannonian Basin) and is a prominent stratigraphic and palaeogeographic element in the geology of Burgenland and of the Styrian Basin (Nebert, 1979; Ebner and Sachsenhofer, 1991; Pahr and Hermann *in* Schönlaub et al., 2000). It is composed primarily of phyllitic shales, green shales and limestone shales of Silurian age and carbonates from the Devonian (Pahr and Hermann in Schönlaub et al., 2000).

Its development shows that the northern part (NNE Jennersdorf) has formed a barrier during the whole of the Miocene until the Early Pannonian (Ebner and Sachsenhofer, 1991). The sedimentation area, together with the south-eastern part of the Styrian Basin, was included in the Pannonian Basin sedimentation environment only through the relocation of the subsidence centres during Pontian times (Ebner and Sachsenhofer, 1991).

The lithological content of the SBH is made up mainly of carbonates and volcanoclastic rocks which are correlated with the Upper Austroalpine appearance of the Grazer Palaeozoic (Ebner and Sachsenhofer, 1991; Pahr and Hermann *in* Schönlaub et al., 2000). The border of the SBH with the Styrian Basin is a normal fault that has developed in the northen part of the eastern edge of the Fürstenfeld Basin since Karpatian times (Ebner and Sachsenhofer, 1991).

The northern SBH has been subdivided by Nebert (1979) into three separate blocks (Rechnitz, Eisenberg and Güssing segments), which are distinguished from each other through faults and have tilted against the Pannonian Basin in early Teritary times, thus their inclusion in the sedimentation environment of the Pannonian Basin (Nebert, 1979).

Further lithologies of the SBH are the so called Tabor Schotter (gravel) (Pahr and Hermann *in* Schönlaub et al., 2000), equivalents of the lignite sequence and a clay-sand succession with *Congeria neumayi* (Ebner and Sachsenhofer, 1991). In wells on the west of the Eisenberg segment, sediments of the Mid- to Upper Sarmatian were the prime evidence of flooding. However, evidence for the exact sedimentation processes in the Lower Sarmatian are missing. In the Mid-Pannonian the sedimentation reached the eastern Eisenberg segment however, it was only in Upper Pontian times when through sedimentation a uniform fresh-water sedimentation body was formed over the whole northern SBH (Ebner and Sachsenhofer, 1991).

The Neogene development of the SBH also shows that this ridge separates environments with different subsidence histories, which can be seen from the thickness and facies comparisons between the equivalent strata of the Styrian and Pannonian Basin (Nebert, 1979). In the basin fill of the Styian Basin the deposits that are involved in the SBH belong to the Lower and Middle Miocene; the Upper Miocene and Pliocene on the other hand are only represented by a thin cover of sedimentsover the previously mentioned deposits (Nebert, 1979). On the other side of the SBH, the Pannonian Basin sediements of the Lower and Middle Miocene are limited to only deep ditches, while the Upper Miocene sediments on the other hand reach considerable thicknesses (Nebert, 1979).

During Ottnangian and Karpatian times, the SBH was part of the landlocked western Pannonian Massif, which included the whole Transdanubian zone within it. Sedimentary-petrographic analyses on the Ubersbach well have shown that the western Pannonian zone was a provenance and erosional zone for the Styrian Basin (Nebert, 1979). The sediement transport of the western Pannonian Massif took place in the direction of the Styrian Basin. This palaeogeographic condition continued until the Middle Badenian (Nebert, 1979). The Upper Badenian and the start of the Sarmatian was the time period where the western part of the western Pannonian Massif started to experience a weak subsidence, which later developed into the so called Raabgraben. The sediment influx into the Styrian Basin continued to come dominantly from the east (Nebert, 1979).

The SBH experienced a continued isolation from the western Pannonian Massif during Pannonian times. The main process that occurred was a slow subsidence which took place at the margins of the Styrian Basin and extended parts of the Pannonian Basin (Nebert, 1979). This subsidence led to the deepening of the Raabgraben (margins) and during Pontian times to the complete flooding of the SBH. It was only during the Upper Pontian that the large scale connection between the Pannonian and Styrian basins took place, where the Styrian Basin took its place as a sub-basin of the Pannonian Basin System (Nebert, 1979).

In the Kirchfidisch area, fresh-water, fossil-rich (molluscs) limestones can be found. A similar fresh-water lithology containing mollusk fauna can be found at the base of the Pontian sediment in that area (Ebner and Sachsenhofer, 1991). This shows that, during Pontian times, the SBH must have been an arid environment, which was exposed through strong karstification. Further evidence for this, are fossil karst fissures and distinct paleokarst surfaces below the Pontian sediments, which are found in the Palaeozoic base complex of the Kirchfidish quarry (Ebner and Sachsenhofer, 1991).

The subsidence of the SBH started in Mid-Pontian and started the development of swamp environments, which caused the whole SBH to become in the Upper Pontian a sedimentation environment (Ebner and Sachsenhofer, 1991). Furthermore, the swamp areas caused for a short period of time optimal conditions for the formation of coal (Ebner and Sachsenhofer, 1991).

4. Data bases used in this study

2D reflection seismic profiles are the most important data elements used in this study complemented with industry well data. The seismic data in the Austrian part of the NW Pannonian Basin were supplied by OMV Austria. Detailed seismic mapping of the area of study uses conventional industry, but also high- and ultra-high resolution multi-channel and single channel data as well. The vintage georeferenced 2D industrial seismic data cover the area around the Neusiedlersee in the Austrian part (e.g Oberpullendorf, Frauenkirchen, Minihof). The parts in NW Hungary covering the broader area between Györ and Köszeg were covered by vintage seismic data used by Tari (1994). The seismic data, either the SEGY-format digital or the scanned/georeferenced versions were loaded into a single Petrel project. Vintage well data for Austria was obtained from old analogue copies of the well summaries of OMV Austria. The well data from Hungary, on the other hand, were summarized from Körössy (1987) and also from Tari (1994) (see Appendices for full well summaries). The well data was used to establish the seismic stratigraphic framework in the basin by defining the signature of various seismic mapping horizons.

4.1. Seismic data base

This project comprises of seismic data from two countries, Austria and Hungary. More specifically, the Austrian data base is made up of vintage scanned seismic lines by OMV Austria acquired in the 1970s and 1980s. The seismic profiles for Hungary were acquired by OKGT (Hungarian National Oil and Gas Trust, the predecessor of MOL) in the 80's and were taken from Tari (1994) for this study. A total of 424 individual 2D seismic lines were made available for this study, representing a total of 5282 km line length of seismic reflection data. However, the actually utilized length of the seismic lines used in this study is approximately 2500 km. In order to constrain the subsurface of the Pannonian Basin for this study, a total of 161 lines were used in the study area, subdivided to 91 dip lines and 70 strike lines. Out of the total 161 seismic profiles used for this study, 44 lines belong to the Austrian part and 117 lines to the Hungarian part. The Austrian seismic lines are of poorer quality than the Hungarian ones as they are older and have been scanned from old hard-copies and loaded into Petrel with a seismic reference datum of 100 m above sea-level. Most seismic sections are migrated time sections with a maximum recording time of 5 second two-way travel (twt) time, which provide reasonable quality information down to about 4 s twt time. The 2D seismic grid is supplemented not only by the well summaries (see Appendices) but also by geologic maps from the Austrian Geological Survey (GBA), which allowed for more exact fault correlation and mapping. In order to integrate and georeferenced the data, ArcGIS was used. In this project the seismic sections have a maximum depth of 5 s twt time, which, assuming an average velocity of approximately 3000-3400 m, translates to about 7.5 to 8.5 km imaging depth below the surface.

Seismic interpretation focused on the Austroalpine basement and syn-rift and post-rift Miocene to Pliocene statigraphy and associated structures. Three stratigraphic horizons (Austroalpine basement, Badenian and Sarmatian) were mapped in all 2D seismic sections with the Karpatian mainly being mapped only around the Eisenstadt Basin (Minihof) area (Fig. 5.1). The seismic mapping horizons were correlated to the general chronostratigraphic framework of the Pannonian Basin using well data. Furthermore, an arbitrary intra-Pannonian horizon has been mapped, mainly in the Hungarian part of the study area. The intra-Pannonian reflector has been chosen arbitrarily, but mainly based on the fact that it could be used as an approximation of the regional top Pannonian prograding sequence in the entire study area, regardless of any well data calibration. The reason for this choice was to investigate the general, regional-scale structure of the Pannonian strata.

4.2. Well data base

The majority of the wells used to constrain the subsurface of the NW Pannonian Basin for this project are located in the Austrian side with a total of 11 wells (see Appendices). In the Hungarian part, while a larger number of wells were drilled in the study area (see Körössy, 1987), only 5 wells were used for calibration purposes (see Appendices). The wells provided constraints for the seismic interpretation through the reported well tops and various geophysical logs such as gamma ray, resistivity, etc. logs.

The seismic horizons separating the Upper, Middle and Lower Miocene successions were defined based on available well data (e.g. well tops), on their seismic appearance and knowledge of the regional geology. Seismic packages were identified on the basis of reflection configuration and attitude (seismic reflection termination pattern, continuity, amplitude and frequency). Well data included well tops, detailed lithological and stratigraphic information (lithologs) and geophysical data such as gamma ray, resistivity logs and also velocity data such as check-shot information on time-depth relationships.

5. Seismic interpretation methods and mapped seismic units

The seismic data base for this study is composed of various vintage 2D seismic profiles from both Austria and Hungary (Fig. 5.1). The vintage seismic profiles in Burgenland were acquired by OMV in the 70’s and 80’s. This data set has been provided by OMV for this study. Additional modern data from the Neusiedl Lake area such as high-resolution seismic profiles acquired on the lake itself were also provided by OMV. The seismic profiles from Hungary, acquired by OKGT in the 80’s, were taken from Tari (1994). The estimated total line length for the seismic data used in this study is about 2500 km.

The well data used in this study is based on wells drilled by OMV in northern Burgenland in the 70’s and 80’s, with the exception of Podersdorf-1 and -2 (1936) and Zillingtal-1 (1944). The wells used for calibrating the seismic data on the Hungarian side were mostly drilled in the eighties and reported by Körössy (1987) and also Tari (1994).

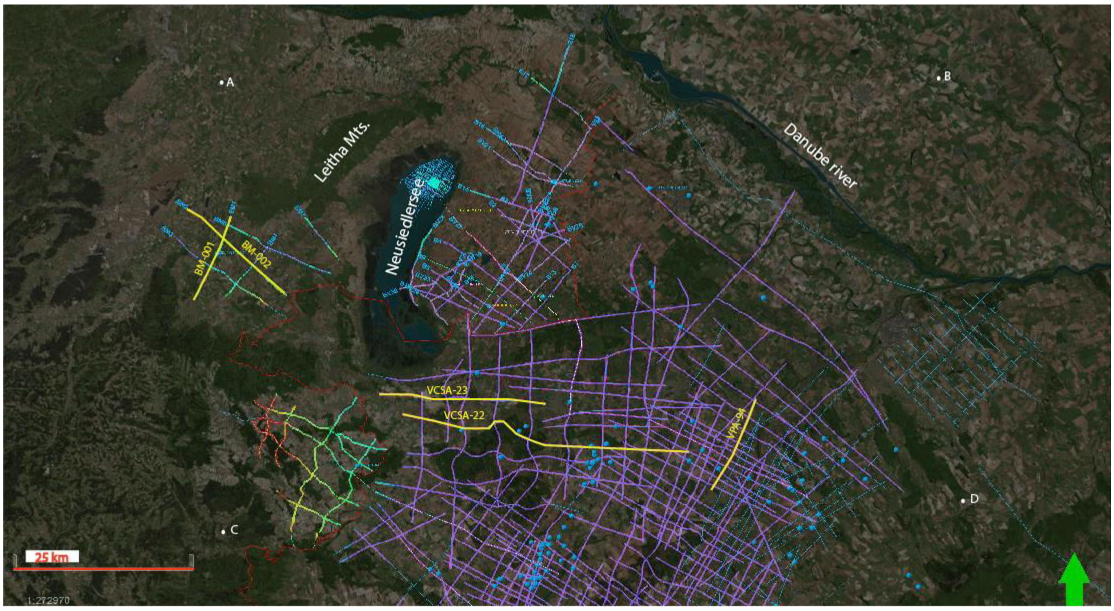

Fig. 5.1 Seismic index map (Google Maps) of the study area between NE Austria and NW Hungary. The state boundary is highlighted in red. Exploration wells reported by IHS are shown as blue dots. Select seismic profiles BM-001, BM-002, VCSA-22. VCSA-23 and VPA-94, which are discussed below are highlighted in yellow.
GPS coordinates: **A**: N 48°4’50.52”, E 16°24’29.03”; **B**: N 48°0’35.611”, E 17°45’10.295”; **C**: N 47°27’1.926”, E 16°24’5.871”; **D**: N 47°27’5.267”, E 17°46’54.436”

5.1. Characteristics of mapped horizons

The stratigraphic horizons mapped for this study have been predominantly picked using well tops provided by OMV Austria. In order to better illustrate the various horizons mapped for this study, seismic segment BM-001 has been chosen (Fig. 5.2). This line is located in the Austrian part of the study area, in the Eisenstadt-Sopron Basin, just south of the Neusiedl Lake in northern Burgenland.

5.1.1. Quaternary

In the seismic database used for this study, the topmost 200-400 ms twt time information in the original seismic data typically was omitted, due to the fact that it has not been considered important for hydrocarbon exploration purposes. Therefore the Quaternary succession could not be mapped in the study area using seismic data. The only areas where the Quaternary is visible is the very high-resolution single-channel lake seismic data, acquired only in the northern part of the Neusiedl Lake

(Figs. 5.1 and 6.7), however, since only one line from that specific dataset has been used for this study, no generalisations can be made.

5.1.2. Pliocene-Upper Miocene (Pannonian)

The Pannonian sequence represents the largest part of the post-rift sedimentary fill in the Pannonian Basin (Fig. 3.3). It is characterised by alluvial and lacustrine sediments and widespread delta sediments, which has been observed in the Hungarian part of the study area. An intra-Pannonian reflector has been picked in order to characterize the overall geometry of the Pannonian succession. The intra-Pannonian marker becomes progressively shallower towards the NW and to the SE and gets terminated at the basin margins. This phenomenon is caused due to considerable post-Pannonian erosion on both flanks of the overall Danube Basin.

Since the Pannonian time period represents the post-rift stage in the basin, in the seismic profiles, this particular package is characterised by parallel and continuous reflectors (Fig. 5.2). These reflectors are largely undisturbed and very rarely there are faults offsetting them. The Pannonian reflectors generally display low to medium amplitudes, however, the chosen intra-Pannonian reflector has higher amplitude than the rest. This horizon is not correlated to any specific chronostratigraphic feature and has been picked as an arbitrary horizon to investigate the general, regional-scale structure of the Pannonian strata.

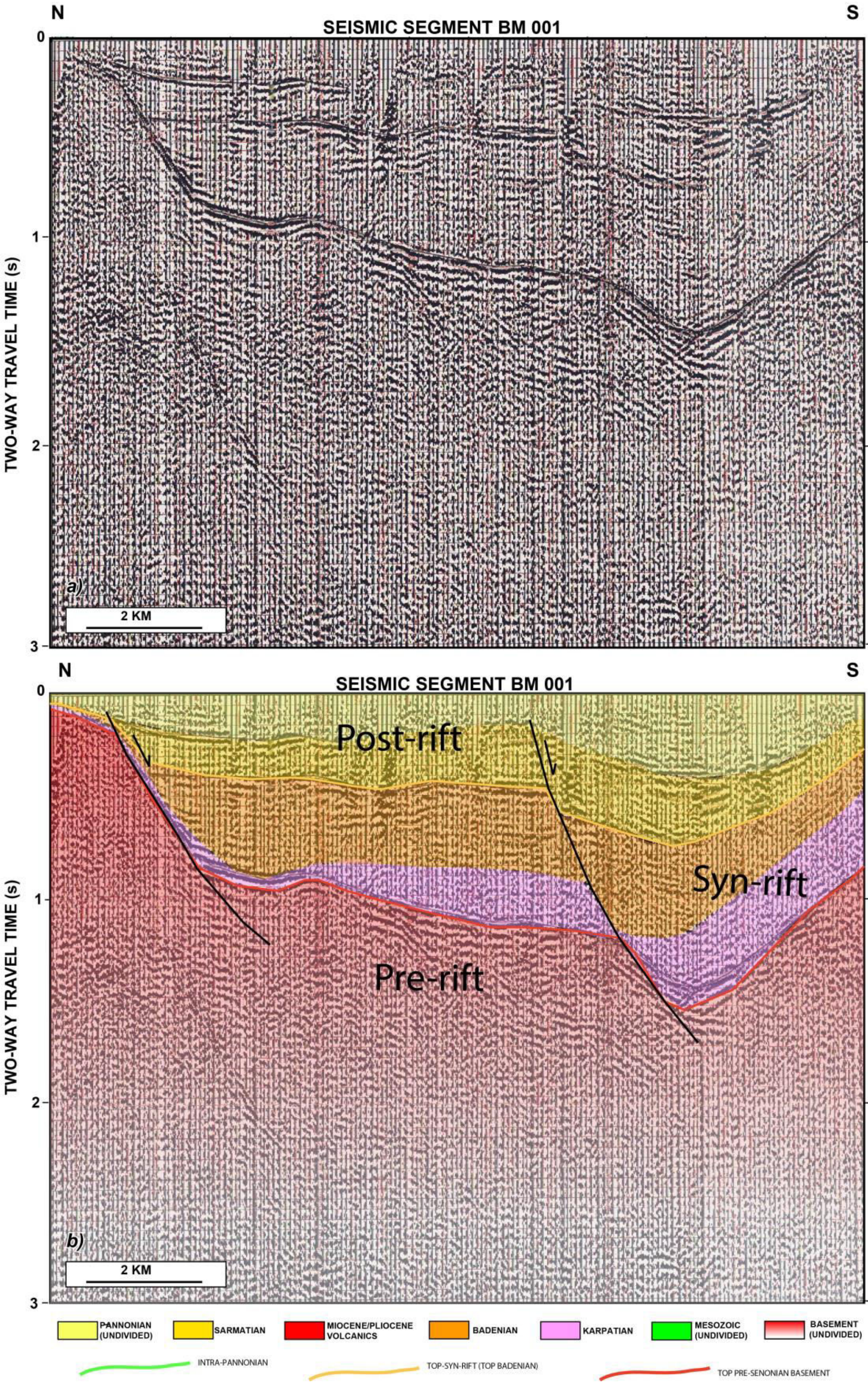

Fig. 5.2 Seismic segment BM-001 located in the Eisenstadt-Sopron Basin, just south of the Neusiedl Lake; a) Seismic segment BM-001 without interpretation; b) Mapped horizons in the BM-001 line, including the pre-Cenozoic basement, the Miocene (Badenian, Karpatian, Sarmatian) and Pannonian successions. See Fig. 5.1 for location in study area.

5.1.3. Upper Miocene (Sarmatian)

In the Pannonian Basin the Upper Miocene, in this case the Sarmatian seismic package, represents the beginning of the post-rift stage (Fig. 3.3). As such, this period is characterised by reflectors which are not offset by normal faults generally (Fig. 5.2). The normal faults that displace the syn-rift stratigraphic units, rarely offset the Sarmatian seismic package, thus making this horizon easily mappable. This period is also characterised by a drastic drop in sea level, moving from the fully marine environments of the Badenian into brackish conditions (cf. Piller and Harzhauser, 2005). Generally, an unconformity, which marks the termination of the syn-rift succession, separates the syn-rift (Karpatian and Badenian) strata from the early post-rift reflectors of the Sarmatian (e.g. Fig. 8.4).

5.1.4. Upper Middle Miocene (Badenian)

The Badenian in the Pannonian Basin represents the last fully marine stage of the Tethys and, as such, is characterised by marine sediments. During the Early Badenian general transgression occurred and the sea-level reached its peak at the end of the Early Badenian. The Badenian succession represents the late syn-rift phase in the Pannonian Basin. Therefore, this succession has been deposited during rifting and thus the Badenian seismic package is offset by normal faults that were formed due to extension (Fig. 5.2). The Badenian succession many times shows the typical fanning geometry usually displayed by syn-rift strata, i.e. a thickening of the strata can be observed towards the footwall of extensional faults. However, the syn-rift growth of the sediments in the various subbasins is not always easy to interpret as the sediments supply was not always sufficient to create “text-book” half-graben fills. The variable thickness of the Badenian basin fill, confined to local subbasins, provides indirect evidence for the syn-rift crustal-scale extension taking place during this time (Horvath et al., 2006).

According to Horvath et al. (2006) a Lower Miocene rhyolite tuff horizon, which is dated as approximately 20 Ma old (Fig. 3.2), is interbedded in the lowermost part of the syn-rift sedimentary beds. This volcanic marker bed, however, could not be detected and mapped on the seismic reflection data used in this study. However, a younger volcanic package, latest Badenian and Sarmatian in age, is very well developed and prevalent in the Pasztori High area in NW Hungary (Schleder, 2001). In the study area in general, there are very few lines where this volcanism of the Pasztori High has a seismic expression which can be mapped (Fig. 6.12).

5.1.5. Lower Middle Miocene (Karpatian)

The Lower to Middle Miocene (Ottnangian to Karpatian) strata mark the start of the syn-rift succession in the Pannonian Basin (Fig. 3.3). In the seismic data set for this project, the Ottnangian has not been accounted for. However some seismic segments, especially in the Austrian side of the study area, display a relatively thick package of Karpatian deposits which can be mapped on several adjacent seismic secions (Fig. 5.2). This occurrence of a seismically resolvable Karpatian, predominantly found in the Austrian part of the study area, is common for this set of strata. Generally, in the Pannonian Basin system, the Karpatian deposits are either found at the deepest parts of half-grabens or at the basin margins, such as the Eisenstadt-Sopron Basin, where the seismic line BM-001 is located (Fig. 5.2). During this time, marine conditions had transgressed and therefore the main environmental conditions were open marine (Horvath et al., 2014).

Since the Karpatian succession represents the early syn-rift phase in the study area, it is always offset by normal faults (Fig. 5.2). These faults generally display a steep-angle fault plane, however, in some cases low-angle normal faults can be observed (Fig. 6.3). In these cases, a tilt of the Karpatian strata on the low-angle fault plane can be observed (Figs. 6.3 and 6.4). This tilt of the Karpatian succession suggests syn-depositional growth and is evidence for significant extension (Tari et al., 1992).

5.1.6. Basement (pre-Cenozoic)

The pre-Cenozoic basement of the Pannonian Basin is composed of various unmetamorphosed Mesozoic and also crystalline basement rocks of Eoalpine (i.e. Cretaceous) origin. The main basement lithologies present in study area have been constrained by the exploration wells made available by OMV Austria (see Appendices for full well summaries). The basement package is predominantly characterised by igneous, metamorphic and sedimentary rocks such as gneisses, granites and phyllites of Palaeozoic and mostly carbonates (marbles) of Mesozoic age. The pre-Cenozoic basement marks the pre-rift stage of the Pannonian Basin and is characterised in a typical seismic section by medium to high amplitude reflectors close to its top which fade away to seismic noise very quickly with depth (Fig. 5.2). Therefore the top basement surface serves as the top acoustic basement. Whereas there are intra-basement reflector packages in certain parts of the study area, their mapping is challenging (Tari, 1994) and therefore this topic was not dealt with in this MSc project.

6. Regional transects and time structure maps

This chapter is intended to describe the regional context of the Danube Basin by showing three regional seismic transects and by highlighting the basin-scale structure on three time structure maps.

6.1. Regional transects

In order to have a better regional understanding of the seismic data and to provide a “big-picture view” of the NW Pannonian Basin, three regional transects have been spliced together using various seismic reflection data (Fig. 6.1). These transects include seismic lines from the Austrian and Hungarian parts of the study area and they have been used to correlate the seismic horizons across the two countries. The 2D seismic lines which make up these transects has been provided by OMV Austria and the Hungarian ones have been reproduced from Tari (1994). A total of 424 individual 2D seismic lines were available for this study, representing a total of 5,282 km line-length of seismic reflection data.

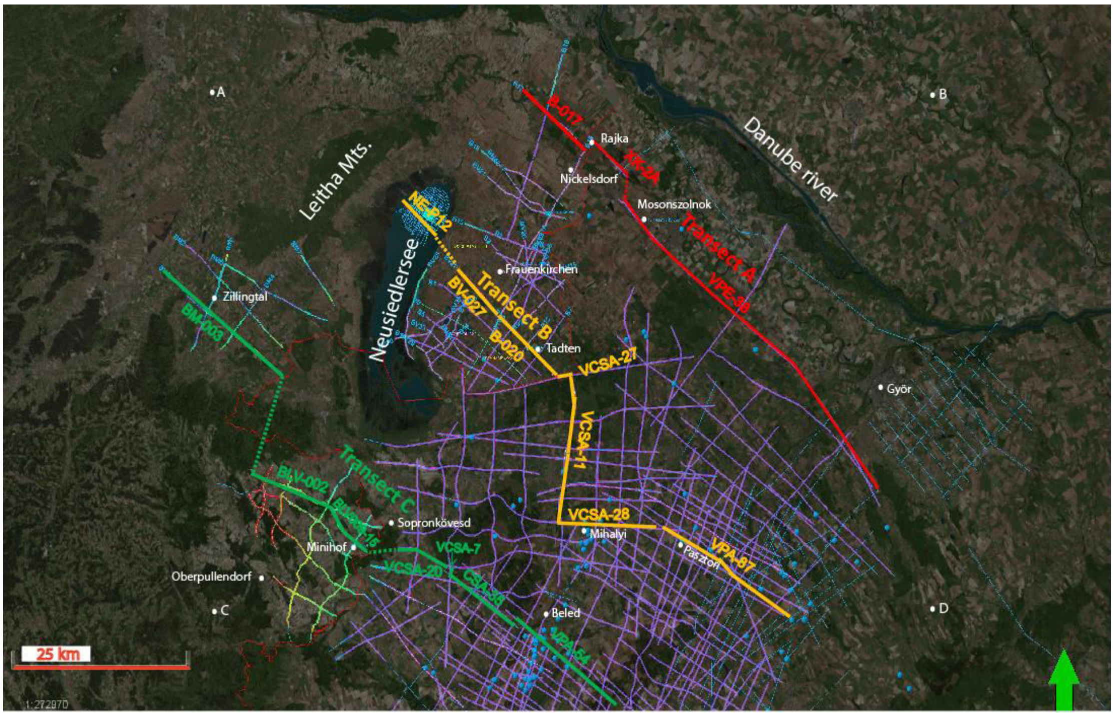

Figure 6.1. Google Maps image of the location of the study area with the trace of the regional transects across NE Austria and NW Hungary, in the southern part of the Danube Basin. Note the position of the Danube and Neusiedlersee for reference. The state boundary is shown as thin red line. Exploration wells drilled in the area are highlighted by blue dots.
GPS coordinates: **A**: N 48°4’50.52”, E 16°24’29.03”; **B**: N 48°0’35.611”, E 17°45’10.295”; **C**: N 47°27’1.926”, E 16°24’5.871”; **D**: N 47°27’5.267”, E 17°46’54.436”

6.1.1. Transect A

Transect A is a composite of three lines, B-017 in the Austrian part and XK-2A and VPE-38 in the Hungarian part (Fig. 6.1), with an approximate total length of about 80 km (Fig. 6.2). This transect is made up of seismic lines located in the northern part of Hungary where the Mosonszolnok-1 well (see Appendix A) can be found (line VPE-38) and in the eastern part of Austria, a few km north of the Neusiedl Lake (Neusiedlersee, Fig. 6.1). Therefore, this transect covers the Danube Basin in Hungary and in Austria, but it does not extend into the Vienna Basin of Austria (Fig. 6.1). This is the “simplest” regional transect in this study, in terms of number of seismic segments used, as it is composed of only 3 seismic profiles.

In a regional sense, the transect traverses the deepest part of the Danube Basin, where the basin fill attains almost 8 km in thickness (e.g. Tari, 1996). Like in most parts of the Pannonian Basin system, the basin fill is dominated by the post-rift (Pannonian to

Sarmatian) fill as opposed to the relatively thin syn-rift (Badenian to Karpatian), which comprise of sediments such as clays, siltstones, conglomerates and sandstones. Moving into the Pannonian, because of the change in environmental conditions from marine to lacustrine, a change in the main facies also occurred with the dominant lithologies being clays, sands and gravels. Note that position of the intra-Pannonian marker (shown in green) which was picked on top of a regionally extensive prograding unit (e.g. Magyar et al., 1999) formed due to a further change in environmental conditions where the main facies became deltaic and fluvial (Cernak and Svasta, 2015). The pre-Cenozoic basement of the Danube Basin is dominated by late Palaeozoic and Mesozoic, mainly Triassic to Jurassic, crystalline rocks and sedimentary sequences (e.g. Zamolyi, 2016). In the given data this can be observed from the lithologic description of Mosonszolnok-1 well (Körössy, 1987), located in the NW part of the VPE-38 seismic segment, where the pre-Cenozoic basement has a Triassic age. Whereas the Quaternary deposits of the Danube Basin are relatively thick (i.e. up to 300 m) in the central part of Transect A, this particular package cannot be seen on the seismic as the topmost 400 ms part of the seismic data has been not processed on the Hungarian side (due to the fact that this part has not been considered for hydrocarbon exploration purposes).

A general trend, which can be observed in Transect A, is that the seismic packages are generally thin in the NW but, as one moves towards the SE, they gradually thicken. Furthermore, there is a general tendency for the seismic reflectors to be truncated towards the surface on both sides of the regional transect. This termination of the sediments occurred due to late stage erosion, certainly post-Pannonian in age. This phenomenon can be observed on the other transects as well.

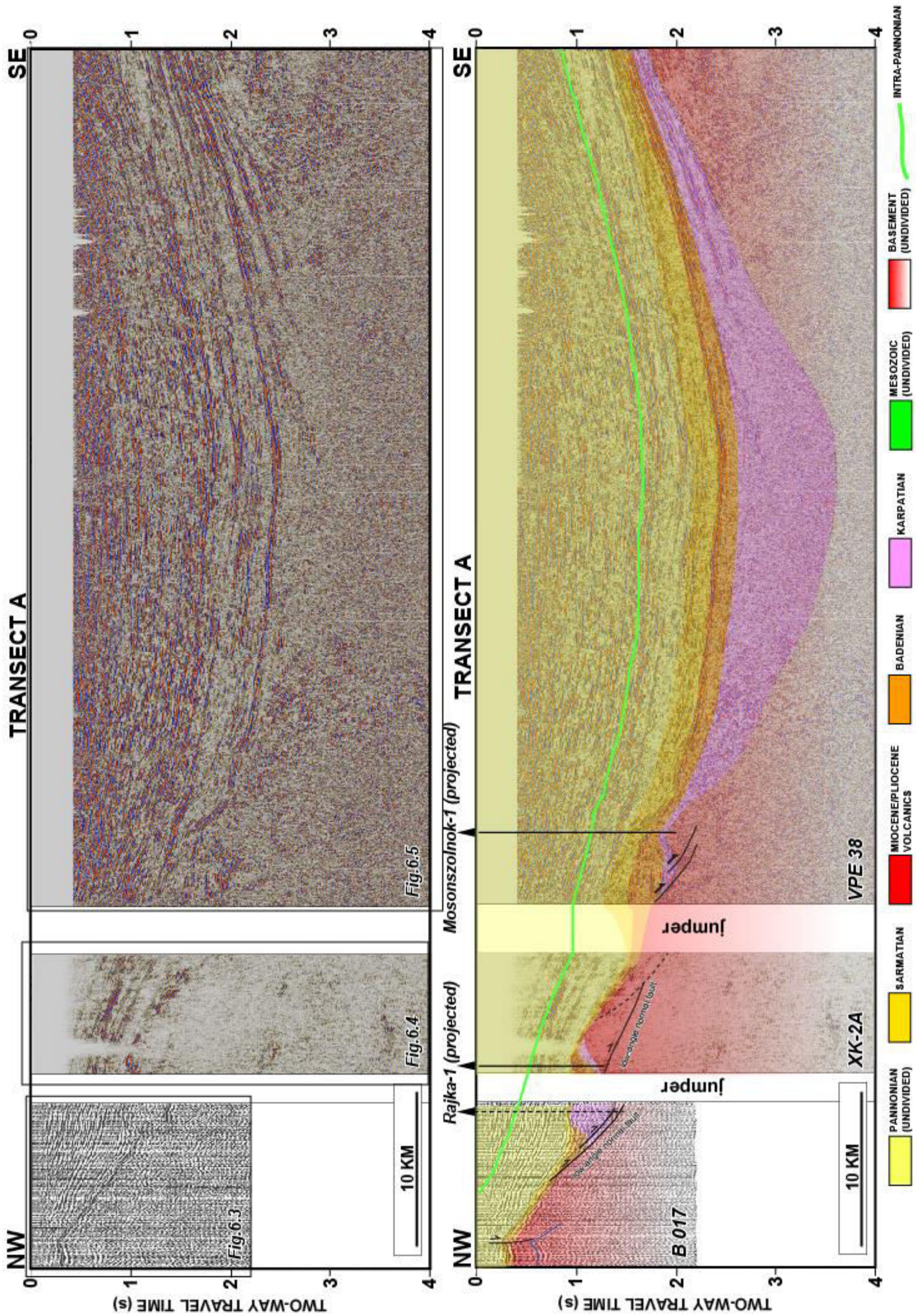

Figure 6.2. Transect A. Above: without interpretation, below: interpetation and jumpers from one line to another shown. See the outline of specific seismic illustrations of segments of the regional transect. See text for detailed description.

Line B-017 (Fig. 6.3), as part of regional transect A, is located in the Danube Basin of the Austrian side of the transect, not far from Nickelsdorf (Fig. 6.1), covers the basin margin where the pre-Cenozoic basement is in the shallowest position for this transect. The seismic record on this particular vintage line reaches a maximum two-way travel (twt) time depth of 2.2 s twt. This specific seismic line displays the Austroalpine basement, which reaches a maximum depth of approximately 1.6 s, Mid-Miocene (Badenian) package, with a depth of 0.2 s twt and Upper Miocene strata (Sarmatian, Pannonian) with a maximum depth of 0.1 s twt and 0.9 s twt, respectively. A Karpatian succession of approximately 0.4 s twt has been interpreted on the SE. Therefore, the Badenian and Karpatian packages, which represent the syn-rift succession, are very thin in comparison to the pre-rift (basement) and the post-rift (Sarmatian to Pannonian) successions. Another feture that can be observed within the B-017 seismic segment are the two normal faults, located in the NW and SE of the line.

In general, the main trend displayed by the various seismic packages of this segment is that they move upward towards the NW and get terminated closer to the surface. This upward truncation of the horizons is due to the erosion of the seismic packages, which can be observed in most of the seismic segments used for this study. Furthermore, the Miocene (Sarmatian and Badenian) and Pannonian seismic packages display a gradual thickening as one moves towards the SE. This phenomenon cannot be observed in the basement package however, since the top basement reaches its highest structural position on the NW-most part of the segment and gets considerably deeper in the SE part of the segment.

This particular seismic line, as is the case with all the Austrian seismic, has been acquired by the OMV in the 70’s and 80’s and therefore, it does not have the high quality that the Hungarian seismic displays. For this reason, features such as the multiple of the top basement reflector (see blue line on Fig. 6.3) are more likely to occur.

Another feature, which is of note on this particular seismic segment, is the thickening of the syn-rift (Badenian and Upper Sarmatian) strata against a NW dipping normal fault displayed in black in Fig. 6.3. As mentioned earlier, towards the SE the Miocene and Pannonian seismic packages gradually thicken, but here the thickening is clearly fault-related. The syn-rift strata experiences a relatively drastic increase in thickness against a NW dipping normal fault in the SE part of the seismic segment. This thickening of strata against a fault is typical for the syn-rift succession in the Pannonian Basin and in any other rift basin. Of particular interest is the fault present in the SE of the segment. This fault has a listric geometry, with its concave-upwards shape and is interpreted as a low angle normal fault (LANF). An interesting observation is that the Karpatian package displays a tilt into the low-angle fault plane of the above mentioned fault. Evidence for this are the faint fault plane reflections. This tilt of the Karpatian (Miocene) reflectors against the low-angle fault plane is interpreted as evidence for syndepositional growth. Furthermore, the pronounced low-angle dip of the fault plane and the strongly tilted Karpatian (Middle Miocene) strata suggest a significant extension (Tari et al, 1992).

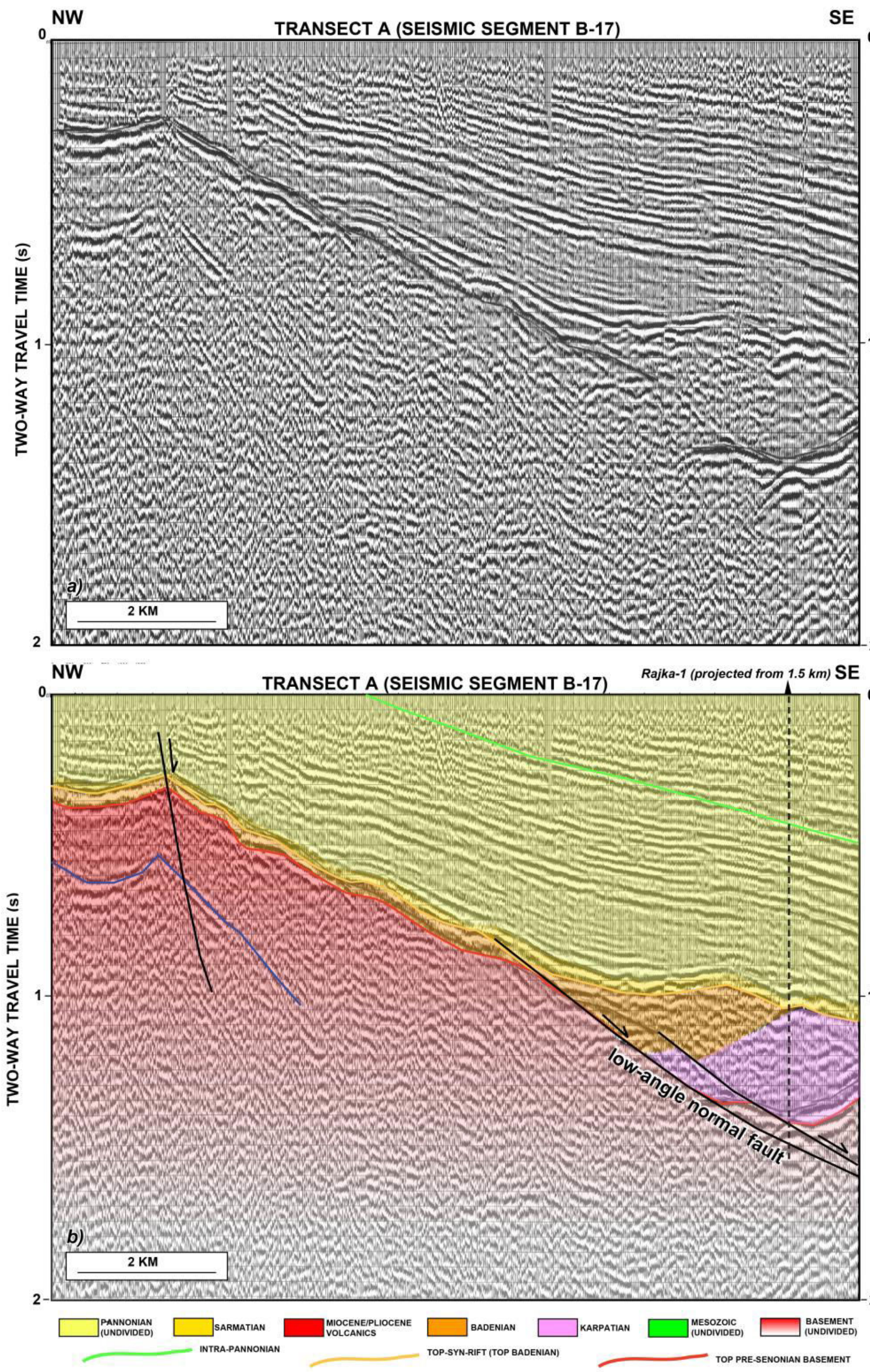

Figure 6.3. a) Seismic segment B-017 without interpretation and b) seismic segment B-017 with interpretation. The blue line within the basement corresponds to a multiple generated by the top basement reflector. NW dipping normal faults displayed in black. See text for detailed description.

Seismic segment XK-2A (Fig. 6.4) is located in the NW Hungarian part of the study area (Fig. 6.1), and is the northernmost seismic segment for the whole study area in general, considering the general SW-NE strike of the basin. In a regional setting, this seismic segment belongs to the Danube Basin of Hungary.

A similar phenomenon to the one observed in the B-017 line can also be seen in the XK-2A line, where the seismic packages display the gradual uptilt towards the NW, where they tend to get truncated as they get close to the surface. The Basement in this line reaches a maximum depth of 0.8 s twt. The Badenian and Sarmatian packages are quite slim, with the Sarmatian being the thinnest of all the packages in this segment. The Badenian reaches a maximum thickness of approximately 0.2 s twt and the Sarmatian reaches a thickness of ca. 0.1 s twt. On the NW part of the segment, the basement package forms a high, which is overlain by a very thin Karpatian package. The Karaptian displays a maximum thickness of approximately 0.15 s twt. The Pannonian package on the other hand, is the thickest package for this segment, with a maximum thickness of about 1.1 s twt. The intra-Pannonian marker, shown in green, has been picked above a delta progradation system, which gets closer to the intra-Pannonian marker as it moves towards the SE. This progradation is typical for Pannonian times and can be observed in almost all the other seismic segments located in Hungary.

All the seismic packages in this seismic segment get truncated towards the NW where they draw nearer to the surface. Closer to the surface the pacakges get terminated, most likely due to the erosion of the seismic reflectors.

The Rajka-1 (Appendix A) well has been projected onto this line, a well located in the northernmost parts of Hungary, across from Nickelsdorf on the Austrian side. The distance between the actual position of this well and seismic segment XK-2A is about 300 m. This well has a total depth of 1,785 m and has reached the basement at 1,540 m. The well location might have been chosen to test the bright spot, located at the Sarmatian/Badenian boundary. The well summary for Rajka-1 (Appendix A) helps give some further insights into the stratigraphy of the seismic line, helping to constrain the lithologies of the seismic packages observed in this segment. The Quaternary succession, which in the seismic is not visible, comprises of gravels, sands, clays and fluvial deposits. On the other hand, while the undivided Pannonian succession, consisting of grey, fine sandstones, interbedded in clay-marl sequences, has been accounted for, the Sarmatian has not been identified in the well and might be very thin or missing. However, a very thin Sarmatian package has been interpreted on the seismic data (Fig. 6.4), as a general observation of having thick Sarmatian between the basement highs and only condensed or missing Sarmatian strata over the structural highs, especially at the basin margin position. According to the well summary of Rajka-1, the syn-rift Badenian succession on the other hand, is displayed as a thick succession of 312 m in the well summary. On top of this succession some 10 m of Leitha-limestone have been observed. The bright spot displayed in the NW of the seismic segment, is accounted for by the Leitha limestone, due to the high velocity of carbonates in seismic sections, which then generated the high amplitude reflectors. The basement succession is of Palaeozoic age and is composed of micaschists.

