Int J Earth Sci (Geol Rundsch) (2017) 106:1695–1721
DOI 10.1007/s00531-016-1383-3

ORIGINAL PAPER

Latest Pannonian and Quaternary evolution at the transition between Eastern Alps and Pannonian Basin: new insights from geophysical, sedimentological and geochronological data

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Received: 11 April 2015 / Accepted: 1 August 2016 / Published online: 30 August 2016

Abstract The transition zone between Eastern Alps and Pannonian Basin is a key area for the investigation of the interplay between regional uplift, local tectonic subsidence and depositional environment. Our study area, the western margin of the Little Hungarian Plain, is characterized by gentle hills, plateaus and depressions, of which several are filled by lakes—including one of Austria's largest and shallowest lakes, Lake Neusiedl. Geological investigation is hampered by the scarcity of outcrops, and thus direct observation of sedimentological or structural features is difficult. Despite a long research history in the area, a consistent landscape evolution model considering all relevant constraints is lacking so far. In this study, we apply multidisciplinary methods to decipher the complex tectonic and fluvial depositional evolution of the region. Local data from shallow-lake drilling and seismic investigation are combined with regional data from industrial seismics and core data to gain new insights into the latest Pannonian (Late Miocene) and Quaternary evolution. Shallow-lake seismic data show the erosionally truncated Pannonian sediments dipping and thickening toward southeast, toward the modern depocenter of the Little Hungarian Plain. Overlying Quaternary fluvial sediments show a very similar thickening trend except for the area on the plateau north of the lake indicating ongoing subsidence in major parts of the basin. Drill cores from locations along the lake seismic lines were analyzed concerning their age, mineralogy and heavy minerals and compared with outcrop samples from the surrounding plains and the plateau to derive indications on sediment provenance. A key observation is the apparent lack of a significant gravel layer on top of the tilted Pannonian sediments beneath Lake Neusiedl. Small-scale faults can be observed in the lake seismic sections along with key sedimentary features. Significant differences of the current elevation of the top Pannonian between the surrounding plains and the plateau indicate post-Pannonian normal faulting, which is a key process in shaping the present-day morphology of the region. Luminescence ages of samples from the Quaternary fluvial gravels on top of the Pannonian sediments are a significantly higher (>300 ka) compared to the gravels in the plain (102 ± 11 and 76 ± 8 ka), suggesting ongoing tectonic subsidence.

Keywords Upper Pannonian sediments · Quaternary structural evolution · Pannonian Basin · Neusiedler See · Shallow-lake seismics · Lake drilling · IRSL dating · Provenance

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Introduction

The transition between the Eastern Alps and the Pannonian Basin (Fig. 1) forms a complex deformation zone that has been active since the Early Miocene (Horváth 1993; Tari 1994; Decker and Peresson 1996; Szafián et al. 1999; Fodor et al. 2005; Fodor 2006; Kováč et al. 2006; Bada et al. 2007). The tectonic processes in this area result from the continental collision of the Adriatic and Eurasian Plates (Horváth et al. 2006) and are dominated by the lateral escape of crustal blocks (Ratschbacher et al. 1989; Linzer et al. 2002) and extensional collapse (Ratschbacher et al. 1991). Subduction retreat beneath the Carpathian mountain range, which acted as a weak lateral boundary, facilitated lateral escape and extension (Ratschbacher et al. 1989). In this tectonic setting, the Danube Basin (Fig. 1) formed as a back-arc basin along low-angle normal faults in the Early Miocene (Tari 1994, 1996; Kováč et al. 2011).

Here, we focus on the Late Miocene (latest Pannonian sensu Rögl 1998) to Quaternary (Fig. 2) evolution of the southern Danube Basin, also referred to as the Little Hungarian Plain (Tari 1994). Our study area comprises the following regions (Fig. 1): (1) Lake Neusiedl, Austria's largest lake; (2) the Hanság area, a historical continuation of Lake Neusiedl to the southeast; (3) the Seewinkel Plain located to the east of the lake; (4) the Parndorf Plateau, an elevated area to the northeast of the lake; and (5) the Leitha Mountains and Rust Hills to the northwest and west of the lake.

While the paleo-environments of the adjacent Vienna Basin (Fig. 1) (e.g., Harzhauser and Tempfer 2004) and the northern Danube Basin (e.g., Kováč et al. 2006) have been reconstructed for specific time spans, similar detailed work is lacking for the study area so far.

The aim of this study is to fill this gap and to present a consistent landscape evolution model for the Late Miocene and Quaternary period of the study area based on the integration of geomorphological, geophysical,

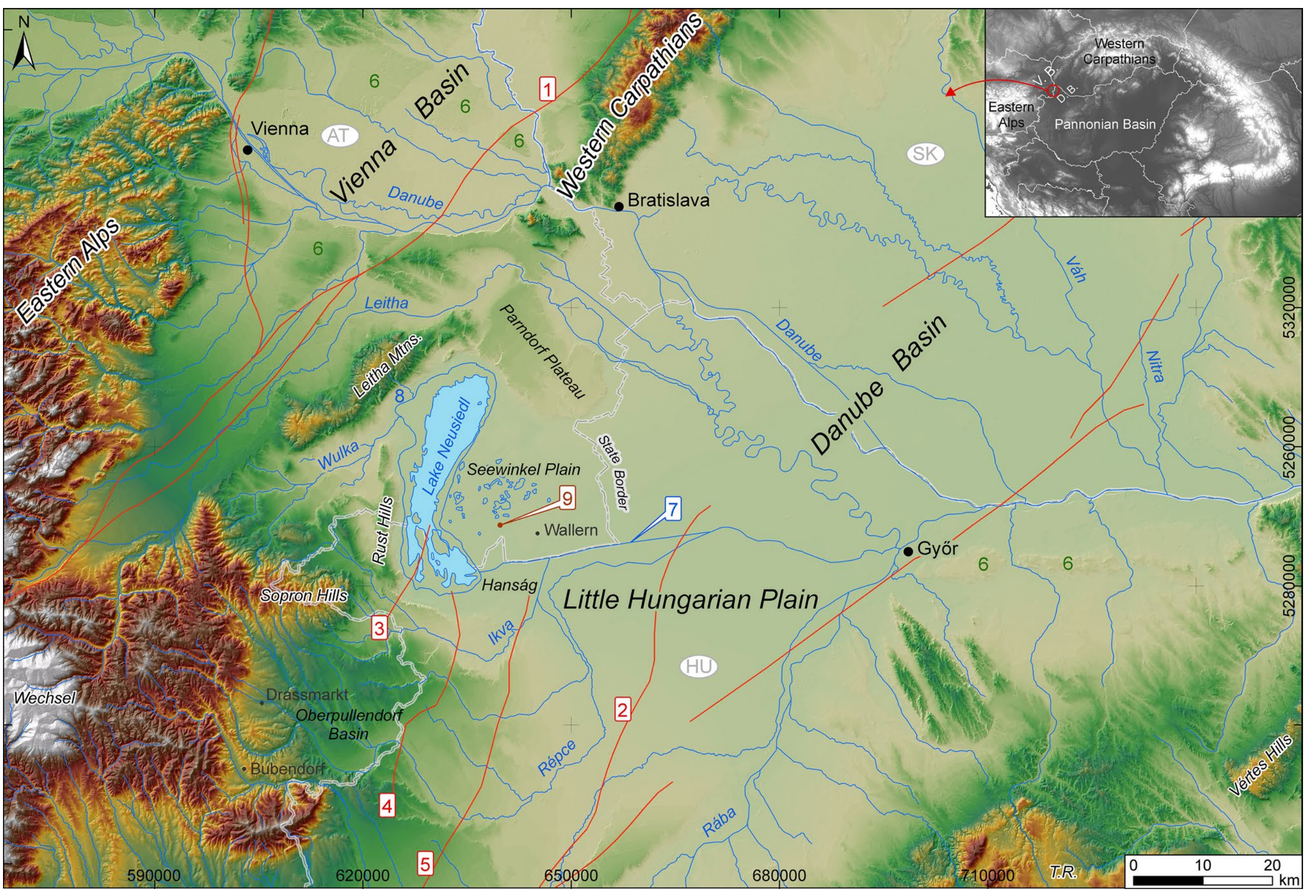


Fig. 1 Location of the study area in the transition zone between Eastern Alps and Western Carpathians. Note the distinct shape of the Parndorf Plateau and its location relative to Lake Neusiedl and the Seewinkel Plain (background: SRTM digital elevation model; coordinate grid: UTM 33 N). *T.R.* Transdanubian Range, *1* Vienna Basin transfer fault, *2* Rába Fault, *3* Fertő Fault, *4* Ikva Fault, *5* Répce Fault, *6* river terraces with elevated margins, *7* artificial drainage channel (Einser-Kanal or Hansági főcsatorna), *8* Angerbach rivulet, *9* deepest topographic point of Austria (Huber-Bachmann et al. 2012)

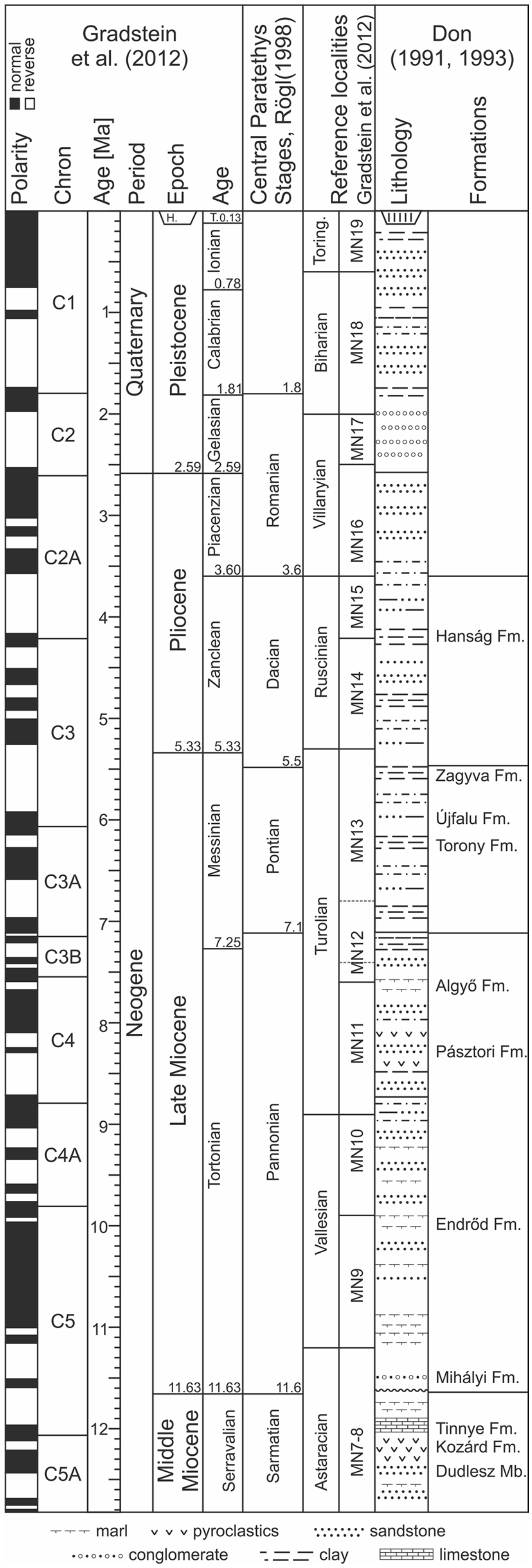


Fig. 2 Stratigraphic table summarizing the absolute ages and chronostratigraphic terminology used in this study along with the names and lithology of characteristic formations of the study area (Gradstein et al. 2012; Rögl 1998; Don 1991, 1993). The age of the Sarmatian–Pannonian boundary is taken from Vasiliev et al. (2010)

geochronological, structural and sedimentological data. We address the origin and age of the sediments of specific geomorphological units (e.g., Parndorf Plateau, Seewinkel Plain), examine the geological processes controlling the modern sediment pattern and the formation of Lake Neusiedl and discuss the timing of deposition and deformation of the main sedimentological units in the study area.