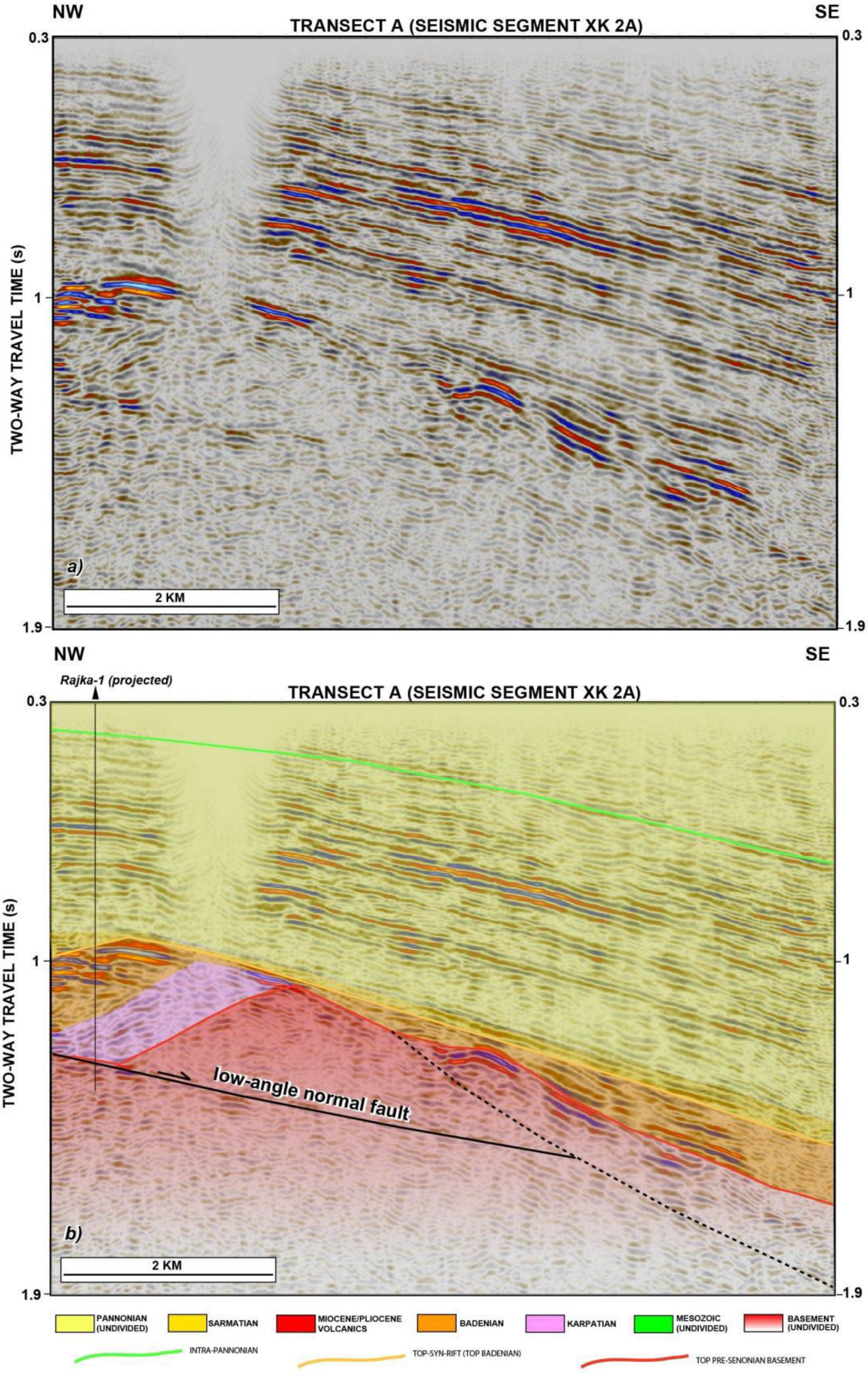

Figure 6.4. a) Seismic segment XK-2A without interpretation; b) Seismic segment XK-2A with interpretation. Low-angle normal fault and the Rajka-1 well also shown. See text for detailed description.

The VPE-38 line (Fig. 6.5) is located within the Danube Basin, near Györ in Hungary (Fig. 6.1). This seismic segment is the longest for Transect A, with a length of approximately 70 km.

This line reaches a maximum depth of 4 s in twt with the Pannonian seismic package being the thickest with approximately 2.2 s twt, which according to the Mosonszolnok-1 (Appendix B) well summary, is translated to 67.5 m. The pre-rift succession (pre-Cenozoic basement) reaches a maximum thickness of ca. 1.3 s twt. The Karpatian package observed in this segment, has a maximum thickness of approxmately 0.9 s twt. The Badenian and Sarmatian reach a maximum thickness of ca. 0.3 s and 0.2 s twt respectively.

Differently from the other seismic segments seen in this transect, line VPE-38 does not display the same trend of the previously shown segments where the seismic packages get truncated as they near the surface on the NW part of the line. While the packages do display a gradual thickening towards the SE, they form a depression in the middle of the transect where they reach their maximum thickness. This depression is the seismic representation of the Györ Basin, located in the N/NW part of Hungary (for a larger-scale view see Figs. 6.22, 6.23 and 6.24).

In the NW part of this line, a basement high can be seen where the projected Mosonszolnok-1 lies. While the well is projected on this seismic segment, its actual location lies very close to the discussed line with a distance of circa 390 m. This well reaches a total depth of 2,931 m and is the deepest well available for this project. The basement lithology is reddish sandstone belonging to the Mesozoic (Triassic). The Pannonian Basin-fill comprises mainly of clays and clay-marls with some sand and sandstone beds. However, some andesite-tuff has been found as part of the Badenian lithology, which is a continuation of the Pasztori sequence from the nearby Pasztori High. This line is also a good showcase for the syn-rift/postrift evolution of the Pannonian Basin as a whole, as the typical wedge formed by the syn-rift strata can be clearly seen in the Badenian package. Furthermore, the Sarmatian and Pannonian horizons are parallel and largely undisturbed. Within the Pannonian seismic package, the Pannonian delta progradation can also be seen, above which the intra-Pannonian marker has been picked. A zoomed in image of the delta progradation sequence observed in this seismic segment has been used later on (Fig. 8.6) as an example of the progradation observed in the Pannonian Basin in general. In the well summary the delta progradation is mainly represented by alternating beds of shale and sandstone (Appendix B).

The top-basement reflector displays a high amplitude and the amplitude of the reflectors above it is also very high. The Pannonian delta progradation sequence on the other hand, displays low amplitude reflectors.

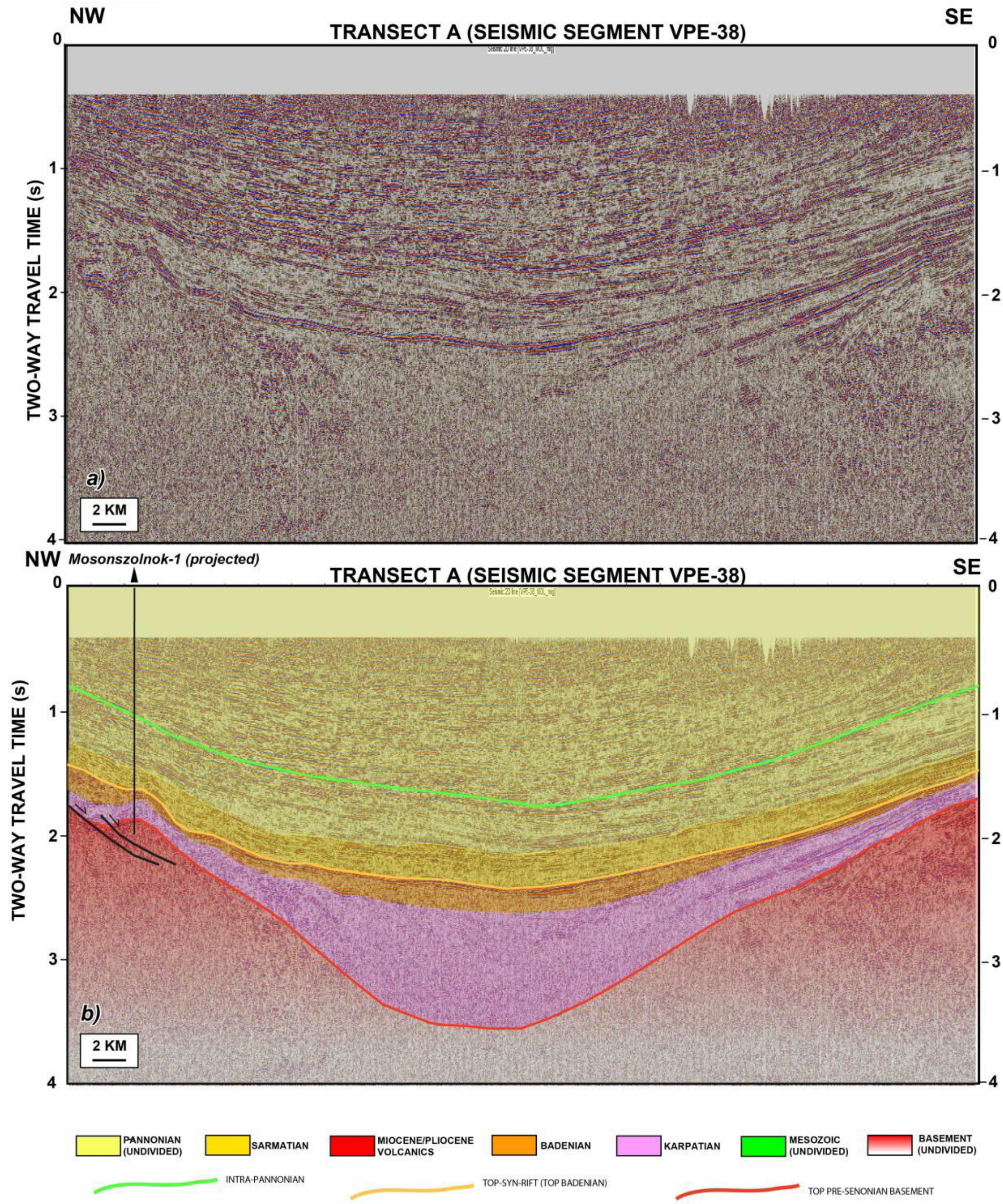

Figure 6.5. a) Seismic segment VPE-38 without interpretation; b) Seismic segment VPE-38 with interpretation. Two normal faults and the Mosonszolnok-1 well also shown. See text for detailed description.

6.1.2. Transect B

Transect B has been spliced together from seismic lines NE-P12, BV-027, B-020 in the Austrian part and VCSA-27, VCSA-11, VCSA-28 and VPA-87 in the Hungarian part (Fig. 6.1).

This transect begins in the northern part of the Neusiedl Lake with seismic line NE-P12, and it continues into the Danube Basin in NE Austria and NW Hungary. This circa 72 km long transect covers a large portion of the Danube Basin in NW Hungary, however, with a circa 6 km data gap between the high-resolution seismic acquired on the Neusiedl Lake and the legacy industry seismic further to SE (Fig. 6.6).

Four wells are projected into the seismic segments of this transect, namely Podersdorf-1 and Tadten-1 in Austria and Mihalyi-2 and Pasztori-2 in Hungary. Since Transect B in its entirety belongs to the Danube Basin, the pre-Cenozoic basement is mainly composed of Austroalpine metamorphic basement in the NW belonging to the Palaeozoic and unmetamorphosed Mesozoic units in the SE. The basin fill is dominated by sand, sandstone and marls (Pannonian and Sarmatian) with intercalated layers of clay and clay-marl (Badenian and Karpatian). As is the case with Transect A, the intra-Pannonian marker overlies a delta progradation sequence, which crosses the transect in its entirety. The intra-Pannonian delta prograding sequence with fairly large clinoforms, mostly can be observed in the Hungarian part of the transect.

The general trend observed in Transect A (Fig. 6.2), whereas the seismic packages get truncated at the basin margins as they get closer to the surface. This truncation of the seismic packages is observed as one moves towards the NW, with the Pannonian package getting terminated against the surface. Moreover, the packages are thinner in the NW and gradually thicken towards the SE. In general, like everywhere else in the Pannonian basin, the syn-rift packages are considerably thinner, compared to the post-rift seismic units (cf. Tari and Horvath, 2006).

Furthermore, another feature, which can be observed within this transect is the volcanism seen in in the SE part of the transect. During Upper Pannonian and Badenian times, basaltic volcanism occurred, which can be mainly seen in the

Pasztori High in Hungary (e.g. Schleder, 2001). The expression of a very large paleovolcano in the Pasztori High can be seen in the seismic and disrupts the contimuity of the basement seismic package underneath.

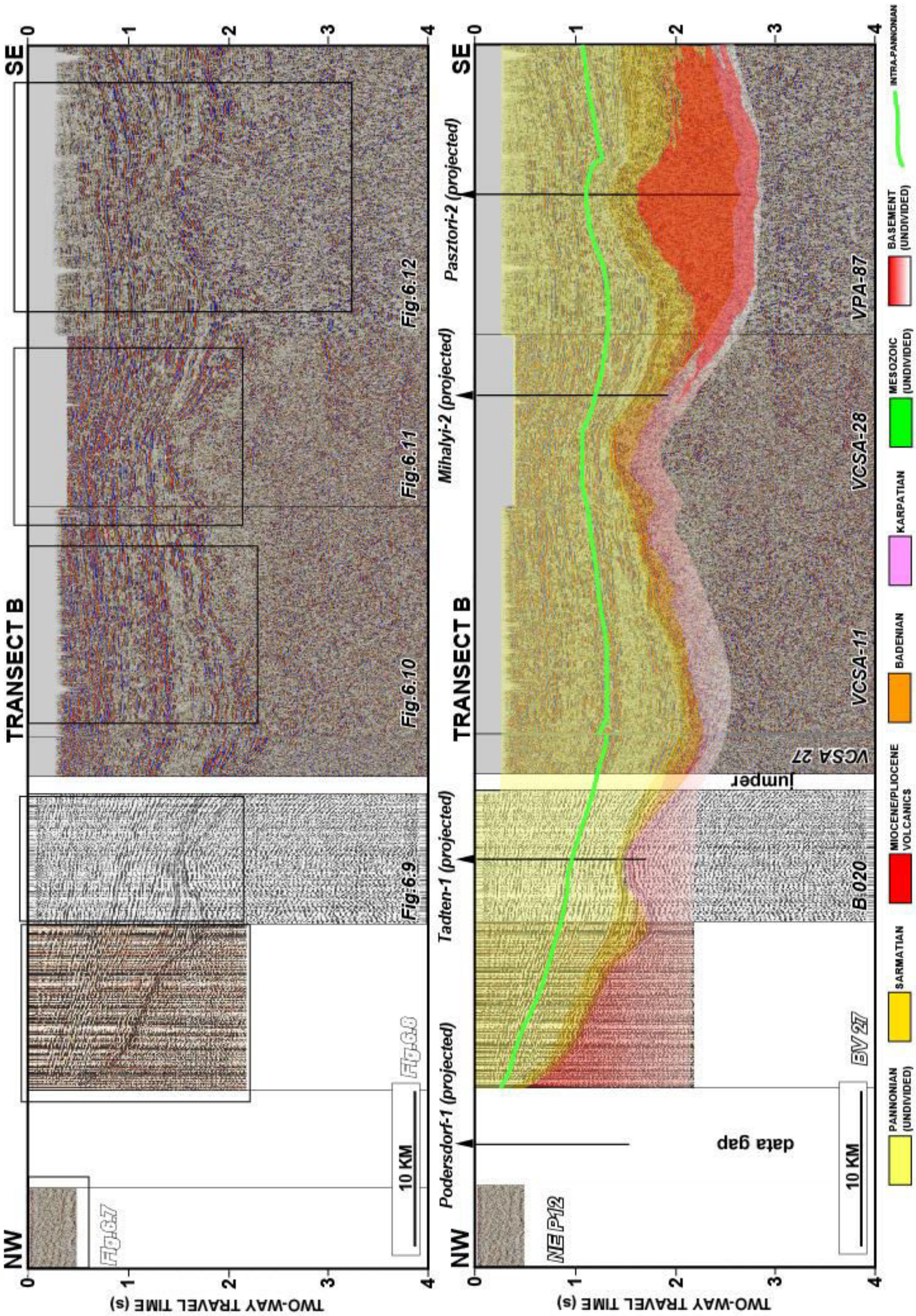

Figure 6.6. a) Transect B; above: without interpretation, below: interpetation and jumpers from one line to another shown. See text for detailed description.

Seismic line NE-P12 is located in the northern part of the Neusield Lake and its pre-Cenozoic basement has the shallowest position for Transect B. This segment is cross-cut by several extensional faults with selected ones being shown in Fig. 6.7.

This seismic segment reaches a maximum depth of 0.5 s twt where the Badenian seismic package is the thickest with a maximum thickness of 0.22 s twt. The Sarmatian package is a close second with a maximum thickness of 0.18 s twt followed by the Pannonian package, which reaches a maximum thickness of approximately 0.1 s twt. The Basement package has the shallowest position for the selected image of the line with a maximum thickness of 0.02 s. twt Therefore, this seismic segment, to a certain degree, breaks the trend set form the previous segments until this point, where the the syn-rift packages (Badenian, Karpatian) have been thinner compared to the post- (Sarmatian, Pannonian) and pre-rift (basement) packages. In this case it is the syn-rift package that is the thickest. Furthermore, differently from the previous seismic lines, while the Pannonian package does thicken gradually towards the SE, the rest get thinner towards the SE. The intra-Pannonian marker, which has been picked in all the other seismic segments composing the regional transects, is not present in line NE-P12 (Fig. 6.7). The reason for this is, that since the intra-Pannonian is truncated against the surface on the NW, it reaches the surface above the Neusiedl Lake and is terminated there. Therefore, this particular horizon cannot be seen on this seismic segment since the segment is too shallow. In this area therefore, the intra-Pannonian has already been terminated due to post-Pannonian erosion (for a larger scale outlook see Fig. 6.22).

The seismic segment NE-P12 displays very high amplitude reflectors throughout, with the various seismic packages getting nearer to the surface towards the NW. The Pannonian reflectors are truncated on top of the seismic section due to erosion. Note that on this high-resolution seismic line there is evidence for a small-scale progradational clinoform set at the base of the Pannonian sequence indicating progradation from the NW to the SE. This small-scale clinoform set, about 100 ms thick, could not be seen on the vintage seismic data set nearby. The highest amplitude on this line can be observed on the top-basement reflector and the later on at the uppermost part of the Pannonian package.

Between seismic lines NE-P48 and BV-27, the Podersorf-1 (Appendix F) well has been projected. This well, located near Frauenkirchen in northern Burgenland is the shallowest well available for this project, with a total depth of 386.5 m. The basement lithology consists of granite, starting at 377.8 m depth and the dominant well lithology consists of clays and clay-marls of Pannonian age. The other successions seem to be missing. The actual position of this well is located circa 3,730 m from the NE-P12 seismic line and 2,930 m from the BV-27 line. Some lignite has been found at 210 m, within a sand layer.

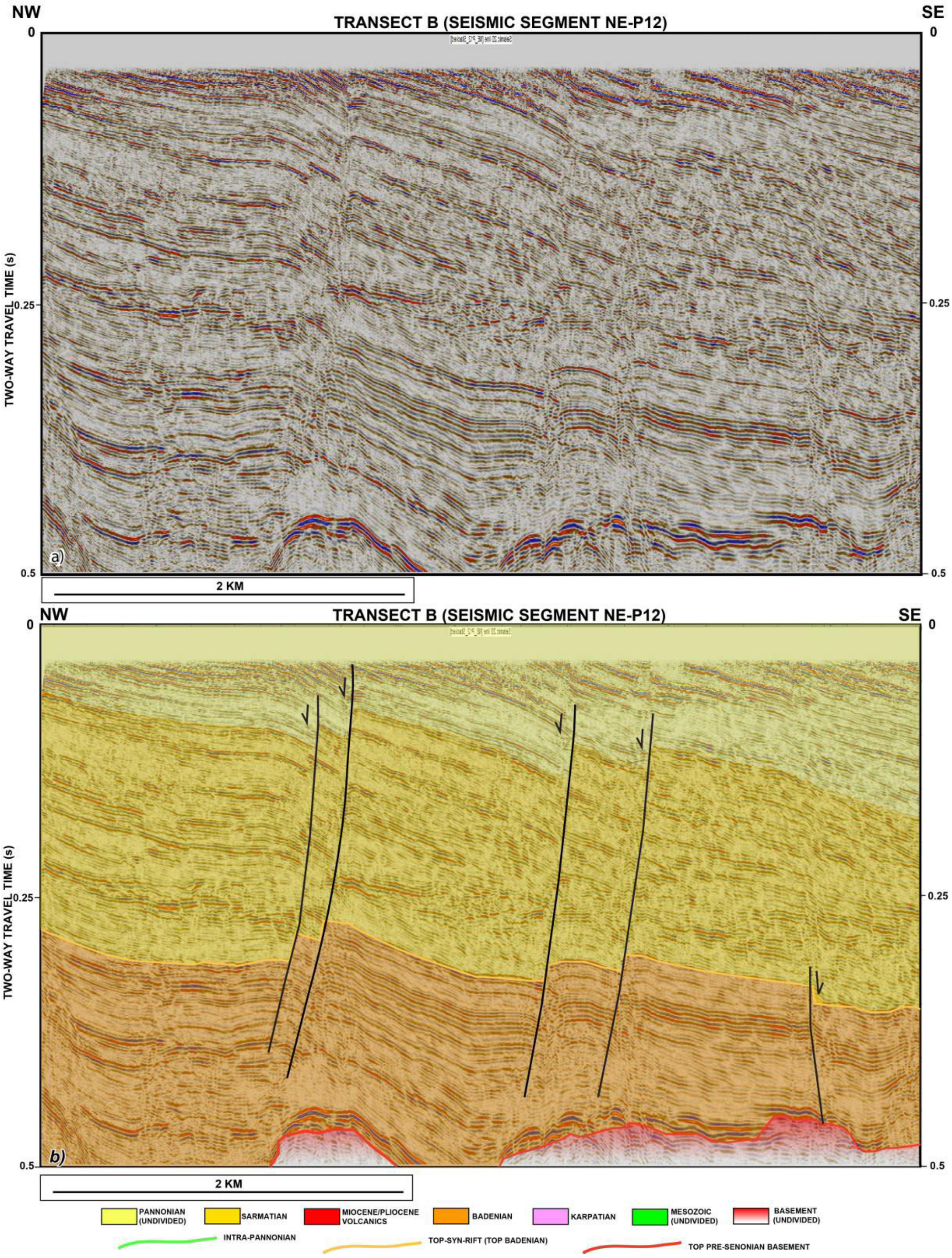

Figure 6.7. a) Seismic segment NE-P12 without interpretation; b) Seismic segment NE-P12 with interpretation and select faults shown. See text for detailed description.

The seismic line BV-27 (Fig. 6.8) is located in the Austrian part of the study area, on the western side of Lake Neusiedl, near Frauenkirchen in northern Burgenland (Fig. 6.1). Therefore, this line belongs to the Austrian part of the Danube Basin.

In the case of line BV-27, the previously established trend continues, where the syn-rift (Badenian) package is thinner than the post- (Sarmatian, Pannonian) and the pre-rift (basement) packages. The basement package, which belongs to the Ausroalpine nappe system, reaches a maximum thickness of 1.7 s twt, thus having the deepest position for this line. The Pannonian package is a close second with a maximum thickness of approximately 1.3 s. twt The Badenian together with the Sarmatian are the thinnest seismic packages and they reach a maximum thickness of ca. 0.3 s twt each.

Moreover, another trend observed in this segment, is the previously mentioned thickening of the seismic packages towards the SE. The basement however, differes from with trend, as its deepest position in this seismic segment is observed in its north-westernmost part and it gradually thins down towards the SE. The other packages however, follow the same trend observed in the prevoius seismic lines.

The seismic packages in this segment get truncated towards the NW, near the surface. This truncation is caused due to extensive post-Pannonian erosion and has been observed in the majority of the seismic segments used for this project. Moreover, the seismic line in general displays high to medium amplitude reflectors, especially the top-basment where the amplitude seems to be highest. High amplitude reflectors can also be oserved within the Pannonian package (Fig. 6.8). Another feature of note in this seismic segment, is the low-angle normal fault located in the SE (Fig. 6.8). The Badenian seismic reflectors display in the SE of the seismic profile a hgh amplitude and a possible tilt into the low-angle fault plane of a suggested LANF. This is evidence for syn-depositional growth and suggests that extension has occurred (Tari et al., 1992).

The Pannonian delta progradation, which is mainly observed in Hungary, can also be seen in this seismic segment (Fig. 6.8). This delta progradation is observed within the

Late Sarmatian and Early Pannonian seismic packages and is a good stratigraphic marker in a line where no well data is present.

The Podersdorf-1 (Appendix F) well, located near Frauenkirchen in northen Burgenland, is projected between the line BV-27 and NE-P12 (Fig. 6.7). The well has a distance of approximately 3,730 m from segment NE-P12 and circa 2,930 m from the BV-27 section. As mentioned above, this well is the shallowest well used for this project with a total depth of 386.5m. The data gap between the BV-27 and NE-P12 seismic segments is very prominent in Transect B (Fig. 6.6) and has a length of approximately 60 km.

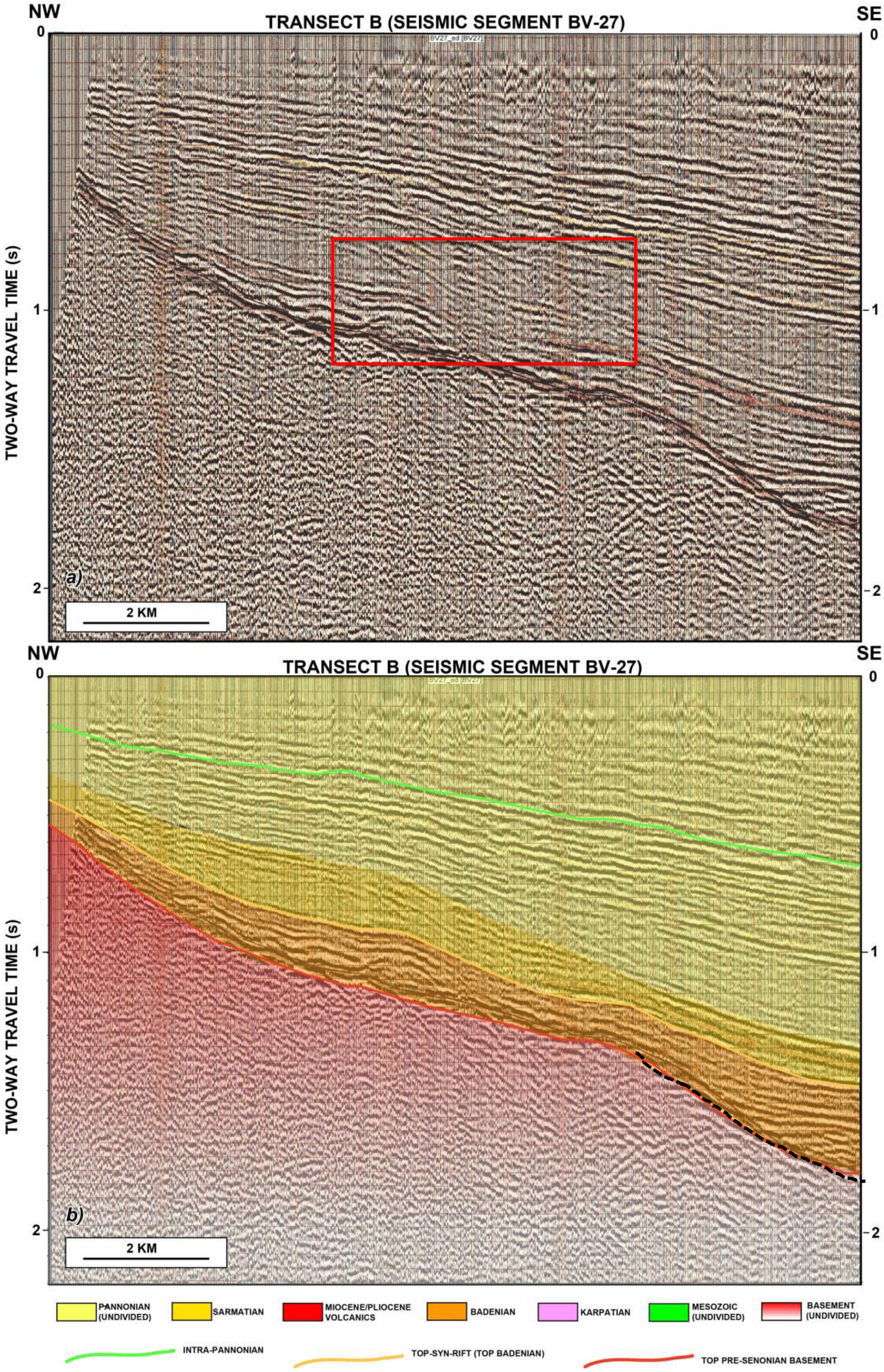

Figure 6.8. a) Seismic segment BV-27 without interpretation; b) Seismic segment BV-27 with interpretation. Possible low-angle normal fault shown as a black dashed line. Enclosed in the red square the Pannonian delta progradation can be seen. See text for detailed description.

The line B-020 (Fig. 6.9) is located in Austria, near Tadten in NW Burgenland (Fig. 6.1), which is also the location that gives the Tadten-1 well (Appendix G), which is projected on this line, its name. Like line BV-27 before it, this line also belongs to the Austrian part of the Danube Basin.

The Austroalpine basement of this seismic segment has a position, which reaches a maximum thickness of approximately 2.4 s twt, making it the thickest seismic package for this segment. Almost at the exact centre of the line, the basement forms a high where the projection of the Tadten-1 (Appendix G) well has been located. This well has a total depth of 2,127 m and reaches the Austroalpine basement at 2,070 m. Through the well summary for Tadten-1 (Appendix G), it has been observed that the basement consists of sericite-mica schist of old Palaeozoic age. The Pannonian package displays a maximum depth of ca. 2.2 s twt and its main lithologies are sands and sandstones with some interbedded clay. The Badenian seismic package onlaps the basement in the NW and SE and is practically non-existant in the central part of the seismic segment where the Sarmatian directly overlies the high formed by the basement package. The maximum thickness of the Badenian is approximately 0.1 s twt, making this package the thinnest in the whole line. The Sarmatian, which is also very thin, reaches a maximum thickness of ca. 0.3 s twt. Overlying the Sarmatian, the Pannonian package consits of a maximum thickness of 2.2 s twt. The position of the well is not too far away from seismic segment B-020 with a distance of ca. 270 m.

Similarly to most of the previously described seismic segments, this particular segment displays the same truncation of the reflectors towards the NW. The reflectors become progressively shallower as they near the NW. This truncation of the reflectors is observed in a much gentler way in this segment, compared to some of the seismic lines described before. The basement package on the other hand, while it does follow this trend to a certain degree, in the central part of the segment, a high was formed. Furthermore, like line BV-27, a gradual thickening of the seismic packages towards the SE can be observed. The Badenian package however, reached its maximum thickness near to the central part of the segment onlapping the basement package.

In general, this seismic line is characterised by medium to low amplitude reflectors. However, the top-basement and top-Sarmatian display a very high amplitude compared to most reflectors in this line.

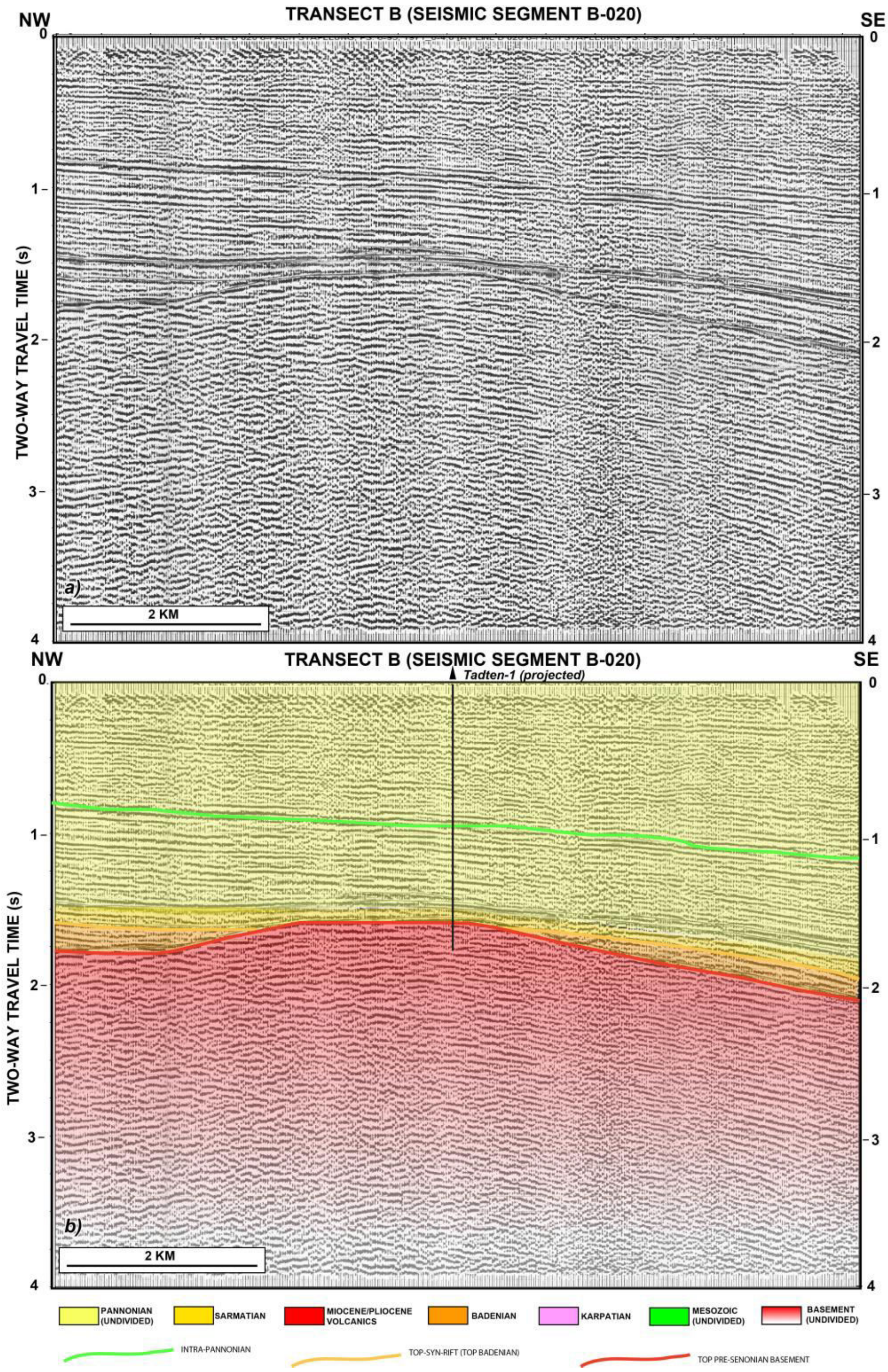

Figure 6.9. a) Seismic segment B-020 without interpretation; b) Seismic segment B-020 with interpretation and the projection of the Tadten-1 well shown in black. See text for detailed description.

The VCSA-11 (Fig. 6.10) seismic segment is located in NW Hungary, near the town Osli within the Danube Basin (Fig. 6.1).

In this seismic segment the basement has the deepest position for Transect B with a total depth of 6 s twt; the last 2 s twt of the seismic have been cut for practical purposes, in order to make it easier to illustrate the interpretation of the seismic segment on Adobe Illustrator. Furthermore, the basement package has the deepest position for this seismic segment, with a maximum thickness of approximately 3.2 s twt. The top-basement reflector displays a high amplitude, compared to the rest of the reflectors in the basemement package. The Badenian package reaches a maximum thickness of ca. 0.5 s twt. The Sarmatian, which overlies the Badenian package has a thickness of approximately 0.2 s twt and is the thinnest package, differently from most of the previously described lines where the syn-rift (Badenian) package was the thinnest. The Pannonian Basin fill reaches a maximum thickness of about 1.5 s twt and the intra-Pannonian marker, shown in green in Fig. 6.10, overlies the previously mentioned delta progradation sequence, which gets closer to the intra-Pannonian marker towards the S.

Generally for this seismic segment, the packages gradually thicken towards the south and they reach their maximum thickness at the southernmost part of the line. The delta progradation sequence however, has attained its maximum thickness on the NW-most part of the segment and gets thinner towards the S. This is also the case for the Pannonian package, where the maximum thickness can be observed in the N of the seismic line, while the package gradually thins down towards the S (Fig. 6.10).

An aspect of seismic segment VCSA-11 that is different from most of the previously described segments, is the termination of the reflectors towards the surface. While in many of the previous lines this termination occurred towards the N/NW, in this case it is towards the S/SE. In the southern part of the seimsic line, truncation of the reflectors takes place due to extensive post-Pannonian erosion, similarly to the previously described seismic segments where this process is displayed.

In general this seismic line is characterised by high amplitude reflectors. The delta progradation sequence however, differs from this trend because the amplitude of the reflectors is very low.

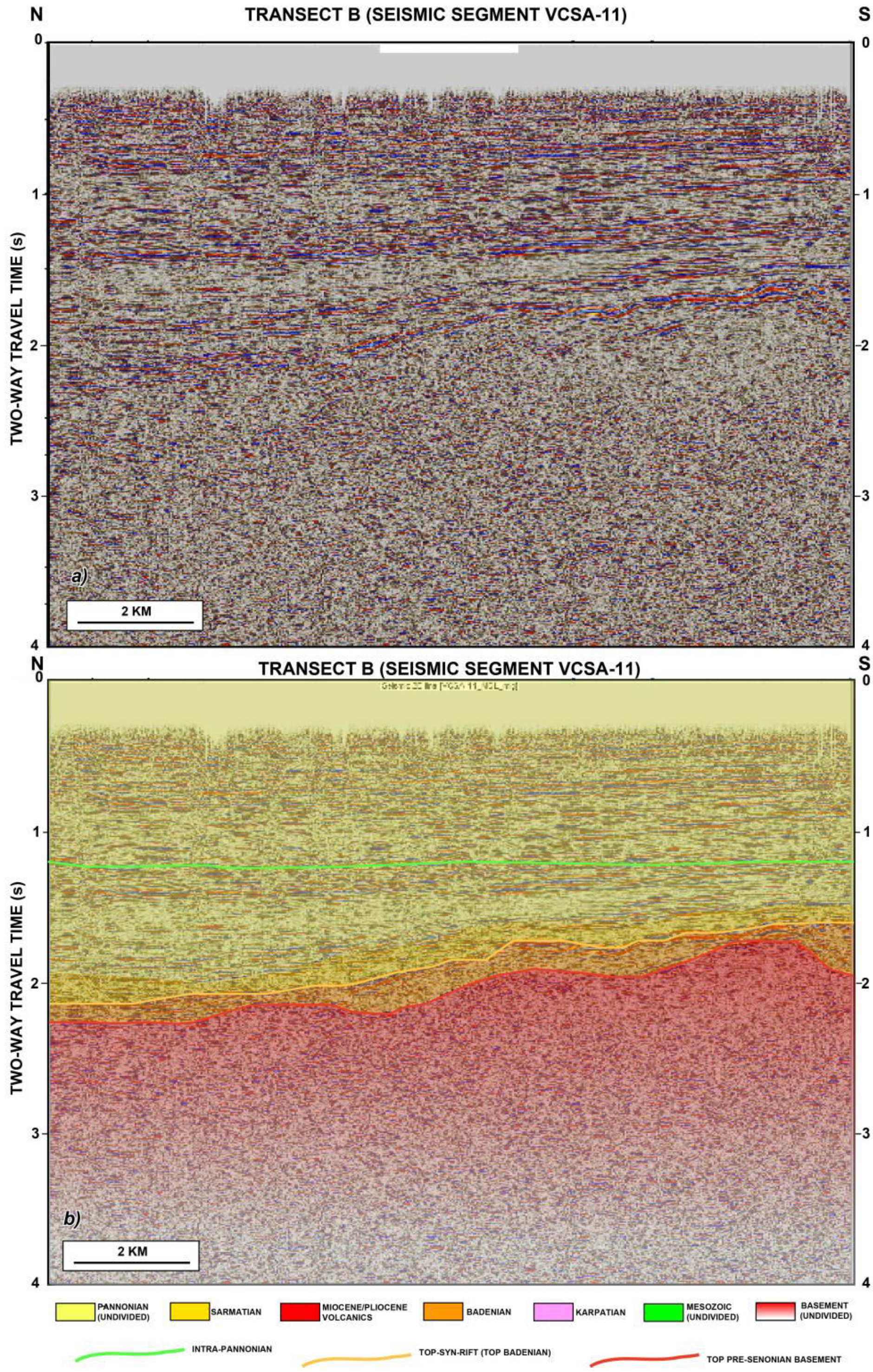

Figure 6.10. a) Seismic segment VCSA-11 without interpretation; b) Seismic segment VCSA-11 with interpretation. See text for detailed description.

Line VCSA-28 (Fig. 6.11), located in NW Hungary within the Danube Basin, near Mihalyi (Fig. 6.1), which is the location that gives the Mihalyi-2 well (Appendix C), which is projected on this line, its name.

This seismic segment has a maximum depth of 4 s in twt. The basement package has the deepest position in this seismic segment, with a maximum thickness of approximately 2.2 s twt. According to the Mihalyi-2 well summary (Appendix C), the basement is composed of metamorphic rocks, which are very finely bedded and folded. The main basement lithologies, seem to be graphite-quartz-chlorite-phyllites. The Badenian is very thin in comparison, with a maximum thickness of 0.2 s twt. This seismic package comprises mainly of gravels and conglomerates. The Sarmatian package overlies the Badenian and reaches its maximum thickness of approximately 0.1 s twt on the eastern part of the seismic segment (Fig. 6.11). The Pannonian package, which overlies the Miocene succession (Badenian, Sarmatian) has a maximum thickness of approximately 1.3 s twt. Therefore, the trend observed in most of the seismic lines described until now has been observed for segment VCSA-28 as well, in which the syn-rift succession (Badenian) is thinner than the post-rift (Sarmatian, Pannonian) successions. The dominant Pannonian lithology, which is also the main lithology of the well in general, are sandy-clays. In the well summary of the Mihalyi-2 well (Appendix C), the Sarmatian has not been accounted for. Instead of it however, a Pontian succession overlying the Pannonian strata, has been identified. This succession is composed of gravels and conglomerates.

The basement package forms a high on the W part of the line. The Mihalyi-2 well (Appenidx C), which is projected on this line, is located on the E part of the high that was formed by the basement. The distance of the Mihalyi-2 well from sesimic line VCSA-28 is approximately 1,678 m. This well, located in the Danube Basin in NW Hungary, has a total depth of 2,507 m, thus making it one of the deepest wells used for this study.

The Neogene package and the top-basement reflector are generally characterised by high amplitude reflectors, with the highest amplitude package being the Pannonian reflectors.

Similarly to previously described seismic segments, there is a thickening of the packages towards the E. The seismic packages are thinner in the western part of the segment and gradually thicken towards the east where they attain their maximum thickness. This phenomenon however, cannot be observed within the basement package. In this package the deepest position has been reached on the west, where the basement high is formed. Similarly, the delta progradation sequence also attains its highest thickness on the western part of the line and gradually thins down towards the east.