Geodynamic setting

The western margin of the Little Hungarian Plain (Fig. 1) is still affected by the most recent major phase in the evolution of the Pannonian Basin system, the ongoing compression that started in the latest Pliocene and triggered further subsidence in the central part of the basin and uplift at its flanks (Horváth 1995; Horváth and Cloetingh 1996; Decker and Peresson 1996; Wagner et al. 2010), dividing the basin into elevated areas and depressions (Horváth and Cloetingh 1996; Gábris and Nádor 2007; Kovác et al. 2011; Minár et al. 2011). Prior to this compressional event, a first, post-Sarmatian (Late Miocene, i.e., younger than 11.6 Ma, Harzhauser and Piller 2004; Vasiliev et al. 2010) basin inversion phase affected the region, resulting in the erosion of parts of the Sarmatian and Lower Pannonian sediments (Horváth 1995). Between these two events, the Pannonian Basin was characterized by subsidence and deposition as documented by thick Upper Miocene (Pannonian) to Quaternary sediments (Horváth 1995; Magyar et al. 1999; Kovác et al. 2006; Gábris and Nádor 2007; Magyar et al. 2013). A modern subsidence rate of 1–2 mm/a in the central part of the Little Hungarian Plain was documented by Joó (1992). As a consequence, the thickness of the Quaternary sediments within the study area (Fig. 3) increases toward the east (Tauber 1959a; Timár and Rácz 2002).

The above-mentioned latest Pliocene–Quaternary compressional event (Horváth 1995) also affects the eastern margin of the Little Hungarian Plain (Fodor et al. 2005). Here, the terrace remnants of the Danube and its incision into the Transdanubian Range (Fig. 1) provide a concise time marker for the regression of the Lake Pannon and the onset of the Pliocene to Quaternary drainage pattern and landscape evolution of the Little Hungarian Plain (Ruszkiczay-Rüdiger et al. 2005a). Based on new ^{10}Be exposure ages, the oldest terrace of the Danube at the eastern margin of the Little Hungarian Plain is estimated to >700 ka before present (Ruszkiczay-Rüdiger et al. 2016).

River terraces within the Vienna Basin are highly influenced by active normal faulting (Decker et al. 2005; Hinsch et al. 2005; Beidinger and Decker 2011; Beidinger et al. 2011), forming tilted and vertically displaced terraces with distinct morphological scarps (Fig. 1). Active tectonics in the Little Hungarian Plain is suggested from vertically

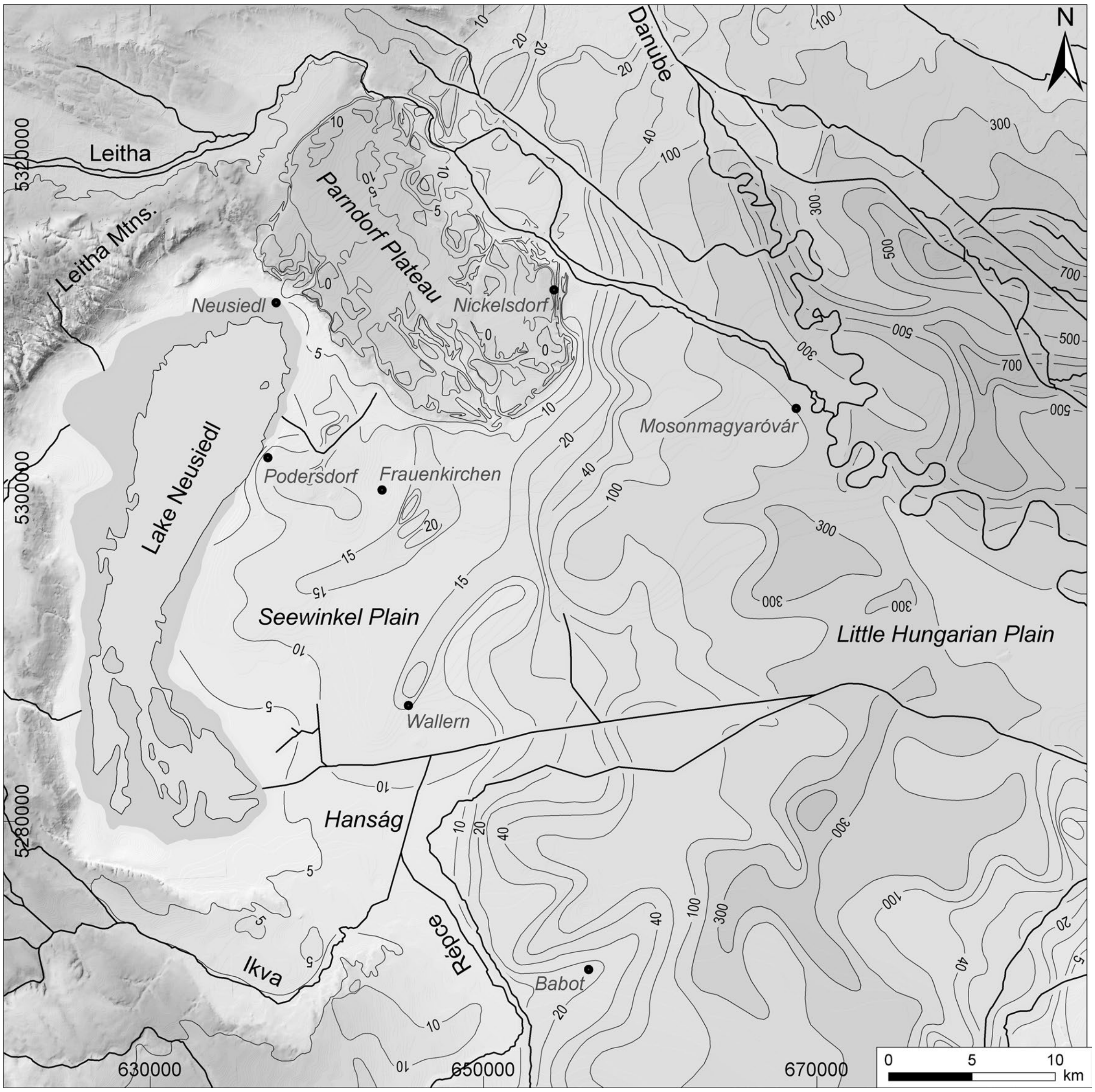


Fig. 3 Thickness of Quaternary sediments in the study area, which comprise mostly fluvial gravels, occasionally overlain by loess deposits of various thickness. While the gravel deposits continuously increase in thickness toward the east in the Seewinkel Plain and adjacent Little Hungarian Plain, their thickness on the Parndorf Plateau shows no trend of thickening in any direction. This sediment geometry supports the view that the plateau was an elevated area before significant subsidence in the Little Hungarian Plain started. Note that significant thickening can only be observed east of the line Nickelsdorf—Wallern. Data have been compiled from Tauber (1959a), counterflush well data (Bohrarchiv, Austrian Geologic Survey), Fahrion (1944), DANREG 2000 project (Scharek et al. 2000b), Don (1991, 1993)

separated fluvial deposits of similar age (Schönlaub 2000) that cover the high-relief topography of Pannonian sediments, by tectonically influenced drainage pattern and channel morphology of local tributaries (Zámolyi et al. 2010), as well as from micro-topographic features (Székely et al. 2009).

The most prominent deformation structures of the Little Hungarian Plain consist of NE–SW-trending normal faults that initiated during the Karpatian (Early Miocene) by the reactivation of Cretaceous thrusts (Tari 1996). Several of these faults (e.g., Fertő-, Ikva-, Répce- and Rába Faults, Fig. 1) were traced on seismic sections in the area south of the Lake Neusiedl region (Tari 1994, 1996; Szafián et al. 1999). The direction of extension in the Karpatian was ENE–WSW and rotated to WNW–ESE during Middle to Late Miocene (Fodor 1991), while present-day extension in the area is oriented NW–SE (Grenerczy et al. 2002). Subsidence occurred—and partly still occurs—at the abovementioned faults (Fig. 1) (Tari 1994; Szafián et al. 1999; Zámolyi et al. 2010).

Geological maps (Scharek et al. 2000a; Schönlaub 2000) display a NE–SW- and NW–SE-oriented fault pattern in the Lake Neusiedl region (Fig. 4). Some of these faults can be linked to seismic activity (Lenhardt et al. 2007; Tóth et al. 2007), and some linear geomorphological features probably are the expression of neotectonic processes (Székely et al. 2009). Normal faults with E–W and NW–SE extension have been observed in Badenian sediments and basement rocks of the Rust Hills (Spahic et al. 2011; Häusler et al. 2014) and at the SW margin of the Leitha Mountains (Fodor 1991).

Geomorphological overview

During the Pleistocene, the study area was not directly exposed to glaciation, although glaciers covered major parts of the European Alps (e.g., van Husen 2004). However, fluvial, coarse-grained deposits and periglacial features do suggest strong climatic impact on sedimentation and geomorphology during distinct cold periods (e.g., Herrmann 2000; Fábián et al. 2014). In historic times, anthropogenic activity increasingly influenced the extent of Lake Neusiedl and the drainage of wetlands (Draganits et al. 2006).

In general, the landscape of the study area (Fig. 1) can be divided into three main geomorphological units: (1) elevated regions with a hilly relief comprising crystalline basement rocks and their Mesozoic cover, (2) fluvial terraces (plateaus) and (3) depressions (partly filled with lakes).

Elevated regions

The first category includes the Leitha Mountains (Leithagebirge), the Rust Hills (Ruster Hügelland) and, further to the south, but still of some importance for this study, the Sopron Hills (Ödenburger Gebirge). The Leitha Mountains are a NE–SW-trending hilly landscape, rising abruptly from the surrounding low-relief areas to 118–484 m above sea level (a.s.l.) and separating the Vienna Basin from the Lake Neusiedl region (Fig. 1). Geologically, the Leitha Mountains represent a NE–SW-striking horst comprising Lower Austroalpine schists, gneisses and amphibolites overlain by Triassic quartzites and dolomites (Schönlaub 2000). At the rim of the Leitha Mountains, these metamorphic rocks are covered by Badenian to Sarmatian clastic sediments and limestones (Pistotnik et al. 1993; Wiedl et al. 2014).

The Rust Hills form a narrow, N–S-trending ridge (118–283 m a.s.l.) at the western boundary of Lake Neusiedl (Fig. 1). They comprise schists, gneisses and amphibolites of the Lower Austroalpine tectonic unit that are almost completely covered by Karpatian to Sarmatian clastic sediments and limestones (Fuchs 1965; Pistotnik et al. 1993). Similar to the Leitha Mountains, the Rust Hills are also regarded as a tectonic horst, bordered by N–S-trending normal faults which affect both the Neogene cover and the basement rocks (Fuchs 1965; Scheibz 2010; Spahic et al. 2011; Häusler et al. 2014).

The Sopron Hills (Fig. 1), the easternmost outcrop of Eastern Alpine rocks, mainly consist of Lower Austroalpine gneisses and mica schists, covered by Tertiary sediments at the rim (Küpper 1957). Topographic elevations range between 250 and 520 m a.s.l. The metamorphic rocks, as well as the Neogene cover rocks, are intensely deformed by brittle faults. Most dominant are NW–SE-striking high-angle faults that probably formed as dextral strike slip faults and were later reactivated as normal faults. Another important set of faults are E–W-striking high-angle faults (Draganits 1996). Both fault orientations are still reflected in the drainage system of the Oberpullendorf Basin (Fig. 1). These brittle faults were best documented in the former coal mines in the western part of the Sopron Hills at Ritzing and Brennbergbánya with displacements of up to ca. 80 m (Kisházi and Ivancsics 1977).

Fluvial terraces and plateaus

The Parndorf Plateau (Parndorfer Platte) represents a fairly even surface comprising Pannonian fine clastic sediments with a thin cover of fluvial deposits. It lies about 25–45 m above the surrounding lowlands (Fig. 1), and its surface gently dips toward the SE (from around 184 m in the NW, to 144 m a.s.l. in the SE), following the overall trend of the Pannonian sediments in the Little Hungarian Plain (Lipiarski et al. 2001). Toward the NW, the Parndorf Plateau forms a narrow connection to Vienna Basin terraces of similar altitudes, while in all other directions, it is delimited by steep slopes (Fig. 4). Based on the elevation of fluvial sediments, Szádeczky-Kardoss (1938) considered the Parndorf Plateau as the direct continuation of the River Danube´s highest (and thus oldest) terrace level in the Vienna Basin, the Laaerberg terrace. Tauber (1959b) corroborated Szádeczky-Kardoss's (1938) view of old Danube sediments on top of the Parndorf Plateau by demonstrating a much higher content of garnet in the heavy mineral fraction. Noticeable geomorphological features are several straight, NW–SE-trending dry valleys dissecting the southeastern part of the plateau (Fig. 5).

The Seewinkel Plain (114–130 m a.s.l.) is a very low relief area adjacent to Lake Neusiedl in the west, the Parndorf Plateau in the northeast and the Hanság depression to the south (Fig. 1). Similar to the Parndorf Plateau, the area

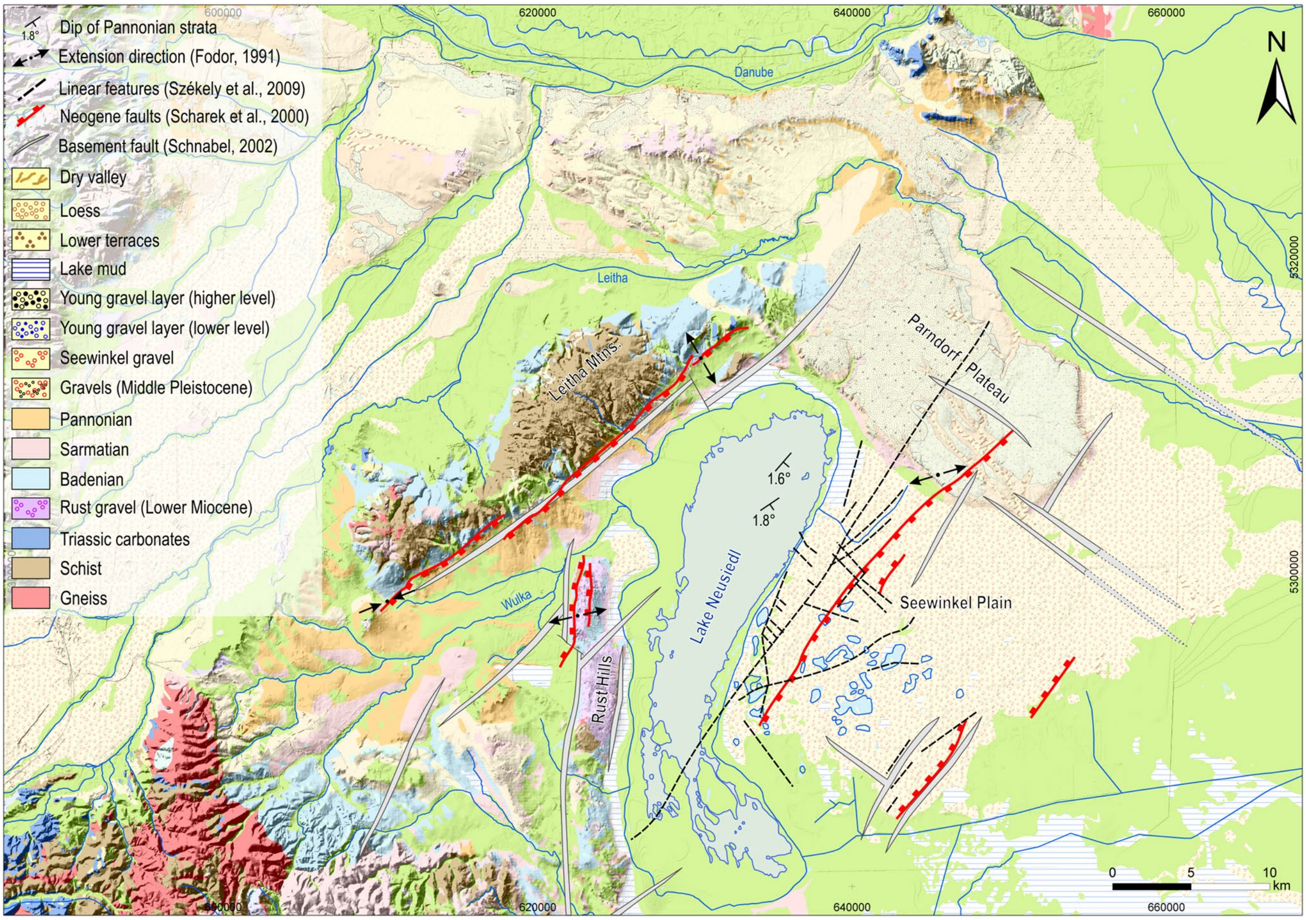


Fig. 4 Geological overview map of the study area after Schönlaub (2000). According to this map, the Parndorf Plateau is covered by three different gravel deposits: Middle Pleistocene age gravels and young gravels of the higher and the lower level. In contrast, the gravel layer deposited on the Seewinkel Plain is shown as a homogeneous unit. Basement and Neogene faults are arranged in a NE–SW- and NW–SE-oriented pattern. *Black arrows* indicate Late Miocene to Pliocene extension directions (Fodor 1991). The *black dashed lines* represent tectono-geomorphic linear features derived from the analysis of an airborne laser scanned digital terrain model (Székely et al. 2009). *Green areas* surrounding Lake Neusiedl refer to the reed belt; elsewhere to Holocene floodplains

is characterized by fluvial deposits on top of Pannonian sediments (Fahrion 1944; Tauber 1959a, c; Häusler 2007). Gravels pinch out toward the west and diminish around the eastern shore of Lake Neusiedl (Figs. 3, 4). The thickness of the Quaternary deposits increases from around zero at the lake shore to up to 25 m at the border to Hungary in the east (Fig. 3; Tauber 1959a). Thickening follows the same trend as the underlying Pannonian sediments (Fuchs and Schreiber 1985).

Depressions

Lake Neusiedl (Neusiedler See or Fertő-tó, Fig. 1), situated at the Austrian–Hungarian border, currently has an area of approximately 285 km^2 (Schmidt and Csaplovics 2011; Király and Márkus 2011) and a lake level at 115.5 m a.s.l. (Bácsatyai et al. 1997). The water level of the lake varied considerably in the past with a historical maximum around 117.7 m a.s.l. (Draganits et al. 2007). The entire lake is very shallow (1–1.7 m maximum, Fig. 5), with the deepest part of the lake bottom at around 113 m a.s.l. (Bácsatyai et al. 1997). The lake has no natural outlet, but for about 100 years the water level has been regulated by an artificial drainage channel (Fig. 1). At present, the main tributaries are the Wulka River and, to a very limited extent, the Angerbach rivulet (Fig. 1). The lake is surrounded by an extensive reed belt except for the eastern shore. According to Tauber and Wieden (1959), hardly any recent sedimentation occurs in the open water area of the lake. Sediment mainly accumulates in the reed areas and forms freshwater sapropel of up to several decimeters in thickness, underlain by sediments of Pannonian

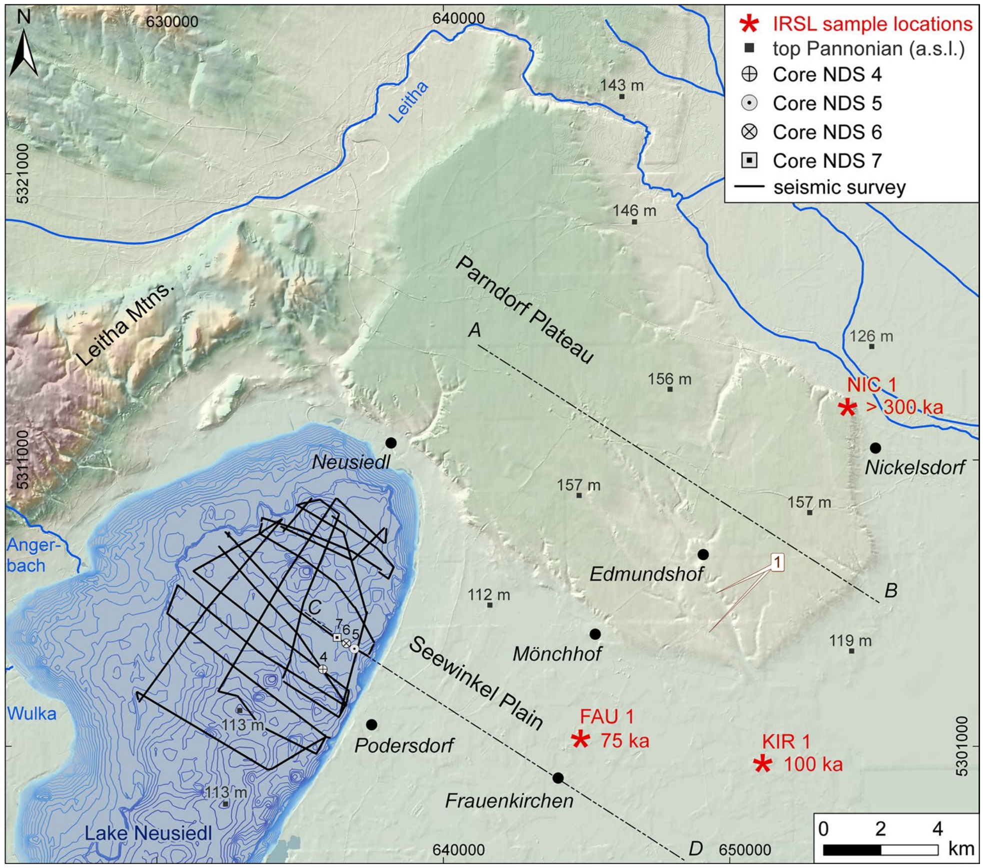


Fig. 5 Layout of lake seismic measurements and locations of IRSL samples. The *profile lines* A–B and C–D refer to profiles in Fig. 12. The *contour lines* of the lake *bottom* (after Bácsatyai et al. 1997) are shown in *blue* and have an interval of 0.1 m. The *deepest* point of the lake bottom lies at 113 m a.s.l. *Background* SRTM digital elevation model; *coordinate grid* UTM 33 N. *1* dry valleys in the southeastern part of the Parndorf Plateau

age (Tauber 1959a and this study). The deepest part of the lake forms a roughly NNE–SSW-oriented depression ending close to the southernmost tip of the Rust Hills (Bácsatyai et al. 1997).

The Hanság depression is a low-lying, extremely flat area bounded by the Seewinkel Plain to the north and by Lake Neusiedl to the west (Fig. 1). This area was part of the lake before anthropogenic drainage, forming a continuous, L-shaped water body with the modern Lake Neusiedl (Draganits et al. 2006).