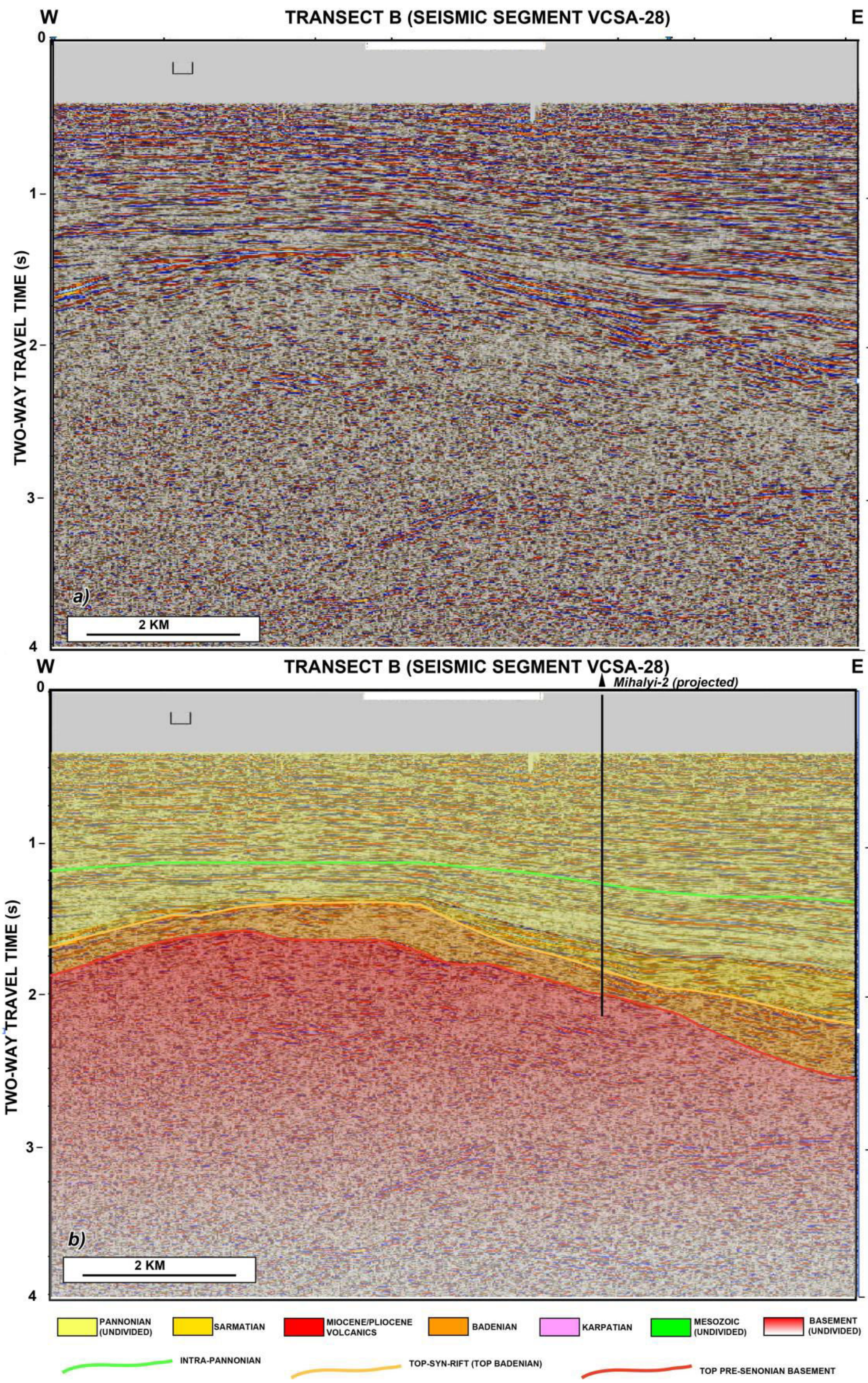

Figure 6.11. a) Seismic segment VCSA-28 without interpretation; b) Seismic segment VCSA-28 with interpretation. See text for detailed description.

Seismic line VPA-87 (Fig. 6.12) is located in NW Hungary within the Pasztory High, which belongs to the Danube Basin (Fig. 6.1).

The basement reaches its deepest position for this seismic segment in the SE with a maximum thickness of approximately 2.2 s twt. The Badenian package has a maximum thickness of 1 s twt and the Sarmatian reaches a thickness of 0.4 s twt. The Pannonian package reaches a maximum thickness of ca. 1.8 s twt. In this case, the Sarmatian instead of the syn-rift (Badenian) package is the thinnest. Furthermore, while the Badenian package gets thicker towards the SE, the other packages are thicker in the NW part of the seismic segment. The Neogene packages are characterised by high amplitude reflectors, while the amplitude of the basement package is relatively low (Fig. 6.12).

The truncation of the seismic reflectors, especially the Pannonian package, can be observed in VPA-87 too. However, instead of this termination of the seismic packages taking place towards the NW, as is the case with most of the seismic segmetns described this far, here the termination occurs towards the SE. Another observation for this seismic segment is that the basement pick does not follow the geometry of the Neogene packages in the SE part. While the Badenian and Sarmatian packages follow the termination of reflectors towards the SE, which could be traced back to erosion, the basement forms a depression. The reason for this is that the SE part of the segment is where the Pasztori High is located. During Badenian and Early Sarmatian times paleovolcanism took place within this High (e.g. Schleder, 2001; Dolton, 2006). Because of the basaltic and blocky lava flows, the basement forms a sructure similar to a depression and does not follow the shape of the Neogene strata.

The Pasztori-2 (Appendix E) well has been projected on this seismic segment, with a distance of approximately 2,966 m from the VPA-87 line. The well reaches a depth of 2,800 m and has been drilled directly on the Pasztori paleovolcano. Because of this, the well has not reached the basement, and its oldest stratigraphic succession belongs to the Badenian, which is the time-period when the volcanism took place. During syn-rift Badenian times, the Pannonian Basin acted as a thin spot generating asthenospheric flow (Harangi et al, 2014). Thus, volcanism occurred. The main Badenian lithologies are andesites and trachiandesites, while the dominant well lithology in general are clays and clay marls belonging to the Pannonian. In the uppermost Upper Pannonian some sandy-clay and conglomerate layers have been observed.

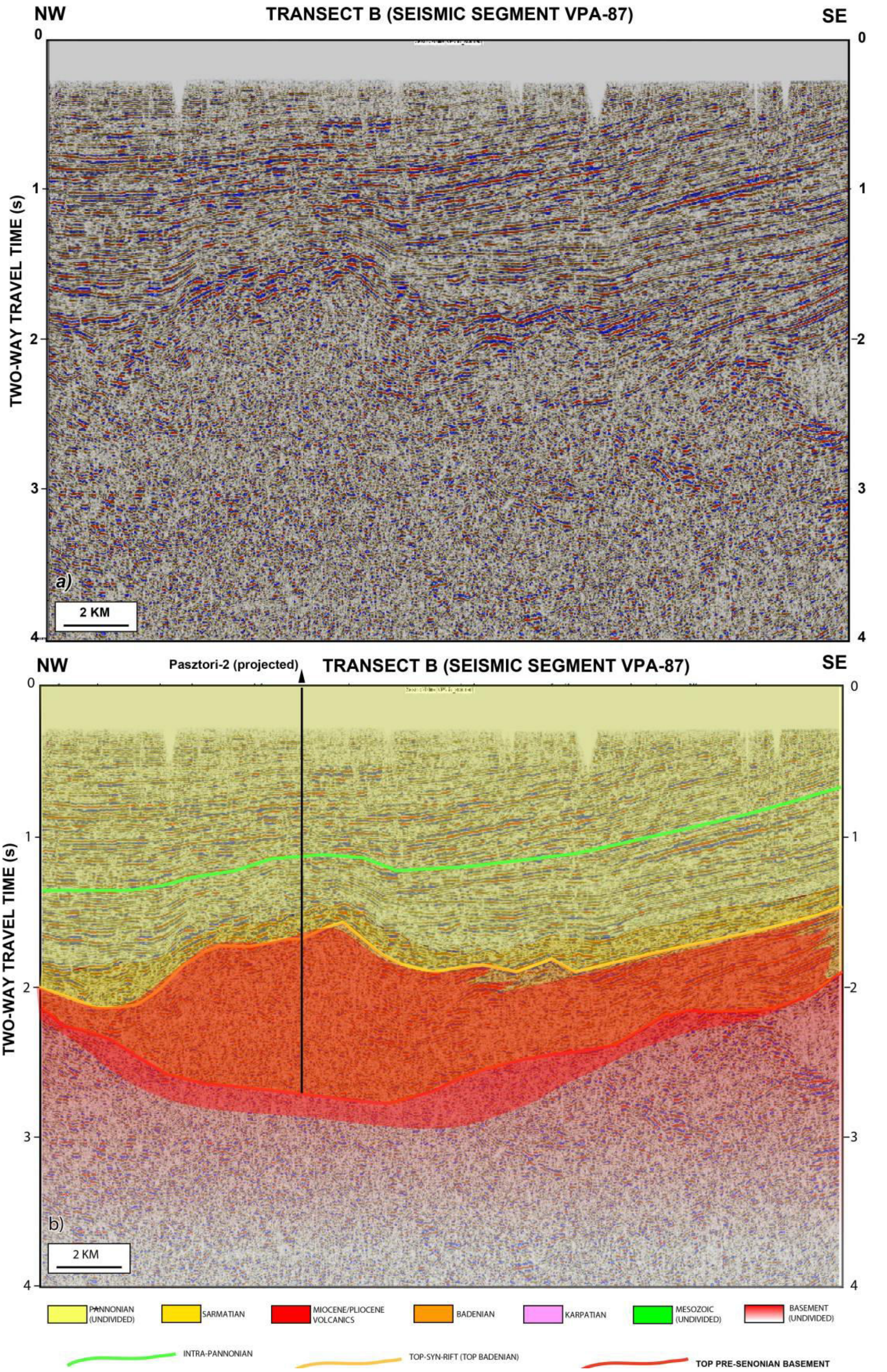

Figure 6.12. a) Seismic segment VPA-87 without interpretation; b) Seismic segment VPA-87 with interpretation. The Pasztori High paleo-volcano shown in red coloring, placed on Adobe Illustrator below the layers of the other seismic packages thus attaining a dark orange colour. See text for detailed description.

The Palaeovolcanism of the Pasztori High is characterised by cinder cones, also named scoria cones. Scoria forms when blobs of gas charged lava are dispersed in the air through a volcanic eruption and cool while they are in flight. They fall as dark vocanic rock, which contains cavities created by trapped gas bubbles. Cinder cones usually have the shape of a steep hill (Fig. 6.13) and they have a crater with a double rim, probably created because of volcanic activity which occurred late in its formation. Cinder cones also have several associated blocky lava flows and a related, widespread ash deposit which is identified km away from the cone.

Figure 6.13. Cinder cone in Mojave Natural Park (https://roadtrippers.com/us/mineral-ca/nature/cinder-cone-natural-area?lat=40.83044&lng=-96.67969&z=5)

The Paleovolcanism of the Pasztori High can be clearly seen in further seismic lines, such as the VPA-94 segment (Fig. 6.14). The lava flows form "wavelets" that cross the whole seismic line from the NW to the SE and they continue deeper within the seismic, up to at least 2.5 s twt.

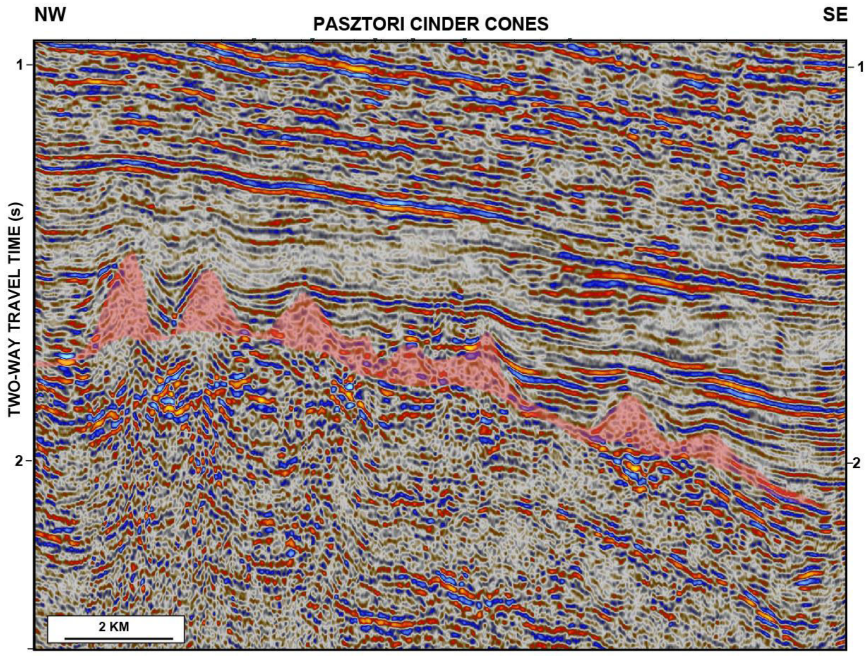

Figure 6.14. Selected Pasztori cinder cones shown in red in the seismic of the segment VPA-94, located in SE Hungary within the Pasztori High. See Fig. 5.1 for location in study area.

6.1.3. Transect C

Transect C is a composite of the seismic lines BM-003 located in the Eisenstadt-Sopron Basin, BLV-002 and BLV-009-15 in the Oberpullendorf Basin in the Austrian part and VCSA-20, VCSA-7, CSA-35 and VPA-54 in the Danube Basin in the Hungarian part (Fig. 6.1). Therefore, this transect covers lines in the Eisenstadt-Sopron and Oberpullendorf Basins in the Austrian part and continues into the Danube Basin in the Hungarian part. Together with Transect B, this transect, with a length of approximately 71 km, is the most complex in terms of number of seismic lines used to compose it, with a total of 7 segments.

A total of five wells are projected within this transect, namely Zillingthal-1 (Appendix H), which is projected on the the seismic segment BM-003, and Minihof-1 (Appendix I), projected on the BLV 009-15, in Austria; on the other hand in Hungary the projected wells, on seismic segment VPA-54, are Mihaily-7, -13 and -20. These wells help to further constrain the subsurface and the stratigraphy of the area. The pre-Cenozoic basement of the transect is mainly composed of granite and belongs to the Palaeozoic. The oldest Neogene deposits in the Eisenstadt-Sopron Basin are of Early Miocene age. They comprise of terrestrial, fluvial and lacustrine deposits which are genetically related to the fluvial system of the southern Vienna Basin (McCann, 2008). As such, the basement fill of the Austrian part of this transect is composed of clay and clay-marls, which dominate the Early and Middle Miocene successions. Some gravels and conglomerates belonging to the Pannonian have also been observed. As it has previously been observed for the other two transects, in this case too, the intra-Pannonian marker overlies a delta progradation sequence, which starts with line VCSA-20 and continues throughout the whole Hungarian part of the transect.

The syn-rift seismic packages (Karpatian and Badenian) are considerably thinner than the post-rift (Sarmatian and Pannonian). This transect in general, is characterised by medium to high amplitude reflectors. The highest amplitudes can mainly be observed in the Hungarian part, where, especially the Pannonian package, shows high relectivity.

The general trend of the previous two transects continues, with the seismic packages getting terminated towards the surface in the NW. Furthermore, the packages are quite thin in the NW and get thicker towards the SE.

Several steep-angle normal faults that offset the seismic segments can be seen (especially in the Austrian part), more so in this transect than in the previous two transects shown (Fig. 6.15). These faults create in different cases a half-graben geometry (Fig. 6.15), which is typical for the pre- to syn-rift successions of the Pannonian Basin and generally for any rift basin.

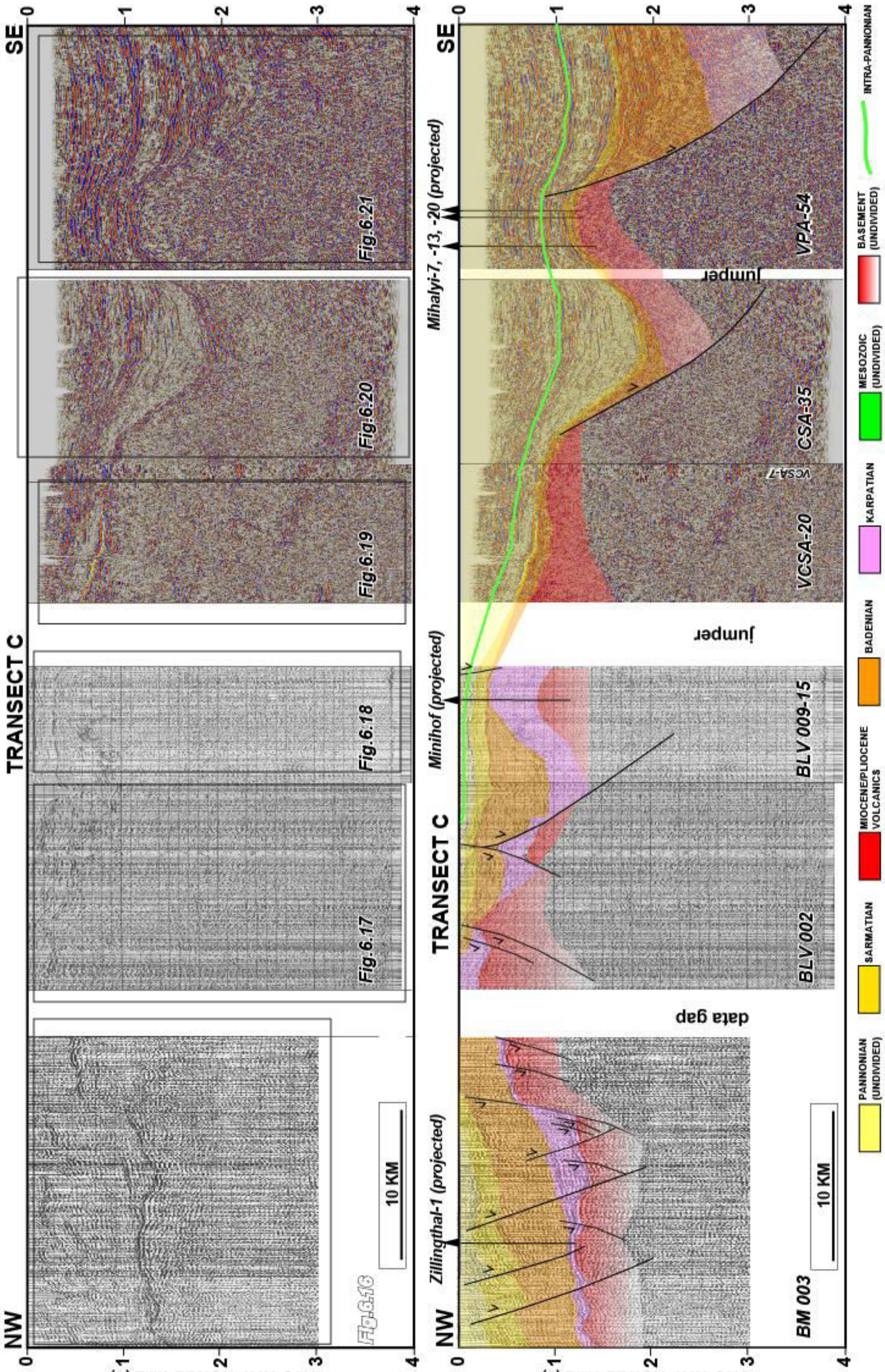

Figure 6.15. a) Transect C; above: without interpretation, below: interpetation and jumpers from one line to another shown. See text for detailed description.

The seismic segment BM-003 (Fig. 6.16) is located in the Eisenstadt-Sopron Basin in Austria, on the western side of the Neusiedl Lake (Fig. 6.1). This seismic line can be found near Zillingthal, which is where the Zillingthal-1 well, located 2,129 m away from this seismic segment, gets its name.

This line has a total depth of 3 s twt and is dominated by steep-angle, normal fault,s which offset the pre-rift (basement), syn-rift (Karpatian, Badenian) and partially the post-rift (Sarmatian, Pannonian) packages. The basement seismic package has a maximum thickness of 2.5 s twt and is at its deepest position for this seismic segment in the SE. Through the well summary availabe from the Zillingthal-1 well (Appendix H), it has been observed that the basement mainly consists of crystalline rocks such as quartzite and amphibolite. The Karpatian is by far the thinnest seismic package with a maximum thickness of ca. 0.4 s twt and is largely offset by extensional faults. Overlying the Karpatian is the Badenian package with a maximum thickness of ca. 0.7 s twt. The Sarmatian, which is also offset by normal faults, has a maximum thickness of approximately 0.2 s twt and the Pannonian reaches a similar thickness of ca. 0.2 s twt. Thanks to the Zillingthal-1 well summary (Appendix H), it is known that the dominant lithology for this seismic segment are clays and clay marls, with some gravels and conglomerates mainly belonging to the Pannonian. Furthermore, according to the Zillingthal-1 well summary, the only Miocene strata for this seismic segment belong to the various subdivisions of the Badenian (Lagenide Zone, Sandschaler Zone and *Buliminen rotalia* Zone) and no Sarmatian or Karpatian successions have been identified. In the seismic segment however, the Lower Miocene (Karpatian) and Upper Miocene (Sarmatian) reflectors could be clearly seen and mapped.

The general trend observed until now of termination of the seismic packages still continues. However, in this case the movement is towards the SE, where especially the Pannonian, Sarmatian and Badenian packages get truncated towards the SE. Furthermore, except for the basement, which considerably thickens towards the NW, the opposite phenomenon is observed for the other packages as they gradually thin down towards the SE. The intra-Pannonian segment has not been picked on this line because the reflector had already been truncated against the surface by this area in the transect. For a better illustration of this see the intra-Pannonian time structure map (Fig. 6.22).

The main feature displayed on seismic segment BM-003 are the several normal faults which offset the various seismic packages. These faults dip to the SW and NE and create the typical pre-rift/syn-rift half graben and full graben geometry, which is characteristic for rift basins.

Generally, this seismic segment is characterised by low to medium amplitude reflectors where the highest amplitude can be observed on the top-basement reflector.

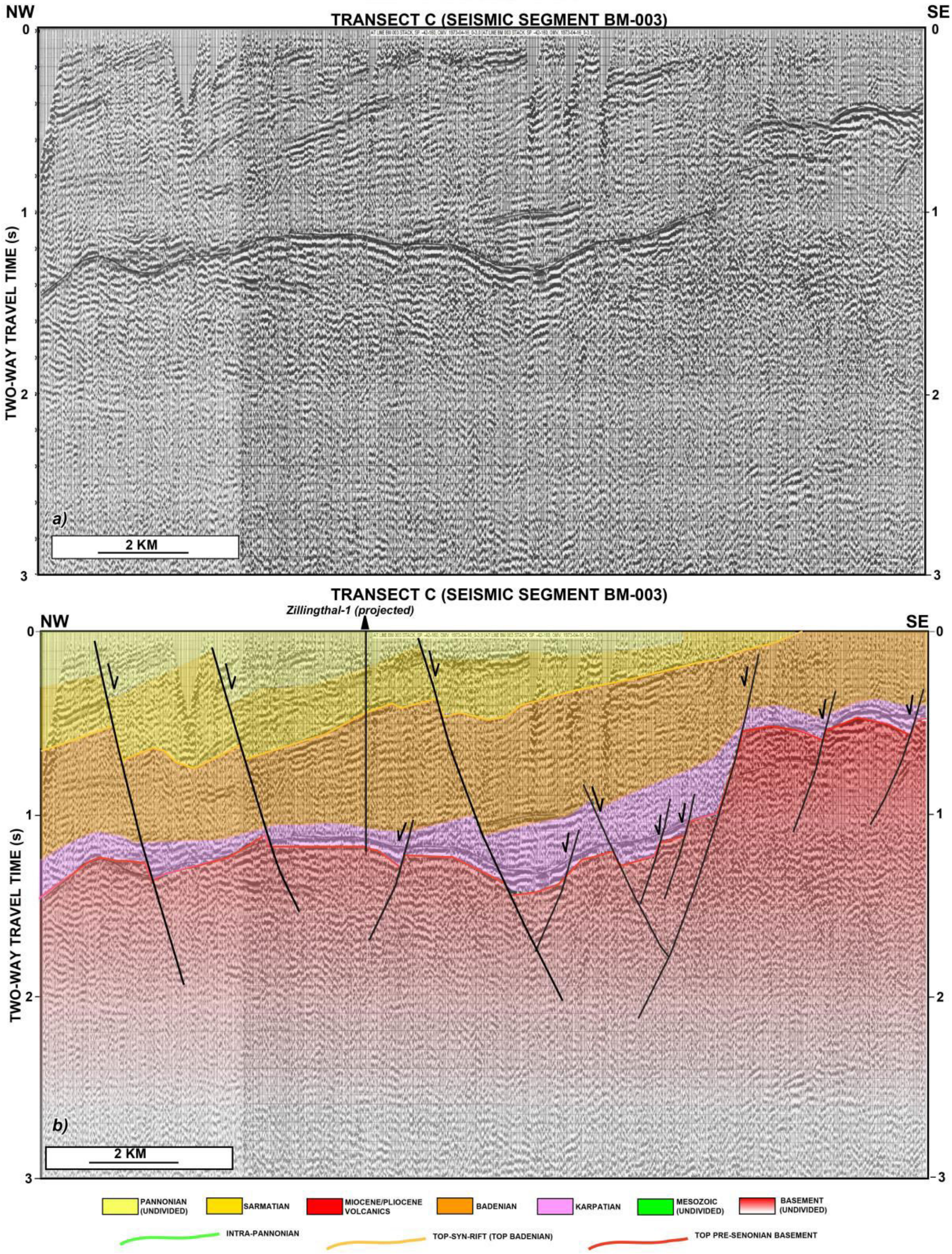

Figure 6.16. a) Seismic segment BM-003 without interpretation; b) Seismic segment BM-003 with interpretation and extensional faults shown. See text for detailed description.

Seismic segment BLV-002 (Fig. 6.17), is located within the Oberpullendorf Basin in Austria, SW of the Neusiedl Lake (Fig. 6.1).

Similarly to seismic segment BM-003 before it, the pre-rift, syn-rift and post-rift seismic packages are also largely offset by normal faults dipping to the NW and SE. The basement, which belongs to the Austroalpine nappe system, is at its deepest position in the NW of the seismig segment, with a maximum thickness of 2.8 s twt. The Karpatian in this line is even more prominent than in the BM-003 segment and has a maximum thickness of 0.5 s twt and the seismic package gets thicker towards the footwalls of the faults. The Badenian package, which overlies the Karpatian, reaches a maximum thickness of approximately 0.6 s twt. The Sarmatian has a thickness of 0.1 s twt and the Pannonian, which reached its maximum thickness of 0.1 s twt, on the SE part of the seismic line. While in many of the previously described seismic segments, the syn-rift succession was the thinnest seismic package, in this case the syn-rift (Karpatian, Badenian) is thicker than the post-rift (Sarmatian, Pannonian) succession. Since this seismic line is located within the Oberpullendorf Basin, it can safely be assumed that the dominant lithologies are clays, sands and gravels (e.g. Irene Zorn *in* Schönlaub, 2000).

The termination of the seismic reflectors towards the NW is clearly evident in this segment. In this case, the syn-rift (Karpatian, Badenian) and post-rift (Sarmatian and Pannonian) packages get truncated against the surface. The intra-Pannonian marker (shown in green) is very short and gets almost immediately truncated against the surface. The reason for this is that the Pannonian has been eroded and does not continue further into the NW; additional evidence for this is seen in line BM-003 (Fig. 6.16) where the intra-Pannonina marker does not continue at all. For a larger scale illustration see time-structure map of intra-Pannonian (Fig. 6.22).

The previously observed trend, where the seismic packages are thinner in the NW and gradually get thicker towards the SE also continues.The basement package however, differs from this trend because it reaches its maximum thickness on the north-western part of the seismic line and gradually gets thinner towards the SE. The Pannonian package particularly, is very thin and exists mainly in the SE-most part of the segment.

This seismic segment is characterised by low to very low reflector amplitude. The highest amplitude can be observed in the top-Basement and top-Sarmatian reflectors. Since this line is a vintage seismic segment captured by OMV in the 70’s and 80’s, thus the quality of the seismic is not very high.

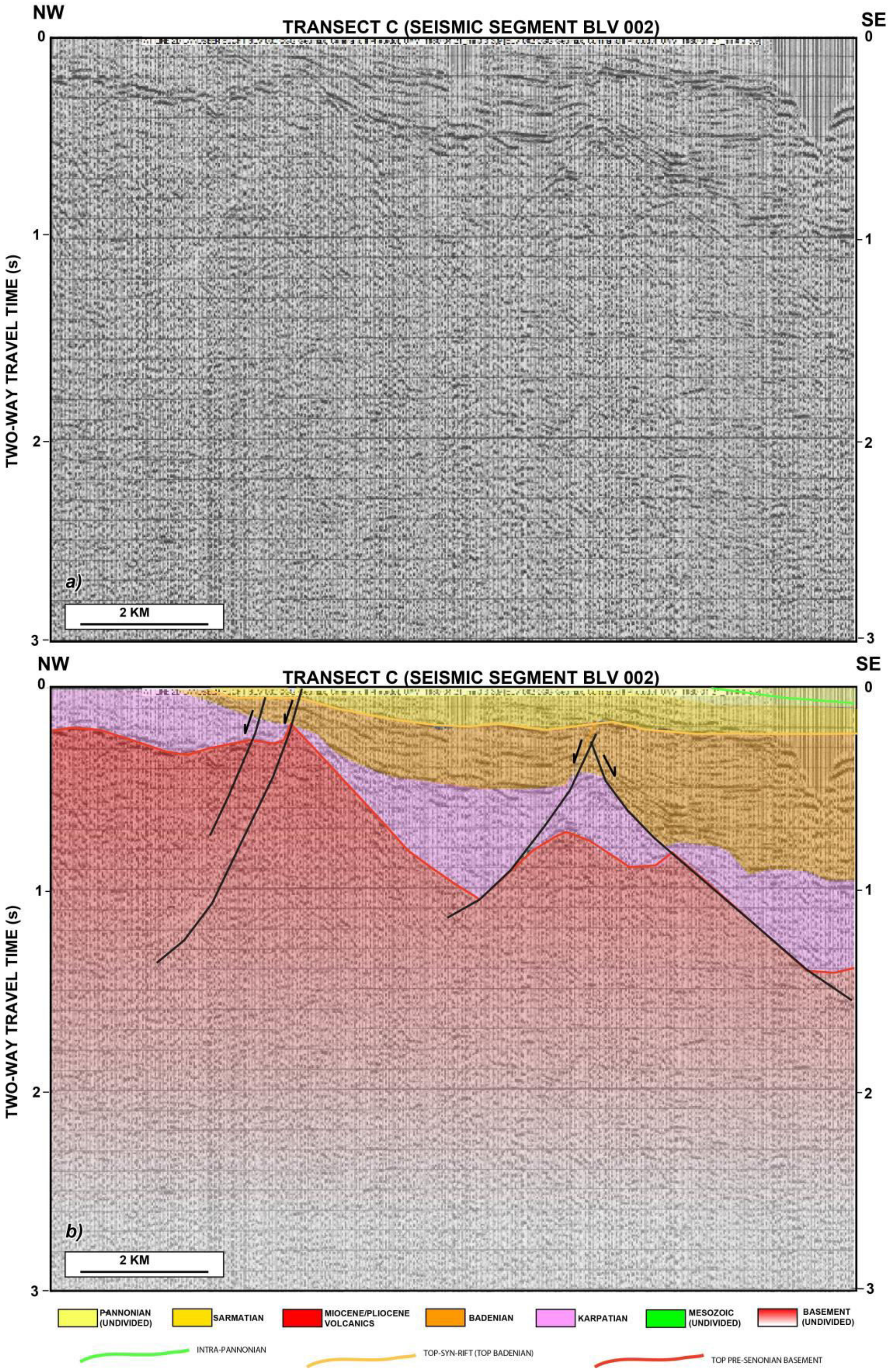

Figure 6.17. a) Seismic segment BLV-002 without interpretation; b) Seismic segment BLV-002 with interpretation and extensional faults shown. See text for detailed description.

The seismic segment BLV-009-15 (Fig. 6.18), similarly to the seismic profile BM-003 before its, is located in the Oberpullendorf Basin (Fig. 6.1).

The Karpatian in this segment is the thickest Karpatian package compared to the packages observed in the two previous segments of this transect, with a maximum thickness of ca. 0.4 s twt. Moreover, it is also characterised by high amplitude reflectors. The basement, which belongs to the Austroalpine nappe system reaches its deepest position of 1.9 s twt, thus making it the thickest seismic package for this segment. The Sarmatian and Pannonian packages show very straight, parallel reflectors and are both very thin with a maximum thickness of 0.2 s and 0.1 s twt respectively. Therefore, the trend which has been observed in most of the previous seismic segments, where the syn-rift (Badenian and Karpatian) successions have been thinner in comparison with the post-rift (Pannonian and Sarmatian), is reversed. In this case the syn-rift succession is considerably thicker than the post-rift strata. The Badenian package displays a high thickness (ca. 0.5 s twt) in the NW part where it onlaps on the basement, in the SE it considerably thins down, and it becomes almost non-existent. The Badenian seismic pacakge contains an unconformity near the top-Badenian reflector. This is the so called Mid-Badenian unconformity, which marks the termination of the syn-rift succession and acts as a boundary between the syn-rift and post-rift strata (Fig. 6.18).

The Karpatian and basement seismic packages in this line gradually thicken towards the SE. However, for the Sarmatian and Pannonian package this thickening towards the SE is almost non-existent as these seismic packages are composed of almost straight, parallel reflectors. The Badenian too does not follow this trend as its maximum thickness can be observed in the NW and it considerably thins down towards the SE.

The Minihof-1 (Appendix I) well, located near Minihof (Fig. 6.1), which is where the well takes its name from, is projected on this seismic segment and has an actual distance of 583 m from it. According to its well summary, the basement of this segment is composed of biotite-gneiss. While the Karpatian and Badenian are not mentioned, a succession called the “equivalent of the Brennberg series”, mainly comprising of sands and clays, is displayed. This formation generally belongs to the

Ottnagian (Irene Zorn *in* Schönlaub, 2000) and in this case encompasses the Karpatian and Badenian together. After it, the Pannonina succession is displayed, dominated by sand and sandstone. The Sarmatian is not present at all in the well summary.

In general this seismic line is characterised by low to medium amplitude relfectors, with the highest amplitude displayed by the top-Karpatian and top-Badenian reflectors.

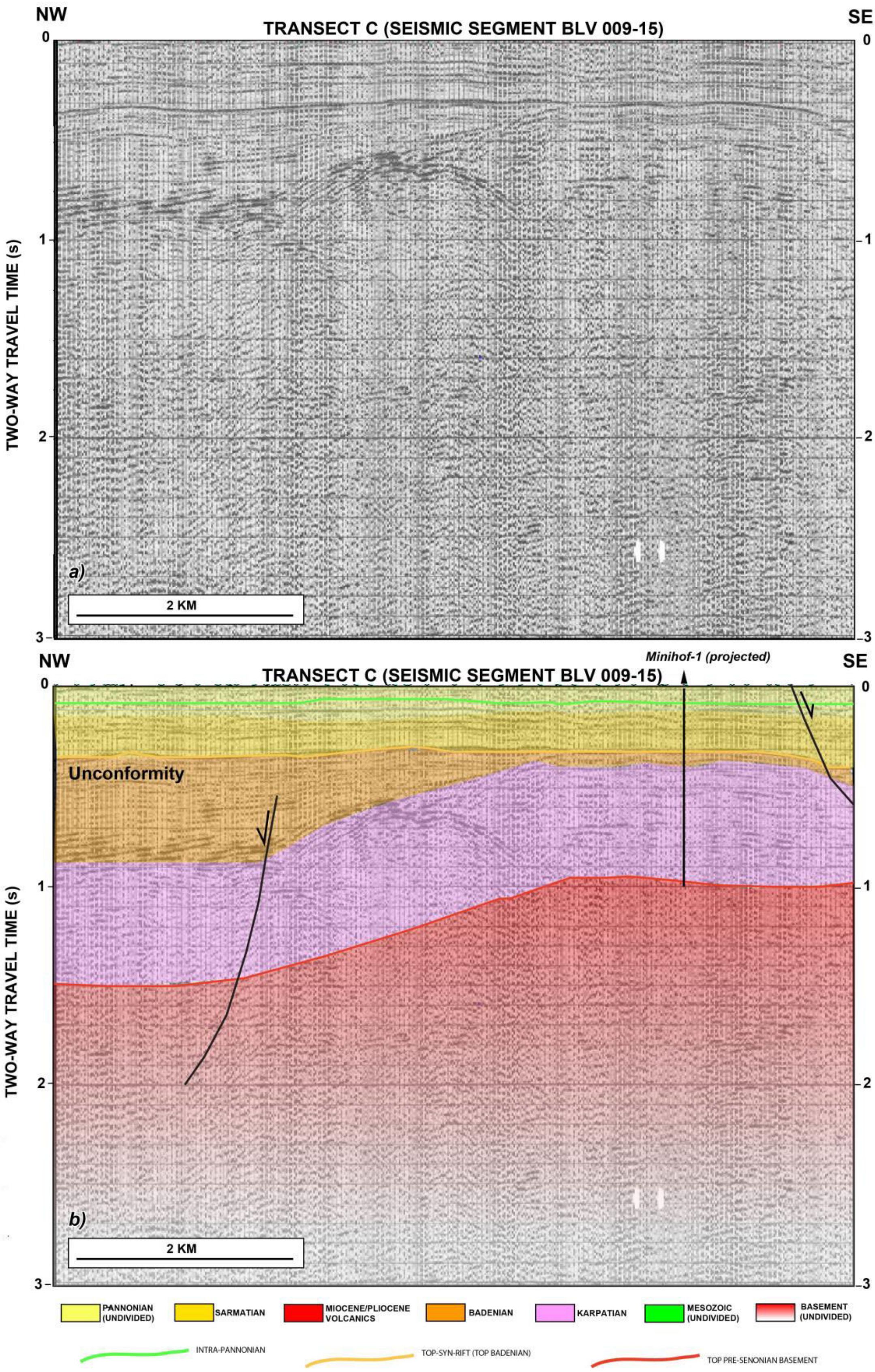

Figure 6.18. a) Seismic segment BLV009-15 without interpretation; b) Seismic segment BLV009-15 with interpretation and extensional faults shown, together with the Badenian unconformity; the projection of the Minihof-1 well is also shown. See text for detailed description.

Segment VCSA-20 (Fig. 6.19), located in the Hungarian part of the study area, near Sopronkövesd in NW Hungary belongs to the Hungarian side of the Danube Basin (Fig. 6.1).

This line has reaches a total depth of 3 s twt. The basement is at its deepest position for this line in the NW, with a maximum thickness of approximately 2.2 s twt. The Badenian is considerably thinner with a thickness of approximately 0.3 s twt .The overlying Sarmatian is even thinner with a thickness of ca. 0.1 s twt, making it the thinnest package for this line. The Pannonian seismic package consists of a thickness of ca. 0.6 s twt. Therfore, for seismic segment VCSA-20, the same trend observed in many previously described lines can be observed, with the syn-rift (Badenian) reflectors being much thinner than the post-rift (Sarmatian, Pannonian) succession.

The truncation of the seismic packages towards the NW can still be observed in this seismic segment, however in this case it is much gentler than in many perviously described segments.

Another observation that can be made for this seismic segment, is the gradual thickening of the seismic packages towards the SE. However, this trend is not followed by all seismic packages, only the Pannonian and basement successions. For the Badenian and Sarmatian on the other hand, the packages are thicker in the NW and thin down drastically (especially the Badenian) towards the SE.

Similarly to the majority of the seismic segments in the Hungarian part of the study area, the delta progradation sequence, which underlies the intra-Pannonian marker, can be observed on line VSCA-20 as well (Fig. 6.19). This progradation, like the seismic packages for this segment, displays a termination of the reflectors near the surface as towards the NW. Moreover, the delta progradation sequence displays the lowest amplitude of reflectors for the whole seismic segment.

Of note in this line is the high reflectivity of the top-Badenian reflector. This reflector seems to have the highest amplitude compared to the rest. The Sarmatian seismic package displays relatively high amplitude reflectors as well with the reflectors reaching medium to high reflectivity.

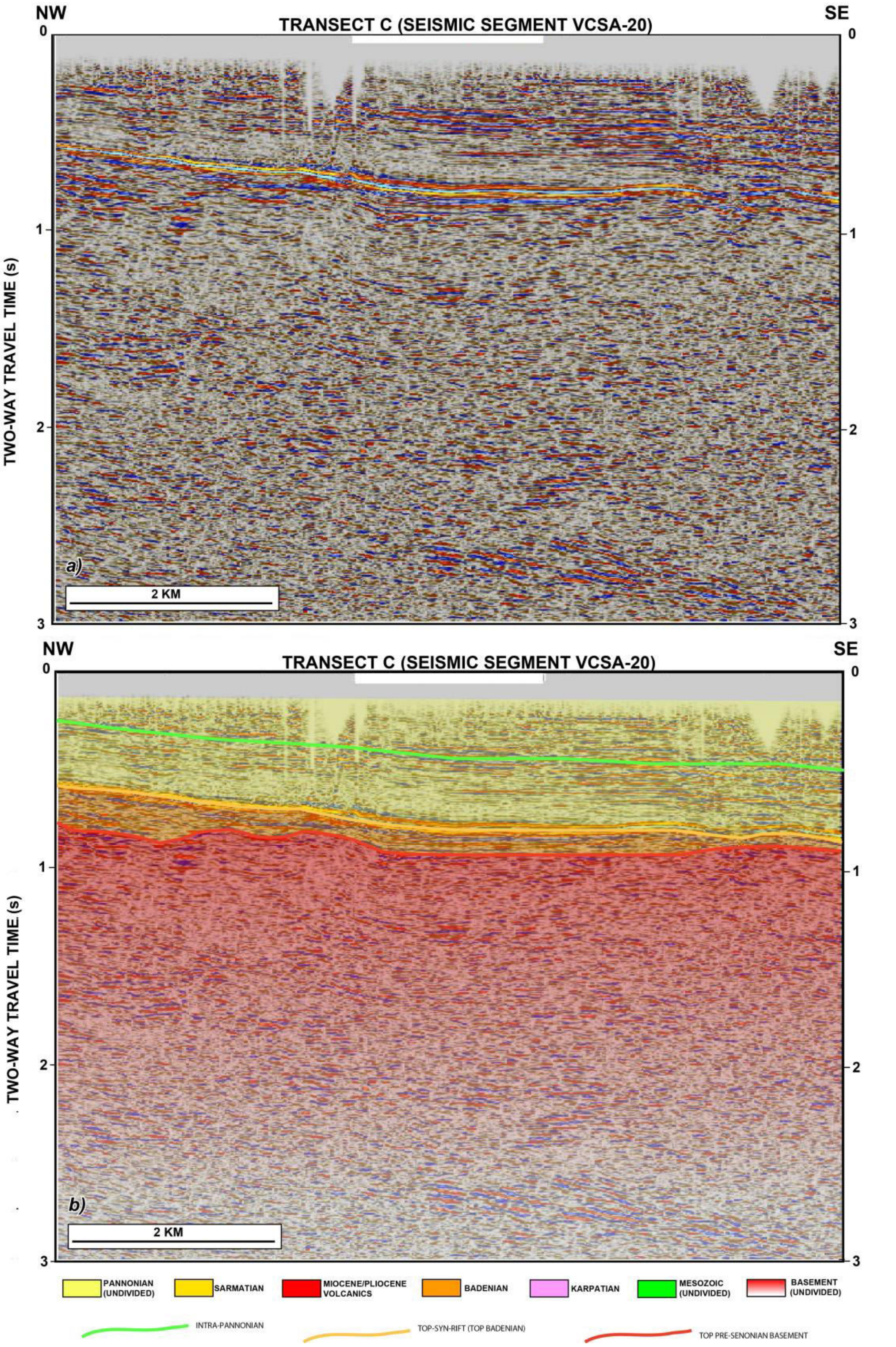

Figure 6.19. a) Seismic segment VCSA-20 without interpretation; b) Seismic segment VCSA-20 with interpretation. See text for detailed description.

Seismic segment CSA-35 (Fig. 6.20) is located in the Hungarian part of the study area (Fig. 6.1), near Beled, which is part of the Hungarian side of the Danube Basin.