Methods

To investigate the structural geologic evolution and depositional history of the study area, we applied a suite of geophysical and geological methods: (1) shallow-lake seismic measurements and interpretation, (2) lake drilling and sedimentological characterization of the drill cores, (3) acoustic velocity measurements of the sediments from the drill cores, (4) heavy mineral investigations and (5) infrared-stimulated luminescence (IRSL) dating. The data were analyzed together with outcrop descriptions and existing data compiled from the literature and scientific reports (including provenance studies, bore logs and industrial seismics).

Shallow-lake seismic data

We use shallow-lake seismic data to study the stratigraphy and deformation structures in a key position of the study area beneath Lake Neusiedl. Lake seismic data were acquired in September 2008 during an international geophysical field course (Timár et al. 2009) using an IKB-Seistec™ single-channel boomer source (1–10 kHz) equipped with eight hydrophones arranged vertically in a cone receiver having a fixed offset. In total, more than 110 km of seismic lines of the sediments beneath Lake Neusiedl has been measured. The grid of lake seismic measurements covers the NE part of Lake Neusiedl with a spacing of approximately 1 km (Fig. 5). The orientation of the grid has been planned orthogonal to a suspected NE–SW-trending fault system within the lake (Tauber 1959d; Tollmann 1985; Schönlaub 2000; Häusler 2007), as well as to faults of similar orientation localized in tectonic-geomorphological studies (Székely et al. 2009). The seismic navigation file was created by a GPS tracking device measuring every 4 s. Processing of the seismic data in the time domain included the removal of the low-frequency trend, correction of minor static shifts due to the motion of the boat and equipment by waves, and the removal of artifacts due to the impedance contrast between water and the lake bottom. Changes in the speed of the boat towing the source/receiver arrangement can cause significant changes in the geometry of the reflectors (e.g., flattening due to decreasing speed, Tóth 2003). However, such velocity effects do not affect the studied sections, because the speed of the boat was constant. Lake seismic data were interpreted in the time domain using the Petrel standard seismic interpretation software (www.slb.com).

To correlate the sedimentary bedding interpreted on the lake seismic sections with the stratigraphy in the Seewinkel Plain, industrial seismic sections (OMV 1970) were combined with counterflush (CF) well log data (Fahrion 1944; provided by the drill core archive, Austrian Geological Survey). The CF wells were placed systematically across the entire Seewinkel Plain during the period between May 1943 and April 1944. The results of these wells that were part of a general prospection in the area were documented by Fahrion (1944). In the present paper, these wells were used for the evaluation of the Quaternary thickness map of the region (Fig. 3).

Lake drilling and drill core sedimentology

Interpretation of lake seismic data helped to locate key sites for a lake drilling campaign, which was conducted in 2009 in cooperation with the company UWITEC (www.uwitec.at). A floating aluminum sampling platform was used with a baseplate placed on the bottom of the lake to ensure stable positioning and drilling. Sediment cores were retrieved by a “Niederreiter” piston corer applying rising and dropping hammer action. The bolt tip allowed for continuous sampling and minimized the effect of crumbling sediment. The cores were taken with 1-m-long metal cylinders with diameters of 9 or 6 cm and later extruded by a hydraulic pump into Plexiglas pipes. The drilling sites were located in the eastern part of the lake, near Podersdorf (Fig. 5). The maximum coring depth reached 3 m below the lake bottom.

Documentation of the drill cores was based on standard sedimentological methods, including lithofacies characterization, analysis of fossil content, color description by Munsell color charts, grain size measurements using a Sedigraph ET5100 and heavy mineral analysis of samples from selected parts of the cores. Table 1 summarizes the samples taken from the cores and results of their basic sedimentological analysis.

Bulk and clay mineralogical compositions were established by X-ray diffraction using a PanalyticalX’Pert PRO diffractometer (CuKα radiation, 40 kV, 40 mA, step size 0.0167, 5 s per step). The bulk samples were analyzed as oriented powders. The clay fraction (<2 µm fraction) was separated by sedimentation and analyzed as oriented clay films on glass slides.

Acoustic velocity measurements

To obtain a detailed velocity profile to link well data (depth domain) to seismic data (time domain), ultrasonic measurements were taken on the core samples using a Proceq TICO ultrasonic instrument (Fig. 6). This device has two metal cylinders with 6 cm diameter. One cylinder acts as an emitter of ultrasonic waves at 50 kHz, and the other records the travel time of the emitted waves. Proceq TICO uses the pulse velocity method to provide information on the uniformity of the investigated material. The measurements were taken in a tandem arrangement (Gräfe 2009) with a coupling paste. A standard material (concrete block) and the air temperature were measured at the beginning of each major measuring phase. Several measurement runs were conducted for the same section of core, and the most robust velocity measurement was used for the depth-to-time conversion. The conversion of the thickness of the sedimentary layers from meters to seconds was done by stretching or squeezing the thickness value with the respective measured acoustic velocity. For layers that yielded no conclusive velocity measurement results (i.e., due to open cracks within the drill core), velocities from analogous layers were used.

Heavy mineral investigation

The samples for heavy mineral analysis were derived from three different regions: (1) samples from the lake drill cores near Podersdorf (Fig. 5), (2) one sample from a sand body within the gravels of the Parndorf Plateau (NIC 1) and (3) two samples from few dm thick sand layers within the gravels of the Seewinkel Plain (FAU 1, KIR 1) (Fig. 5). Samples NIC 1, FAU 1 and KIR 1 lay within the uppermost gravel layers. Sample NIC 1 was taken at 147 m a.s.l, 8 m below the surface of the Parndorf Plateau (Fig. 7d), FAU 1 was taken at 123 m a.s.l, 1.5 m below surface, and KIR 1 (Fig. 7c) was taken at 125 m a.s.l, 2 m below the surface. The fraction between 63 and 400 µm was used to investigate the heavy mineral assemblage of the samples. Heavy mineral separation and counting followed standard procedures (Mange and Maurer 1992; Wypyrsczyk et al. 1992).

For provenance analysis, our heavy mineral data were compared with those from the Seewinkel Plain (Husz 1965), from Danube terraces (Csapó 1998; Frasl 1955), from the catchment of the Répce, also called Rabnitz (Nebert et al. 1980; Schoklitsch 1962), and from Danube tributaries in the Vienna Basin (Szabó 1961).

Infrared-stimulated luminescence dating (IRSL)

Samples NIC 1, FAU 1 and KIR 1 (Fig. 5) were used for IRSL dating of sand bodies within the gravel layers on the Parndorf Plateau and in the Seewinkel Plain. The samples

Table 1 Overview of sample locations and results of grain size measurements from the lake drill cores

Core no.	Sample no.	From cm	To cm	Water loss [%]	Grain size [%]			TOC [%]
					Sand	Silt	Clay	
NDS-4-1	NDS-4-1-1	4.0	6.0	33	13.7	34.7	51.6	1.38
	NDS-4-1-2	9.0	12.0	28	48.1	18.9	33.0	1.19
	NDS-4-1-3	41.5	45.0	20	74.5	16.2	9.3	0.47
	NDS-4-1-4	78.0	81.0	18	96.9	2.5	0.6	0.22
NDS-4-2	NDS-4-2-4	8.0	14.0	17	92.3	6.1	1.6	0.14
	NDS-4-2-3	18.0	22.0	20	90.8	7.6	1.5	0.26
	NDS-4-2-2	42.0	45.0	20	93.9	5.3	0.8	0.30
	NDS-4-2-1	93.0	97.0	17	94.6	4.7	0.7	0.26
NDS-4-3	NDS-4-3-1	14.0	17.0	17	93.4	5.7	0.9	0.21
	NDS-4-3-2	63.0	66.0	24	32.1	60.8	7.1	0.41
	NDS-4-3-3	82.0	84.5	26	3.7	76.2	20.1	0.76
NDS-5-1	NDS-5-1-1	17.1	20.0	20	0.7	62.5	36.9	0.34
	NDS-5-1-2	51.5	54.0	24	3.0	52.0	45.0	0.29
	NDS-5-1-3	77.5	80.7	19	29.1	49.1	21.8	0.16
	NDS-5-1-4	88.3	91.3	19	5.2	72.6	22.3	0.26
NDS-5-2	NDS-5-2-1	2.0	7.5	19	46.2	25.2	8.4	0.29
	NDS-5-2-2	24.7	28.0	20	21.7	67.6	10.7	0.18
	NDS-5-2-3	41.8	44.6	22	3.3	70.7	26.0	0.29
	NDS-5-2-4	78.5	81.0	21	0.1	76.6	23.4	0.38
NDS-5-3	NDS-5-3-1	12.5	16.0	22	0.0	63.7	36.3	0.34
	NDS-5-3-2	29.3	33.0	20	0.5	57.9	41.6	0.30
	NDS-5-3-3	40.0	43.3	16	11.6	50.8	37.6	0.18
	NDS-5-3-4	55.0	59.5	17	1.7	68.1	30.2	0.23
NDS-6-1	NDS-6-1-1	0.4	3.5	17	66.8	4.5	3.6	0.97
	NDS-6-1-2	19.5	21.7	33	6.8	32.5	60.7	2.17
	NDS-6-1-3	54.5	57.2	20	1.0	67.1	31.9	0.35
	NDS-6-1-4	82.0	84.5	22	14.3	32.5	53.2	0.15
NDS-6-2	NDS-6-2-1	11.2	15.5	22	17.3	34.5	48.2	0.13
	NDS-6-2-2	46.0	50.2	17	22.2	47.5	30.4	0.36
	NDS-6-2-3	86.2	90.0	17	65.0	26.7	8.4	0.14
NDS-6-3	NDS-6-3-1	12.0	16.5	18	56.4	35.0	8.6	0.23
	NDS-6-3-2	33.0	37.3	15	58.3	29.0	12.7	0.47
	NDS-6-3-3	44.5	49.0	18	17.4	66.5	16.1	0.30
	NDS-6-3-4	57.0	60.7	21	7.0	70.0	23.0	0.28
	NDS-6-3-5	71.0	74.8	19	11.8	61.0	27.2	0.32
	NDS-6-3-6	79.5	83.0	18	29.0	48.1	22.9	0.12
	NDS-6-3-7	86.5	90.0	16	35.1	53.7	11.2	0.14
NDS-7-1	NDS-7-1-1	11.0	14.0	20	1.8	36.5	61.7	n/a
	NDS-7-1-2	16.0	20.0	19	25.8	39.9	34.3	n/a
	NDS-7-1-3	41.0	44.0	19	43.2	40.0	16.8	n/a
	NDS-7-1-4	55.5	59.0	21	12.5	63.7	23.8	n/a
	NDS-7-1-5	86.0	92.0	19	50.6	44.7	4.6	n/a
NDS-7-2	NDS-7-2-1	3.5	6.2	24	9.4	73.5	17.1	0.22
	NDS-7-2-2	9.5	12.5	24	47.1	44.4	8.5	0.19
	NDS-7-2-3	30.3	33.0	27	1.4	74.0	24.5	0.30
	NDS-7-2-4	47.0	50.0	26	0.4	79.4	20.2	0.29
	NDS-7-2-5	70.5	73.0	24	4.3	80.5	15.2	0.19
	NDS-7-2-6	82.5	86.0	21	45.5	51.4	3.1	0.13

Table 1 continued

Core no.	Sample no.	From cm	To cm	Water loss [%]	Grain size [%]			TOC [%]
					Sand	Silt	Clay	
NDS-7-3	NDS-7-3-1	1.5	4.5	23	16.2	51.8	32.0	n/a
	NDS-7-3-2	9.0	11.5	23	7.9	84.4	7.6	n/a
	NDS-7-3-3	21.0	24.0	17	31.4	65.3	3.3	n/a
	NDS-7-3-4	28.5	32.0	21	25.3	71.1	3.6	n/a
	NDS-7-3-5	42.5	46.5	9	70.7	27.5	1.8	n/a
	NDS-7-3-6	50.5	52.5	21	8.4	83.4	8.2	n/a
	NDS-7-3-7	58.0	61.0	18	31.5	63.0	5.5	n/a
	NDS-7-3-8	67.0	69.5	21	7.4	77.7	14.9	n/a
	NDS-7-3-9	77.0	80.0	21	2.7	84.5	12.7	n/a
	NDS-7-3-10	90.0	93.0	18	39.0	57.7	3.2	n/a

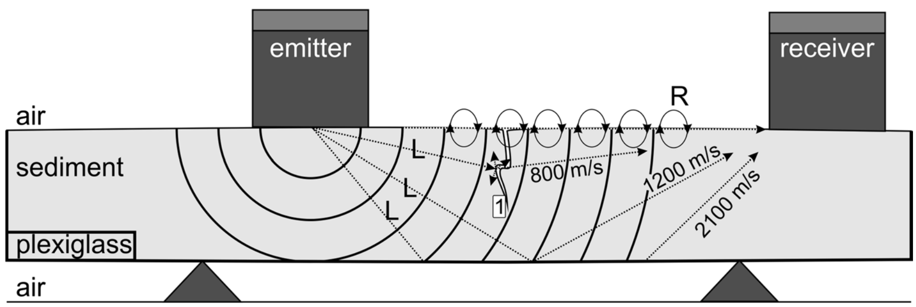


Fig. 6 Arrangement of acoustic velocity measurements showing the different set of acoustic velocities derived and their possible causes. Velocities measured depend on the type of wave involved. For simplicity, two types of waves are depicted: longitudinal wave (L) and Rayleigh wave (R). The acoustic axis of each cone was below the first critical angle; thus, the longitudinal wave was recorded. Additional factors that lead to the recording of different velocities are scattering and absorption as well as noise due to the grain size of the sediment and air within the pore space (Gräfe 2009). For the depth-to-time conversion, the most robust velocity value derived from several measurement runs was used

were dated in the luminescence laboratory in Vienna using a single-aliquot regenerative-dose infrared-stimulated luminescence protocol (Wallinga et al. 2000; Blair et al. 2005) of the potassium-rich, coarse-grained feldspar fraction. Dose rates were determined by laboratory gamma spectrometry. The quartz grains were not suitable for OSL measurements due to very low strength of the luminescence signals.

Results

Seismic interpretation

A multitude of sedimentological and tectonic features could be documented in the lake seismic data, including presence/absence of gravels, tilting of sedimentary bedding, erosional truncation of beds, channel structures, thickness variations and normal faults (Figs. 8, 9). However, the major NE–SW-striking fault postulated in the northern part of the lake in several earlier publications (Tauber 1959d; Tollmann 1985; Schönlaub 2000; Häusler 2007) could not be detected.

The seismic data, together with the lake drill cores, and Quaternary thickness maps from the literature (Figs. 3, 8, 9) support the observation that no significant Quaternary fluvial gravel layer exists on top of the tilted sediments in the observed part of Lake Neusiedl. The dip of the Pannonian strata is generally gentle and terminates with an angular unconformity toward the bottom of the lake (Figs. 8, 9). No consistent tilting of the Pannonian beds could be observed in the northwesternmost part of the survey, where sub-horizontal undulating surfaces prevail. Further to the east and south, SW–NE-oriented sections reveal a general tilt toward SW (Fig. 9a, c). In the section in Fig. 9a, the bedding dips away from the Parndorf Plateau. However, in a parallel section, 2 km to the SE, no significant tilting was observed. In perpendicular NW–SE sections, the sedimentary bedding dips toward the SE (Fig. 8b, c). The dip of reflectors in the close surroundings of the lake drilling

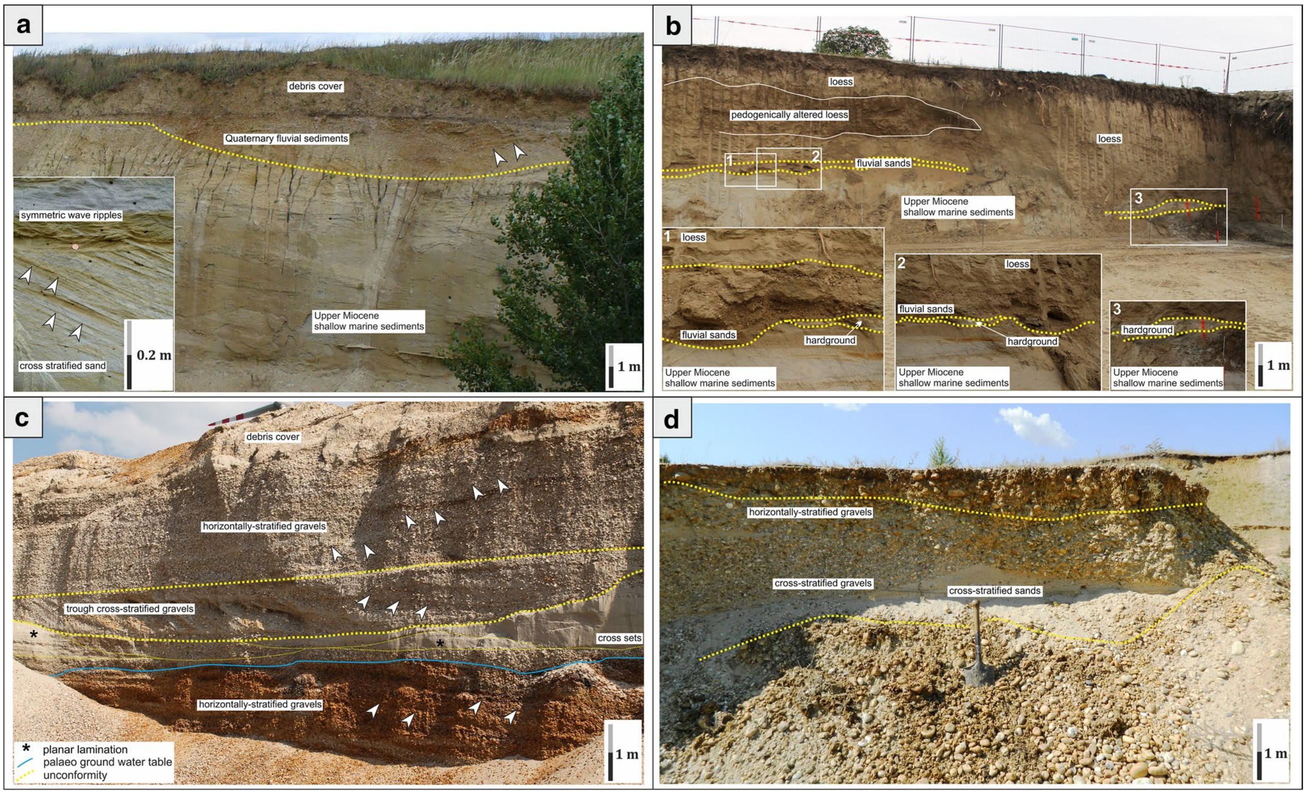


Fig. 7 Overview of outcrops in the study area. **a** Quaternary channel incising in Upper Miocene strata at Edmundshof (Parndorf Plateau). Note the otherwise very thin Quaternary cover of the Upper Miocene shallow marine deposits. **b** N of Mönchhof, loess deposits are juxtaposed to the Upper Miocene shallow marine deposits. **c** The outcrop at Halbturn (Seewinkel Plain) shows sand cross-sets from which the luminescence sample KIR 1 was taken. **d** Sample location for IRSL dating and heavy mineral analysis at the outcrop of Nickelsdorf. The sample NIC 1 was taken from the cross-stratified sands at the spade (10 m below the topographic surface of the Parndorf Plateau). *Arrows* indicate stratification planes

locations was converted to true dip based on the results of the acoustic velocity measurements. Accordingly, the dip data for the bedding in that area are around 2° toward SE (Fig. 4).

Using the acoustic velocity measurements, it was possible to convert drill core depth into seismic time and thus correlate distinct sedimentary successions of the lake drill cores with characteristic reflectors of the lake seismic sections (Fig. 8). The seismic facies generally fits well to the drill core lithology. In Fig. 8a, cross-sets downlap toward SE on an erosion surface represented by a rather continuous package of strong reflectors. The fill of this NE–SW-oriented channel corresponds to the approximately 1-m-thick section of medium-grained sand with thin plant remains and laminae of coarse-grained sand (Fig. 9a). The high amplitudes of the erosion surface can be explained by the impedance contrast to the underlying clay succession. The alternating clay–sand layers of the drill core NDS 5 (Fig. 9b) are easily recognizable in the thin, but continuous high-amplitude reflectors of the seismic section (Fig. 8b). The bottommost layer of the drill core (gray silt with oxidation speckles) passes into a zone of wavy, fragmented reflectors indicating disturbed sedimentary bedding. At the stratigraphically deeper NDS 6 and NDS 7 drill core locations, layers of heterogeneous seismic facies disrupt the generally consistent SE-dipping reflector packages (Fig. 8c, d). The silty sand with in situ roots in the middle section of NDS 6 (Fig. 9c) indicates a sub-aerial surface that is overlain by a silt package with dislocated root remnants followed by clays. This succession was affected by an erosional event represented by a channel-like feature in the eastern side of the section and truncated reflectors (Fig. 8c). The complex seismic pattern in Fig. 8d corresponds well with the highly variegated lower part of NDS 7 that contains different layers of fine sand with laminar cross-bedding (Fig. 9d).

In some areas, especially close to the western shore, the sedimentary bedding is cut by channels of various sizes (Fig. 8c, d). The smaller of the two prominent features in Fig. 8c shows well-defined reflector terminations and very low amplitudes within the channel complex, indicating a

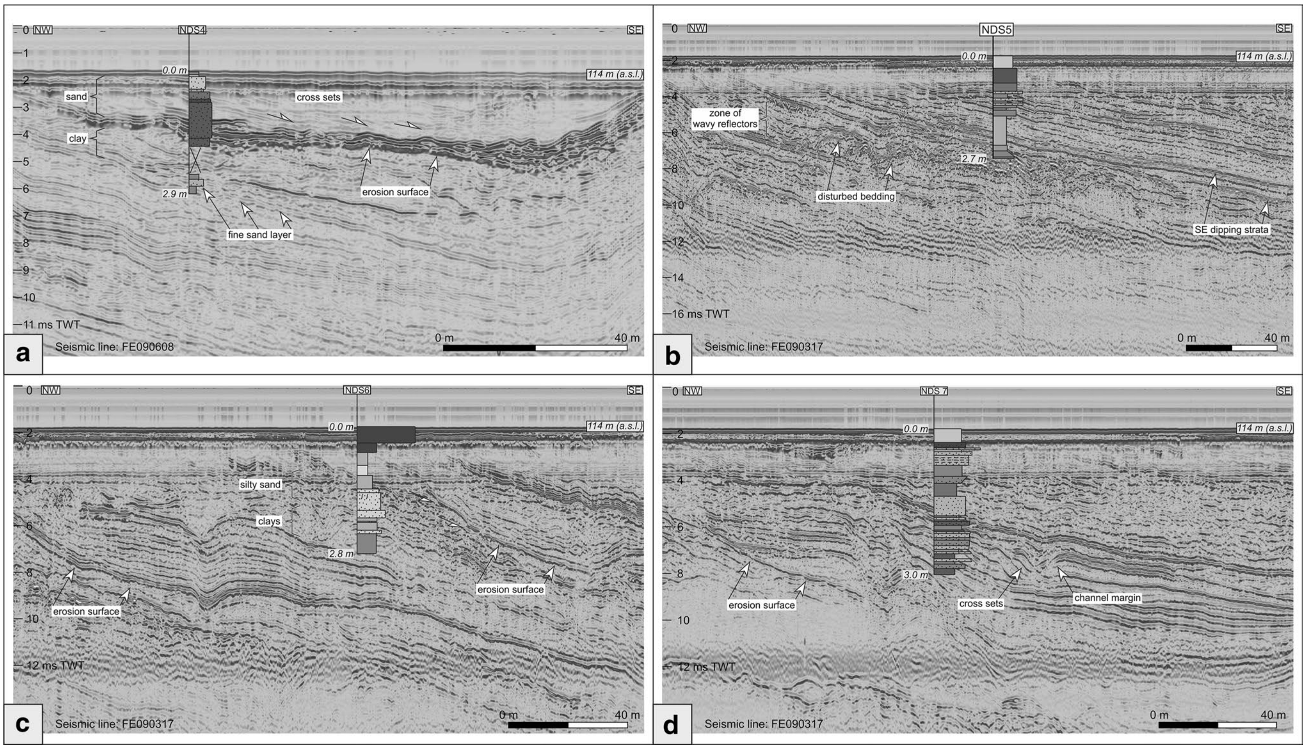


Fig. 8 Lake seismic sections in time domain shown with the correlated lake drilling sections. The correlation was done by depth-to-time conversion based on the results of the acoustic velocity measurements. Individual sections with uniform acoustic velocities were stretched or squeezed *en bloc*. The lithologic description of the lake drilling cores is shown in Fig. 10. Note that the first multiple of the lake *bottom* shows up in the seismic sections as a weak, sometimes vanishing, horizontal reflector package at 4 ms TWT