Within this seismic segment, the basement forms a depression which is subsequently filled by the Pannonian and Miocene seismic packages. For this seismic segment a maximum thickness of 2 s twt can be observed, located in the NW part of the line. The Badenian follows the geometry of the basement, where it reaches its maximum thickness (0.2 s twt) in the area overlying the basement depression, therefore close to the centre of the seismic line. The Sarmatian seismic package is also very thin, with a maximum thickness of 0.1 s twt, making it the thinnest package for this line. Furthermore, this package is characterised by high amplitude reflectors showing high reflectivity. The maximum thickness of the Sarmatian has also been reached close to the central part of the segment right above the depression formed by the basement. The Pannonian package on the other hand, is the second thickest seismic package for the segment, with a maximum thickness of approximately 1.8 s twt. Like the underlying seismic packages mentioned earlier, the Pannonian package has also reached its maximum thickness above the basmement-formed depression. Furthermore, the Pannonian package displays reflectors of very high amplitude, especially close to the surface.

The general trend observed in this seismic line is that the packages, except for the Pannonian, have a higher thickness in the NW and gradually thin down towards the SE. However, while the other packages reach their maximum thickness near the central part of the segment, above the depression formed by the basement, the basement package itslef is at its deepest position for this seismic segment in the NW part of the line. The Pannonian package on the other hand, is thinner in the NW and thicker in the SE. All the seismic packages in this line become progressively shallower towards the NW (Fig. 6.20).

The delta progradation sequence observed in most of the Hungarian lines used for this project is present in this line as wel,l and the seismic reflectors that comprise it have a very low amplitude compared to the rest. The delta progradation sequence underlies the intra-Pannonian reflector and gradually thickens towards the SE. Similarly to the other seismic packages, the progradation sequence reaches its maximum thickness near the central part of the seismic segment, overlying the depression formed by the basement. Moreover, the delta progradation sequence, like all the other seismic packages, displays the same truncation of the reflectors towards the surface pattern.

The main reason for this basement-formed depression is the location of this seismic segment. CSA-35 is located within the Mihalyi High, which is bound by a large normal fault in the SE (shown as a black line in Fig. 6.20) (Tari, 1996). This fault displays a large offset, which is translated into the depression displayed in Fig. 6.2 (see Fig. 6.24 for larger outlook in time-structure map).

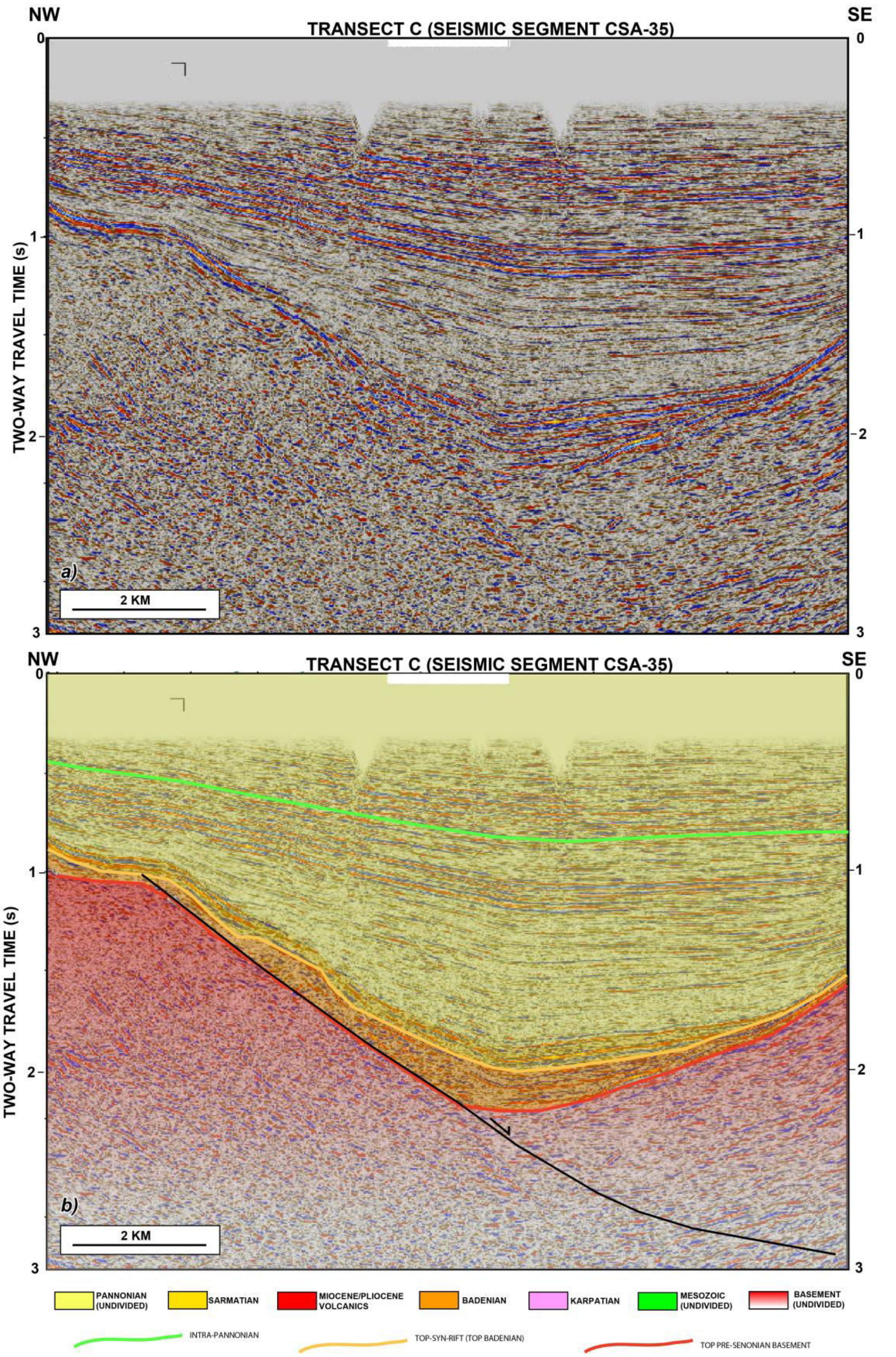

Figure 6.20. a) Seismic segment CSA-35 without interpretation; b) Seismic segment CSA-35 with interpretation and large normal fault where the Mihalyi High is bound also shown. See text for detailed description.

Seismic segment VPA-54 (Fig. 6.21) is located in the Hungarian part of the study area (Fig. 6.1), near Beled in NW Hungary, which belongs to the Danube Basin. The wells Mihalyi-7, -13 and -20 are also projected on this line.

This line displays a depth of 4 s twt and the basement package in this segment forms a high with high amplitude reflectors at the top. In the SE the basement forms a depression, which has been filled by the Miocene and Pannonian strata. Because of the presence of the basement high, several wells have been drilled which are projected on this segment namely the Mihalyi-7, -13 and -20 wells. The actual distance of these three wells from the seismic line is approximately 926 m for Mihalyi-7, 676 m for Mihaly-13 and 1471 m for Mihalyi-20. Since all three wells projected on this line are very close to each other, the well summary for the Mihaly-13 (Appendix D) well was chosen as a representative for all three and has been used in order to have a better understanding of the subsurface of the area. The basement seismic package reaches its deepst position for this segment in the NW where the high is formed, with a thickness of ca. 2.7 s twt. According to the well summary the basement consists of dark, grey schists and phyllites of the Upper Austroalpine. The top-basement reflector displays a high amplitude. The Badenian package onlaps on the basement and it fills the depression formed by the basement in the SE. As it reaches the high, the Badenian considerably thins down and then thickens more towards the NW. The Badenian has a maximum thickness of approximately 0.9 s twt and consists of light, yellowish sandstones. The Sarmatian is considerably thinner compared to the other seismic packages with a thickness of 0.1 s twt. This seismic package has not been accounted for in the well summary. The overlying Pannonian package has a maximum thickness of 1 s twt, making it the second thickest package for this line and it displays high amplitude reflectors throughout the package. According to the Mihalyi-13 well summary, the Pannonian seismic package is dominated by sandstone, with some interbedded clay and clay-marls. In the first couple of metres of the Upper Pannonian succession, some brown coal has been found, which has limnic origin.

All the seismic packages, except for the basement, reach their maximum thickness near the SE, where the top-basement forms its depression. Furthermore, except for the basement package, all the other seismic packages gradually thicken towards the SE. The basement however, is thickest in the NW and gradually thins down towards the

SE. The Neogene seismic packages display the opposite geometry of the basement package, meaning that where the basement is deepest the other packages are at their shallowest point and vice-versa.

The main reason for this top-basement geometry is the location of this seismic segment. VPA-54, similarly to CSA-35 is located within the Mihalyi High, which is bound by a large normal fault in the SE (shown as black line in Fig. 6.21) (Tari, 1996). A large offset displayed by this fault is the reason why the top-acoustic basement forms a depression-like geometry in the SE part of the segment. (Fig. 6.24 for larger outlook in time-structure map). The basin-fill mirrors the top-basement geometry and is a result of fault-controlled subsidence and possible compaction during the post-rift stage.

The seismic packages in this segment get progressively shallower towards the SE. There they get terminated, especially the Pannonian package whose reflectors get truncated against the surface.

The delta progradation sequence is present in this seismic segment as well and, similarly to all the other packages, reaches its deepest point in the SE part where the basement depression has been formed. This sequence has low amplitude reflectors.

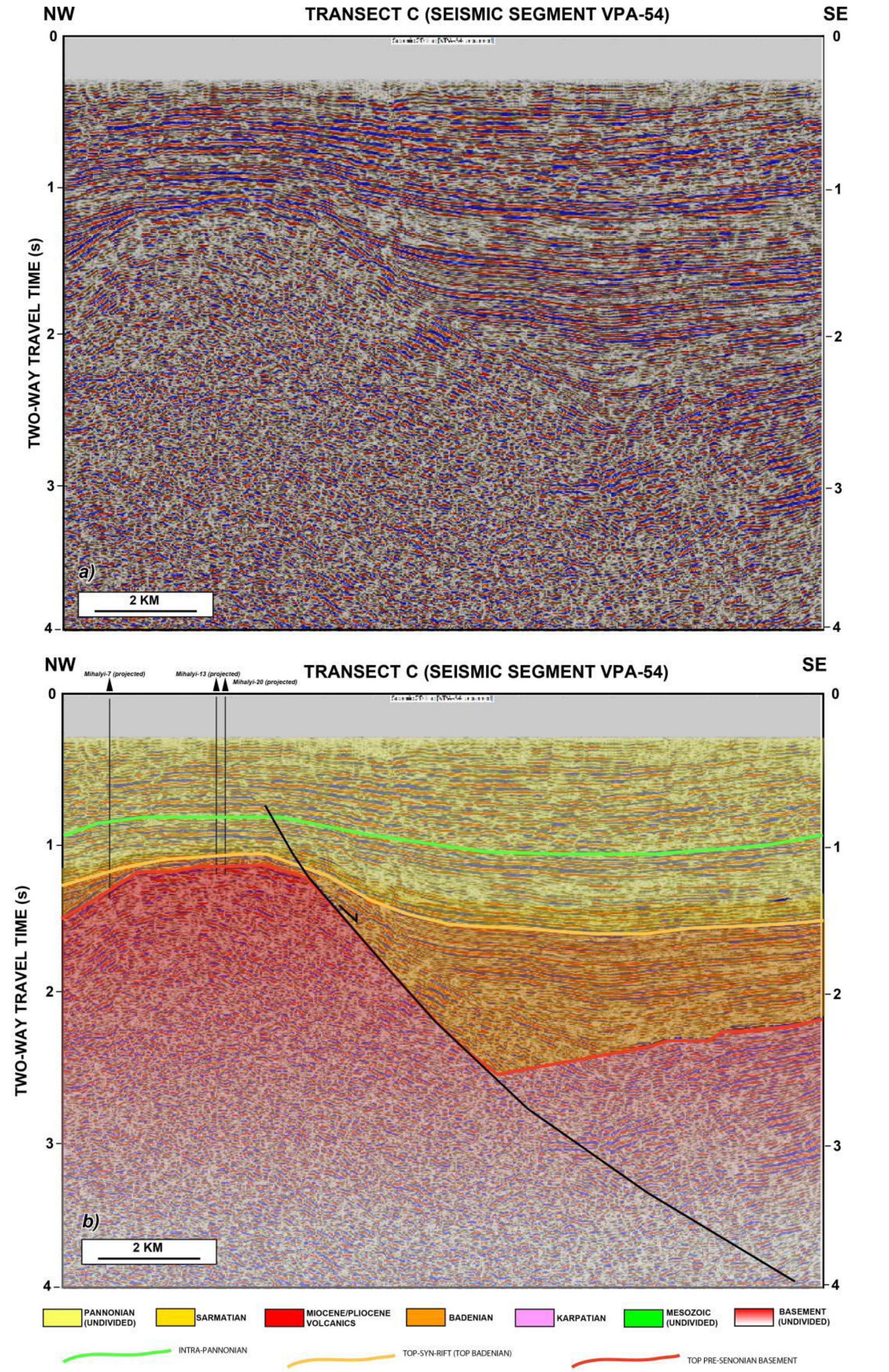

Figure 6.21. a) Seismic segment VPA-54 without interpretation; b) Seismic segment VPA-54 with interpretation with the Mihalyi-7, -13 and -20 wells also displayed. Normal fault represented by a black line. See text for detailed description.

6.2. Time structue maps

In order to further understand the regional context of the Pannonina Basin throughout the study area one must have a larger scale outlook. This has been achieved through the use of time-structure maps, which have been created using Petrosys. Instead of the small scale, detailed view that the seismic segments from the regional transects provide, the time-structure maps' aim is to give a large scale view of the mapped horizons. The horizons used for the creation of the time-structure maps are the intra-Pannonian, top-Badenian and top-basement.

6.2.1. Intra-Pannonian

The intra-Pannonian horizon has been mapped without any correlation to any specific chronostratigraphic feature and has been picked as an arbitrary horizon to investigate the general, regional-scale structure of the Pannonian strata.

The first thing that can be observed from the time-structure map is the depression located in the northern part of the map (Fig. 6.22). That area of low elevation is located only in the Hungarian part of the study area and it corresponds to the Györ Basin. The Györ Basin is a sub-basin of the larger Danube Basin. For a closer look of the subsurface of this depression, the seismic line VPE-38 where the Mosonszolnok-1 well is located (Fig. 6.5) offers a more detailed view of the depression. The Györ Basin forms a linear depression, which was created due to rifting. Using the seismic provided it can be observed that it has a relatively thick basin fill of Pannonian and Miocene age (Sarmatian, Karpatian, Badenian) and a pre-Cenozoic, crystalline basement. The basement is mainly composed of igneous and metamorphic rocks such as granite and gneiss (Fig. 6.5).

On the SE part of the time-structure map, just south of the Györ Basin, an area of relatively high elevation can be observed. This area represents the Pasztori High in Hungary where, during Pannonian and Badenian times volcanism occurred (for seismic see Fig. 6.12).

Another feature of note in this time-structure map is the fact that the map surface hardly extends to the Austrian part of the study area. Except for a very small part in the Oberpullendorf Basin, on the western part of the map and the Austrian part of the Danube Basin in the N/NW of the map, this surface does not continue over the Neusiedl Lake (Fig. 6.22). A first hint as to why this is the case, is given by the high elevation of the Austrian part of the surface (high elevation range yellow to red). This evidence suggests that the intra-Pannonian marker gets progressively shallower towards the NW and further into Austrian territory e.g. Eisenstadt Basin, the reflector gets truncated against the surface. The reason for this truncation is the post-Pannonian erosion of the Miocene and Pannonian strata. This phenomenon can also be observed over the Neusiedl Lake where the intra-Pannonian goes above it and gets terminated against the surface. In order to see the seismic version of this line NE-P12 must be viewed (Fig. 6.7).

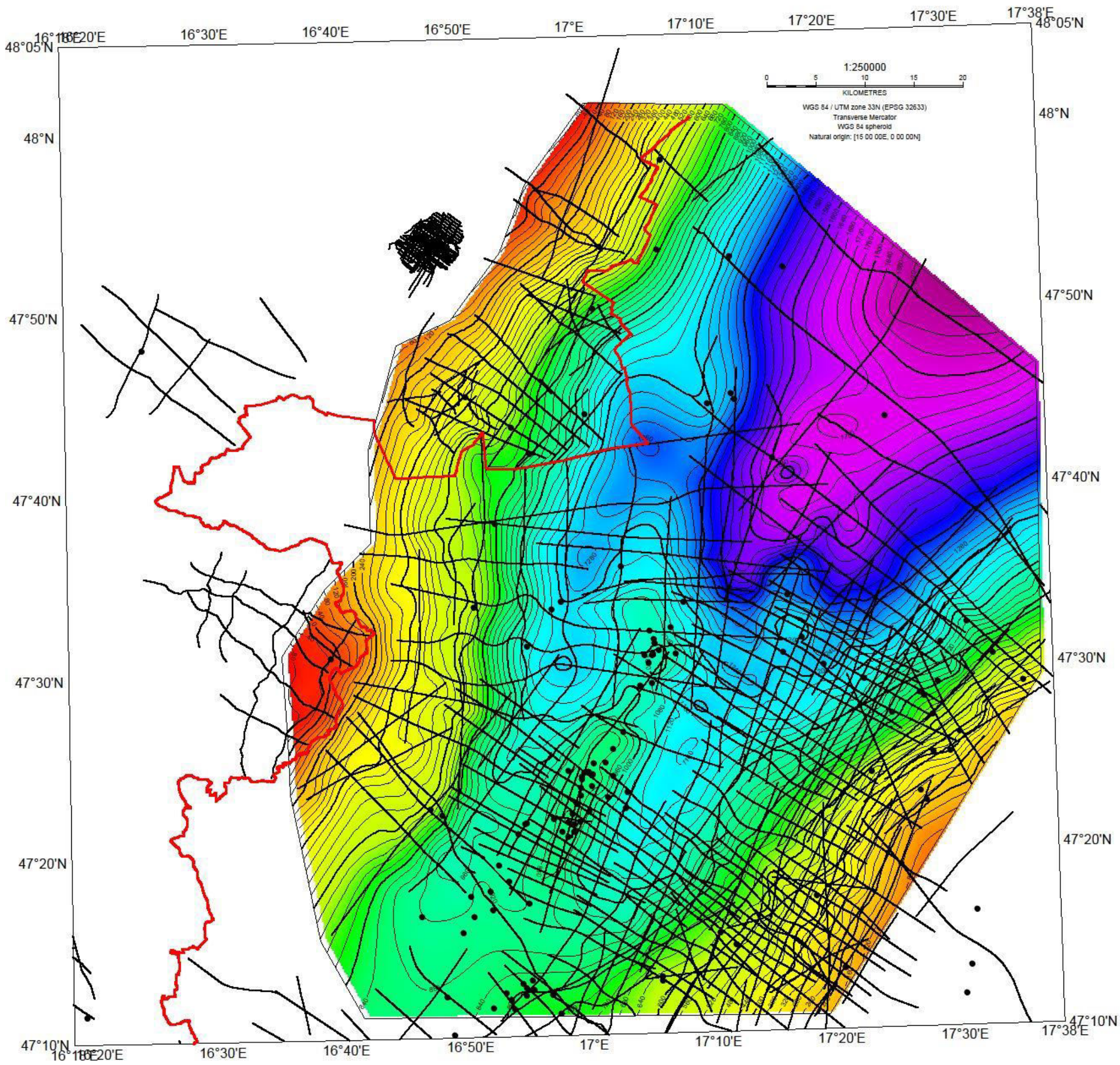

Figure 6.22 Time-conversion map of the Pannonian with no faults included. Red shows the highest elevation and purple the lowest elevation. The boundary between Austria and Hungary is shown thorugh a red line. The seismic lines interpreted for this project are shown in black; wells are represented as black dots.

6.2.2. Badenian

The Badenian horizon has been mapped through the use of well data such as well tops and the lithological summary of the wells provided by OMV for this study. The time-structure map has been created using the top-Badenian reflector mapped throughout the study area.

The first feature, which can be observed on the Badenian time-structure map (Fig. 6.23) is the fact that the surface created extends throughout the whole study area, in both the Austrian and Hungarian parts of it. The surface reaches its highest elevation in the Austrian part, located in the NW side of the map and more specifically the NW side of the Austrian part, in the Oberpullendorf Basin. This high elevation is also evidenced in the seismic (seen in most Austrian and Hungarian lines; as an example see Fig. 6.8) where the seismic packages, in this specific case the Badenian, g towet progressively shallower towards the NW. Therefore, the reason for this high elevation is the observed decrease of the distance of the reflectors in relation to the surface, which gets more pronounced towards the NW.

Another feature of interest is the low elevation in the Hungarian part of the study area, which is displayed in the N/NE part of the time-structure map. This low elevation area represents the Györ Basin in Hungary. This depression has been shown earlier in the intra-Pannonian time-structure map (Fig. 6.22). An aspect that was not seen in the intra-Pannonian time-structure map shown above, is the low elevation zone which can be seen in the centre of the time-structure map. This zone extends from the western part of the main Györ Basin further south near Bük in Hungary. This area of low elevation is the Csapod Basin, which is a sub-basin of the Györ Basin. In the Csapod Basin the Badenian syn-rift fill is slightly assymetric (Tari, 1996).

The Pasztori High is still visible in the Badenian time-structure map, with its relatively high elevation in the map, just south of the Györ Basin. In this area volcanism occurred during Pannonian and Badenian times and is mainly characterised by scoria cones (for seismic see Fig. 6.12).

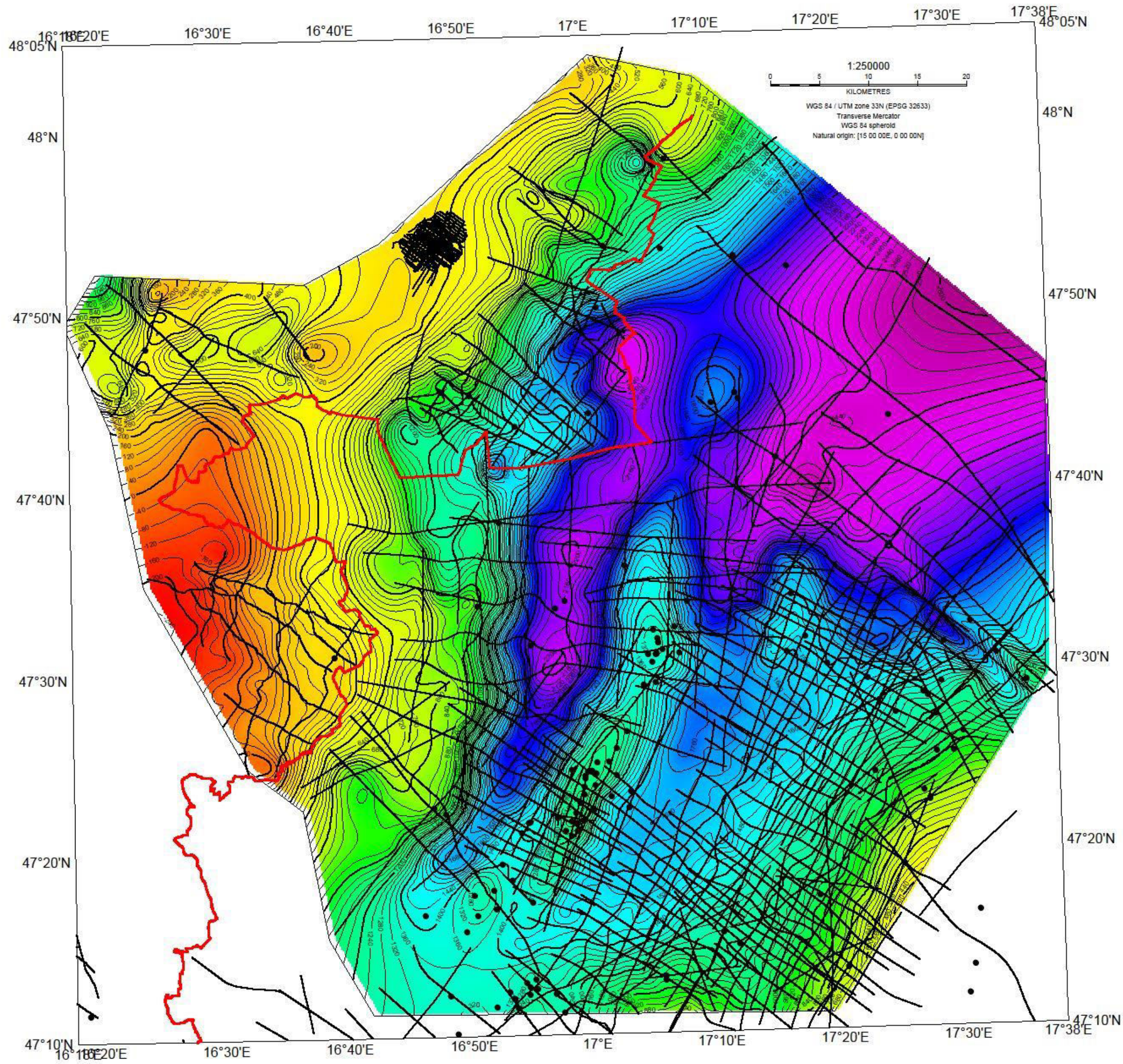

Figure 6.23 Time-structure map of the Badenian pick with no faults included. Red shows the highest elevation and purple the lowest elevation. The boundary between Austria and Hungary is shown thorugh a red line. The seismic lines interpreted for this project are shown in black; wells are represented as black dots.

6.2.3. Pre-Cenozoic basement

The pre-Cenozoic horizon has been mapped using well data such as well tops and well summaries of the wells provided for this study. The time-structure map has been created using the top-basement reflector picked throughout the study area. The surface generated by the time-structure map extends thorughout the study area and can be seen in both the Austrian and Hungarian parts of it.

A low elevation zone (in purple) can be observed in the N/NE art of this time-structure map (Fig. 6.24). This zone is the representation og the Györ Basin, which can also be observed on the other two time structure maps described earlier (Fig. 6.22, 6.23). The seismic expression for this depression can be seen quite well in the VPE-38 (Fig. 6.5) seismic segment belonging to Transect A and located in the northern part of Hungary.

A further low elevation zone can be seen in the SE part of the time-structure map, within the Hungarian part of the study area and south of the Pasztori High. This low elevation zone is the Kenyeri sub-basin of the Danube Basin in Hungary (Tari, 1996). This small basin is evidenced in the seismic by lines CSA-35 (Fig.6.20) and VPA-54 (Fig. 6.21). These seismic segments display depressions formed by the basement package on their SE part. These depression have then been subsequently filled by the basin fill of the Pannonian Basin, namely Miocene (Sarmatian and Badenian) and Pannonian sediments. Therefore, these small depression created by the crystalline basement accounts for this low elevation seen in the time-structure map surface. Furthermore, for these two seismic segments the pronounced basement depression is caused by a large normal fault, bounding the Mihalyi High, seen as a zone of high elevation just west of the Kenyeri Basin (Fig. 6.24) (Tari, 1996).

Similarly to the other two time-structure maps before it, the highest zones of elevation in this map are located in its NW part in the Austrian side, more specifically in the NW part of Austria, in the Oberpullendorf Basin. This high elevation is accounted for by the seismic packages getting progressively shallower towards the NW. The reason for the highest elevation being within the Oberpullendorf Basin is the relative shallowness of the sesmic lines located there. The three seismic lines from the

Oberpullendorf Basin used to create Transect C, lines BM 003 (Fig. 6.16), BLV-002 (Fig. 6.17) and BLV 009-15 (Fig. 6.18), have a total depth of only 3 s twt, which is quite low compared to the Hungarian seismic segments, which reach a maximum depth of at least 4 s twt.

The Pasztori High can also be observed in this time-structure map, like the previous two maps. It is located just south of the Györ Basin (Fig. 6.24).

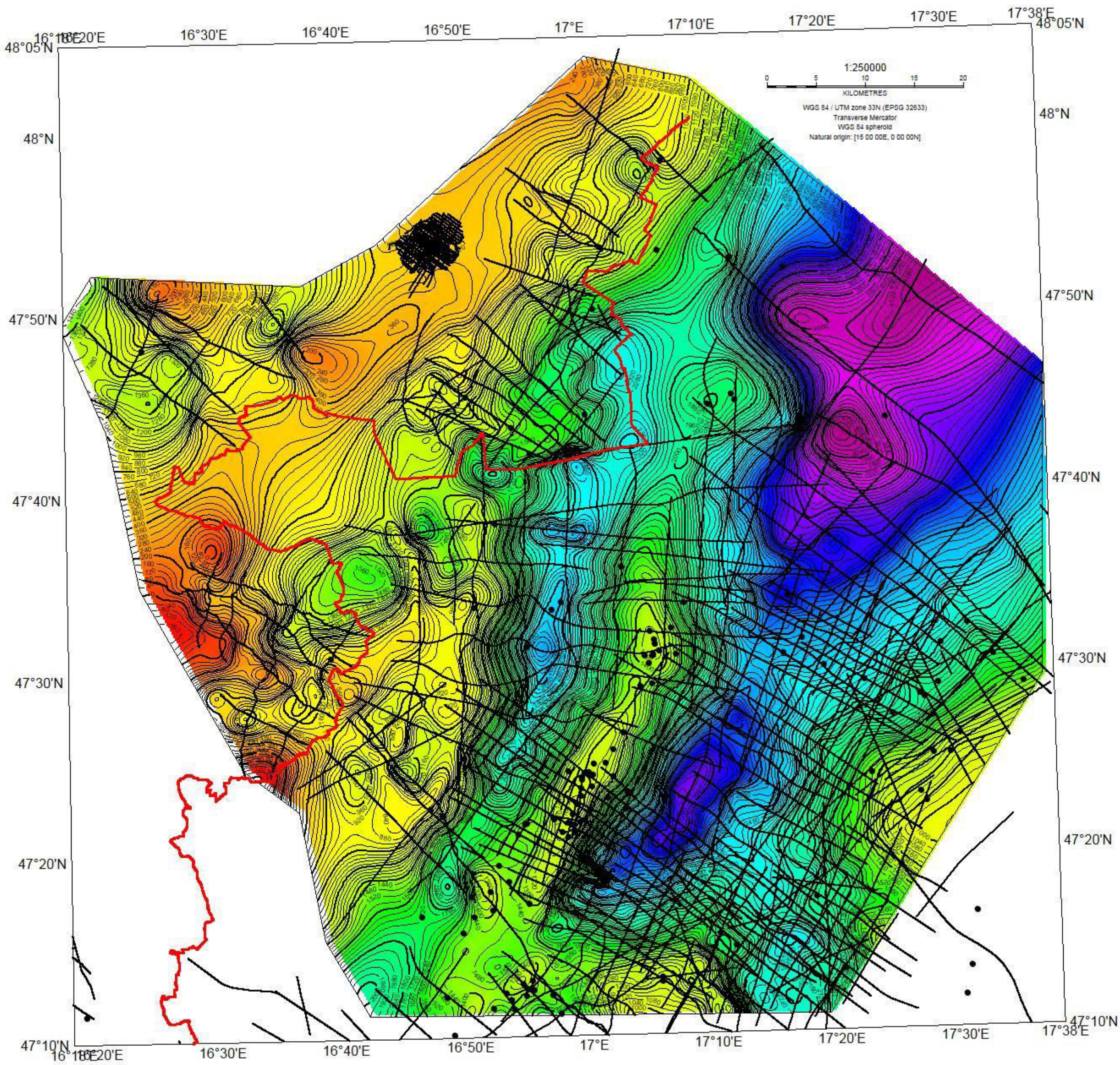

Figure 6.24 Time-structure map of the Basement with no faults included. Red shows the highest elevation and purple the lowest elevation. The boundary between Austria and Hungary is represented by a red line. The seismic lines interpreted for this project are shown in black; wells are represented as black dots.

7. Fault geometry and styles of deformation

Rift basins are complex structures, which are characterised by several structural features. Using 2D and 3D reflection seismic data, these features can be constrained the best and they can help to describe the different phases of rifting in a basin. The most common of these features are extensional faults, which have been observed within the study area and also in the Pannonian Basin system in general (e.g. Royden and Horvath, 1988; Tari et al., 1992; Decker and Peresson, 1996; Horvath et al., 2006; Spahic et al., 2011; Häusler et al., 2014). This chapter is intended to give a closer view of these faults by using 2D seismic images taken from the study area. Moreover, a digital elevation model (DEM) is used to illustrate the connection between the Austrian and Hungarian parts of the study area.

7.1. Extensional Faults

The most common faults within rift basins are normal faults (Fossen, 2010 and citations therein). Many of these normal faults are deep seated and involve the crystalline basement, while others may detach into sediments above the basement, or into salt or shale (Withjack et al., 2002). Many of these extensional faults accommodate the extension across the Earth's crust (Holdsworth and Turner, 2002). A large number of extensional faults can accumulate up to hundreds of kilometres of horizontal extensional strain. Extensional faults are typical for basins, which have been formed due to rifting, especially in the syn-rift phase, where the strata are offset by several extensional faults. In general, rift basins are bound on both sides by basement-involved normal faults, meaning faults that cut the crystalline basement. These extensional features can reach depths of several kilometres; can be tens of kilometres wide and hundreds of kilometres long (Withjack et al., 2002).

In the Pannonian Basin extensional faults are very common, especially during the syn-rift phase, during which a stretching occurs and major fault complexes form (e.g. Royden and Horvath, 1988; Tari et al., 1992; Horvath et al., 2006). Regional fault mapping for the 2D lines provided by OMV Austria mainly focuses on Lower, Middle and Upper Miocene structures, specifically the Sarmatian, Badenian and sometimes Karpatian successions. As an example of basement-involved, steepely dipping normal extensional faults within the study area, the BM-002 (Fig. 7.1) seismic segment has been selected. The seismic segment BM-002 is located in the Austrian part of the study area (Fig. 2.1), within the Eisenstadt-Sopron Basin, just a few km away from the Sopron Mountains (Ödenburger Pförte) themselves. In this seismic segment (Fig. 7.1) the Neogene sediments overlying the pre-Cenozoic basement reaches a maximum thickness of about 1 s in TWT, including approximately 0.2 s twt thick Upper Miocene (Sarmatian) sediments, 0.4 s thick Middle Miocene (Badenian) sediments and circa 0.3 s thick Lower Miocene (Karpatian) sediments. The Pannonian package reaches a maximum thickness of approximately 0.9 s.

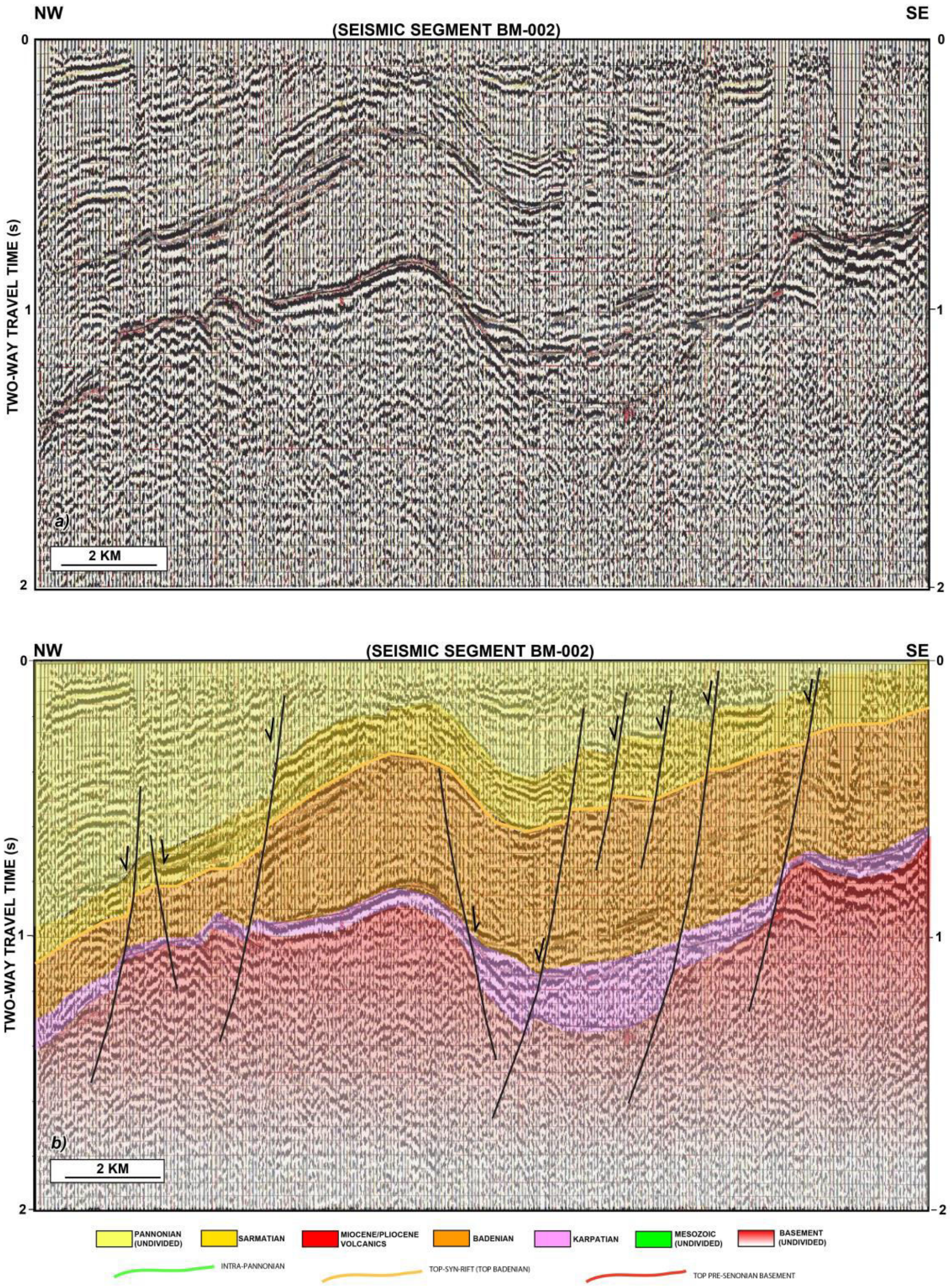

Figure 7.1. a) Seismic segment BM-002 without interpretation and b) seismic segment BM-002 with interpretation including the pre-Cenozoic basement (Austroalpine) and the Neogene succession (Karpatian, Badenian, Sarmatian and Pannonian). See Fig. 5.1 for location in study area.

The main structural element seen in the seismic segment BM-002, which has also been observed in the whole study area, are the extensional faults dipping to the NW and SE, displayed throughout the seismic profile. The extensional faults offset the pre-rift (basement), syn-rift (Karpatian and Badenian) and post-rift (Sarmatian and Pannonian) successions. These extensional faults could be used to establish the extent of syn- and post-rift successions by analysing the offset across them. This area seemingly has undergone considerable NW-SE directed extension, which can be inferred from the large number of normal faults observed on this relatively poor quality vintage seismic profile. If we had more modern seismic data, it is very likely that we could observe many faults, i.e. it is an issue of data quality.

Regardless, the majority of the faults on the BM-002 segment display consistently steep-dipping fault planes. Many other faults in the study area and the Pannonian Basin at large however, display low-angle fault planes (Figs. 6.3 and 6.4). In several of the seismic segments used for this study, a really pronounced tilting of the Miocene reflectors into the low-angle fault planes can be observed (Fig. 6.4), which according to Tari et al. (1992) is evidence for the presence of LANFs. The pronounced low angle dip of the fault planes of the extensional faults and the strongly tilted Middle Miocene strata into the low-angle fault plane, indicate significant extension.

Within the BM-002 seismic segment, the slight thickening of the syn-rift (Karpatian, Badenian) strata towards the fault planes can be observed (Fig. 7.1). This observation points as well toward syn-depositional growth and therefore the extensional faults that offset the seismic packages of this seismic line can also be seen as growth faults. Extensional faults typically interact with pre-existing basement features (e.g. Withjack, 2002). This interaction could be inferred on seismic segment BM-002 (Fig. 7.1) as the trend of Miocene syn-rift normal faults coincide with the pre-existing Alpine SW-NE trending structural fabric.

Generally, the style of deformation in the Pannonian Basin was controlled by the collapse of an overthickened, warm and thus weak lithosphere inherited from the Alpine orogeny. Within this tectonic setting, pre-existing Alpine nappe boundaries and thrust planes played the role of weakness zones and were subsequently reactivated as low-angle and listric normal faults in an extensional (transtensional) regime (Tari, 1996).

The amount of extension in the sub-basins of the Pannonian Basin system has not been systematically constrained by structural studies, but rather estimated through subsidence and thermal data (Royden and Horvath, 1988). In the Styrian Basin for example, numeric models of the temperature history were calibrated with vitrinite reflection data in order to have a better understanding of the extension rates ((Sachsenhofer et al., 1997). The most important features gathered from these studies in the Styrian Basin include Miocene extensional phases, the first one associated with a Karpatian to early Badenian magmatic event, followed by a minor Sarmatian extensional event, and, finally, a Pannonian east- to southeast-ward tilting of the easternmost part of the basin. (Sachsenhofer et al., 1997).

7.1.1. St. Margarethen Fault

The St. Margarethen Fault is located within the Eisenstadt-Sopron Basin, west of the Neusiedl Lake and SE of the Leitha Mountains (Fig. 7.2). The St. Margarethen fault has been extensively studied by many authors including Spahic et al. (2011), Häusler et al., (2014); and Spahic and Rundic (2015).

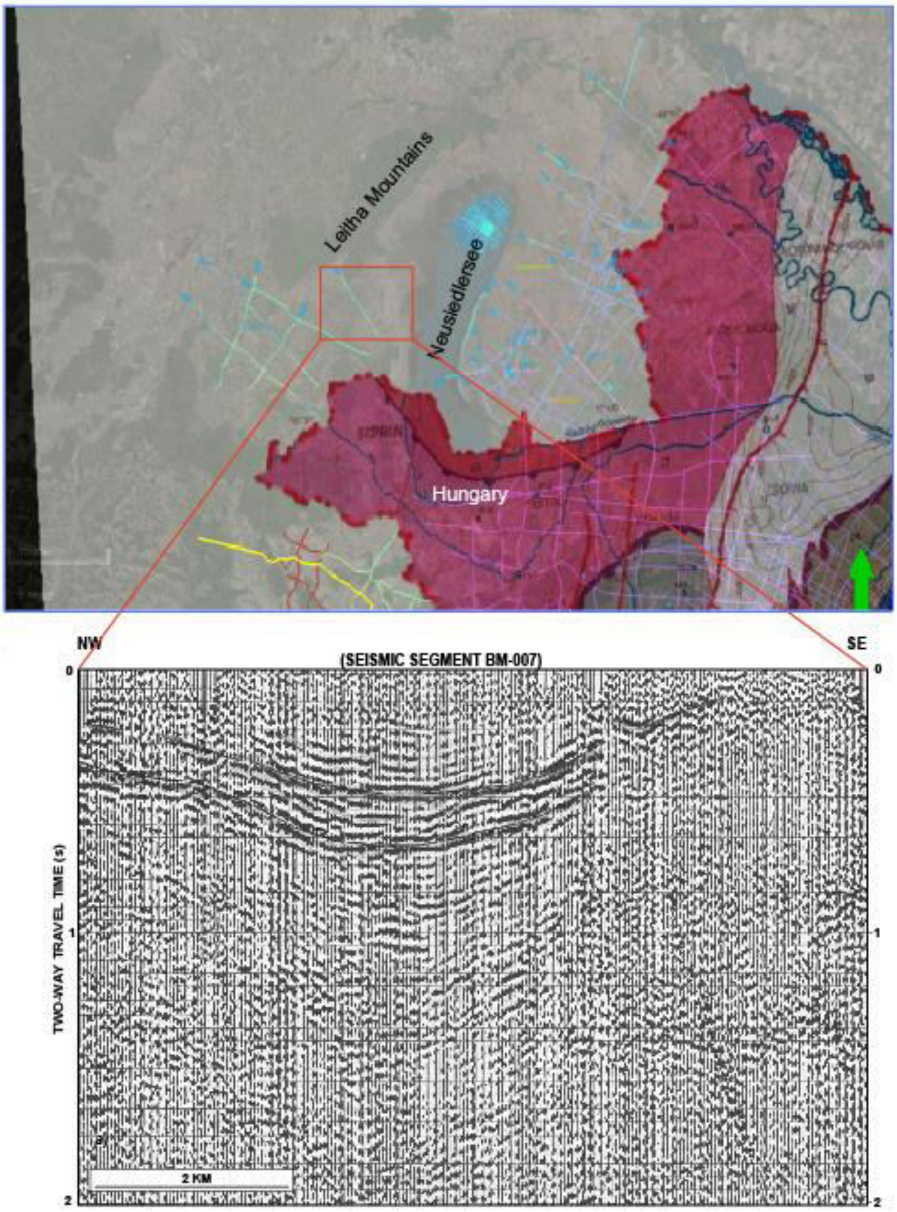

Figure 7.2. Location of the BM-007 seismic segment where the St. Margarethen fault is imaged on the uninterpreted BM-007 seismic segment. For an interpretation, see Fig. 7.4. Leitha Mountains, Neusiedler Lake and the northern part of Hungary also shown for reference.