homogeneous fill. Note that the section is 10 times vertically exaggerated. Taking this into consideration, the feature is 30 m wide and 12 m deep, approximately twice the size of the river channel of the modern Répce River. The size of the larger feature in Fig. 9c is not clear: Reflectors continue into the weak amplitude region indicating a probable smaller size. Figure 8d shows indications of a point-bar system of considerable width in the center of the lake. Strong, continuous reflector triplets represent the eroded top of older sediments. The individual point-bars have faint borders, marked by the termination of the shorter, wavy reflectors. The internal structure of each point-bar is very heterogeneous with sub-parallel and diverging reflector packages. Similar features can be observed in Fig. 9a, b. However, in this case small-scale normal faulting occurs. The sub-vertical boundaries of the reflector packages dip in the direction of the bedding slope, whereas internal reflections dip in the opposite direction, especially in Fig. 9b. Thus, a syn-tectonic wedge forms at the top of each duplex. Also, the reflectors of the older bedding diverge toward the faulted region. The faults are localized within a layer of constant thickness not crossing the basal reflector. Across the entire area covered by the seismic data, no indication of significant thickening of sediments was detected (Figs. 8, 9).

Description of lake drill cores

The four lake drillings at the lake bottom of Lake Neusiedl (NDS 4—NDS 7) reached depths between 2.6 and maximum 3 m due to high compaction of the sediments. Table 1 provides an overview of the analyzed samples and summarizes the results of the grain size measurements. No significant amount of gravels could be observed in any of the drill cores, supporting the lack of significant gravel deposits within the lake as also observed in the lake seismic data. Paleontological analysis yielded no age-indicative fossils in the drill cores (pers. comm. M. Harzhauser 2011). However, the combination of seismic sections with well data and the calculation of true dip values based on the seismic interpretation of this study allowed the correlation of the reflectors onto adjacent onshore industrial seismic sections (OMV 1970), as well as nearby CF well data in the Seewinkel Plain (Fig. 12). This correlation indicates a probable Late Pannonian age of the sediments beneath the lake bottom.

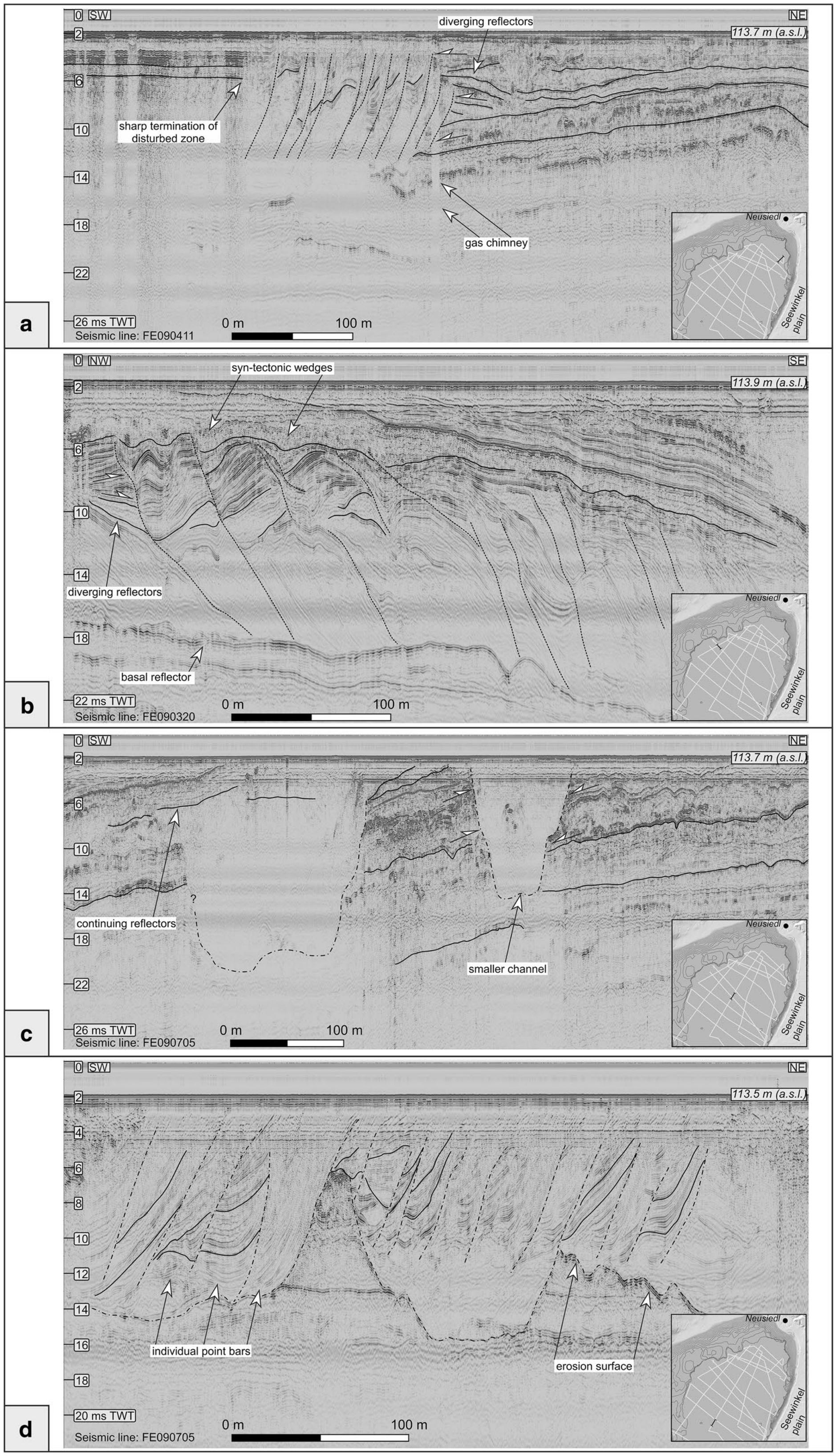


Fig. 9 Selected lake seismic sections showing key sedimentological and tectonic features beneath Lake Neusiedl. **a** No consistent tilting could be observed toward the southern margin of the Parndorf Plateau, only minor normal faults. **b** Similar minor faults were identified elsewhere in the lake. **c** Symmetric channels and **d** a *point-bar* system indicate syn- to post-Pannonian fluvial erosion. *Continuous lines* indicate sedimentary bedding; *dashed lines* are interpreted faults; and *dash-dotted* lines represent erosional surfaces

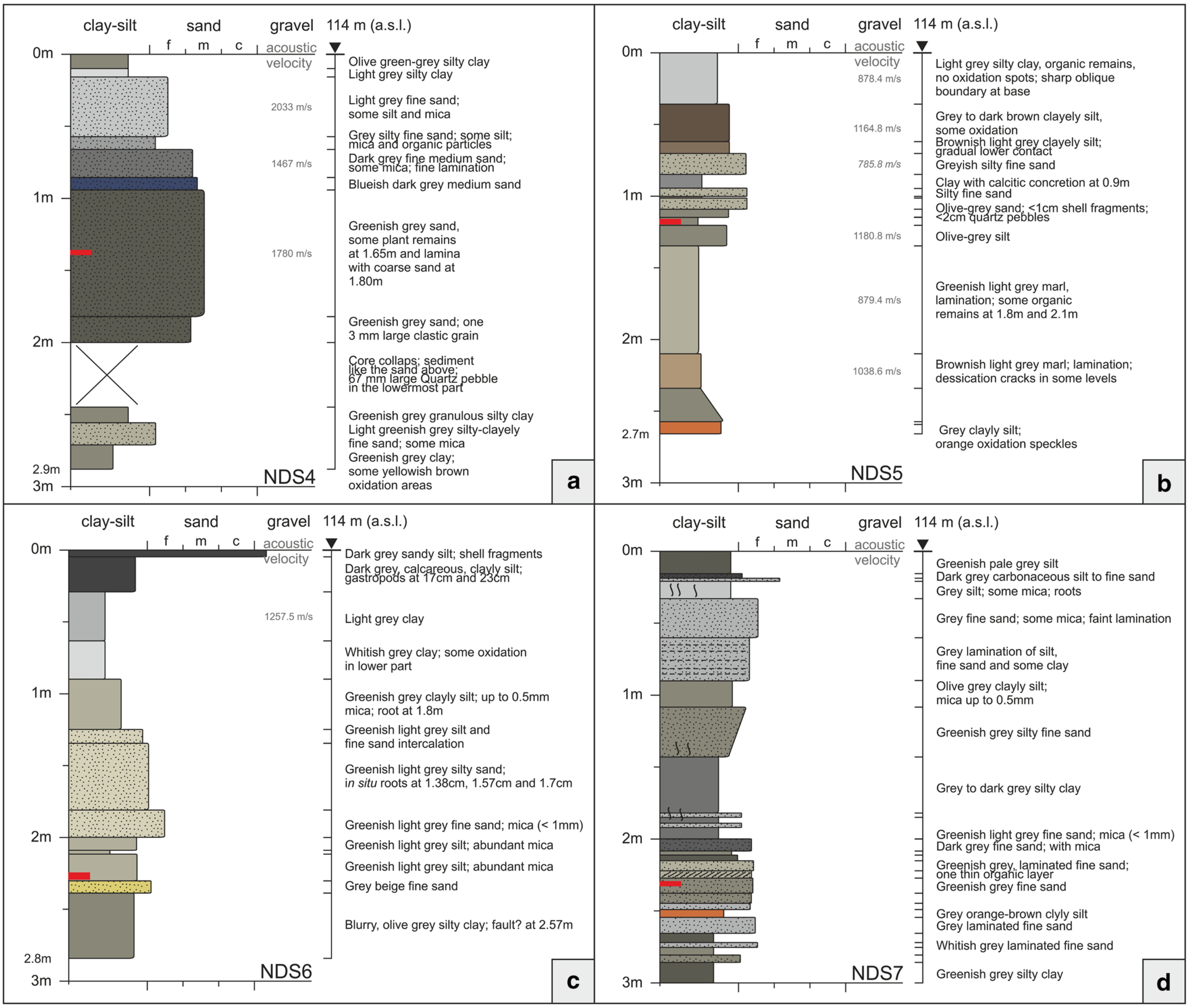


Fig. 10 Sedimentological logs of the lake drill cores. Note that no significant gravel layer could be observed in the lake drill cores. The *red rectangle* shows the sample locations for heavy mineral analysis. Results of the acoustic velocity measurements are indicated in *light gray* for each section

The mineralogy of drill core NDS 7−1 was investigated in detail. Eight samples were taken at 0–4, 11–14, 16–20, 28–31, 41–44, 55.5–59, 68–71.5 and 86–92 cm depth. The uppermost 20 cm of the core consists of dark gray, silty clay, followed by light gray to greenish clayey silt interbedded with layers of fine- to medium-grained sand. The bulk samples consist of muscovite, chlorite, quartz, feldspar (albite and microcline), calcite and dolomite throughout the profile. However, the uppermost two samples are slightly different, showing a pronounced magnesium calcite peak between very broad calcite and dolomite peaks in the X-ray diffractograms. Calcite and dolomite show better crystallization further downhole, and the magnesium calcite peak disappears at a depth of 60 cm. Furthermore, the upper two samples contain less feldspar than the other samples. The clay fraction (<2 µm fraction) gives further evidence that the uppermost samples are different. Illite and chlorite are the dominant clay minerals until a depth of 20 cm. The deeper samples show, in addition to illite and chlorite, pronounced peaks of smectite and some minor kaolinite.