According to Häusler et al. (2014), the features associated with the St. Margarethen fault are closely connected to the formation of the Eisenstadt-Sorpon Basin, and the Rust Range within it. Furthermore, they need to be put into a broader context with the formation of the Vienna Basin and its Austroalpine frame. During Miocene times, an eastward lateral extrusion of a major Alpine-Carpathian block caused the opening of the Vienna Basin, along bended left- lateral strike-slip faults. During Late Karpatian times, thrusting developed into lateral extrusion. This tectonic regime change has been locally documented as a major regressive event, during which fluvial systems entered the Vienna Basin from the south. Unconformities and younger sedimentary gaps are well documented in both the Vienna Basin and Eisenstadt-Sopron Basin due to the syn-rift to post-rift successions. In addition to their role as boundaries that separate the different depositional regimes within the basin, they also represent erosional structures related to sea-level falls at the base of the Rust Formation as well as during Upper Badenian to Sarmatian times (Strauss et al., 2006). This northeast-trending Austroalpine range has been described as the result of updoming (in German "geotektonische Aufwölbungszone", Häusler et al., 2014). Therefore, Häusler et al. (2014) concluded that the Miocene extension of the Vienna Basin and the subsidence of the Eisenstadt-Sopron Basin were contemporarily accompanied by updoming of their Austroalpine frame, which included the Leitha and Hainburg Mountains, the Rust Range and the Neusiedl Lake region.

Using geophysical methods such as electrical resistivity tomography (ERT), seismic reflection imaging and gravimetric measurements, Häusler et al. (2014) created several profiles across the St. Margarethen fault segment (Fig. 7.3). The master fault depicted in the seismic section separates the Rust Range from the Neogene deposits of the Eisenstadt Basin. In the western part of the seismic profile reflectors, which have been interpreted by Häusler et al. (2014) as eastward dipping and thickening Upper Miocene beds. In combination with the density model, the fault zone is characterised by a decreasing angle of dip and a curved surface which displays a slightly concave upward shape, thus classifying it as a listric fault. Furthermore, in the 350-400 m zone of the ERT-profile (Fig. 7.3) a low resistivity zone can be observed, which is then followed by a broader zone down to a depth of 350 m. This zone has been interpreted as a fault damage zone, along which the deposits of the eastern Eisenstadt-Sopron Basin slid down to the western margin of the Rust Range (Häusler et al., 2014). The reflectors of the section east of the St. Margarethen fault, located between 450 and 750 profile metres (Fig. 7.3) and at a depth of approximately 100 m above sea level, display an undulation and are parallel to each other. This undulation has been interpreted as a folded crystalline basement overlain by clastics belonging to the Rust Formation. Since the folding of Neogene formations along the Rust Range can be excluded, it has been surmised that the undulation at the base of the Rust Formation probably marks a pre-Karpatian relief filled up by fluvial deposits.

Since the Neogene succession on top of the northern Rust Range includes the Leitha Limestone of Middle Badenian age and since the margins of the Range are unconformably overlain by limestones of Upper Sarmatian age, “epirogenetic” uplift of the Rust Range during Upper Badenian to Sarmatian times is concluded (Häusler et al., 2014). Through the comparison of the present altitude of the base of the Badenian Leitha Limestone on top of the Rust Range (200 m above sea level) with its base at the eastern and western margin (130 m above sea level), it has been surmised that the central Rust Range has experienced an uplift of at least 70 m. In the ERT-profile (Fig. 7.3) Häusler et al. (2014) have depicted a Leitha Limestone antiform with an axis in the north-south direction plounging gently to the south. They also assumed conjugate pairs of faults, which are believed to have compensated for the tension caused by updoming.

The exploration well Zillingtal-1, some 13 km to the West (Appendix H) located on seismic segment BM-003 (Fig. 6.16) just a few km south of the St. Margarethen fault in the western Eisenstadt-Sopron Basin, on Transect C (Fig. 6.15), reaches a total depth of 1,415 m. At that depth, the well reached the Austroalpine basement and is characterised by 1,105 m thick Badenian deposits and 265 m thick deposits of Sarmatian age. Therefore, Häusler et al. (2014) conclude that continuous subsidence of the Eisenstadt Basin is in accordance with the period of updoming of the Rust Range during Lower Miocene times. Ongoing subsidence of the Eisenstadt-Sopron Basin along the listric master fault in front of the uplifted Rust block during Upper Miocene times resulted in growth-strata dipping to the east and fault drags indicate a hanging-wall syncline.

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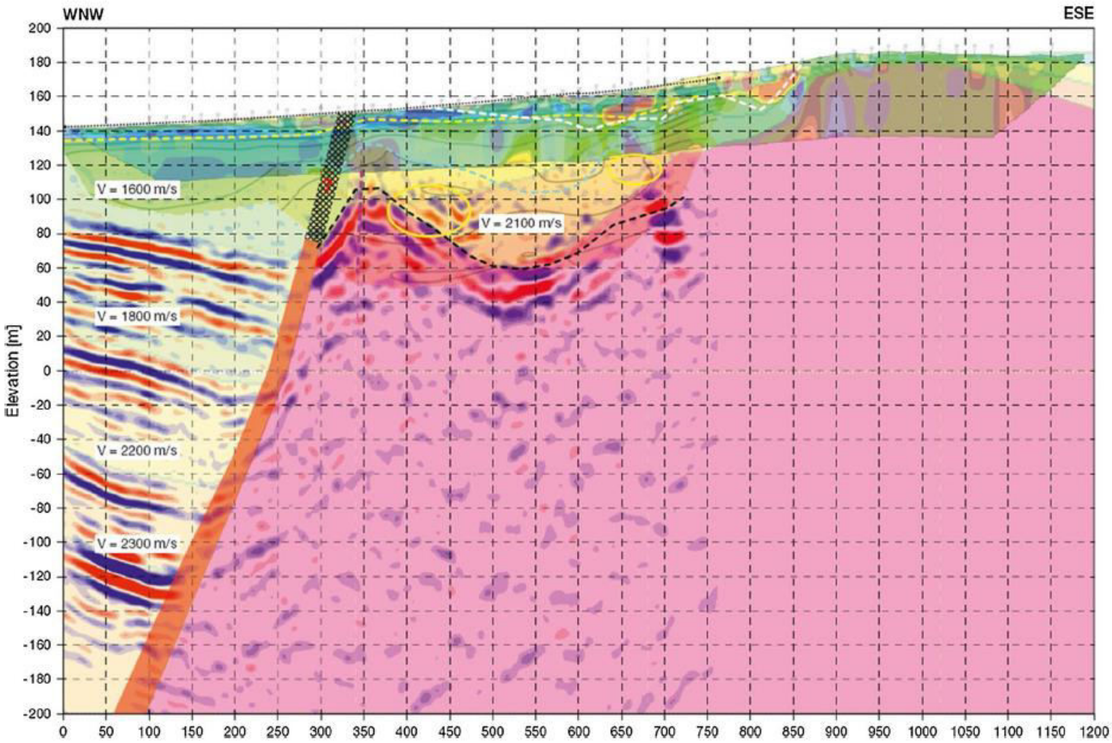

Fig. 15 Synoptic view of gravimetric-, seismic- and ERT-profile along the road Oslip–Rust (Figs. 12, 13, 14) at same *scale*. The St. Margarethen Fault zone is drawn as fault damage zone, which separates the Miocene growth-strata and syncline of the Eisenstadt Basin in the west from the Rust Range in the east

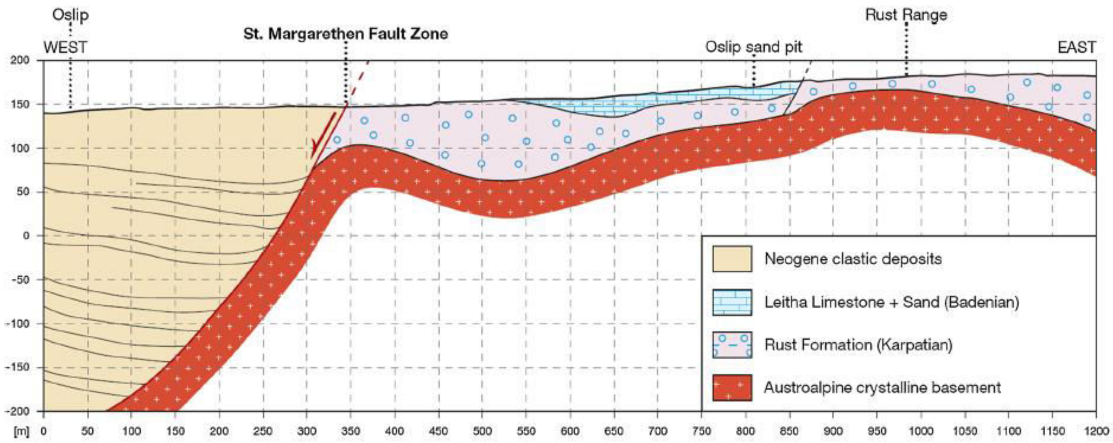

Figure 7.3. Top: Synoptic view of gravimetric-, seismic- and ERT-profile along the road Oslip-Rust, Bottom: Geological profile drawn based on the geophysical sections overlain (Häusler et al., 2014).

Within the study area, the St. Margarethen fault is also included and is displayed on seismic segment BM-007 (Fig. 7.4). This seismic profile, just S-SE of the Leitha Mountains, displays a major offset in the Austroalpine basement, with a minimum vertical relief change of at least 0.5 s in twt time. The syn-rift package, interpreted as the Karpatian and Badenian successions, display a maximum thickness of 0.2 s twt and 0.3 s twt respectively. The Sarmatian package has a more even thickness of about 0.2 s twt, making these Karpatian and Sarmatian units the thinnest for this particular profile. The Pannonian succession on the other hand, displays a maximum thickness of approximately 0.5 s twt.

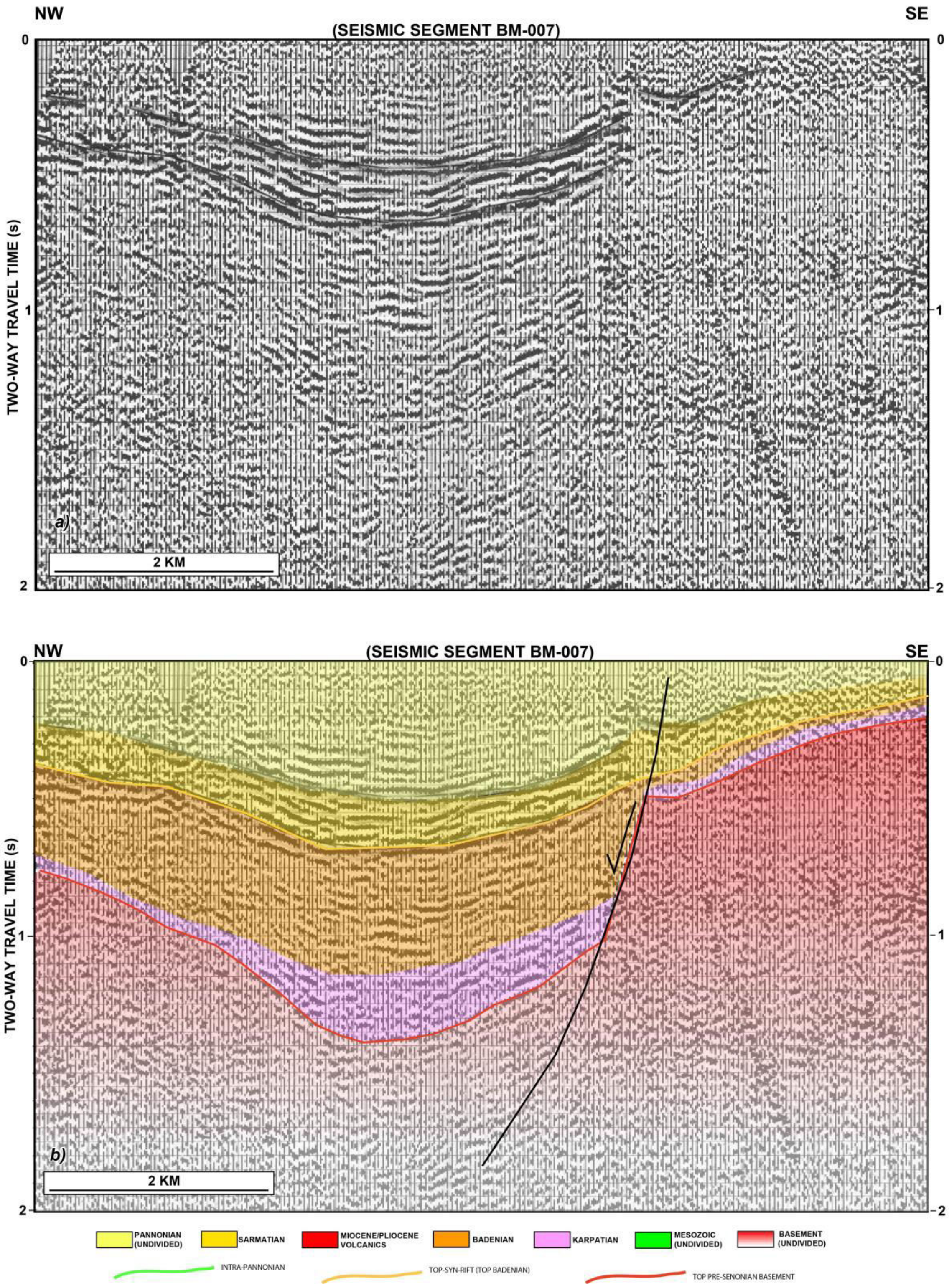

Figure 7.4. a) Seismic segment BM-007 without interpretation; b) Seismic segment BM-007 with interpretation and main extensional fault (Master fault) shown.

Like several of the seismic segments shown in the Regional Transects section (Chapter 6) the seismic packages of the BM-007 segment display a truncation of the reflectors towards the SE. Furthermore, the seismic packages, except for the basement package, get thinner towards the SE. Moreover, all the seismic units are offset by a large fault near the SE part of the seismic line. This fault, similarly to the seismic and ERT-profile created by Häusler et al. (2014), can be seen as a master fault with a concave upwards shape. The basement displays the largest offset in this seismic profile. The hanging wall of the St. Margarethen Fault displays a thickening of the Miocene sediments against the fault plane. In the case of the Karpatian, Badenian, Sarmatian and Pannonian seismic packages, while the gradual thickening of the packages towards the footwall of the fault is still displayed, on the hanging wall side the strata drastically thins down towards the SE (Fig. 7.4). Further similarity between the smaller scale seismic section published by Häusler et al. (2014) and the BM-007 seismic line is the slight undulation of the seismic reflectors east of the master fault. In the BM-007 line the undulation is very slight and not as prominent as it is seen in the ERT- and gravimetric profiles (Fig. 7.3). A slight undulation is best observed in the top basement reflector and it has been described as a folding of the crystalline basement, including the overlying Sarmatian package (Häusler et al., 2014). Furthermore, similarly to the gravimetric and ERT-profile, the reflectors directly east of the master fault are parallel to each other (Fig. 7.3).

Häusler et al. (2014) suggested ongoing subsidence of the Eisenstadt-Sopron Basin along the listric master fault. The vintage OMV seismic profile certainly suggests a very young age for the St. Margarethen Fault as all the seismic reflectors seem to be offset along it (Fig. 7.4).

While, the BM-007 seismic segment used for this project indicates very similar conclusions supported by the gravimetric, seismic and ERT-profile made by Häusler et al. (2014) for the St. Margarethen fault area, a few differences also exist. For instance, the Karpatian package, which has been described by Häusler et al. as part of the Rust Formation, is very prominent in Fig. 7.3 and covers almost entirely the area east of the master fault. In the BM-007 seismic line however, the Karpatian package is very thin and it becomes even thinner on the eastern part of the fault, similarly to the other Neogene deposits (Fig. 7.4). Moreover, in the ERT-gravimetric profile a thin layer of Leitha limestone has been accounted for, which overlies the Rust Formation (Karpatian) deposits. This Leitha limestone layer forms an antiform with conjugate pairs of faults which have compensated for the tension caused by updoming (Häusler et al., 2014). In the BM-007 segment however, this Leitha limestone layer cannot be seen. As evidence for the presence of Leitha limestone on the east of the master fault, high amplitude reflectors should be seen. Due to the high velocity of carbonates in seismic sections, high amplitude reflectors are generated. Therefore, the lack of high amplitude reflectors suggests a lack of Leitha limestone on the eastern side of the Master fault (Fig. 7.4).

In order to better understand the tectonic geomorphology of the area where the St. Margarethen fault is located, a digital elevation model (DEM) has been used. This DEM was created using a 2 m horizontal resolution data base, courtesy of the Amt der burgenländischen Landesregierung. The DEM (Fig. 7.5) displays the area west of the town Rust in N Burgenland, where the BM-007 seismic segment (Fig. 7.4) is located. This seismic line, trending NW-SE, is located to the west of the Rust Range, between St. Margarethen and Oslip, and on its southeastern end covers the western edge of the range, just north of the road connceting St. Margarethen and Rust.

The surface geology of the Rust Range was superimposed on the DEM to highlight the present-day geomorphology of this large rotated footwall block controlled by a master fault system on its western edge (Fig. 7.5). Close to the master fault, there are patchy outcrops of the pre-rift basement aligned in a N-S direction. Similarly, the Badenian Leitha limestone laos forms prominent ridges along the western flank of the range. However, most of the outcroppping Rust Range is dominated by the so called Middle Miocene “Ruster Schotter” (Rust Gravel) of Karpatian age (Häusler et al., 2014). These Miocene syn-rift sediments overlie the crystalline basement and dip to the East with an average estimated dip of about 10-20 degrees.

The importance of this observation is that it highlights the slightly back-rotated character of the entire Rust Range as a footwall block, consistent with an array of large basement-involved normal faults on its western edge. This geometry is more consistent with the interpretation of a steeply dipping planar normal fault, being responsible for the formation of the Rust Range, than a large listric fault (see dicussion below).

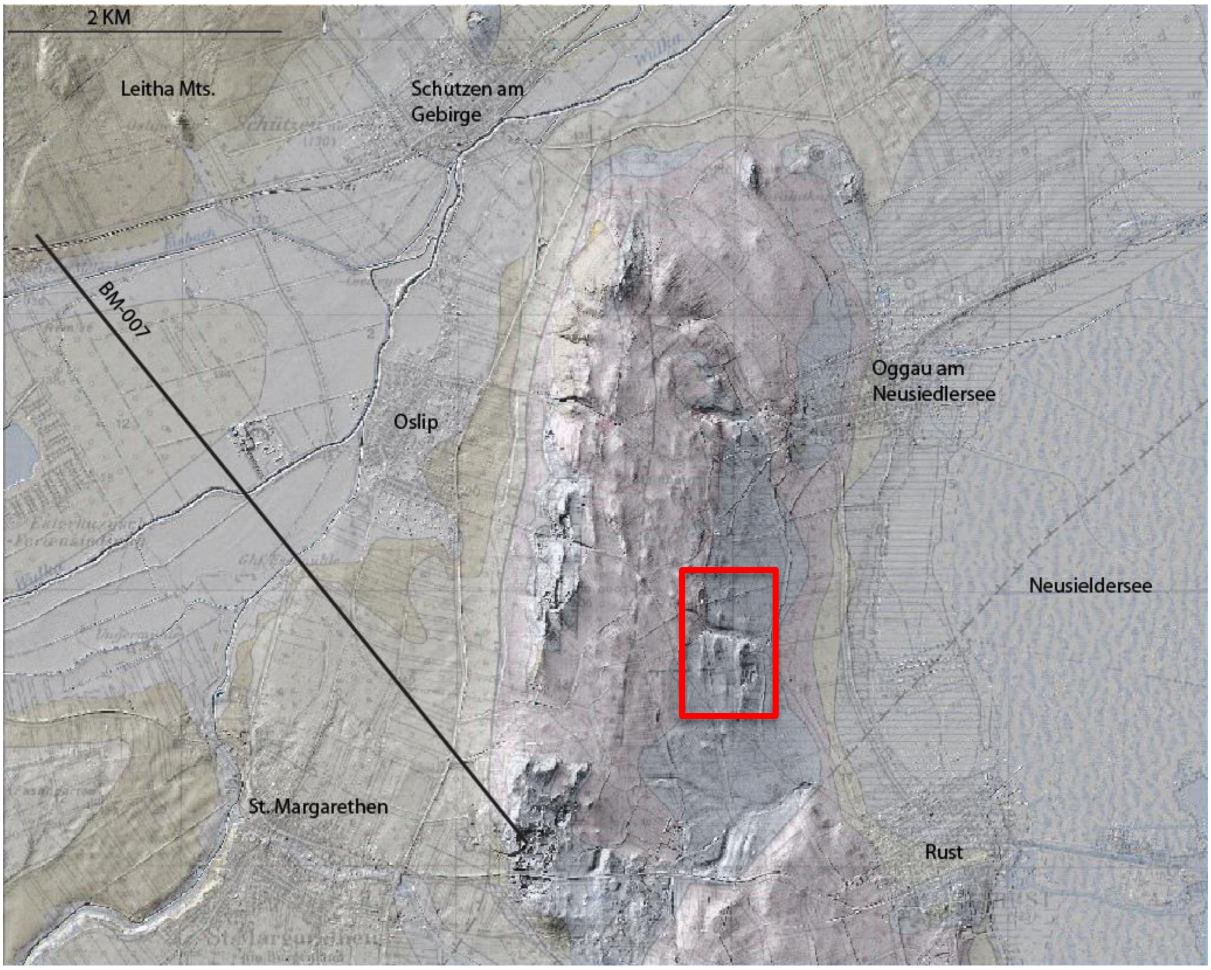

Figure 7.5 Digital elevation model (DEM) of the Rust Range superimposed over the Rust #78 1:50 000 map. The towns Oggau am Neusiedlersee, Rust, St. Margarethen, Oslip and Schutzen am Gebirge shown for reference. The BM-007 seismic segment (Fig. 7.4) is also displayed (black line). Selected cuestas, enclosed within the red square, are shown on a Google Earth satellite image in Fig. 7.13.
GPS coordinates of area within red square: N 47°48’53.986”, E 16°39’12.798

As mentioned above, Häusler et al. (2014) indicate that the St. Margarethen fault has a listric shape although no ductile footwall that can mechanically support this claim is present. Listric faults can be described as concave-up normal faults (e.g. Grasemann et al, 2005; Fossen, 2010 and citations therein). They can also be described as shovel-shaped faults, in which the dip decreases with depth resulting in the characteristic concave-up shape. (e.g. Grasemann et al., 2005; Spahic et al., 2011). Two main features are considered as typical for listric faults: 1) a steep upper part of the normal fault flattening downwards or merging with a low-angle detachment and 2) the down-warping of reverse drag of the hanging wall block forming a rollover anticline

(Grasemann et al., 2005; Spahic et al., 2011). Often, in order to find out whether a fault is listric or not fault shape is taken into account. It is often assumed that a hanging wall rollover implies listric fault geometry. However, according to Grasemann et al. (2005) this assumption doesn't work too well. First, although listric faults appear common, not all normal faults have listric geometries. As an example of this seismic reflection data can be used. These data sets indicate that normal fault traces that are not concave up in cross-sections. Second, reverse drag and rollover-like geomoetries can occur at all scales and be part of a broad range of different homogenous and heterogenous rheologies, including faults that have non-listric geomoetries. Furthermore, many mechanical models of planar faults show reverse drag therefore, listric fault geometries are not necessary for reverse drag to develop since reverse drag can also be a consequence of heterogenous perturbation deformation as a result of fault slip (Grasemann et al, 2005).

According to Spahic et al. (2011) a large number of models explain rollover structure, or reverse drag. These models account for the fact that a fault of finite length records lateral and vertical variations in displacement and magnitude. Such a displacement gradient causes wall-rock strains, which eventually lead to a bending, in this case reverse drag, of markers at a high amplitude to the fault plane (Grasemann et al., 2005). The faults depicted in these models are planar and not listric, and according to Spahic et al. (2011) even slip gradients along so called "anti-listric" faults may often result in reverse drag.

If this model is applied to the outcrop in St. Margarethen, the reverse drag observed in the hanging wall Sarmatian sediments may also be explained by a slip gradient along a planar master fault (Fig. 7.6). The St. Margarethen fault seems to display characteristics of both, listric fault and planar fault models, with Spahic et al. (2011) preferring the planar fault model as an explanation for the fault geometry where displacement gradient was seen as the primary mechanism of drag for the Sarmatian sediments. For the BM-007 seismic segment (Fig. 7.4), available for this study, it seems like the master fault is a steeply dipping, basement involved normal fault instead of a typical listric fault. Thus, in this case the planar fault model is preferred.

(a)

(b)

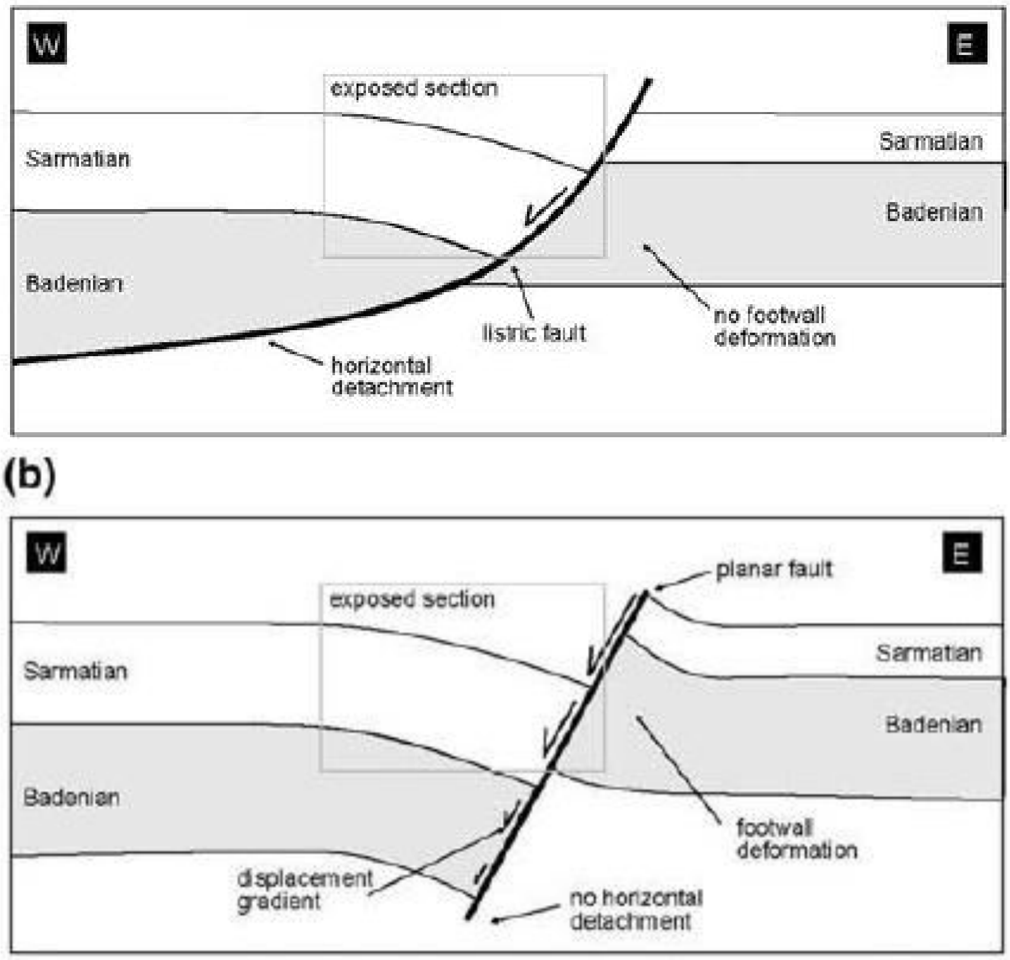

Figure 7.6. a) Listric fault model with constant displacement along a fault, which flattens at depth into a sub-horizontal detachment. The hanging wall is deformed into a rollover anticline, but there is no deformation within the footwall. b) Model of a planar fault of finite length recording a displacement gradient. Fault movement induced perturbation strain that causes reverse drag in the hanging wall and in the footwall. The exposed section in St. Margarethen records nearly identical geometry that characterizes both models (Spahic et al., 2011).

7.2. Digital Elevation Model

To better understand the connection between the subsurface and the surface geology of the area, a digital elevation model (DEM) was used. The DEM was created using a 2 m horizontal resolution public domain ArcGIS data base in Burgenland (Amt der burgenländischen Landesregierung) and was taken of a 10 km^2 area covering the exposed footwall blocks of two syn-rift faults, just west of the village of Jois, in northern Burgenland (Fig. 7.7). As it can be seen in on the geologic map and the oblique Google image (Fig. 7.7), in these footwall blocks the pre-rift Austroalpine basement is exposed. This footwall block trend displays two NE-SW trending en-echelon fault planes, with the fault planes dipping to the SE.

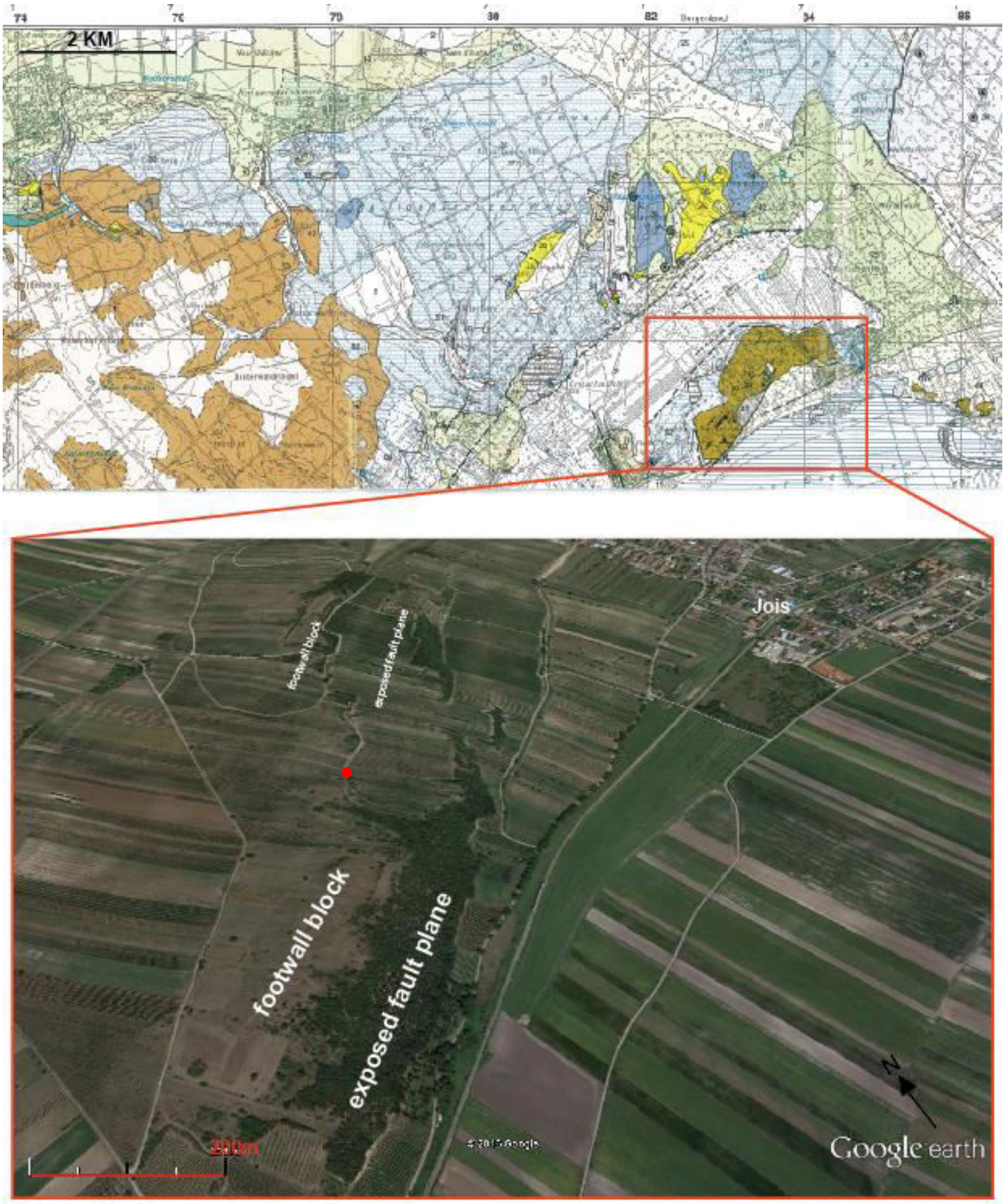

Figure 7.7. Above: geologic map of the NW part of the Neusiedlersee and the Leitha Mountains (Häusler et al., 2010) highlighting an isolated outcropping basement high just SW of the village Jois in northern Burgenland. Below: Oblique Google Earth image, looking towards the NE of the exposed footwall of en-echelon fault blocks trending NE-SW with the fault planes dipping to the SE, towards the Neusiedlersee.

GPS Coordinates of red dot: N 47°57’10.519”, E 16°46’30.025”

The geology of the area is quite diverse and has been displayed on the 1:50,000 scale, Austrian geologic map sheet #78 Rust (Häusler et al., 2010). The Austroalpine basement high itself consists of chlorite-sericite-biotite-quartzite schist, belonging to the Lower Austroalpine unit. The chlorite-sericite-biotite-quartzite schists have a brown-grey to green-grey colour and are strongly folded. Importantly, the chlorite and sericite dominated lithologies tend to behave as non-resistant units when sub aerially exposed and subjected to erosion. In contrast, the biotite and quartzite-dominated lithologies form much more resistant geomorphological features. As seen in Fig. 7.7, the crystalline basement between the Jois and Winden villages is dominated by the chlorite-sericite-biotite quartzite schists (Fig. 7.8). On the northwest flanks of the footwall high closer to Winden, the syn-rift Leitha Limestone (Leithakalk) can be found in the vineyards as loose clasts mixed with the soil (Fig. 7.9). This limestone has a shallow marine origin and belongs to the Middle Miocene (Badenian stage, see Fig. 3.1). The Leitha Limestone is a fossil-rich well-bedded neritic carbonate sequence, containing bivalves, corals and algae and shown to overlie the Austroalpine basement rocks (Häusler et al., 2010; Fig. 7.7). Due to the traditional agricultural activity of the nearby wineyards, the Leitha Limestone is only present in this area as loose gravel to cobble size material, without any outcrops where its dip/strike could be measured (Fig. 7.9). The new observation which was made here, is that the DEM displays the gently NW-dipping Leitha limestone beds as cuestas (or hogbacks, Fig. 7.10). These subtle cuestas have long/gentle dip-slopes and short/steep scree slopes in the vineyards. These geomorphological features can only be seen on the 2 m grid-sized digital elevation model (DEM) as slightly arcuate features and could not be depicted from the geologic map alone (cf. Figs. 7.7. to 7.12).

Figure 7.8. A chlorite-sericite-biotite-quartzite schist belonging to the Austroalpine basement in the Junger Berg-Hackelsberg area. GPS coordinates: N 47°57’10.634”, E 16°46’25.431”

Figure 7.9 Leitha Limestone (Leithakalk) in the Junger Berg-Hackelsberg area present as loose gravel on the field. GPS coordinates: N 47°57’10.634”, E 16°46’25.431”

A better understanding of the footwall basement high displayed in Fig. 7.7 is provided by the digital elevation model (DEM), which displays the relief of the exposed fault block (Fig. 7.10). The DEM was superimposed on the geologic map of Häusler et al., (2010) in the very same area (Fig. 7.11) and thus it gives a better idea of the geomorphological expression of the different lithologic units exposed in the footwall. As it can be seen, the composite fault block reaches its highest elevation on the NE part of it, with a height of 210 m (Fig. 7.10). The lowest elevation on the other hand, can be observed on the southern part with a height of 140 m. A general trend that can be observed in this fault block is the fact that the crest of the range falls to the NW of the interpreted fault planes (Fig. 7.11).

The cuestas formed by the Leitha limestone, mentioned above, can be seen quite well in the DEM on the NW and W flank of the range of the Junger Berg and Hackelsberg (Figs. 7.10. and 7.11).

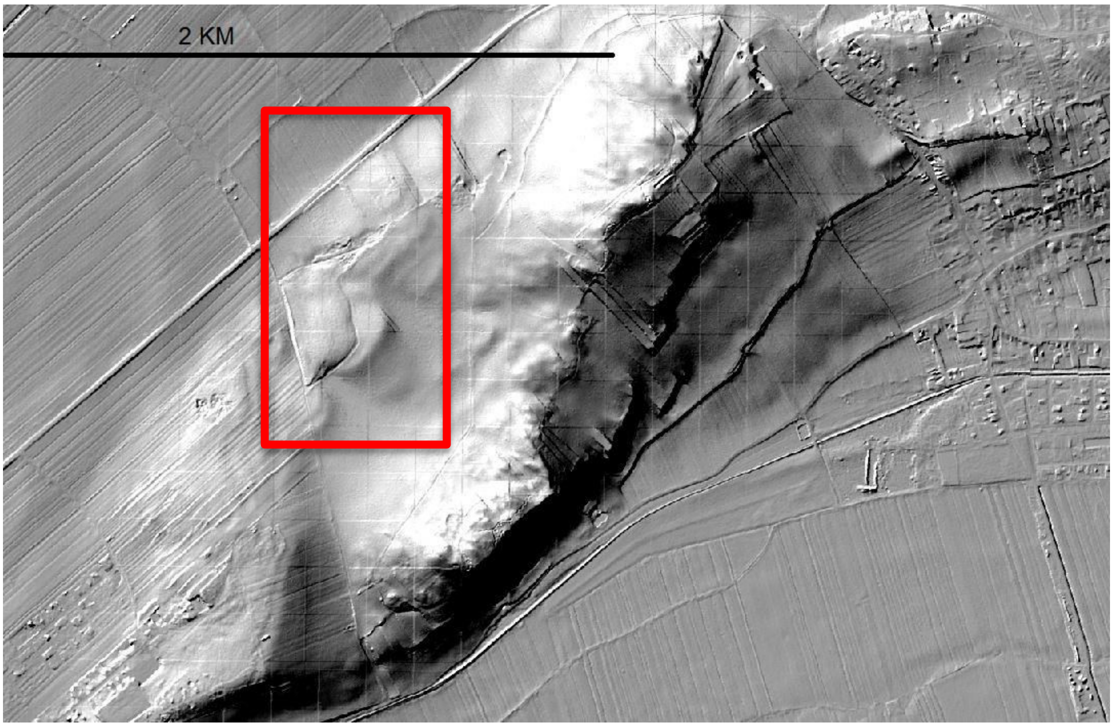

Figure 7.10. Digital Elevation Model (DEM) of the outcropping basement high shown in Fig. 7.7. Also compare it with Fig. 7.11 where the DEM was superimposed on the geologic map. Some of the cuestas formed by the Leitha limestone are framed by the red rectangle; see Fig. 7.11 for better details, Fig. 7.12 for their expression on the field (Burgenland) and Fig. 7.13 for their analogue seismic expression in the nearby Hungarian Pannonian Basin. GPS coordinates of area within red rectangle: N 47°57'10.634", E 16°46'25.431"

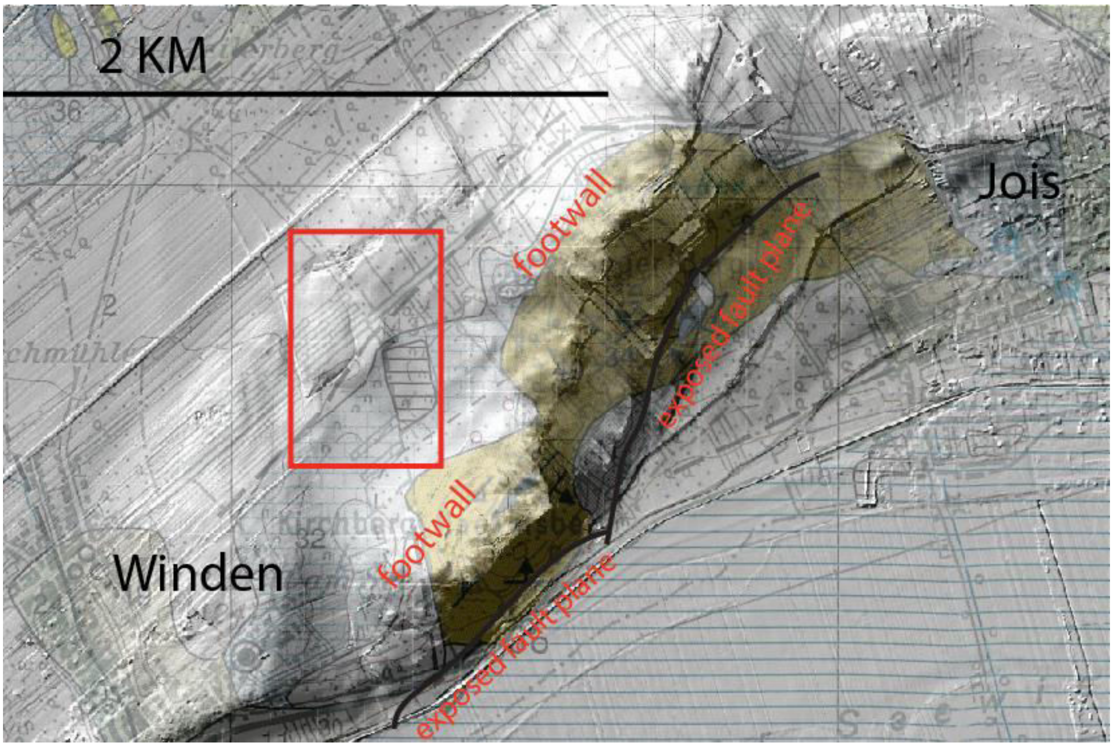

Figure 7.11. Digital Elevation Model (DEM) of the basement high shown in Fig. 7.10 superimposed over the map of the Junger Berg and Hackelsberg range (Fig. 7.7). The footwalls and exposed fault planes shown on Fig. 7.7. in the Google Earth image are displayed here as well. The red rectangle frames a few of the cuestas of the Leitha limestone and the black lines represent the tips of the partially eroded normal faults separating the footwall blocks. GPS coordinates of area within red rectangle: N 47°57'10.634", E 16°46'25.431"

A large-view image of the cuestas from the Junger Berg-Hackelsberg area can be seen on Fig. 7.12 This picture has been taken on top of Hackelsberg and displays the cuestas, which can be observed on its western side. On Fig. 7.12 the cuestas have been marked with a yellow line and one can see that they display a very gentle slope. This is in contrast with the steep slope and step-like geometry displayed in arid environments. The reason for this is the large amount of vegetation present on the area and also the agricultural activity due to the nearby wine yards (also pictured). Because of this, the Leitha limestone beds cannot be seen and the Leitha limestone is only present as loose gravel in this area (Fig. 7.8).

Figure 7.12. Field photo of the Leitha Limestone cuestas (highlighted in yellow transparent polygons) taken from slightly above, from near the top of the Hackelsberg, looking towards the NW. The presence of Leitha Limestone beds is shown by white stripes in the brownish soil getting prepared for the planting of new vines. The slope of the cuestas is very gentle (estimated to be about 5-15 degrees) and they do not display dramatic steepness and step-like shape, often seen in natural outcrops, especially in arid environments. The reason for this is the historical agricultural activity in the entire area on the gentle NW flank of the footwall block. GPS coordinates of area: N 47°57'10.634", E 16°46'25.431"

Another are where cuestas can also be observed is the Rust-Oslip DEM where the BM-007 seismic line is also located (Fig. 7.5). The DEM clearly shows N-S trending ridges over the Rust Ridge which are interpreted as hogbacks (cuestas) related to the slightly easterly tilted Miocene stratigraphy. Whereas there were no field checks of these cuestas, an inspection of the geomorphology of the Rust Range using Google Earth underlined the validity of this interpretation (Fig. 7.13).

Figure 7.13. Oblique view of a selected part of the Rust Range using Google Earth satellite imagery. The approximate location of the area shown (looking north) is shown on Fig. 7.5 as a red rectangle. Whereas most of the area is subject to agricultural activities, “smoothing” the pre-existing natural surface, still, the N-S trending ridges observed on Fig. 7.5 can observed as whitish bands. These whitish bands are underlain by Leitha Limestone debris among the top soil, reworked by the agricultural activity from the underlying beds tilted to the right (to the East). The small forested area in the center may possibly correspond to a larger hogback (with a small abandoned quarry on its western, i.e. scree-slope side) which migh have been proved to be difficult to use for agricultural purposes. The overall crestal area of the Rust Range is interpreted to show the same subtle hogback (cuesta) geomorphology over a slightly, but coherently tilted footwall block, like in the case of the Jungerberg exposed footwall fault block, discussed elsewhere in this study.
GPS coordinates of yellow pin: N 47°48’53.986”, E 16°39’12.798”

Whereas most of the area is subject to agricultural activities, the N-S trending ridges observed are highlighted in whitish bands on Fig. 7.13 as they are underlain by Leitha Limestone beds tilted to the East. This area is interpreted to show the same subtle hogback (cuesta) geomorphology over a tilted footwall block like the case of the Jungerberg exposed footwall fault block discussed elsewhere in this study.

The area in northern Burgenland, shown in Fig. 7.7, displays a very interesting and unique outcrop example of a syn-rift fault block where even the pre-rift basement is exposed. Unfortunately, there are no seismic profiles nearby to provide the seismic expression of this structural configuration. Therefore, the geometry of this specific structure, plunging to the subsurface along strike, cannot be studied directly. However, a very similar fault structure, with footwall fault blocks separated by normal faults is displayed in the seismic located in NW Hungary (Fig. 7.14).

Seismic segment VCSA-23 (Fig. 7.14) is located in NW Hungary, crossing the Pinnye High (e.g. Tari, 1996), a syn-rift high range parallel and NW of the Mihalyi-High. Generally, this line displays the same seismic packages, which have been observed in the other seismic segments used for this project, namely the Austroalpine basement, Badenian, Sarmatian and Pannonian packages, together with the intra-Pannonian reflector. The really important feature in this seismic segment, however, is the geometry of the syn-rift faulting as the Pinnye High is controlled by normal faults on its south-eastern side, just like the Junger Berg-Hackelsberg range described above.

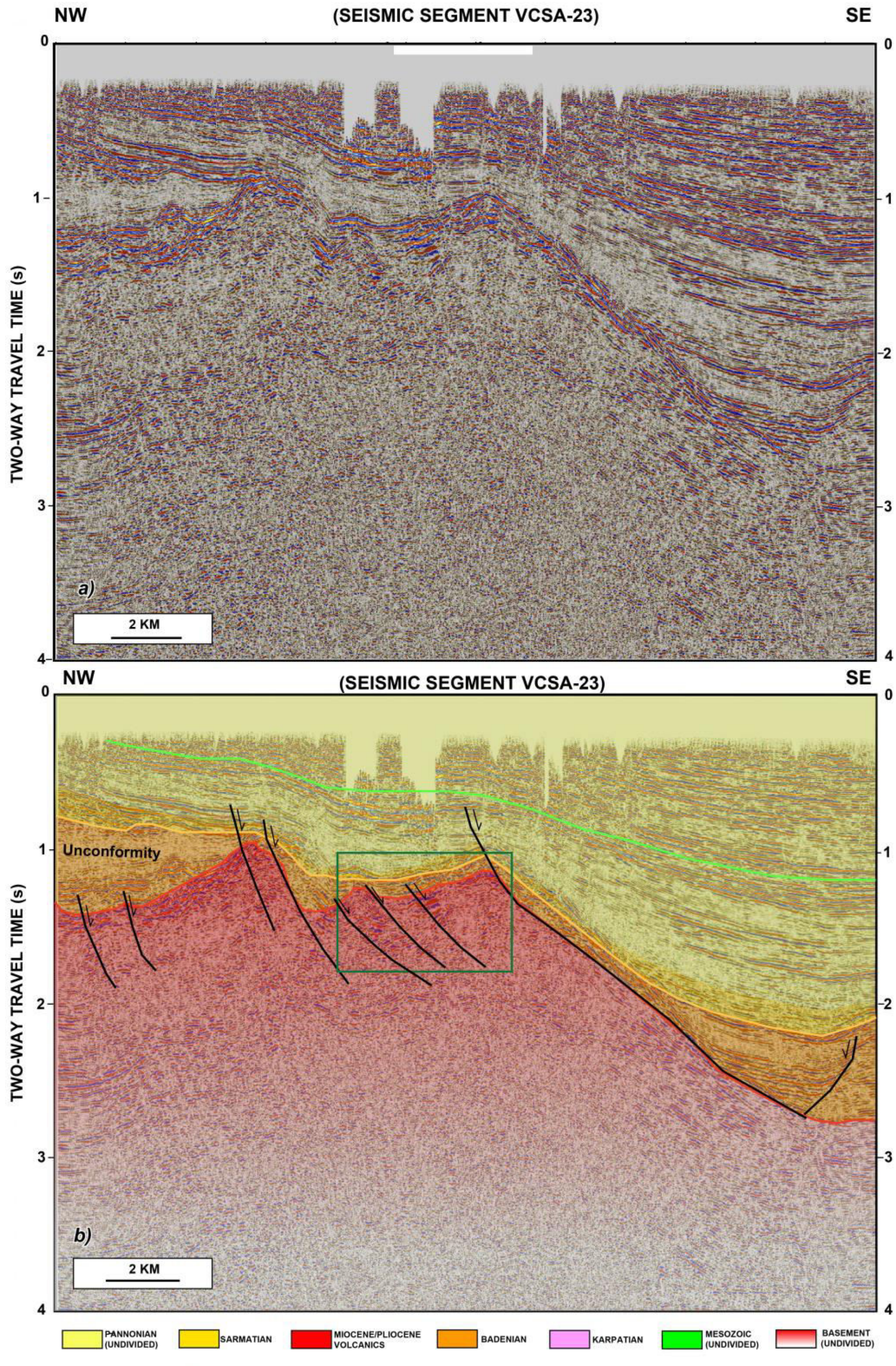

Figure 7.14. a) Seismic segment VCSA-23 without interpretation and b) seismic segment VCSA-23 with interpretation, the fault blocks displayed on Fig. 7.7. are also shown; the green square denotes the zoomed-in area displayed in Fig. 7.15. See Fig. 5.1 for location in study area.

Fig. 7.15 shows a zoomed-in view of the footwall fault block (cf. Fig. 7.14), where the different sub-blocks are separated from each other by synthetic normal faults with the same dip as the master fault. The domino-style geometry is clearly evident, as the normal faults were rotating synchronously during the syn-rift period. All these faults offset the Austroalpine basement, but they also offset the overlying syn-rift seismic packages, to a certain degree. Cuestas, analogous to the ones seen in the Hackelsberg area (Figs. 7.10-7.13) can also be seen in the zoomed-in seismic of segment VCSA-23 (Fig. 7.14). The possible cuestas interpreted on the seismic section are highlighted in light blue, on top of the Badenian syn-rift succession (Fig. 7.15).

Therefore, the VCSA-23 seismic segment coupled with the surface geology information described above for the Junger Berg-Hackelsberg range (see also Häusler et al., 2010), provides a good example of how a regional study can help explain the geology of particular sub-areas within the Pannonian Basin. In this case, the Austrian surface example, outcropping in the vicinity of Jois and Winden, where there is no seismic data available, could be understood better using analogue subsurface observations on a similar syn-rift structure in the Hungarian side of the basin, some 35 km to the SE.

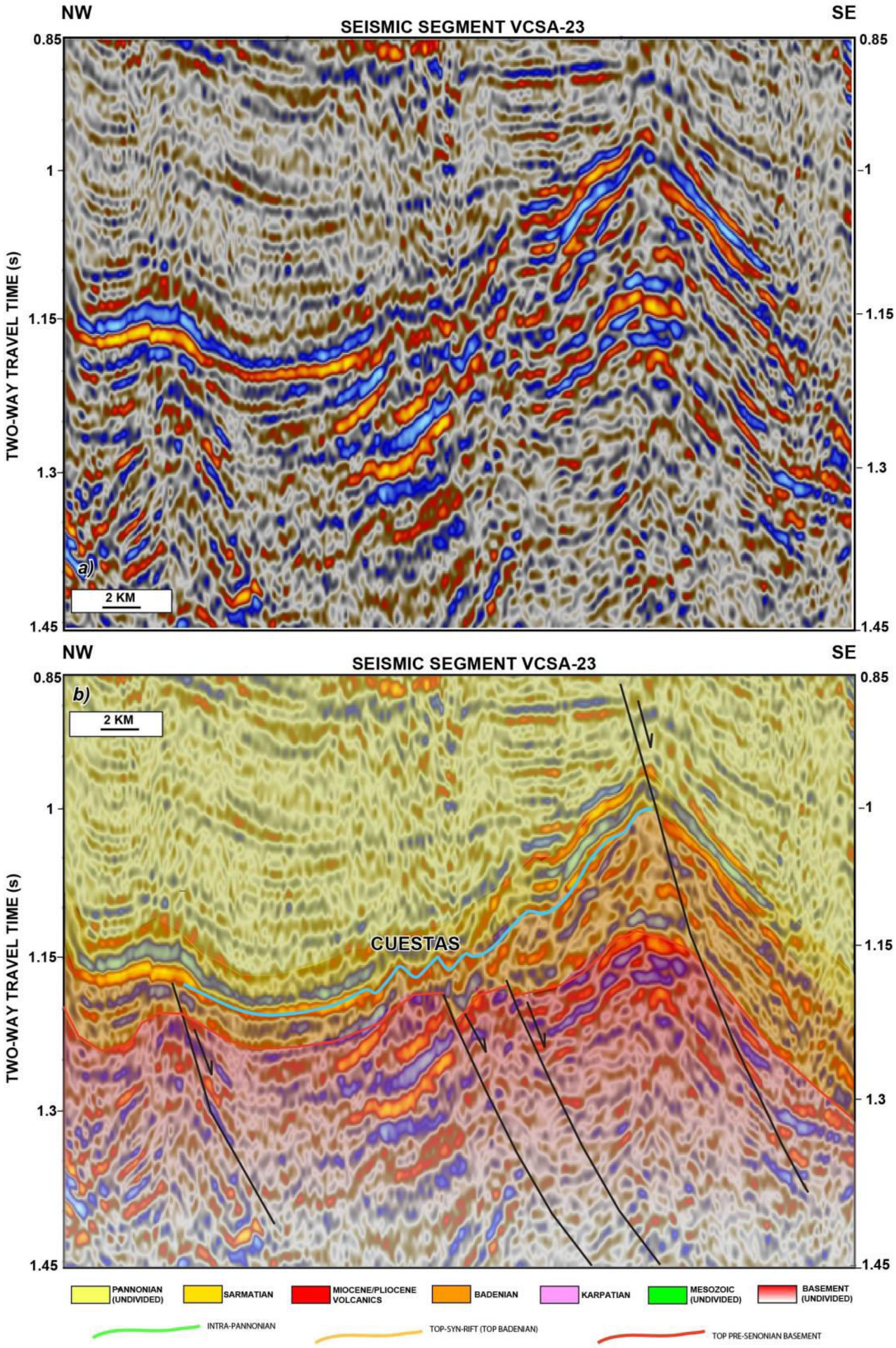

Figure 7.15. a) Subsurface seismic example of the footwall fault blocks of the Pinnye High, NW Hungary, analogous to the ones shown in Fig. 7.7. b) Interpreted image of the same VCSA-23 profile segment, showing the normal faults in black, the Austroalpine basement, Badenian, Sarmatian and Pannonian seismic packages. The cuestas on top of the syn-rift sequence are considered here as very good subsurface analogues to the ones shown in Figs. 7.11, 7.12 and Fig.7.13 and are highlighted in light blue.

8. Tectonic evolution of the study area

Chapter 3 of this study describes the geologic and regional setting of the study area, located in northern Burgenland in Austria and NW Hungary, in the context of the entire Pannonian Basin. Therefore, this chapter will focus on the tectonic evolution of the study area itself (see Fig. 8.1 for location), more specifically, on the various stages of rifting which took place from the Early Miocene (circa Ottnangian) until the present day. Furthermore, the inversion of this part of the Pannonian Basin will be discussed, which started during the Late Pannonian and continued until Recent. While the general tectonic evolution description will be of the Pannonian Basin system, with the help of seismic correlations with borehole data, the evolution of the study area will also come to light. In order to have a better understanding of the sub-surface of the study area, out of the various wells used for this study, four well summaries (2 from Austria and 2 from Hungary) have been correlated with their corresponding seismic segments, in which they have been projected. The wells in question are Rajka-1 (Appendix A) and Mosonszolnok-1 (Appendix B) in Hungary and Zillingtal-1 (Appendix H) and Minihof-1 (Appendix I) in Austria (see Fig. 8.1 for the location of the correlated wells). The Neogene tectonic history of the Pannonian Basin system, and therefore of the study area, has been summarised in a pre-rift (pre-Cenozoic), syn-rift (Early to Mid-Miocene) and post-rift (Late Miocene to Quaternary) framework mentioned in the following sections.

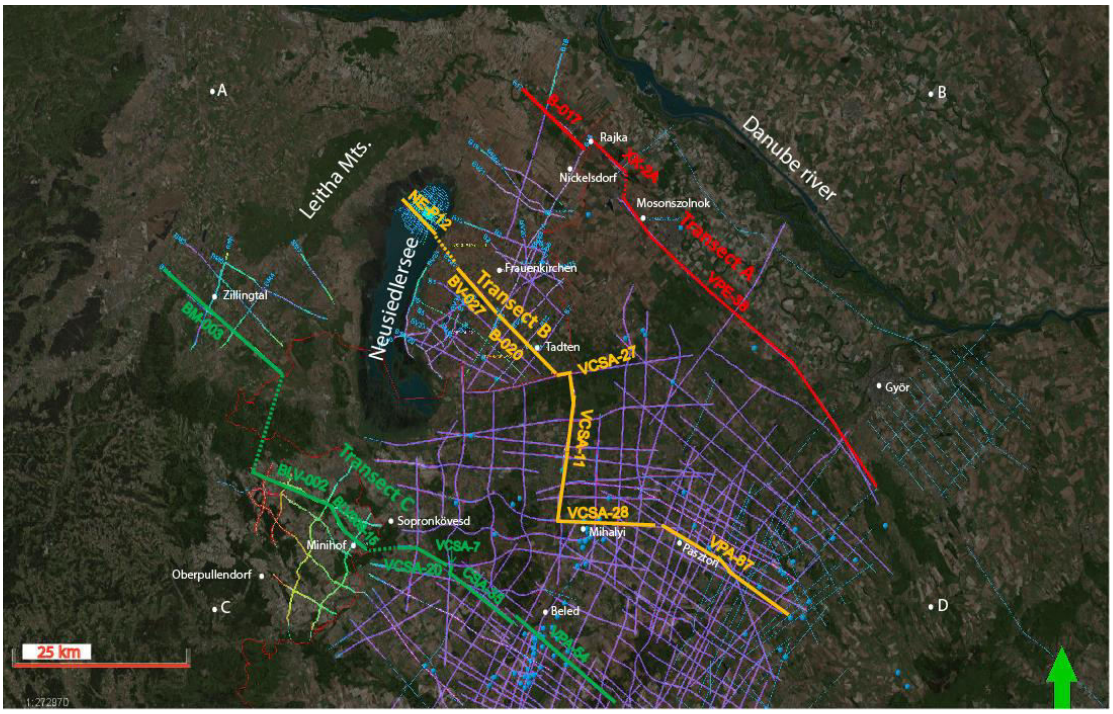

Figure 8.1. Location of the study area with the trace of the regional transects across NE Austria and NW Hungary, in the Danube Basin. Note the position of the Neusiedlersee and Danube River, and also the state boundary in red, for reference. The location of the wells described this chapter is marked in yellow. GPS coordinates: **A**: N 48°4’50.52”, E 16°24’29.03”; **B**: N 48°0’35.611”, E 17°45’10.295”; **C**: N 47°27’1.926”, E 16°24’5.871”; **D**: N 47°27’5.267”, E 17°46’54.436”

8.1. Pre-rift succession

The pre-rift succession is a set of strata, which were deposited prior to extension, thus, before rifting occurred. As rifting began, these sediment layers, which were deposited very early in the basin’s history were deeply buried and offset by syn-rift normal faults. A good example of this can be seen in Fig. 8.2, which displays the correlation of the seismic segment BM-003 with the lithology log of the well Zillingtal-1 (Appendix H) that is projected on the line. In this figure it can be observed that the Austroalpine basement is offset by several normal faults dipping to the SE and NW. Many of the faults that generally offset the pre-rift succession are either steeply dipping (Fig. 8.2) or low angle normal faults (LANFs, see Fig. 8.6). Also, some faults in the study area have been described as listric (Häusler et al., 2014) due to their concave upwards shape.

In the Pannonian Basin, the top of the pre-rift succession marks the onset of rifting, which according to Horvath et al. (2006) is marked by a regional unconformity that acts as a boundary between the pre-rift strata and the overlying Early Miocene (Eggenburgian to Ottnangian) deposits (Fig. 8.3).

Huismans et al. (2002) suggested that pre-rift crustal thickening in the area of the future Pannonian Basin started in the Late Oligocene and continued until the Early Miocene. This thickening took place in a N-S to NW-SE compressional stress regime. In general, the pre-rift succession coincides with the pre-Cenozoic basement, which is mainly of Palaeozoic age and in a large part of the study area belongs to the Austroalpine nappe system. Typically, the pre-Cenozoic basement of the Pannonian Basin, consists of Mesozoic age rocks (e.g. Tari and Horvath, 2006). Using the well lithology logs correlated with their respective seismic sections has constrained the specific age for the basement in the study area. In the wells located in the Austrian part of the study area, whose correlations are displayed in this section, Zillingtal-1 (Fig. 8.2) and Minihof-1 (Fig. 8.4), the Austroalpine basement belongs to the Palaeozoic. However, in the Hungarian well Mosonszolnok-1 (Appendix B) the basement has a Mesozoic age, more specifically belonging to the Triassic (Fig. 8.5). For the Mihalyi-13 well (Appendix D) the basement, similarly to the Austrian wells, is of Palaeozoic age (Fig. 8.6) and is part of the Upper Austroalpine.

As mentioned in Chapter 3.1 of this study, which deals with the stratigraphy of the Pannonian Basin, the dominant lithologies of the pre-rift consist of metamorphic, igneous and sedimentary rocks. Using the well lithology logs, it can be observed that the pre-Cenozoic basement of the study area falls well within the typical pre-Mesozoic lithology-range of the Pannonian Basin basement. The main lithologies of the basement, documented by the wells are mica-schists, gneiss and granite (Figs. 8.2, 8.4, 8.5 and 8.6).

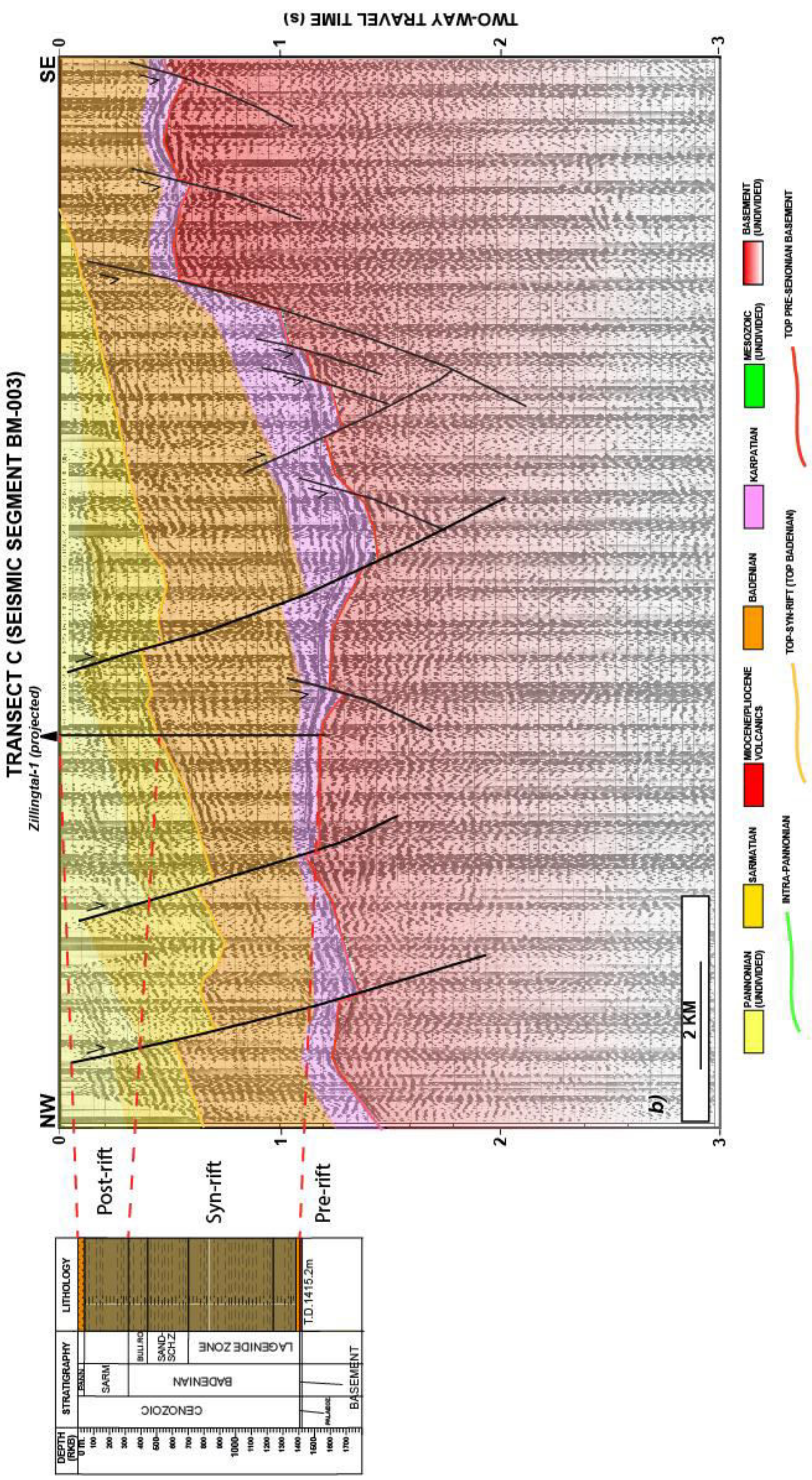

Figure 8.2. Seismic segment BM-003 correlated with the borehole data of the well Zillingtal-1 (Appendix H), which is projected on this line from a distance of 2.1 km from the SW. Zillingtal-1 is located in the Eisenstadt-Sopron Basin, a sub-basin of the Pannonian Basin system, just 21 km west of Lake Neusiedl.

8.2. Syn-rift succession

The syn-rift succession marks the phase where strata were deposited during rifting and it is believed to have started as early as during Eggenburgian or Ottnagian times (e.g. Huismans et al., 2002). In the Pannonian Basin, this phase is characterised by an unconformity (Fig. 8.3) between the pre-rift (pre-Cenozoic basement) and the Early to Mid-Miocene (Ottnangian to Badenian) sediments.

The boundary between the pre-rift and syn-rift successions has been placed by Tari (1994) at 15.8 Ma in the Hungarian part of the Danube Basin, between the Early and Lower Badenian. While this boundary has been considered a good local approximation, the pre-rift/syn-rift boundary is not synchronous across the whole Pannonian Basin system (Tari et al., 1999).

Using the well summaries correlated with their respective seismic segments, a better understanding of the seismic data base and sub-surface of the study area can be had. The main lithologies, which belong to the syn-rift succession consist of coarse-grained conglomerates, sandstones, marls and shales, which are overlain by transitional and shallow marine conglomerates (Irene Zorn *in* Schönlaub et al., 2000). The well summaries presented in this chapter seem to agree with this statement, with sands and clay-marls being the dominant lithologies. Due to the fact that the Badenian, which is the latest stage of the syn-rift succession, was also the last fully marine stage in the Pannonian Basin, marine lithologies are to be expected. A good example of this is displayed in the well correlation for Rajka-1 (Fig. 8.6) where at 1,128 m, which corresponds approximately to 1 s twt, Leitha Limestone (Leithakalk) has been found. The Leitha Limestone is a well-bedded, fossil-rich limestone containing corals, bivalves and algae, thus giving evidence for its marine origin. Due to the high velocity of carbonates in seismic sections, creating a promiment velocity impedance contrast, the Leitha-Limestone is represented by high amplitude reflectors displayed at the top-Badenian (Fig. 8.6).

In general, within the study area, the syn-rift succession is represented by the Karpatian and Badenian strata. This can be observed in three of the four wells which have been correlated (Figs. 8.2, 8.4, 8.5 and 8.6) and generally in almost all the wells used for this study. The only well where this is not the case is the Minihof-1 well (Appendix I). This well is located in the Austrian part of the study area, near the town Minihof (see Fig. 6.1), which is where the well gets its name. In the corresponding well summary the syn-rift succession is represented by a formation called "equivalent of the Brennberg series" (Fig. 8.4). As mentioned in chapter 3.1, which deals with the stratigraphy of the study area and of the Pannonian Basin in general, the Brennberg series is a freshwater formation of Ottnangian age (e.g. Häusler et al., 2014). This particular series is found near the Rust Formation in the Eisenstadt and Sopron basins and its main lithologies consist of sands and coal beds scattered throughout. In the Minihof-1 well (Fig. 8.1), the so called "equivalent of the Brennberg series" includes the Ottnangian, Karpatian and Badenian time-periods and its dominant lithology is sand, with some clays and clay-marls (Fig. 8.4). Therefore, the time periods and lithologies displayed concur with the time-frame and typical lithologies of the syn-rift succession in the Pannonian Basin system. In general, the syn-rift succession is relatively thin and is usually present in fault-bounded grabens (Tari and Horvath, 2006). This graben geometry can be observed quite well in the seismic section with the Zillingtal-1 well as a calibration (Fig. 8.2).

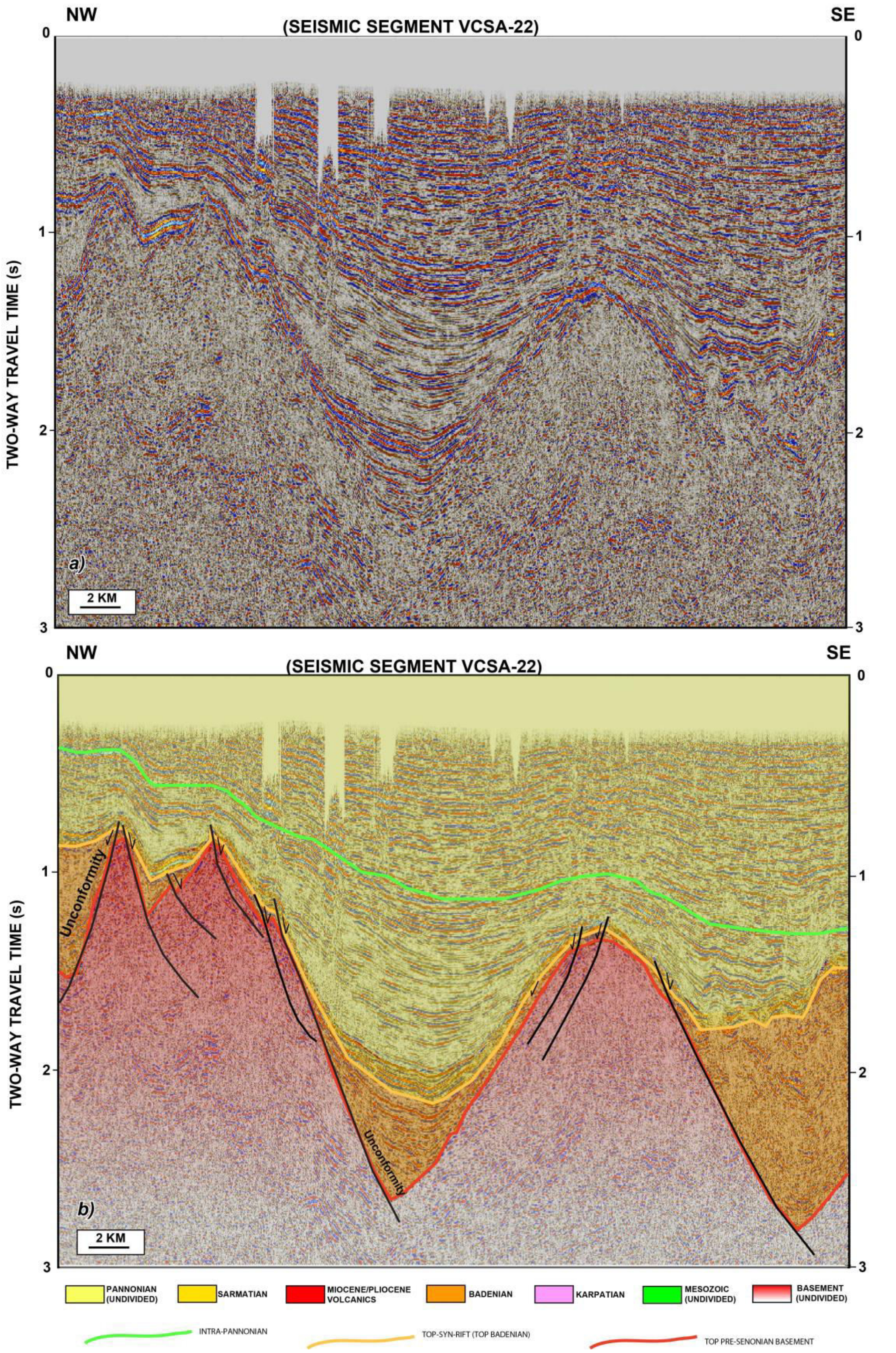

Figure 8.3. Seismic segment VCSA-22, located in the Danube Basin in NW Hungary, is used here as a showcase for the unconformity separating the pre-rift from the syn-rift succession, shown in red. Several normal faults (shown in black) offset the pre-rift (basement) and syn-rift (Badenian) successions. These faults form a graben geometry which is typical for extensional basins. See Fig. 5.1 for location within the study area.

Typically, syn-rift successions in seismic imaging display abrupt thickness changes across growth (extensional) faults with hanging wall thickening and footwall thinning (e.g. Fossen, 2010). A good example of this can be seen in the Rajka-1 well correlation (Fig. 8.6) where the syn-rift succession (Karpatian and Badenian) experiences a thickness increase against a SE dipping low-angle normal fault, quite common for the syn-rift succession in high-strain rift basins (e.g. Tari et al., 1992). This fault is interpreted here as a typical LANF and therefore it indicates large syn-rift extensional displacement in the study area. As it can be seen from the well-seismic correlation of the Mosonszolnok-1 well (Fig. 8.5) the syn-rift succession for this well, as is the case for the whole study area, is represented by Karpatian and Badenian packages. Especially the early part of the syn-rift, the Karpatian seismic package displays a strong tilt towards the fault plane (Fig. 8.5). The prominent tilt can be interpreted as evidence for syn-depositional growth. These packages form a depression, or "wedge", in the central part of the seismic segment, which is offset by two normal faults in the NW. In the well correlations shown in this section (Figs. 8.2, 8.4, 8.5 and 8.6) all the extensional faults displayed offset the pre- and syn-rift (Karpatian and Badenian) seismic reflector packages, however they usually do not offset the post-rift (Sarmatian and Pannonian) succession.

According Tari et al. (1999), the termination of the syn-rift period in the Pannonian Basin, is typically, but not categorically, marked by a Mid-Badenian unconformity. An example for such an unconformity in the study area can be observed in the Minihof-1 well-seismic correlation (Fig. 8.4). This unconformity is the most promiment in the northern part of the seismic segment, where it has an pronounced angular unconformity between the Badenian and Pannonian successions, and thus marks the end of the syn-rift period. The Badenian is interpreted on this seismic section as mostly missing in the Minihof-1 well which appears to be targeting the apex of a roll-over anticline.

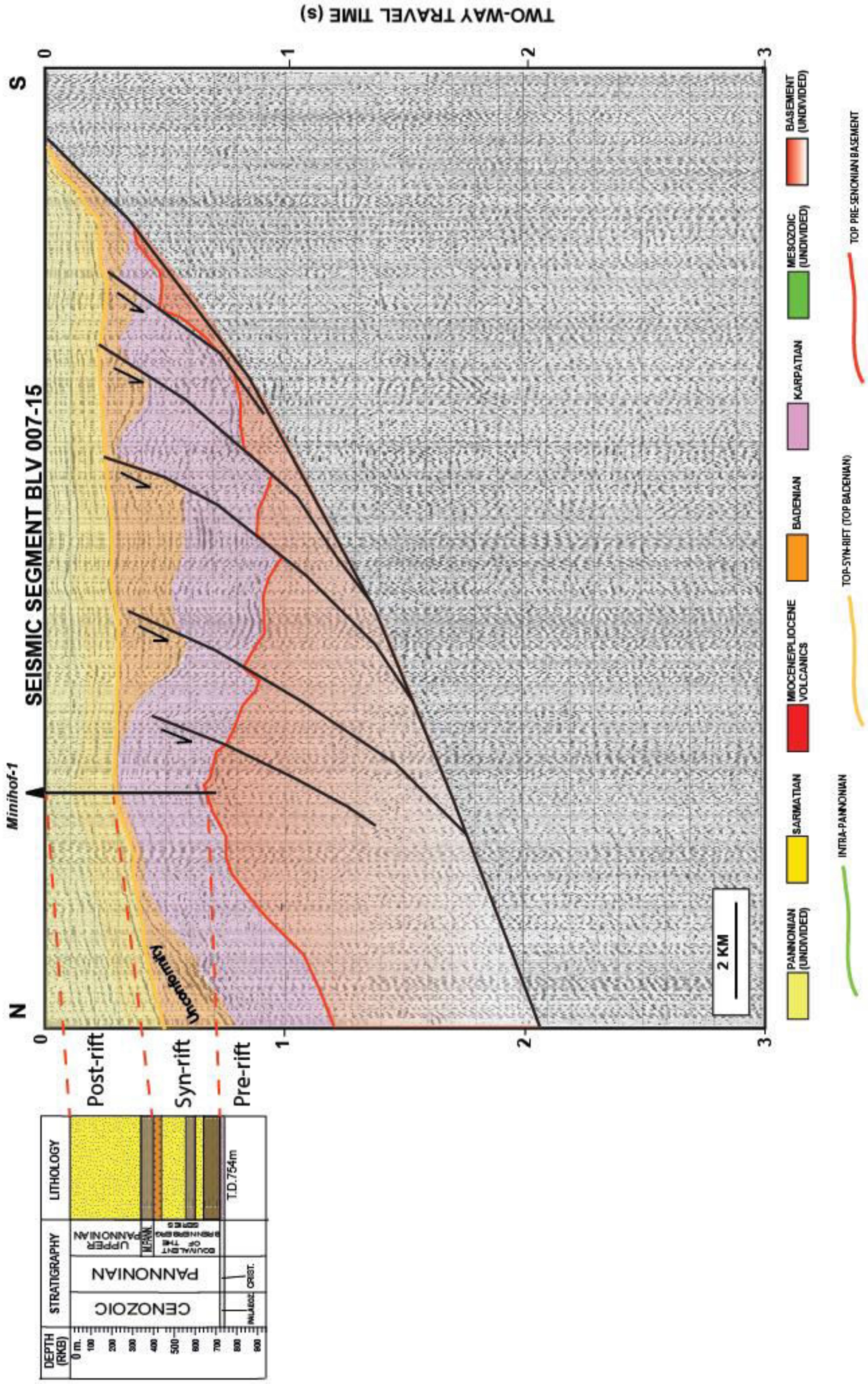

Figure 8.4. Seismic segment BLV 007-15 correlated with the borehole data of the well Minihof-1, which is located on this lines. The Minihof-1 well is located in the Oberpullendorf Basin, a sub-basin of the Pannonian Basin system in Burgenland.

8.3. Post-rift succession

The post-rift succession corresponds the deposition of sediments after rifting has occurred. In the Pannonian Basin the post-rift phase started during the late Middle Miocene (approximately 12 Ma) and is manifested by a regional unconformity between the (middle) Badenian and Sarmatian. The Sarmatian seems to seal most of the rift-related faults in the broader Pannonian Basin (e.g. Ebner and Sachsenhofer 1995; Horvath et al., 2006).

During the post-rift succession in the Pannonian Basin major sediment influx systems got established at the perimeter of the basin complex. According to Tari and Horvath (2006), in the various sub-basins the post-rift sediments tend to be very thick, compared to the relatively thin syn-rift sequence, and can even reach a thickness as much as 5 km. This thickness can be clearly observed in the well-seismic correlation for the Mosonszolnok-1 well (Fig. 8.5). The post-rift (Pannonian) package in the center of this seismic segment is approximately 2.2 s twt time thick, which, assuming an average 2000 m/s seismic velocity, translates to about 2,200 m.

Generally speaking, the post-rift succession in the study area (Sarmatian and Pannonian) is indeed thicker than the syn-rift succession (Karpatian and Badenian) (see Figs. 8.5 and 8.6), with only very few exceptions (Figs. 8.2 and 8.4). The regional unconformity that separates the syn-rift and post-rift successions also sealed most of the rift-related extensional faults with Upper Miocene (Sarmatian) and Pannonian strata. Thus, the post-rift sediments are largely undeformed and unfaulted, unlike in the neighboring Vienna Basin where there are lots of neotectonic features dissecting the post-rift basin fill (e.g. Strauss et al., 2006; Hinsch et al., 2005).

Furthermore, with the end of the syn-rift period, the marine depositional conditions in the Pannonian Basin almost came to an end as well. Traditionally, the Sarmatian stage was interpreted as a brackish transition between the marine Badenian syn-rift and the lacustrine Pannonian post-rift stages. However, Piller and Harzhauser (2005) showed that brackish water conditions could not have prevailed during the Sarmatian as foraminifera, molluscs, serpulids, bryozoans, dasycladacean and corallinacean algae as well as diatoms clearly indicate normal marine conditions for the entire Sarmatian.

Therefore the early post-rift period still had marine depositional environment during the Sarmatian and it is the later post-rift, the Pannonian stage, which marks the beginning of and lacustrine, marsh, fluvial and alluvial depositional conditions. Using the well-seismic correlations (Figs. 8.2, 8.4, 8.5 and 8.6), the main post-rift lithologies for the study area can be concluded. From them it can be observed that the post-rift succession in the study area consists mainly of clay, clay-marls, sand and conglomerates (Schönlaub et al., 2000). Thus, the study area displays the typical post-rift sediments, which can be found in the Pannonian Basin.