The sediments below the uppermost 20 cm display some cm to maximum 1.3 m thick layers of clay to coarse-grained sand, including isolated cm-sized gravel clasts (see Fig. 10 for detailed sedimentological logs). The colors range from gray to greenish gray; irregular orange oxidation spots are common. Sub-horizontal lamination is the only visible sedimentary structure. Relatively large detrital white-mica flakes and low calcite contents are characteristic of the sediments below 20 cm. The probable Late Pannonian age is supported by our correlation, mineralogical findings and data by Szontagh (1904), Blohm (1974) and Fuchs and Schreiber (1985).

Heavy mineral data

The heavy mineral data represent assemblages from lacustrine Upper Pannonian strata (lake drill cores) as well as from Quaternary fluvial sediments (Parndorf Plateau and Seewinkel Plain; Table 2). Heavy mineral assemblages from the Pannonian sediments in the lake drill cores (Table 2) show high abundances of garnet, apatite, staurolite and epidote. Some common heavy minerals include zircon, tourmaline, zoisite/clinozoisite, kyanite and transparent amphibole. This means that the heavy mineral spectrum is dominated by metamorphic minerals. Minerals of the ultrastable ZTR (zircon, tourmaline, rutile) group indicative of transport and weathering (Hubert 1962) range up to a maximum of a few percent (Fig. 11a). Chloritoid, chromium spinel, titanite, brown amphiboles are also present, but in very low quantities. It is important to note that staurolite dominates over chloritoid and that sillimanite and kyanite are quite abundant. All in all, heavy minerals from a low- to high-grade metamorphic source area dominate the assemblages.

In the ternary plot (Fig. 11a), the three samples from the Quaternary gravels plot very near the Upper Pannonian samples, indicating either reworking or the same, mainly metamorphic hinterland.

The sample from the Parndorf Plateau (NIC 1) shows high abundance of garnet, staurolite, epidote. Green hornblende is also common, but in significantly lower amounts compared to the samples from the Seewinkel Plain (KIR 1, FAU 1). Additionally, zircon, tourmaline, fibrolithic sillimanite, zoisite/clinozoisite, kyanite are common. Rutile, transparent amphibole, titanite and apatite are present in very low amounts (Table 2). In comparison with the Parndorf Plateau, the heavy mineral assemblages from the Seewinkel Plain (KIR 1, FAU 1) are dominated by green hornblende and garnet and contain higher amounts of fibrolithic sillimanite and titanite, but less amphibole (Table 2).

Log ratio plots of the main heavy minerals epidote and chloritoid versus garnet, and green amphibole *versus* staurolite (Fig. 11b, c), result in a separation of the Quaternary samples from Pannonian samples. The amount of green hornblende is higher than or equal to the amount of

Table 2 Results of the heavy mineral analysis of the samples from the Late Miocene lake drill cores (NDS 4 to 7) and from the Quaternary outcrop samples in the Seewinkel Plain (KIR 1, FAU 1) and Parndorf Plateau (NIC 1)

	Zircon	Tur.	Rutile	Apatite	Garnet	Chloritoid	St.	Epidote	Chromium spinel	Hbl. (gray)	Amp.	Sil.	Zoisite	Kyanite	Titanite	Hbl. (brown)	Biotite	
NDS 4-2-2	5	4	1	13	130	2	12	33	0	49	5	10	5	4	1	1	1	pcs.
	2	1	0	5	47	1	4	12	0	18	2	4	2	1	0	0	0	%
NDS 5-2-2	3	12	0	70	76	2	46	25	1	1	4	0	19	4	0	0	0	pcs.
	1	5	0	27	29	1	17	10	0	0	2	0	7	2	0	0	0	%
NDS 6-3-3	4	14	2	37	130	2	27	35	0	2	1	0	11	11	1	0	3	pcs.
	1	5	1	13	46	1	10	13	0	1	0	0	4	4	0	0	1	%
NDS 7-3-7	3	8	1	36	110	2	50	43	0	4	0	1	8	5	0	0	1	pcs.
	1	3	0	13	40	1	18	16	0	1	0	0	3	2	0	0	0	%
KIR 1	8	7	3	0	75	0	21	34	0	133	2	6	7	9	2	0	0	pcs.
	3	2	1	0	24	0	7	11	0	43	1	2	2	3	1	0	0	%
FAU 1	1	1	2	4	90	0	17	15	0	80	0	3	12	2	1	0	0	pcs.
	0	0	1	2	39	0	7	7	0	35	0	1	5	1	0	0	0	%
NIC 1	5	2	1	1	50	1	10	13	0	12	0	8	2	3	3	0	0	pcs.
	5	2	1	1	45	1	9	12	0	11	0	7	2	3	3	0	0	%

Tur. Tourmaline, *St.* Staurolite, *Hbl.* Hornblende, *Amp.* Amphibole, *Sil.* Sillimanite, *pcs.* pieces

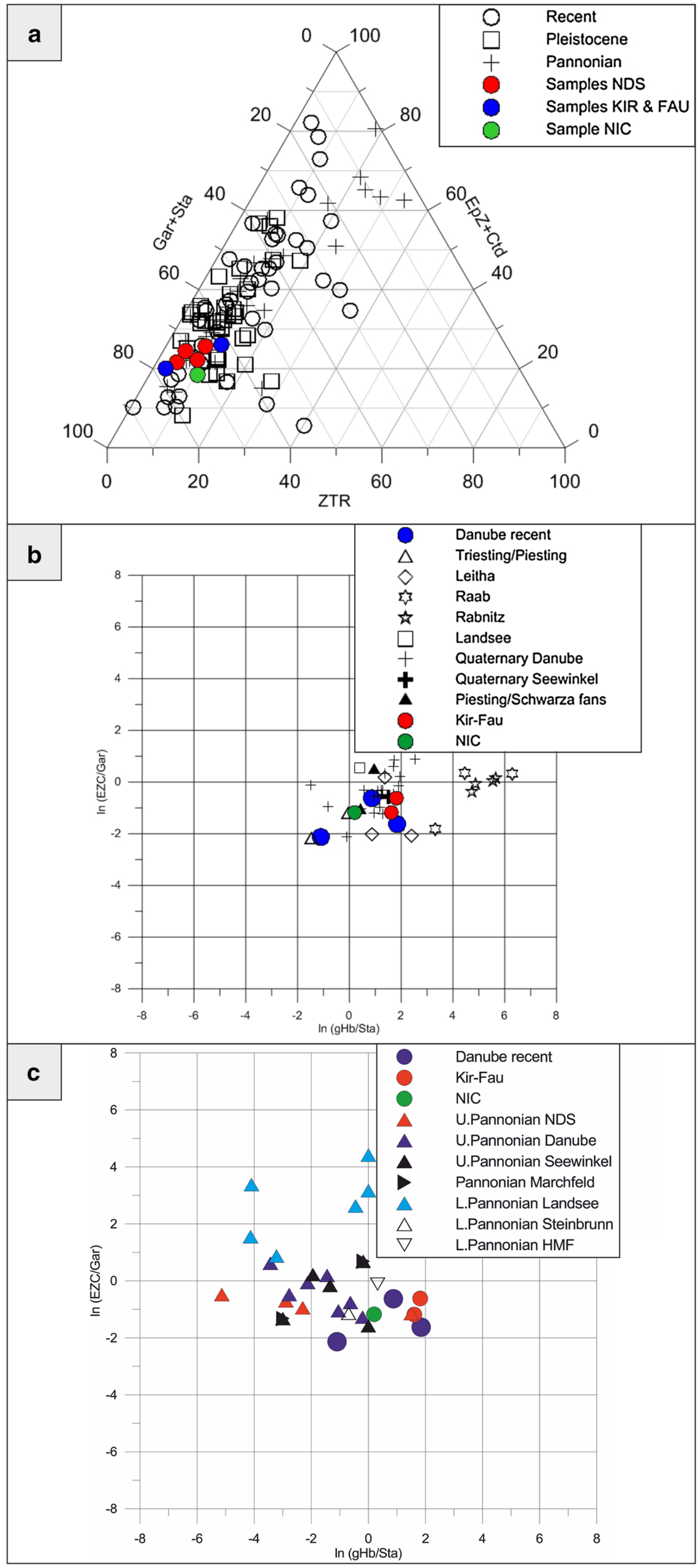


Fig. 11 Heavy mineral analysis diagrams showing **a** a ternary plot ZTR (zircon, tourmaline, rutile) versus low-grade metamorphic (epidote group and chloritoid) versus higher-grade metamorphics (garnet and staurolite), **b** log ratio diagram of the main heavy minerals epidote group + chloritoid versus garnet and green amphibole versus staurolite of recent samples and **c** of Upper Miocene samples. Data of this paper (KIR 1, FAU 1, NIC 1 and NDS samples) are compared to data from Frasl (1955), Wieseneder and Maurer (1958), Szabo (1961), Schoklitsch (1962), Husz (1965) and Fuchs (1974)

staurolite in the Quaternary samples, whereas in the Pannonian samples the amount of green hornblende is less than or equal to the amount of staurolite, except for the sample NDS 4-2-2 (Table 2) that contains much more green hornblende than staurolite.

Quaternary fluvial sediments of the Parndorf Plateau and the Seewinkel Plain

In the fluvial sediments of the Parndorf Plateau and the Seewinkel Plain, three main lithofacies classes were recognized: (1) poorly sorted, matrix-supported gravels, (2) laminated sands and sands showing trough cross-bedding and (3) alternating open- and filled-framework gravels.

The sediments of the Seewinkel Plain generally consist of loose, sandy, medium- to coarse-grained gravels often intercalated with medium- to coarse-grained sands in bodies with cm to few dm thickness and some couple of meters length. These sand bodies appear commonly laminated, often showing thin stringers of pebbles. Gravel clasts are rounded to well-rounded. Periglacial features within the fluvial sediments of the Seewinkel Plain are rare and represent involutions within the top decimeters. Typical loess deposits are virtually absent in the Seewinkel Plain. Paleo-groundwater levels were frequently observed in outcrops of the Seewinkel Plain at a few meters depth, represented by distinct, yellow to dark brown and blackish layers especially within open-framework gravels (Fig. 7c).