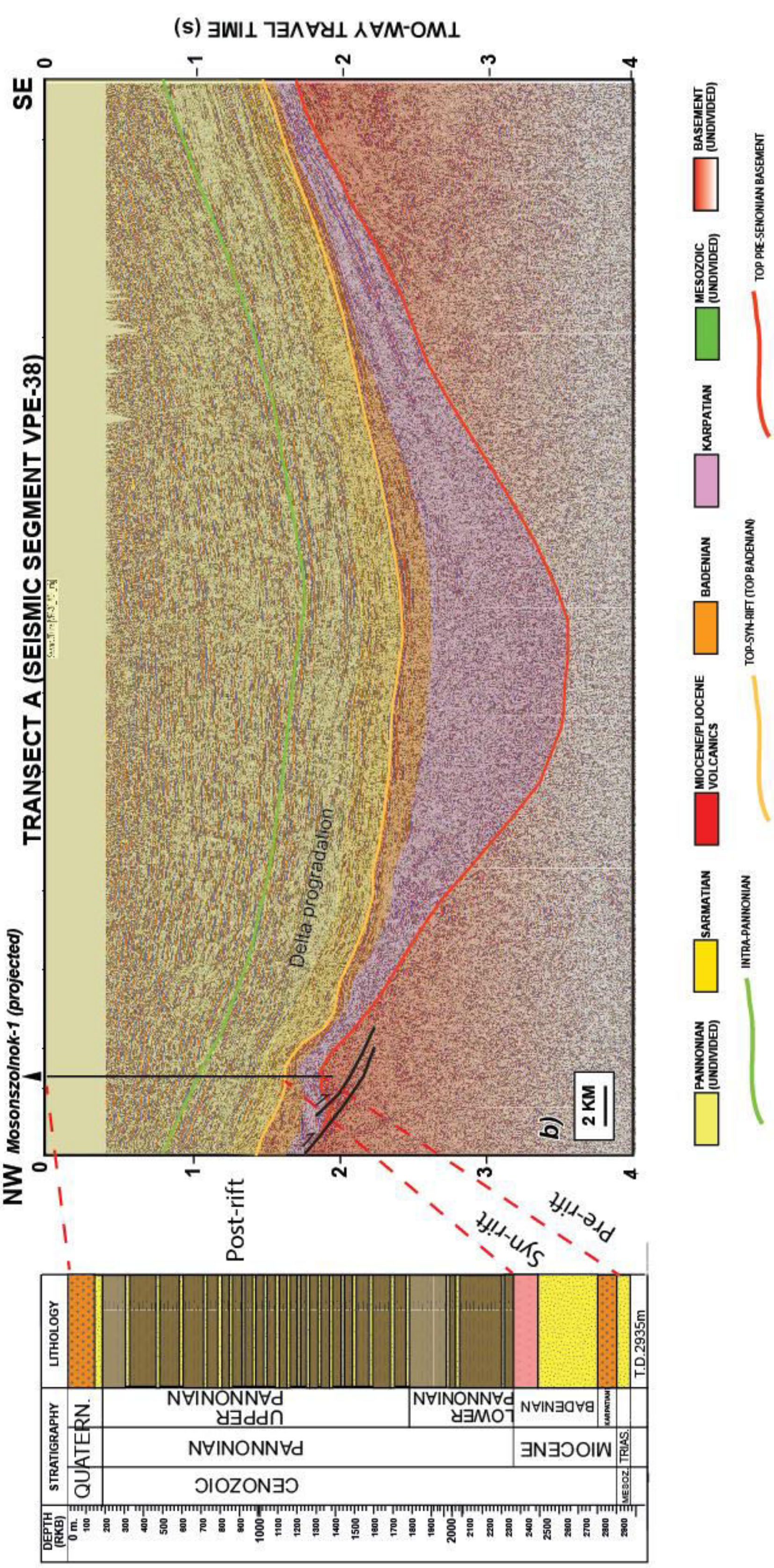

Figure 8.5. Seismic segment VPE-38 correlated with the borehole data of the well Mosonszolnok-1, which is projected on this line from 0.4 km NE. Mosonszolnok-1 is located in the Danube Basin in NW Hungary, a sub-basin of the Pannonian Basin system. Pannonian delta progradation sequence also shown

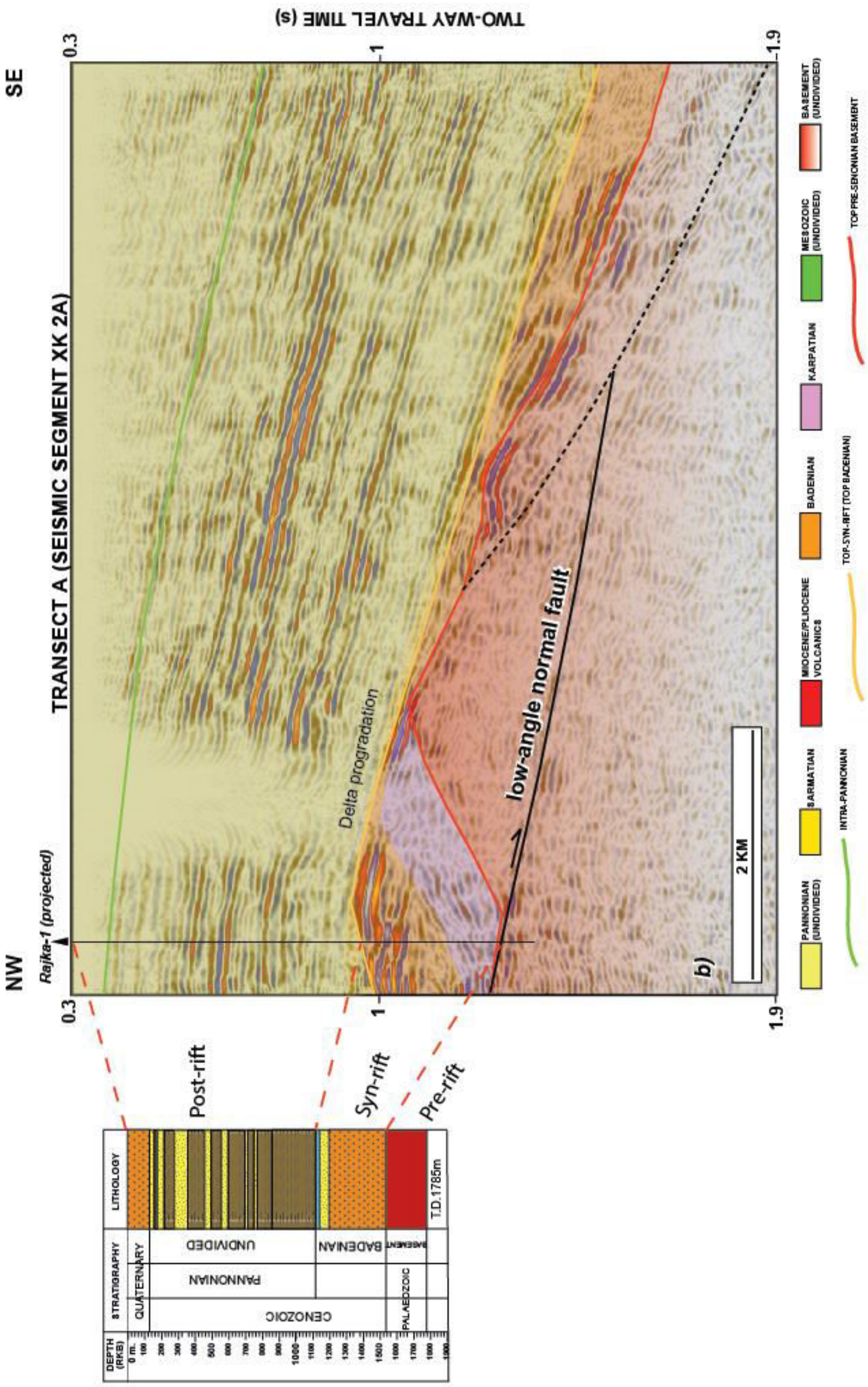

Figure 8.6. Seismic segment XK-2A correlated with the borehole data of the well Rajka-1, which is projected on this line. Rajka-1 is located in the Danube Basin in NW Hungary, a sub-basin of the Pannonian Basin system. Pannonian delta progradation sequence also shown.

The Sarmatian and Pannonian strata are clearly visible on the seismic data used in this study. The Quaternary, however, cannot be seen on the topmost 200-400 ms of the reflection seismic data used here due to the fact that it has not been considered important for hydrocarbon exploration. Therefore, while the Quaternary succession is recorded in the well summaries, the correlated seismic does not display it.

8.3.1. Pannonian delta progradation

Seismic data from the Hungarian part of the Pannonian Basin, combined with well-log interpretation and core-sample analysis, has shown that the basin filled up by a fluvial dominated delta system, which prograded from the basin margin towards its interior (e.g. Tari et al., 1992). This non-marine post-rift sedimentary fill of the Pannonian Basin can be clearly seen from the reflection seismic data showing delta progradation during Pannonian times. According to various authors (e.g. Tari et al, 1992; Vakarcs et al., 1994; Horvath and Cloetingh, 1996; Magyar et al., 2013; Sztano et al., 2013), these sequences are apparently associated with changes in the water level of the Pannonian Lake and are considered to be third-order sequences. This delta progradation sequence crosses the whole Pannonian Basin and can be clearly observed in the Hungarian part of the study area. In this section it can be observed in Figs. 8.5 and 8.6.

During Late Miocene times, the intra-Carpathian area became isolated within the Paratethys. This phenomenon occurred due to the uplift of the Alpine-Carpathian orogen and a major sea-level drop at the end of the Sarmatian (e.g. Magyar et al., 1999). Because of this change, a very large brackish mass of water was developed, which is now known as Lake Pannon (Magyar et al., 1999). At the beginning Lake Pannon was only a group of interconnected shallow lakes with several islands and peninsulas. However, due to post-rift subsidence coupled with an increase in the volume of the lake water due to precipitation, approximately 11.6-10 Ma ago, most of the islands were flooded (Sztano et al., 2013). Because of the uplift of adjacent mountain rangess, the Alps in particular, large amounts of sediments were derived, from about 10 Ma onwards, which were deposited in Lake Pannon. These sediments were transported by a large river systems towards the Lake Pannon, including the precursor of the Danube River. During the Late Miocene and Early Pliocene, the so called paleo-Danube, together with other rivers, filled the Pannonian Basin system with sediments, creating a very thick latest Neogene to Recent non-marine depositional sequence (Sztano et al., 2013; Magyar et al., 2013). Seismic studies have shown that the post-rift infill of the Pannonian Basin is characterised by advancing delta systems from the northwestern, northern and northeastern margins of the basin (e.g. Tari et al., 1992). Delta development during the Pannonian was subdivided into two stages; during the first stage, deltas prograded into a 800-900 m deep lake. During this first phase the rates of subsidence and sediments supply were very high. The second stage, however, was characterised by progradation into shallower water, of approximately 200-400 m depth. Finally, the rate of thermal subsidence was exceeded by the rate of sediment supply, which resulted in a complete infilling of the Pannonian Lake (Magyar et al., 2013). Using seismic and electro-facies patterns, the Pannonian Basin has been divided into basal transgressional, aggradational deep-water, progradational delta and aggradational alluvial sedimentary units (Vakarcs et al., 1994). For this seismic study the main interest within the Pannonian sequence is the spatial and temporal development of progradational deltas.

It is mainly believed that depositional sequences and system tracts are caused by short term changes in the rates of relative sea-level changes (Posamentier et al., 1988). Within the Pannonian Basin several depositional sequences, mainly type-1, meaning that the sea level fell below the boundary between shelf and slope, and system tracts, can be identified (Tari et al., 1992). The main unconformities which exist between these sequences are third-order sequence boundaries. Within the progradation of delta systems into the deep basin, a geometry similar to shelf margin settings can be observed. Furthermore, the lacustrine depositional sequences of the Pannonian Basin show similar stratal patterns to the marine ones (Vakaracs et al., 1994).

Seismic segment VPE-38 in NW Hungary, is located in the Danube Basin and the delta progradation of the Pannonian Basin can be observed quite well on it (Fig. 8.7). A phenomenon observed at large within the seismic data base, which is quite clearly seen in the VPE-38 line (Fig. 8.7), where the Mosonszolnok-1 well is projected, is the diachronous character of the delta progradation sequence observed during Pannonian times (Magyar et al., 2007; 2013).

Regional-scale delta system at the basin margin seems to have started during the late syn-rift stage (Late Badenian-Early Sarmatian) and has continued into the post-rift stage (Pannonian). The general trend of the relative sea-level can also be surmised from the blue stars showing the “shelf-break point”, meaning the boundary between shelf and slope. Whereas on the NW end of the seismic profile, a steady rise in relative sea-level can be observed (Fig. 8.7). Moving towards the SE, however, in the central part of the seismic section, a relative stagnation can be observed, marked by the sub-horizontal shelf-break points. In the SE end of the section another relative sea-level rise can be observed. At this point the shelf break points reach the intra-Pannonian reflector which was purposefully picked on top of the entire progradational sequence within the study area.

According to Vakarcs et al. (1994), the progradational sequence, as is the case with all the major depositional sequences in the Pannonian Basin, is a composite of a few third-order sequences. These sequences can be further subdivided into system tracts such as low-stand (LST), transgressive (TST) and highstand (HST) system tracts. In the case of line VPE-38, as it has been generally observed in the Pannonian Basin by Sztano et al. (2013) for progradational sequences, the progradational clinoforms are recognised by their toplap terminations at the shelf-margin break. Sztano et al. (2013) claimed, based on their study of the Mako Trough in SE Hungary, that aggradational clinoforms can be regarded as transgressive to early highstand system tracts, while progradational ones can be seen as mainly late highstand system tracts.

The main phenomenon to be observed on the delta progradation sequence of line VPE-38 however, is its strongly diachronous character (Magyar et al. 1999; 2007). In this seismic segment it can be observed that as one moves from the NW to the SE, the delta progradation sequence gets progressively younger and therefore nearer to the basin-wide intra-Pannonian marker mapped in this study. As it can be seen in Fig.8.7 the clinoforms in the northwestern part of the section have a distance of ca. 0.7 s twt and as the sequence moves to the SE the distance becomes almost 0s. In Fig. 8.8 an image from the Sztano et al. (2013) study has been shown as a comparison with the delta progradation sequence displayed in the VPE-38 seismic segment. As it can be seen from both figures, the delta progradation in the north Hungarian VPE-38 line and south Hungarian Mako Trough is almost identical and therefore, this comparison serves to illustrate how this progradation is basin-wide and can be observed regardless of where one might find themselves in the Pannonian Basin.

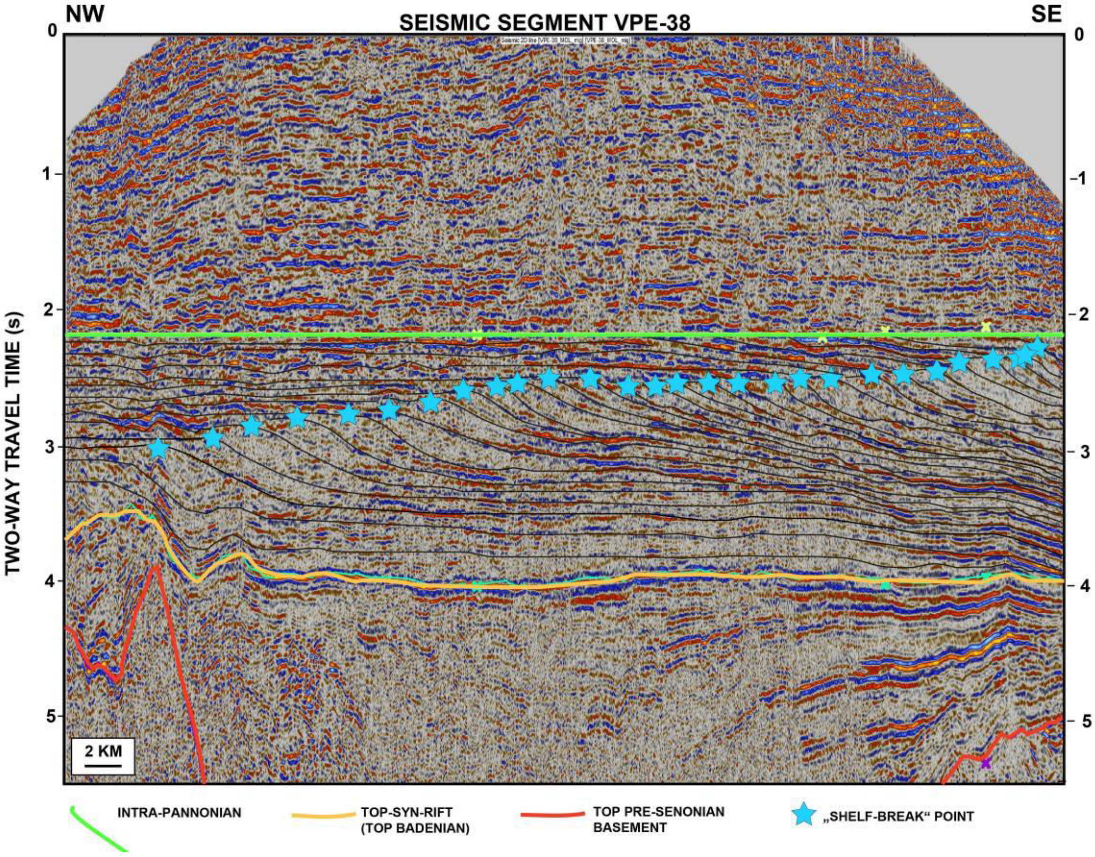

Figure 8.7. Line VPE-38 (with flattened intra-Pannonian reflector) showing the basement, Badenian and intra-Pannonian horizons. In black the progradational delta sequence is shown, with an oblique shape. Of notice is the distance of the clinoforms from the intra-Pannonian pick, where on the NW they have a maximum distance of 0.7s and moving to the SE the distance becomes almost 0s.
The blue star shows the so called "shelf-break point", namely the boundary between shelf and slope; the general trend observed is that, while moving to the SE, there has been a rise in sea level, which then became stagnant and which rose again at the closest point with the intra-Pannonian pick.

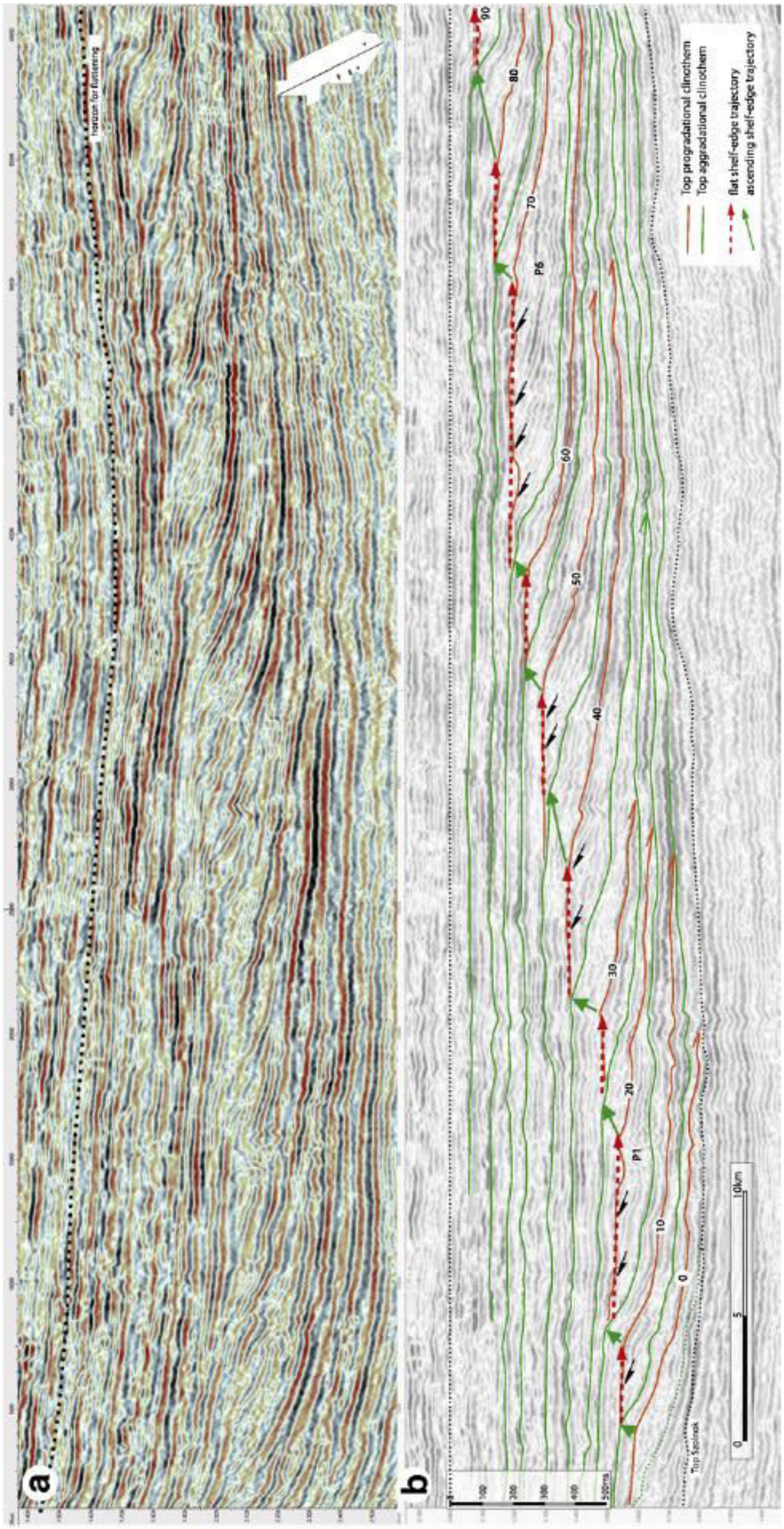

Figure 8.8. Seismic profile from Sztano et al. (2013) (a) approximately parallel with the direction of slope-progradation in the Makó Trough. The same profile is flattened (b) to a horizon representing a surface of ancient alluvial- to delta-plain. When compared to the VPE-38 line (Fig. 8.7) it can be clearly seen that the two profiles are very similar. This comparison between the two serves to illustrat the large-scale character of the delta progradation sequence since the VPE-38 line is located near Mosonszolnok in northern Hungary and this profile is located in the Mako Trough in south Hungary.

The identified third-order sequences and system tracts in the Pannonian Basin have as building blocks higher order depositional sequences. These higher order sequences are also seen as fourth-order sequences and believed to be associated with Milankovich-type fluctuations in the drainage areas of rivers flowing into the Pannonian Lake (Vakarcs et al., 1994). The origin of the third-order depositional sequences in the Pannonian Basin remains an open problem, however (Tari et al., 1992). According to more recent studies on the matter, it is believed that lake-level changes, and subsequently the reason for delta progradation, was caused due to climatic variations in general and particularly due to the amount of precipitation and evaporation (Sztano et al., 2013; Magyar et al, 2013). The sustained brackish water of Lake Pannon and the evolution of its biota suggest that this lake did not communicate with sea water and therefore, had no effective permanent outflow for large periods during the Late Miocene. However, several large rivers with drainage areas in the uplifting Alps and Carpathians discharged water into the lake basin. Discharge, which was ultimately controlled by precipitation, caused the lake-level rise. Evaporation on the other hand, caused a decrease in lake-level when it exceeded inflow and water precipitation. Therefore, it is believed that cyclic climatic fluctuations controlled lake-level changes and rate of slope advance (Sztano et al., 2013). Another factor that caused the change in lake-level is considered to be subsidence. In a lacustrine setting subsidence must not necessarily result in lake-level rise however, in a large lake such as Lake Pannon, where areas of varying subsidence coexist, even in the case of constant water volume the lake-level will fall over areas of low rate subsidence and it will rise over areas of high rate subsidence (Sztano et al., 2013; Magyar et al., 2013). However, while these studies give very valid reasons as to how the depositional sequences might have been formed, they are still not conclusive due to insufficient seismic coverage.

8.4. Basin inversion

The reactivation of pre-existing faults is the most obvious when the movement on normal faults is reversed defined as positive structural inversion (Harding, 1985). This phenomenon, together with its opposite, namely when reverse faults are reactivated as normal faults, is commonly referred to as structural inversion, in general (e.g. Fossen, 2010).

Positive basin inversion is a characteristic feature for many extensional basins, such as the Pannonian Basin, where the lithosphere went through a so-called late-phase tectonic compression (Ziegler and Cloetingh, 2004). Rheological changes at the lithosphere scale play a very important role in the mechanics of basin inversion. Inversion is often believed to interrupt post-rift basin subsidence, which is controlled by the cooling of the lithosphere. In Central Europe, the mechanics of basin inversion have been well documented with the Pannonian Basin undergoing late Neogene-Quaternary inversion, which occurred during the late stage collision between Africa and Europe (e.g. Jarosinski et al., 2011).

During Late Pliocene to Quaternary times, the evolution of the Pannonian Basin was characterised by tectonic reactivation, manifested by accelerated subsidence, uplift and young, neotectonic faulting (Horvath et al., 2006). This late stage structural process in the Pannonian Basin caused significant tectonic inversion of the basin, including the inversion of former normal faults and uplift in the western and eastern parts of the basin. The inversion also accelerated subsidence and renewed strike-slip faulting in the certain parts of the basin (Tari, 1994). The main evidence for this basin inversion is the contemporary stress data (Bada et al., 2007), present-day seismicity pattern, reflection seismic profiles and Quaternary subsidence history. This late stage inversion is also thought to be responsible for the partial exhumation and erosion of the Pannonian Basin fill (Tari et al., 1999; Horvath et al., 2006).

The inversion of the Pannonian Basin started a few millions years after the syn-rift period had ended (ca. 11-8 Ma), when a regional compressional stage started. During this time, uplift and erosion took place at certain parts of the basin system (Horvath et al., 2006). The compressional event began in the Late Pliocene (during the

Pannonian), which has continued until present times (approx. 4-0 Ma). In the young post-rift basin fill neotectonic compressional faults can be observed, especially in western Hungary. These features indicate that the inversion of the basin had already begun (e.g. Vakarcs et al., 1994). The local, neotectonic uplift of the basement resulted in the characteristic "inselberg" pattern of the present day Pannonian Basin. In other areas, where the uplifted basement did not reach the surface, unconformities between the Neogene and Quaternary strata were formed due to erosional truncation (Horvath et al., 2006). According to numerical and stress-field modelling results, the main cause for these compressional events is the ongoing Adriatic indentation (Bada et al., 2007). The stress field for the inversion in the Pannonian Basin is characterised by ENE-WSW to E-W compression (Fig. 8.9). In the central Pannonian area, NE-SW trending faults were reactivated as sinistral strike-slip faults (Huismans et al., 2002).

This change from a Middle Miocene extensional stress regime to a Late Miocene to Pliocene compression stress field (Fig. 8.9) resulted in a complete reorganization of the kinematics in the Alpine-Carpathian-Pannonian area (Peresson and Decker, 1996). The Late Miocene stress change in the Pannonian Basin played a very important role in the shift from syn-rift to post-rift subsidence. The change from tension to compression of the subsiding Pannonian basin system may have led to the noticeable post-rift subsidence, documented during Late Miocene times (Peresson and Decker, 1996). This subsidence is believed to have been led and modified by the stress-induced downward movement of the Pannonian lithosphere. The E-W compression of the Pannonian Basin continued for a time interval of approximately 3.5 Ma, between the Late Pannonian and Pliocene times. After the E-W compression came to an end in the Pliocene, a roughly N-S compressive stress field took its place. This N-S stress field is currently active in the Pannonian Basin (Peresson and Decker, 1996).

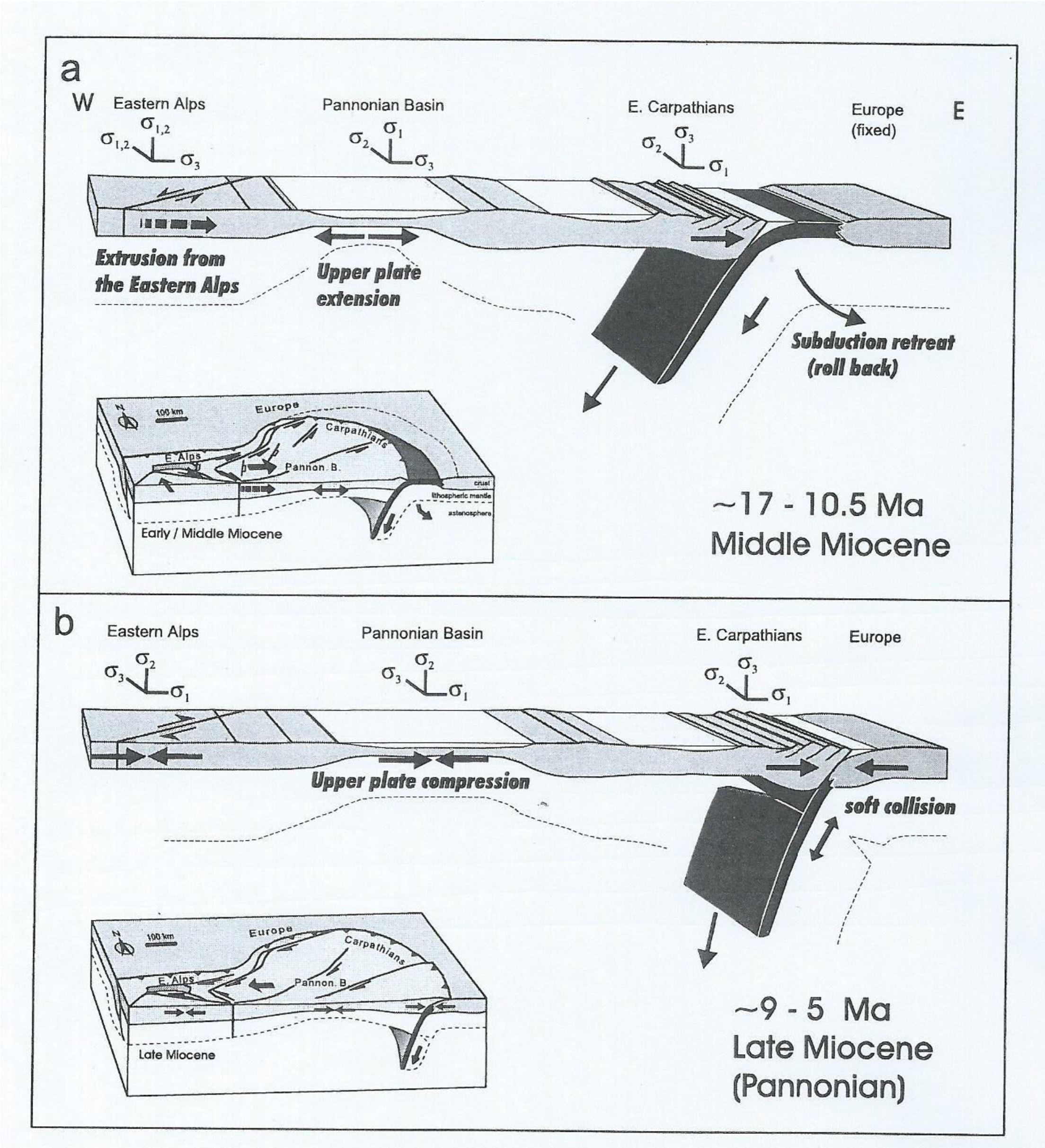

Figure 8.9. Schematic E-W directed lithospheric cross sections through the Alpine-Carpathian-Pannonian tectonic region (Peresson and Decker, 1996).

a) Situation during Middle Miocene times. Rifting of the Pannonian basin system occurred in a stress regime with generally E-W directed σ_3. During this time the Pannonian Basin was undergoing an extension period; this was also the time-frame when the syn-rift period occurred.
b) Situation during Late Miocene times. Subduction retreat in the Eastern Carpathians was locked after the entrance of thick buoyant continental crust into the subduction zone which terminated both, upper plate extension of the Pannonian area and lateral extrusion in the Eastern Alps (Peresson and Decker, 1996). During this time the Pannonian Basin underwent a E-W compressional phase, during which inversion occurred.

9. Discussion and further work

The Pannonian Basin system has been studied extensively for a number of years (e.g. Horvath et al., 2014). Many models have been created to explain its evolution and there are ongoing discussions regarding various structural elements in it. The present study aimed to constrain the subsurface of the NW Pannonian Basin system by using 2D reflection seismic and well data obtained from hydrocarbon exploration and other general purpose wells. Whereas the present work resolved some of the issues in the study area, there are still some open-ended problems that need fine-tuning. Therefore, some new objectives were defined here for future research.

Firstly, the seismic data, especially the seismic lines belonging to the Austrian part of the study area, are of relatively poor quality, mostly because of its vintage from the seventies and eighties. Furthermore, the Austrian seismic data set is comprised of seismic lines which had been scanned/vectorized and then loaded/georeferenced into the Petrel project for this study. Among many other shortcomings, the poor signal/noise ratio, the prevalent seismic multiples in the low-fold and not properly processed data sometimes made the seismic mapping quite challenging. For example, such a case was shown in Fig. 6.3. Furthermore, in almost all the seismic lines in the Hungarian part of the study area, the topmost part of the seismic data, typically the Quaternary, has not been processed since that particular stratigraphic sequence has not been considered for hydrocarbon exploration purposes. Thus, in order to achieve a better understanding of the study area in the NW Pannonian Basin system modern seismic lines should be used in the future, ideally, where the topmost part of the seismic data is also imaged. Also, future 3D seismic data sets acquired in the study area will make a big difference. This way, all the aforementioned problems could be avoided and the better quality seismic data would provide more information about the stratigraphy and structure of the study area.

Secondly, in Chapter 7, dealing with fault geometry and styles of deformation, a digital elevation model has been presented (Subchapter 7.2). This model integrated the geological information from the Rust 1:50K-scale geologic map and the sub-surface data from the adjacent Hungarian area, helped to illustrate how the seismic data from one part of the study area (Hungary) could help to understand the information about the subsurface of another part (Austria). However, for this section, only a limited amount of field work was done to double check the interpretation put forward in this work based on the surface geological and the DEM data. Therefore, for a more thorough analysis of this particular area with an outcropping basement footwall block near Jois in northern Burgenland would require the integration of detailed field observations with a properly processed and analysed DEM.

Thirdly, in order to constrain the subsurface of the study area many exploration wells (see Appendices) from OMV and from published literature (Körössy, 1987) were used. In the Hungarian part of the study area, also many wells have been drilled and the ones used for this study are all very deep. In the Austrian side, however, there is a relative scarcity of wells, with only 8 in the Burgenland area, all of which are relatively shallow, with the Tadten-1 well having the deepest total depth reached (2127 m). The relative lack of deep wells in the Austrian part makes it more difficult to age-date the different horizons, especially since the well tops present were not of particularly high quality. Therefore it is more difficult to precisely age-date the specific seismic packages. A more detailed stratigraphy could also lead to an improved regional correlation, which is challenging in an area of the scale of the NW Pannonian Basin system.

Fourthly, one of the striking features observed in the seismic data base of the study area, is the strongly diachronous character of the intra-Pannonian delta progradation sequence (e.g. Magyar et al., 1999; 2007). The main observation is that, as one moves from the NW to the SE, the delta progradation sequence gets progressively younger and therefore nearer to the basin-wide intra-Pannonian marker which was mapped in this study. While this feature has been described in Chapter 8, dealing with the tectonic evolution of the study area in part 8.1., and there have been addressed in a few papers in the past in the Pannonian Basin in the context of third-order sequences (e.g. Tari et al., 1992, Vakarcs et al., 1994), more work could still be done to describe the map-view pattern of delta progradation and the occasional large lateral facies shifts seen in the prograding sequence. According to Tari et al. (1992), one of the most commonly overlooked factors in the generation of depositional sequences is the rate of sediment supply. The source areas of sediments, which were deposited in the prograding deltas, were located in the surrounding areas, at that time in the uplifting

Alps and Carpathians. While Vakarcs et al. (1994) have given some ideas as to how these third-order sequences might have formed (e.g. as composites of higher order sequences driven by climate changes), at present few to no definitive statements can be made about the origin of the third-order depositional sequences, which have been observed in the non-marine post-rift sedimentary fill of the Pannonian Basin (Tari et al., 1992; Magyar et al., 2013). More recent studies have attempted to shed some light into the formation of these depositional sequences, such as Sztano et al. (2013) and Magyar et al. (2013). These authors argue that there are two main factors governing the changes in lake-level of the Pannon Lake. The first and main factor is considered to be the regional subsidence of the basin (Magyar et al., 2013). The second suggested factor is climate change, especially precipitation and evaporation, with precipitation causing the lake-level to rise and evaporation to decrease (Sztano et al., 2013). However, these studies still are inconclusive as there is insufficient seismic data coverage, or sometimes the seismic does exist but the features that need to be observed are not within range of the seismic resolution (Sztano et al. 2013; Magyar et al, 2013). Therefore, in order to better constrain the explanations as to how the third-order depositional sequences have formed, more sequence stratigraphic work needs to be done, regardless of the obvious uncertainties about the mechanism that has governed their development (Tari et al., 1992). Furthermore, a larger quantity of higher resolution, preferably 3D seismic reflection data sets should be used.

Another area, which warrants further work, or could be an interesting topic for further research, is the Pasztori paleo-volcano (e.g. Körössy, 1987; Schleder, 2001). In the Hungarian part of the study area, in the seismic segment VPA-87 (Fig. 6.12) the volcanic build-up of the Pasztori High is displayed. This volcanism masks the geometry of the underlying basement seismic package due to multiple lava flows and cinder cones (seismic segment VPA-94, Fig. 6.14). As only one public-domain study exist on the volcanism in this area (e.g. the MSc thesis of Schleder, 2001), further work could be done integrating the seismic data with that of the core descriptions of the several wells partially penetrating this large paleo-volcano. For this specific project only a few seismic lines displayed the volcanism seen in the Pasztori High therefore, additional, more target-oriented seismic interpretation could help to better understand the volcanism in the area, coupled with more volcanological and geochemical studies into the volcanics themselves. Furthermore, the detailed study of the Pasztori paleovolcano may provide additional information about the possibility of exploring for oil and gas in this particular area as some of the wells drilled here had gas shows in the volcanic sequence (Körössy, 1987).

Lastly, in Chapter 7, dealing with fault geometry and styles of deformation, the St. Margarethen fault in northern Burgenland has been presented (Figs. 7.2 and 7.3). This fault has been extensively researched and a lot of fieldwork has been done on the matter (e.g. Häusler et al., 2014; Spahic et al., 2011; Spahic et al., 2015). Häusler et al. (2014) claim that the St. Margarethen fault is a listric fault due to its concave upwards shape. Furthermore, directly on the eastern side of the master fault, a folding of the crystalline basement has been observed, which has been interpreted by Häusler et al. (2014) as a rollover anticline, formed due to reverse drag (Fig. 7.3). Rollover anticlines are usually one of the two main features, together with the flattening downwards of the steep upper part of the normal fault, that define a fault as listric (Grasemann et al., 2005; Spahic et al., 2011). However, Grasemann et al. (2005) argue that many mechanical models of planar faults show reverse drag therefore, it is not necessary for a fault to be listric for reverse drag to develop. Reverse drag can also develop due to heterogeneous deformation of fault slip. Spahic et al. (2011) believe that the St. Margarethen fault might just be a planar fault where the reverse drag may be explained through a slip gradient along a planar master fault (Fig. 7.5). While the seismic segment available for this study that contained the St. Margarethen (Fig. 7.4) fault show some similarities with the observations made by Häusler et al. (2014), it rather shows a steeply dipping, basement involved normal fault than a typical listric fault. According to Spahic et al. (2011) the St. Margarethen fault displays features of both models, with the preferred model being the planar fault model. The data set used by Häusler et al. (2014) has a relatively shallow penetration (e.g. 0.2s twt time) and therefore it could not be used to argue convincingly that the fault has a truly listric shape at depth. For the current study, only one seismic line captured the St. Margarethen fault (Fig. 7.4), thus even this data set has a limitation. Therefore, in order to form a better documented conclusion about the fault geometry, a newer study could be conducted, which uses more and deeper seismic lines that image the St. Margarethen fault better.

10. Conclusions

In the Pannonian Basin, about 90% of the pre-Cenozoic basement and approximately 60% of the pre-Middle Miocene strata are covered by the sedimentary fill of the Pannonian Basin. Due to this occurrence, sub-surface data is very important in studying the Pannonian Basin. The aim of this project was to study specifically the NW Pannonian Basin in Austria and Hungary, for the first time, using sub-surface and well data from both sides of the border zone.

- The seismic database for this study is composed by 2D single-channel and multi-channel seismic profiles. Through the use of well data and seismic interpretation, four major stratigraphic units have been mapped, namely the pre-Cenozoic (Austroalpine) basement, the Middle-Miocene (Karpatian and Badenian), the Late Miocene (Sarmatian) and the Pannonian packages.

- Using single-channel and multi-channel seismic images from Austria and Hungary, the tectonic history of the study area has been subdivided into three major structural stages. Thus, a pre-rift (pre-Miocene), syn-rift (Early to Mid-Miocene) and post-rift (Late Miocene to Quaternary) phase have been identified.

- Using three composite regional seismic transects created for this study, a better understanding of the NW Pannonian Basin in Austria and Hungary has been formulated. It has been observed that in general, the post-rift (Sarmatian and Pannonian) succession is thicker than the syn-rift (Karpatian and Badenian) strata (Fig. 6.10). The Sarmatian seismic package taken individually, however, is generally thicker in the basin margins, mainly in the Austrian part of the study area (Figs 6.7 and 6.8). On the other hand, the Sarmatian appears to be considerably thinner towards the central part of the Pannonian Basin, for example in the Danube Basin (Fig. 6.3).

- Within the Pannonian succession of the study area a delta progradation sequence has been observed (Fig. 8.7). This sequence is mainly observed in the Hungarian part of the study area therefore, but it is concluded here that the Pannonian delta progradation sequence is indeed present basinwide and can be observed anywhere in the Pannonian Basin if the resolution (or the quality) of the seismic data is sufficient (Fig. 6.7).

- The syn-rift succession in the Pannonian Basin started in the Early Miocene and is represented in the study area by siliciclastic Karpatian and mixed, i.e. siliciclastic and carbonate Badenian strata. In the Pasztori High area of NW Hungary, however, the syn-rift strata comprise lots of such as andesites and trachyandesites. During Badenian to Early Sarmatian times the Pasztori High experienced extensive volcanism documented by several wells drilled into it (e.g. Appendix E). For the first time, some volcanogenic features are interpreted on the vintage 2D seismic data, such several cinder cones (Fig. 6.14) located on the flank of a very large stratovolcano complex (Fig. 6.15).

- Due to its character as an extensional basin, the Pannonian Basin is characterized by various normal faults. These normal faults are either a) steeply dipping normal faults or b) low-angle normal faults (LANF). In this study many structural features in the NW Pannonian basin has been interpreted as bound by steeply dipping normal faults (e.g. Rust and the Hackelsberg/Junger Berg outcropping basement highs), (Figs. 7.4 and 7.12) and less frequently by LANFs, such as in the case of the Rajka and Rechnitz basement highs (Figs. 6.4 and 8.4). Moreover, the low-angle normal faults (LANF) often have seismic packages (Karpatian) tilting into their low angle fault plane (Figs. 6.3 and 6.4).

- As to the age of the normal faults, typically they offset the pre-rift (basement) and syn-rift (Karpatian and Badenian) successions, however they rarely offset the post-rift (Sarmatian and Pannonian) packages. In some cases observed on the seismic lines the tilting of the syn-rift strata into the low-angle fault plane provides clear evidence for syn-depositional growth. However, typically the syn-rift growth associated with the normal faults, expressed by the fanning of the seismic reflectors, is relatively subtle in the study area.

- In the Pannonian Basin the top syn-rift (or “break-up”) unconformity is typically mid-Badenian in age and marks the termination of the syn-rift period. Whereas seismically this unconformity typically is subtle in the seismic data set of this study (e.g. Fig. 6.21) but there are clear cases where the seismic data displays this unconformity as an angular one by the truncation of syn-rift strata below (Fig. 8.4).

- In the Pannonian Basin the subsurface observations are typically decoupled from surface observations, especially the signature of the structural and stratigraphic relationships in the present-day geomorphology. For the first time, an attempt was made to draw an analogue between seismically observed hogbacks (cuestas) and their corresponding surface equivalents seen on DEM images and on the field as well (e.g. Figs. 7.9 to 7.13). The limited amount of field observations in this study underlines the potential importance of future work in this regard.

- During Late Pliocene to Quaternary times the Pannonian Basin was affected by a tectonic reactivation. This basinwide positive inversion was characterized by accelerated uplift at the basin margins. Based on the regional seismic time-structure maps generated in this study by seismic interpretation, it has been observed that an arbitrary regional intra-Pannonian marker becomes progressively shallower towards the NW and eventually gets truncated at surface at the basin margin. Therefore, the missing intra-Pannonian marker in the Neusiedl Lake area is interpreted as the manifestation of considerable post-Pannonian erosion due to basin margin inversion and uplift. The magnitude of the missing section remains to be quantified by low-temperature geochronological tools.

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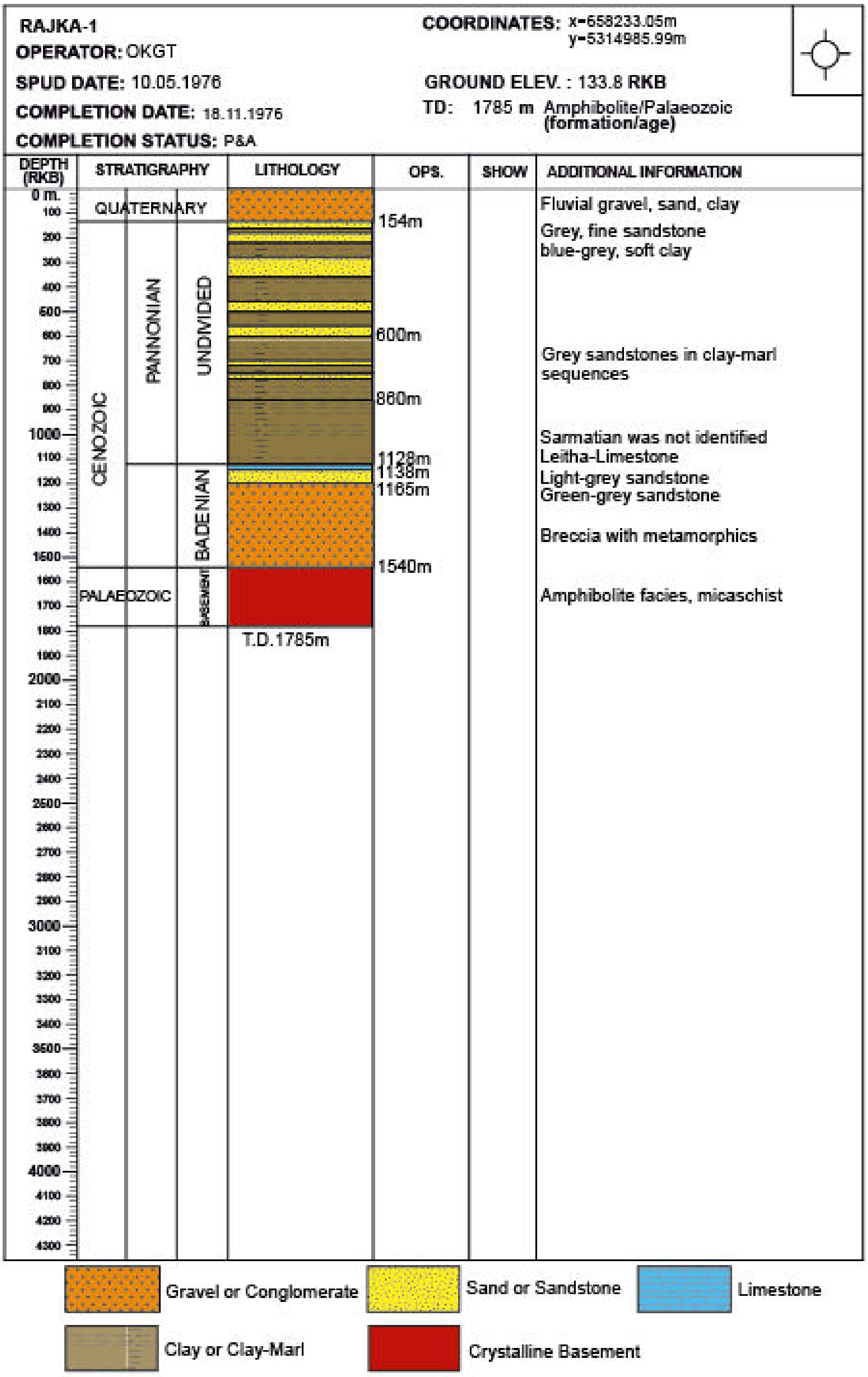
APPENDICES

APPENDIX A – Rajka-1



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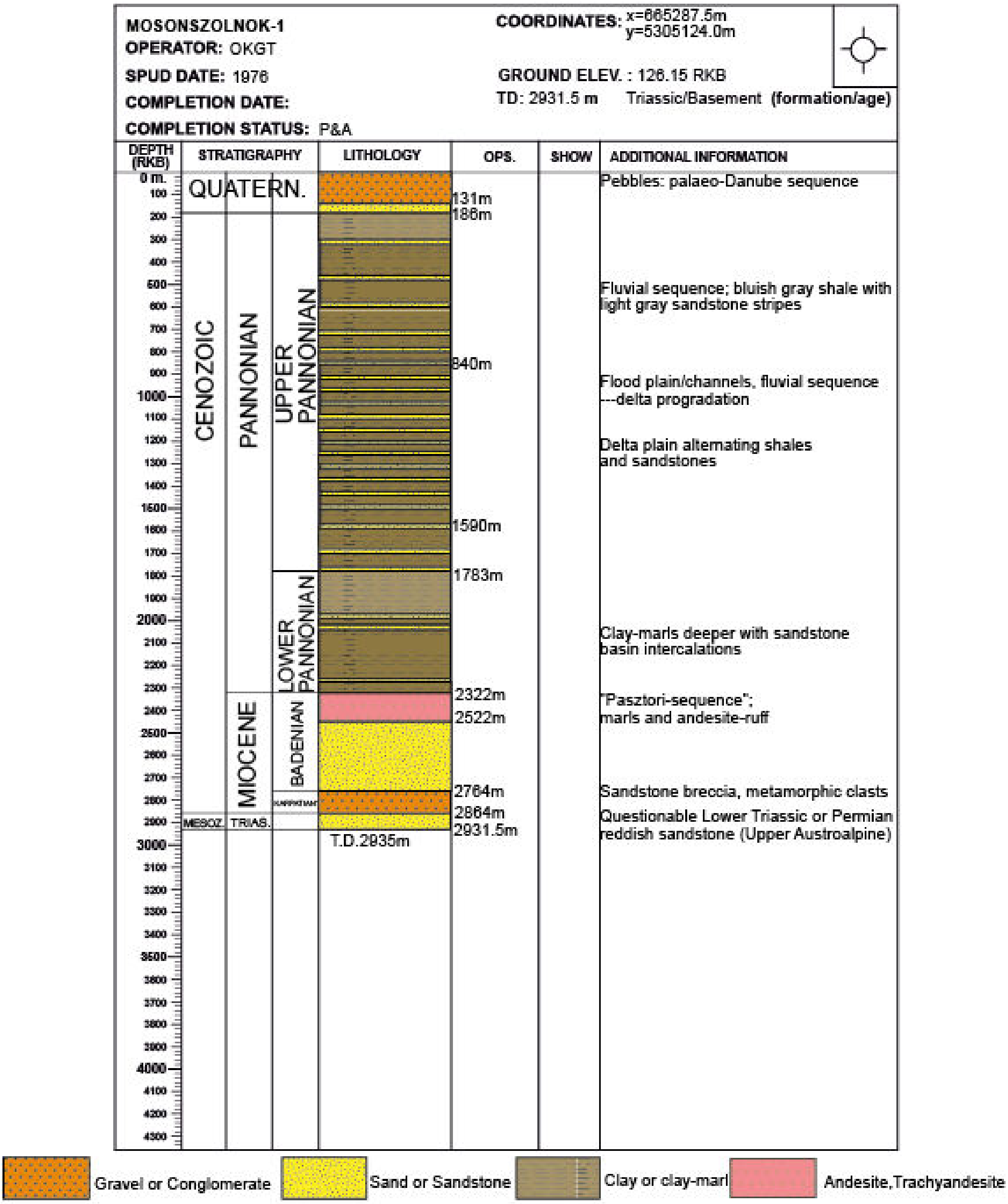
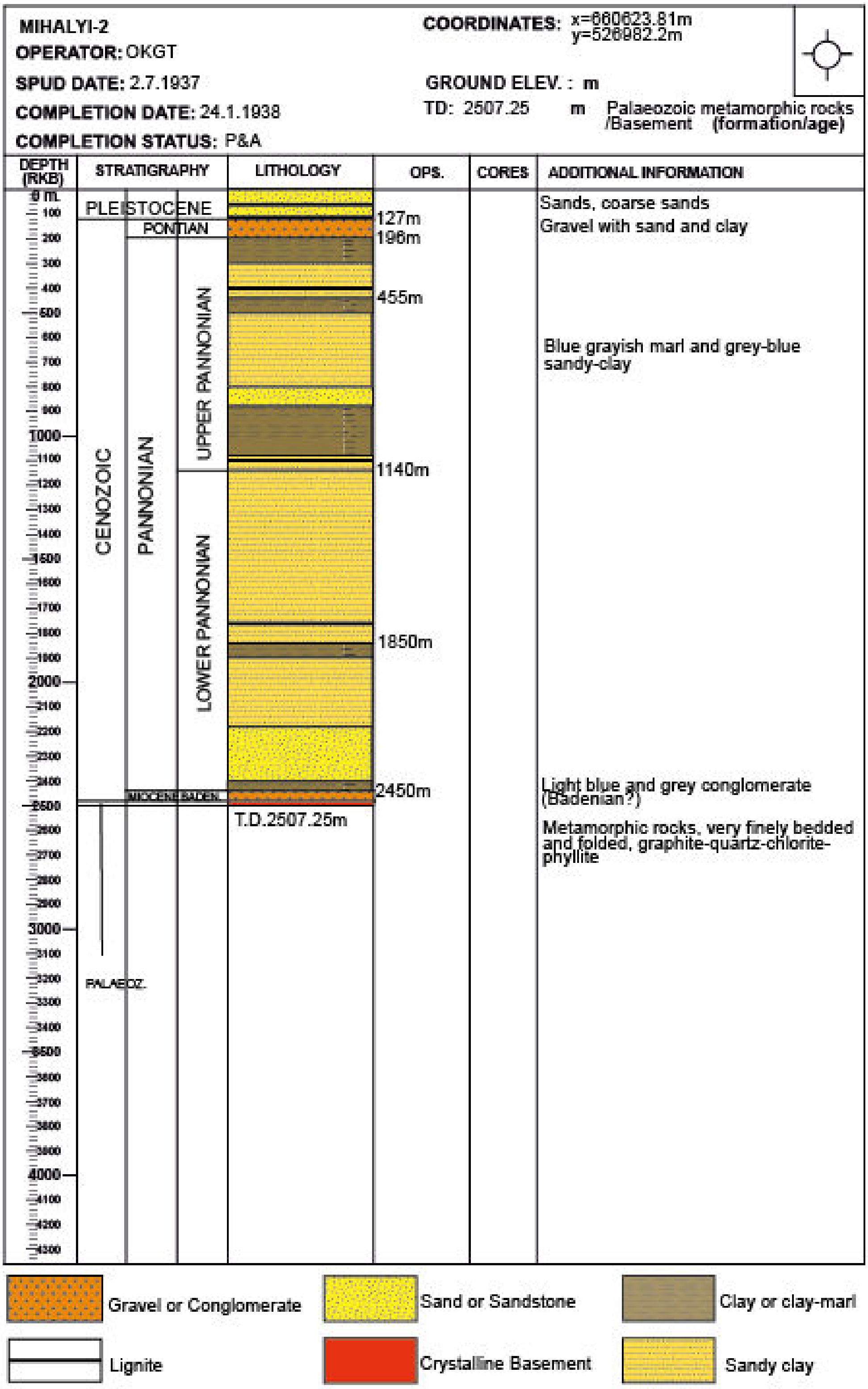


APPENDIX C – Mihalyi-2



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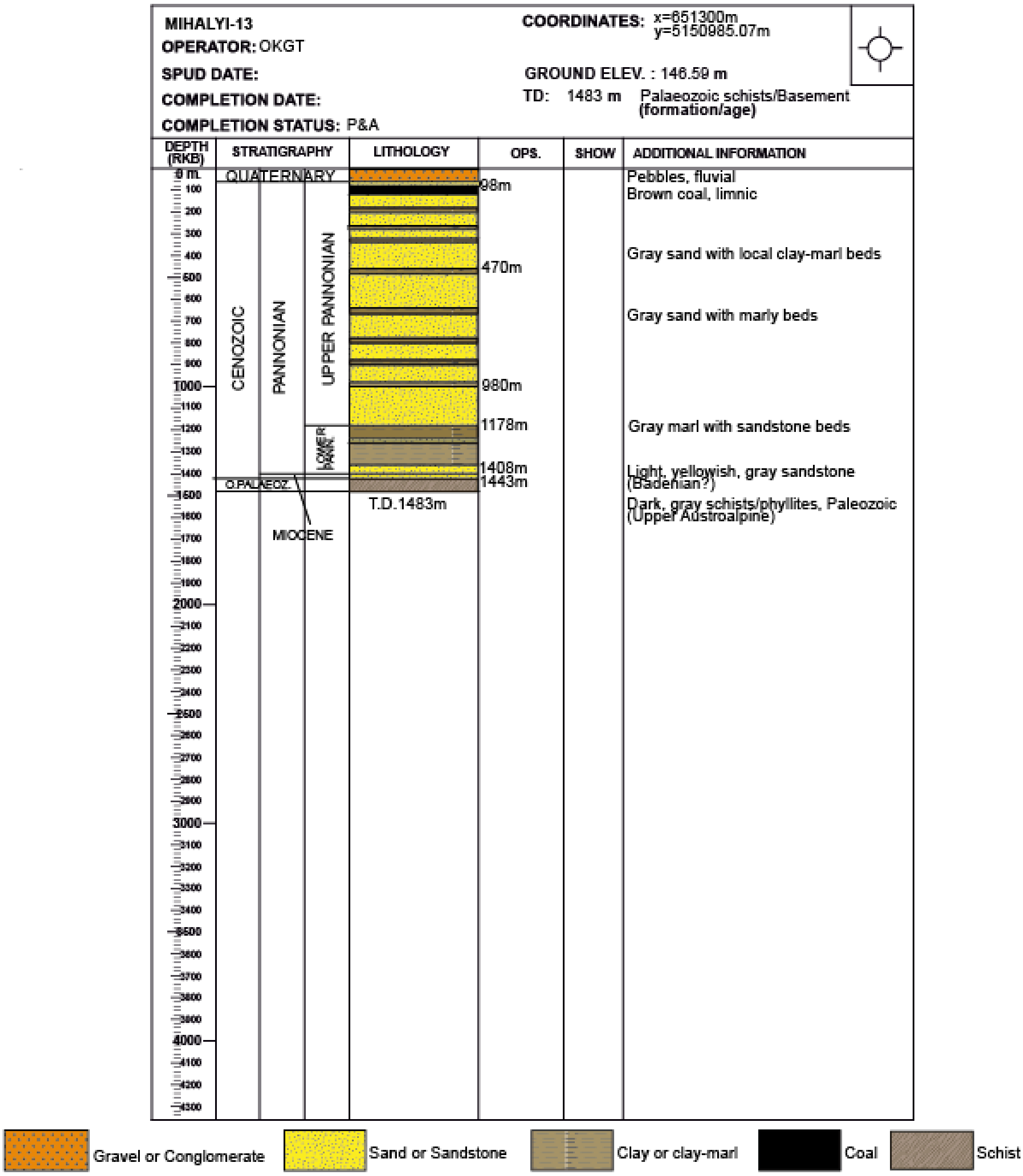
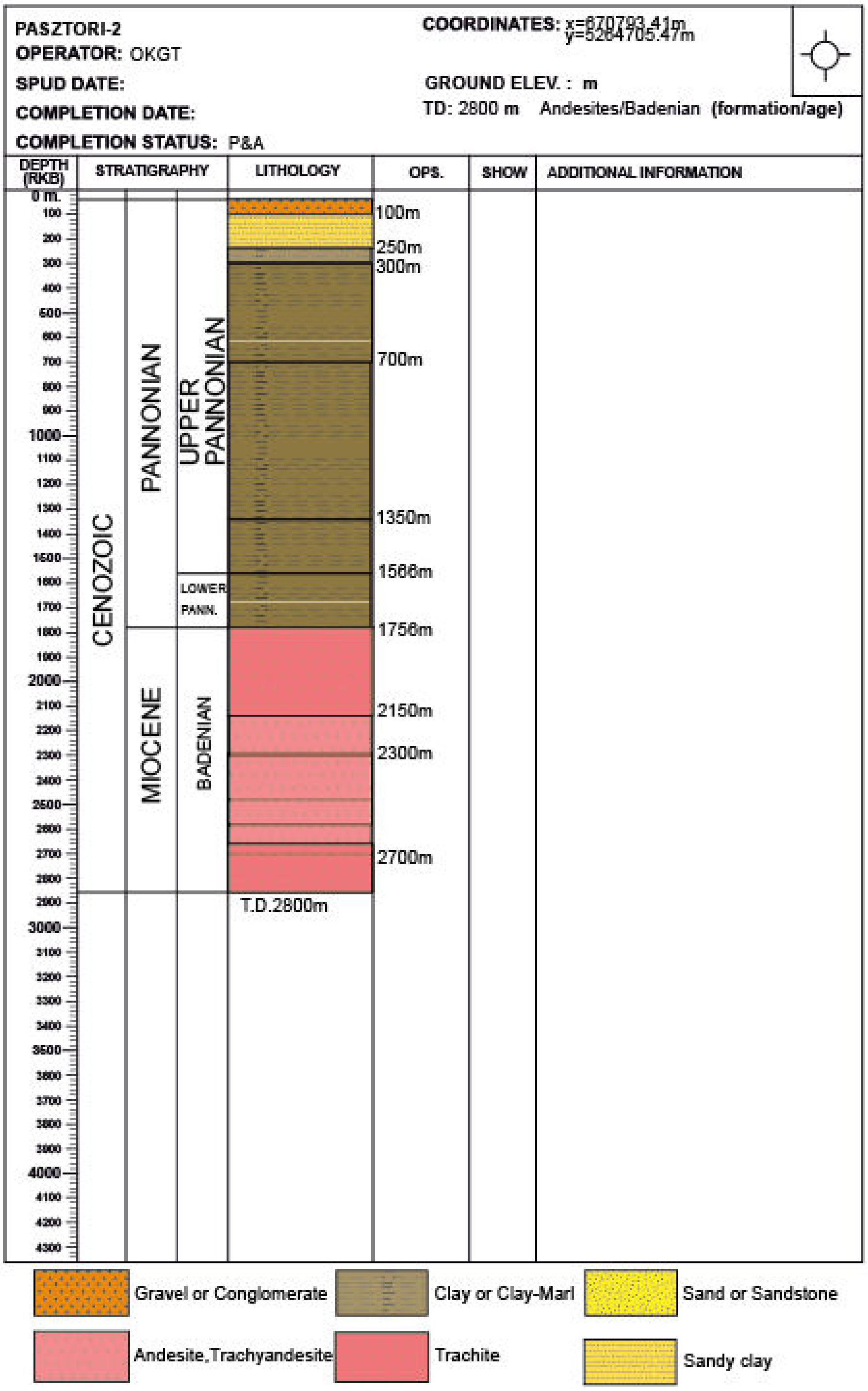
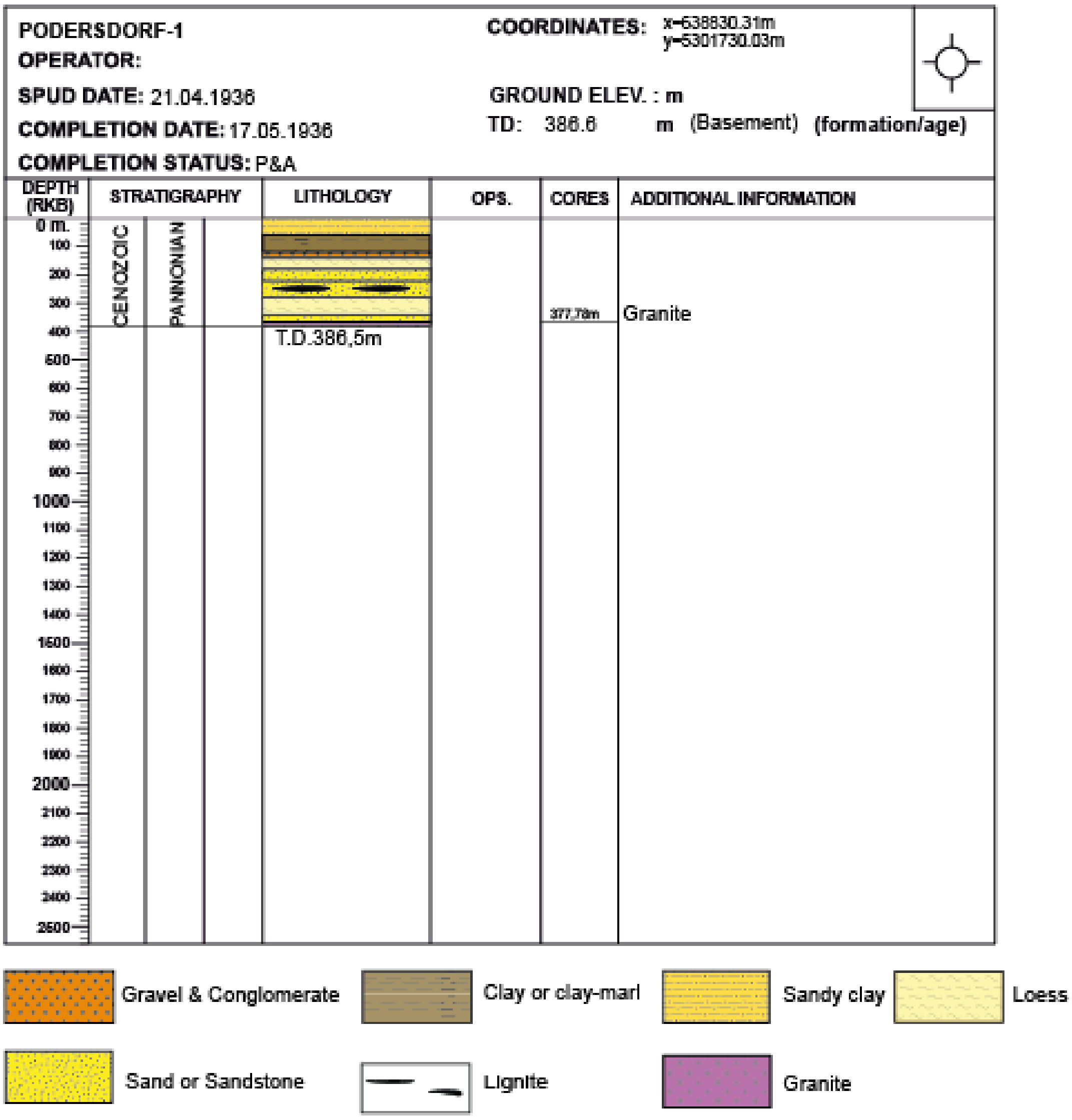


APPENDIX E – Pasztori-2



APPENDIX F – Podersdorf-1



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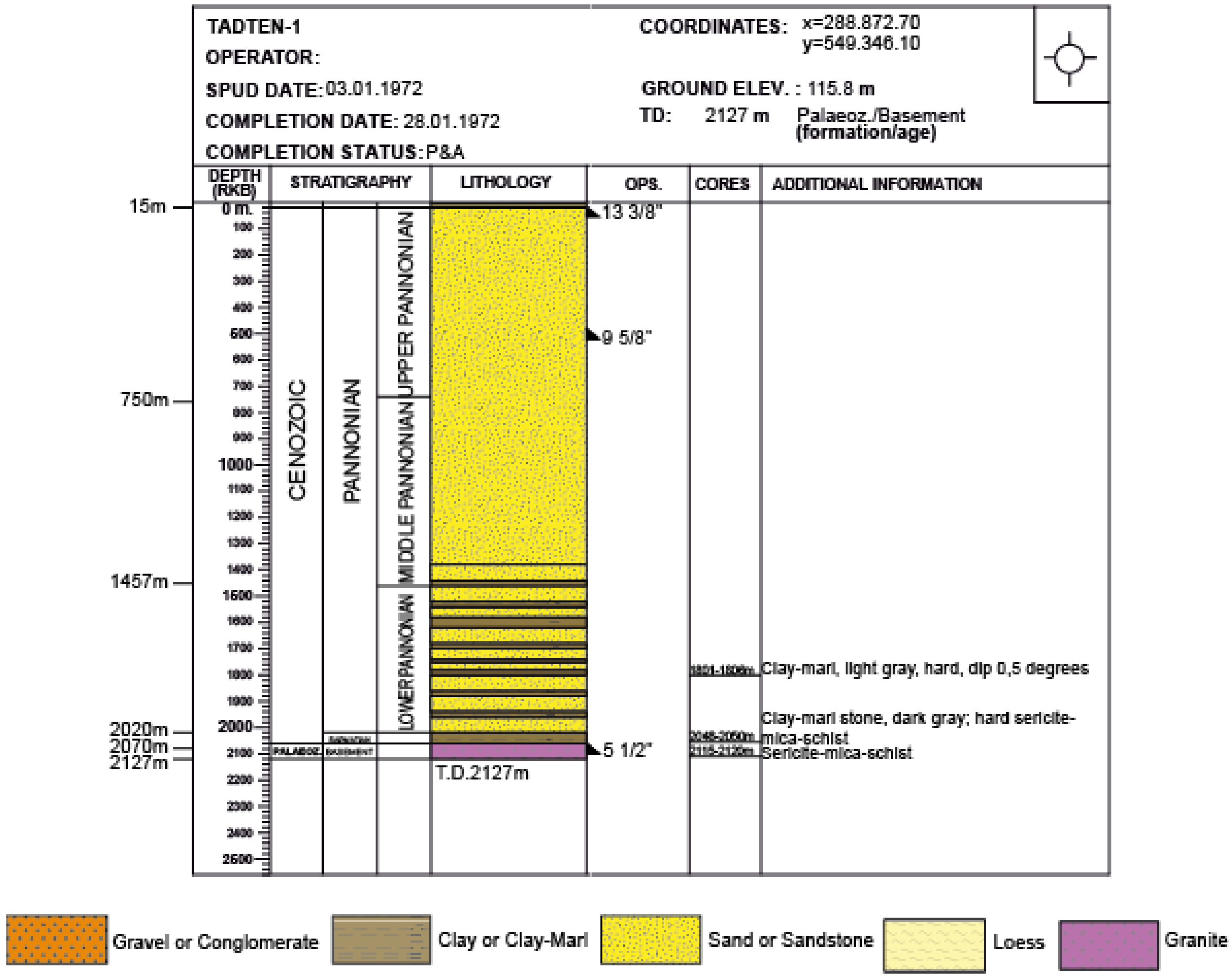

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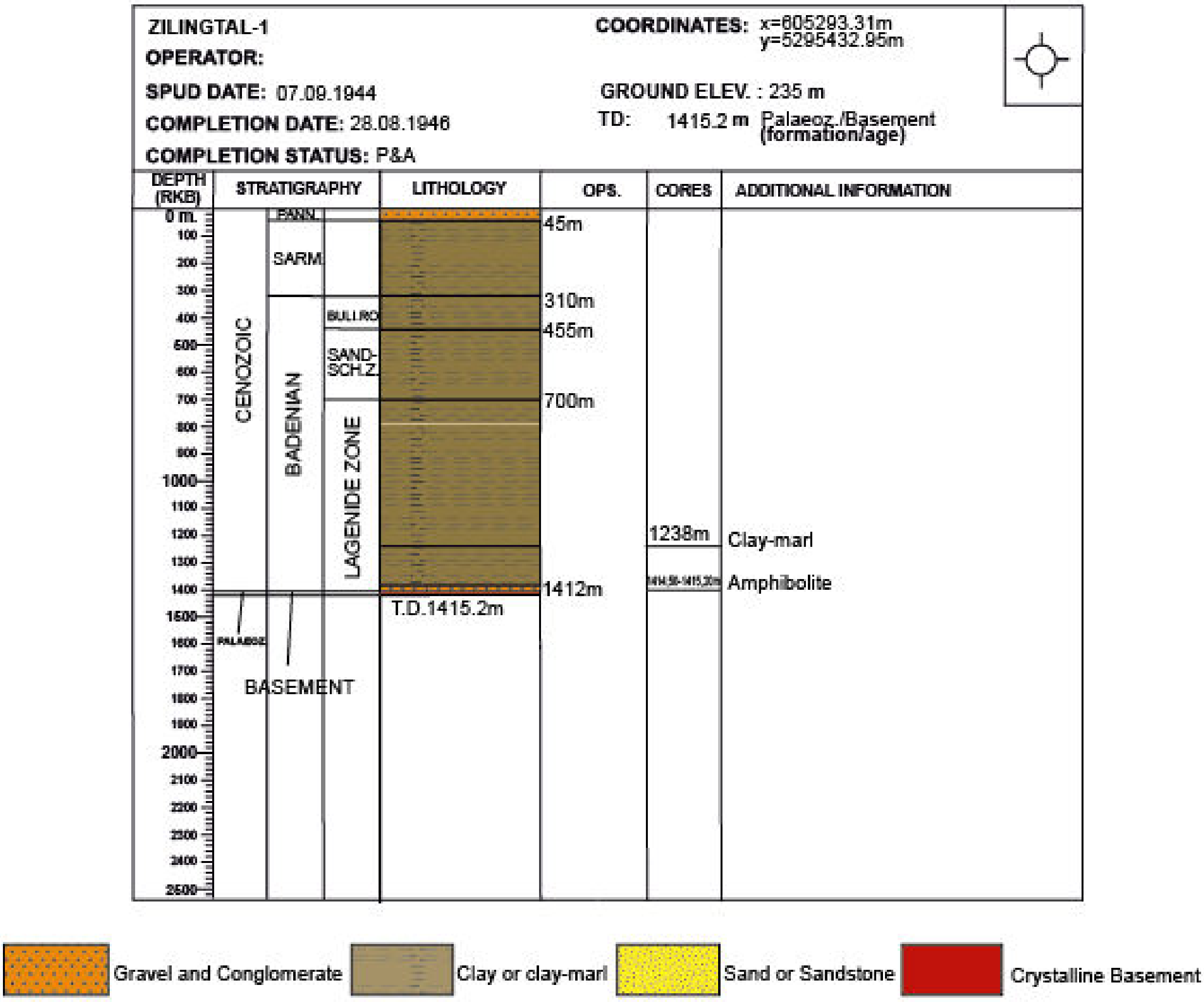
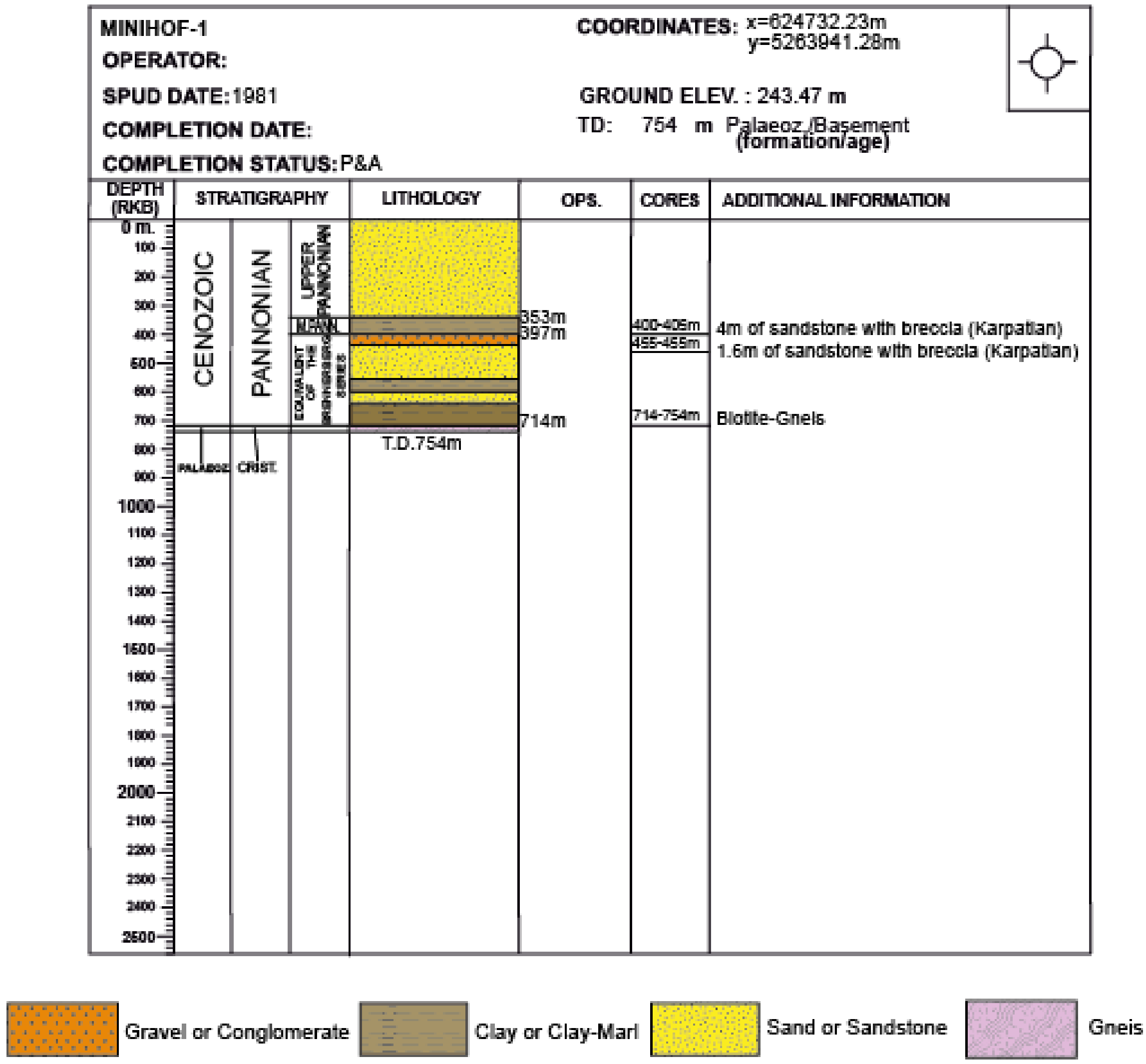
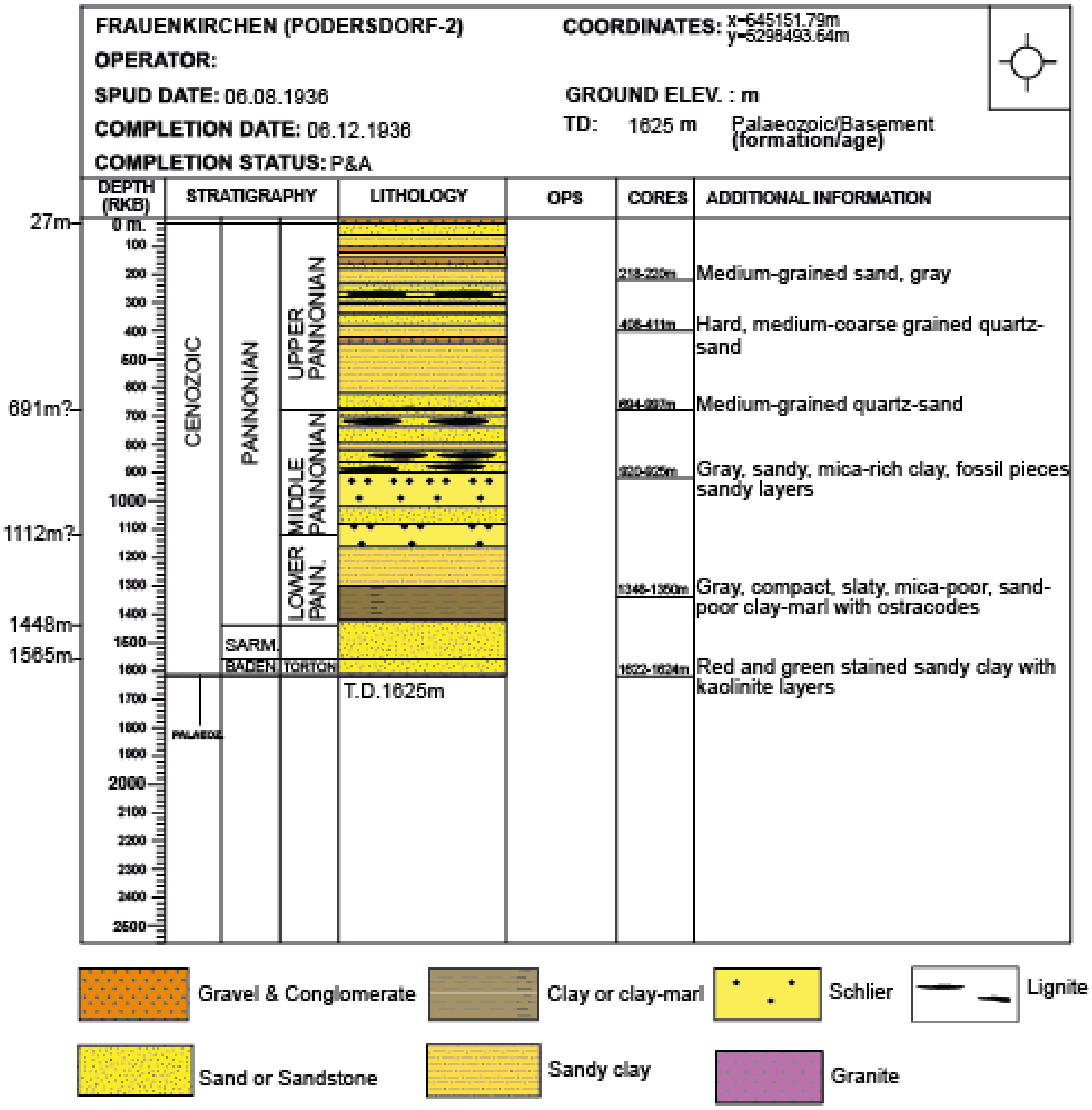


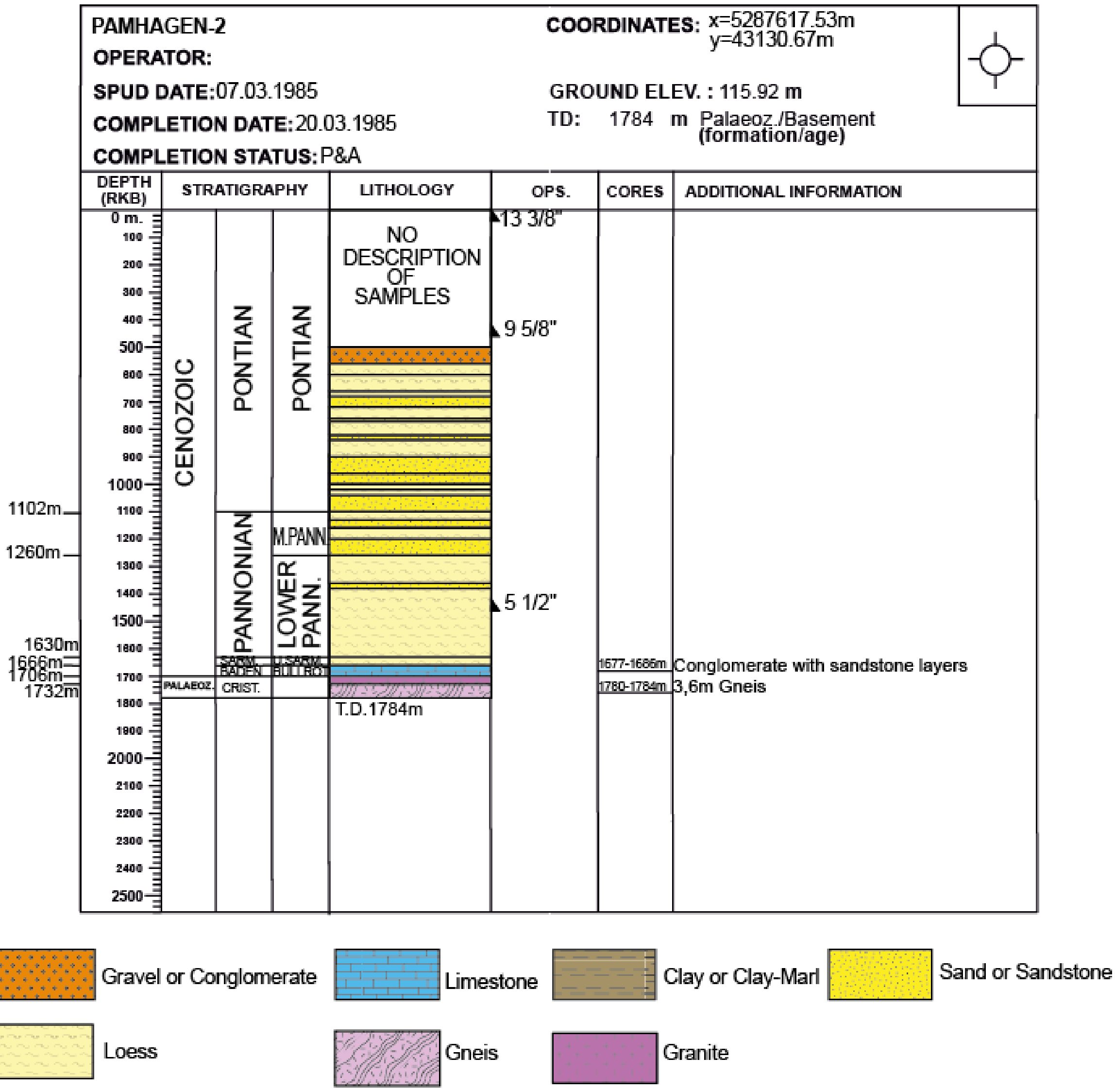
APPENDIX I – Minihof-1



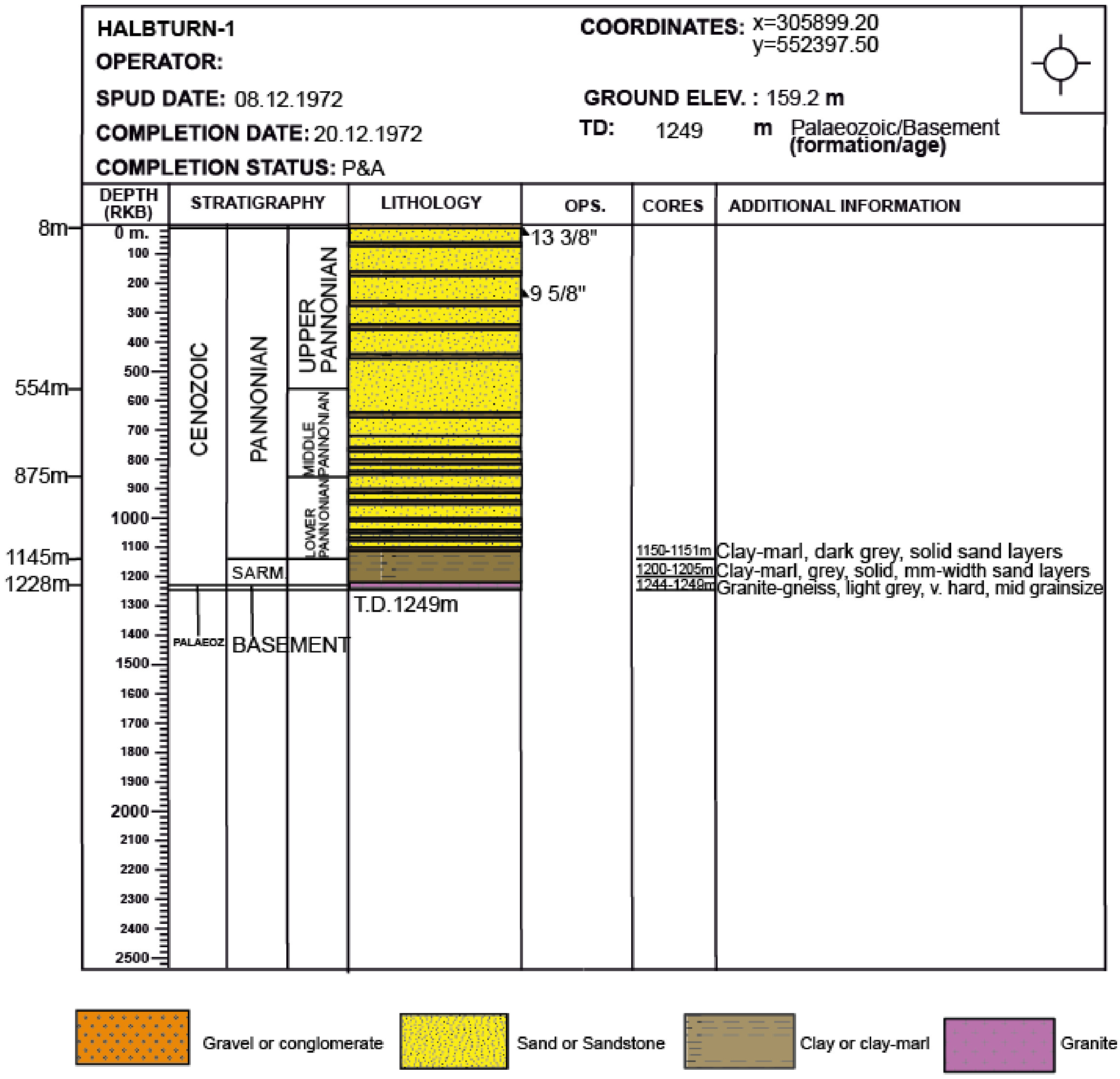
APPENDIX J – Podersdorf-2



APPENDIX K – Pamhagen-2



APPENDIX L – Halbturn-1



APPENDIX M – Halbtrun-2