Logs from CF wells in the Seewinkel Plain highlight the clear lithological contrast between the Quaternary fluvial strata and the finer-grained Upper Pannonian sediments (Fahrion 1944). The Quaternary sediments comprise sand lenses and gravels with an average thickness of 10 m and with a thickening trend toward the east (Fig. 3). The CF wells did not pass through the entire Pannonian strata. The Upper Pannonian is formed of a sequence of clays, clayey marls, and sand layers with varying thickness. Precise biostratigraphic dating of the above-mentioned strata was not successful due to the lack of fossils (Fahrion 1944). Two selected wells, from near Neusiedl (CF N 6) and Frauenkirchen (CF FR 28), are shown in Fig. 12 to delimit the top of Upper Pannonian sediments.

On the Parndorf Plateau, Quaternary sediments appear as a thin layer of only up to few meters thickness on top of Upper Miocene strata. Fluvial gravels are characterized by a similar depositional character as those observed in the Seewinkel Plain, but show a higher matrix content, a higher grade of chemical weathering and frequent large-scale periglacial features (such as involutions or sand wedges). The higher degree of weathering is also supported by the almost complete absence of limestone or dolomite components. The crystalline components from the Parndorf Plateau include a granulite clast with garnets bearing a biotite rim and fine-grained granites (pers. comm. F. Neubauer 2014). Similar to the sediments of the Seewinkel Plain, they are generally loose and not cemented. Several-meter-thick loess deposits were observed at, for example, the southern scarp of the plateau (Figs. 5, 7b). If occurring, they appear clearly thinner on top of the plateau.

IRSL ages of Quaternary fluvial sediments of the Parndorf Plateau and the Seewinkel Plain

IRSL dating (Fig. 5; Table 3) of the sample NIC 1 from the Parndorf Plateau indicates an age in excess of the method (>300 ka). The luminescence signal of this sample was in saturation and thus only yielded a minimum actual equivalent dose (De) and age. The samples from the Seewinkel Plain show potassium-feldspar IRSL ages of 102 ± 11 ka (FAU 1) and 76 ± 8 ka (KIR 1) (Table 3).

Discussion

Age and provenance of the sedimentary units

The IRSL and mineralogical data presented in this study, together with heavy mineral spectra and lithological information of certain pebbles from the gravel layers, are used to identify the age and possible provenance areas of the investigated sedimentary units. Previously, age correlation was almost exclusively based on the altitude of terraces, diagenetical alteration of the sediments and heavy mineral composition (e.g., Szádeczky-Kardoss 1938; Tauber 1959a; Fuchs et al. 1985; Wessely 2006). This is especially problematic in tectonically active areas such as the Little Hungarian Plain (Székely et al. 2009).

The distribution of sediments in the study area can be outlined as follows: Pannonian (Upper Miocene) strata occur throughout the study area. They gradually thicken toward the depocenter of the Little Hungarian Plain further to the east as shown by shallow-lake seismics and industrial seismic data, and also supported by published studies (e.g., Tauber 1959a; Mattick et al. 1996). The Pannonian sediments are covered by Quaternary sediments, predominately fluvial sandy gravels, except for major parts beneath Lake Neusiedl as indicated by the shallow-lake seismics and lake drill cores of this study. Detailed mineralogical analysis of drill core NDS 7 from Lake Neusiedl indicates that the uppermost few centimeters represent Holocene lake sediments. The lack of a significant gravel layer directly beneath Lake Neusiedl (Tauber 1959a) is also supported by previous cores from the lake (Blohm 1974) and geoelectric measurements (Szarka et al. 2003). In the field, the (erosive) contact between Pannonian sediments and Quaternary gravels could only be observed on the Parndorf Plateau (Fig. 7a).

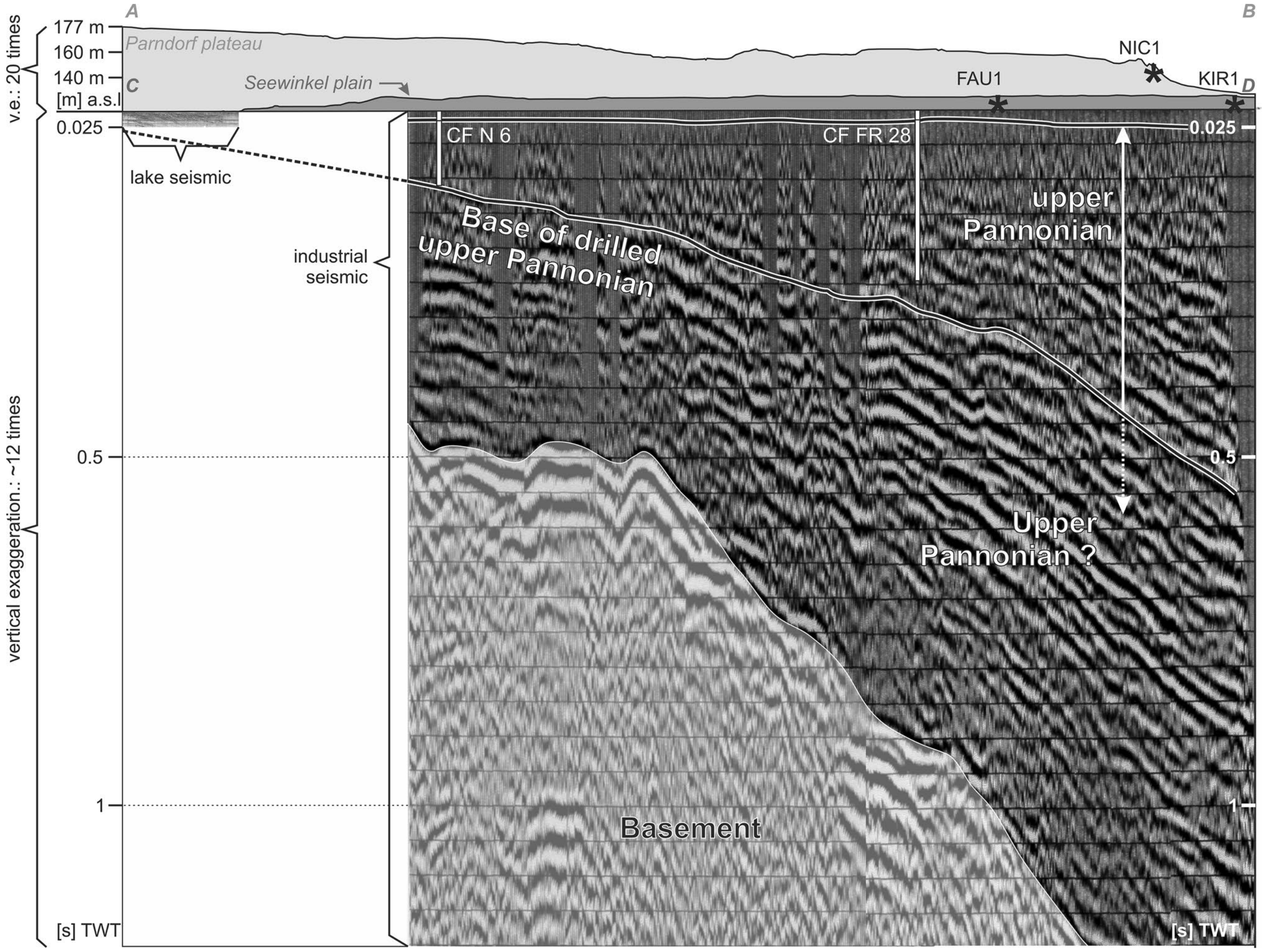


Fig. 12 Cross section of the study area with correlation of sediments within Lake Neusiedl to an onshore industrial seismic section (OMV 1970) rendered feasible by the acoustic velocity measurements and the link of seismic to well data. Sediments in the lake correspond to Upper Pannonian strata onshore. The deepest reflector that was still identified as upper Pannonian (Upper Miocene) with the help of the counterflush well CF N 6 is shown as "Base of the drilled upper Pannonian." The counterflush well CF FR 28 also ended within upper Pannonian strata. Note that two topographic sections (indicated in Fig. 5) and the IRSL sample locations have been projected onto the cross section

The measured IRSL ages from sand bodies within the Quaternary fluvial gravels indicate Late Pleistocene deposition of the upper gravel layer in the Seewinkel Plain and a Middle Pleistocene or older deposition of the gravels on the Parndorf Plateau. Häusler (2010) provided an OSL age of 95 ± 10 ka from the upper part of a gravel pit east of Wallern in the Seewinkel Plain (Fig. 1), supporting our geochronological data.

Lithological inspection of individual components of the uppermost gravel layer was performed in this study to determine the provenance of the Quaternary units. Some components from the KIR 1 sample were identified as gneisses and greenschist facies mylonites similar to Lower Austroalpine metamorphic rocks from the Wechsel unit (pers. comm. F. Neubauer 2014), which lies to the southwest of the study area (Fig. 1). Similar greenschist facies mylonites are also found in the Mesozoic basement rocks in the Leitha Mountains (Erkmen 2012). This observation is partly in accordance with Bernhauser (1962), who described gravel deposits below 120 m a.s.l. containing a variety of crystalline components, most probably from the Leitha Mountains or the Rust Hills, but possibly also from the Sopron Hills. Thus, the analysis of the gravel components from the study area does not show the source area unequivocally.

Heavy mineral assemblages from (Upper) Pleistocene sediments (FAU 1, KIR 1) indicate high amounts of garnet and staurolite, minor epidote and chloritoid, and varying, but significant amounts of green hornblende, attesting to a significant higher-grade metamorphic source area. The high abundance of garnet in the samples from the Seewinkel Plain (FAU 1, KIR 1), together with fibrolithic

Table 3 Overview of IRSL age measurement results

Sample ID	NIC 1	KIR 1	FAU 1
UTM coordinates			
x (m)	654116XX	651159 XX	644800 XX
y (m)	5312846XX	5300405 XX	5301258 XX
De (Gy) uncertainty	>600	228	221
		10	11
Measured radionuclide concentrations			
% K	1.08	1.06	1.40
Error (%K)	0.02	0.01	0.02
Th (ppm)	2.00	5.14	8.83
Error (ppm)	0.07	0.15	0.24
U (ppm)	0.38	1.23	2.28
Error (ppm)	0.01	0.03	0.04
Total dose rate (Gy/ka)	1.97	2.23	2.92
Error	0.19	0.21	0.27
Age (ka)	>300	102	76
Error		11	8

sillimanite and kyanite, points to upper greenschist metamorphic to lower amphibolite facies rocks and minimizes the possibility that the Leitha Mountains was a source for the sediments of this area (Fig. 1) (Schuster et al. 2001). The Leitha Mountains and adjacent Rust Hills also contain mica schists, but almost no garnet (Tauber 1959a). The heavy mineral data of upper Pleistocene sediments of this study more likely indicate a southern provenance by the presence of staurolite and kyanite in all samples (Table 2). They potentially derive from the metamorphic rocks of the Sopron Hills, which contain staurolite, andalusite and kyanite schists in higher tectonic levels and also occurrences of fibrolithic sillimanite within the Óbrennberg-Kaltes Bründl Series (Draganits 1998). A southerly provenance would be further supported by the lack of chromium spinel (Table 2), a mineral that is typical for many Gosau units in the Eastern Alps (Wagreich and Marschalko 1995), and the minor amounts of epidote (Table 2), which dominate the Upper Pleistocene fill of the Mitterndorf Basin within the southern Vienna Basin (Salcher 2008).

However, the recent sands of the southerly-derived Répce (Rabnitz) and Rába (Raab) Rivers (Schoklitsch 1962) show also high amounts of garnet, but plot further to the right in the log ratio diagrams (Fig. 11b) due to higher amounts of green hornblende and/or lower amounts of staurolite. Therefore, no clear distinction can be made between Danube-derived and southerly-derived (Répce/Rába Rivers) Pleistocene deposits using heavy minerals. Additionally, reworking from older, Miocene sediments (see below) cannot be excluded.

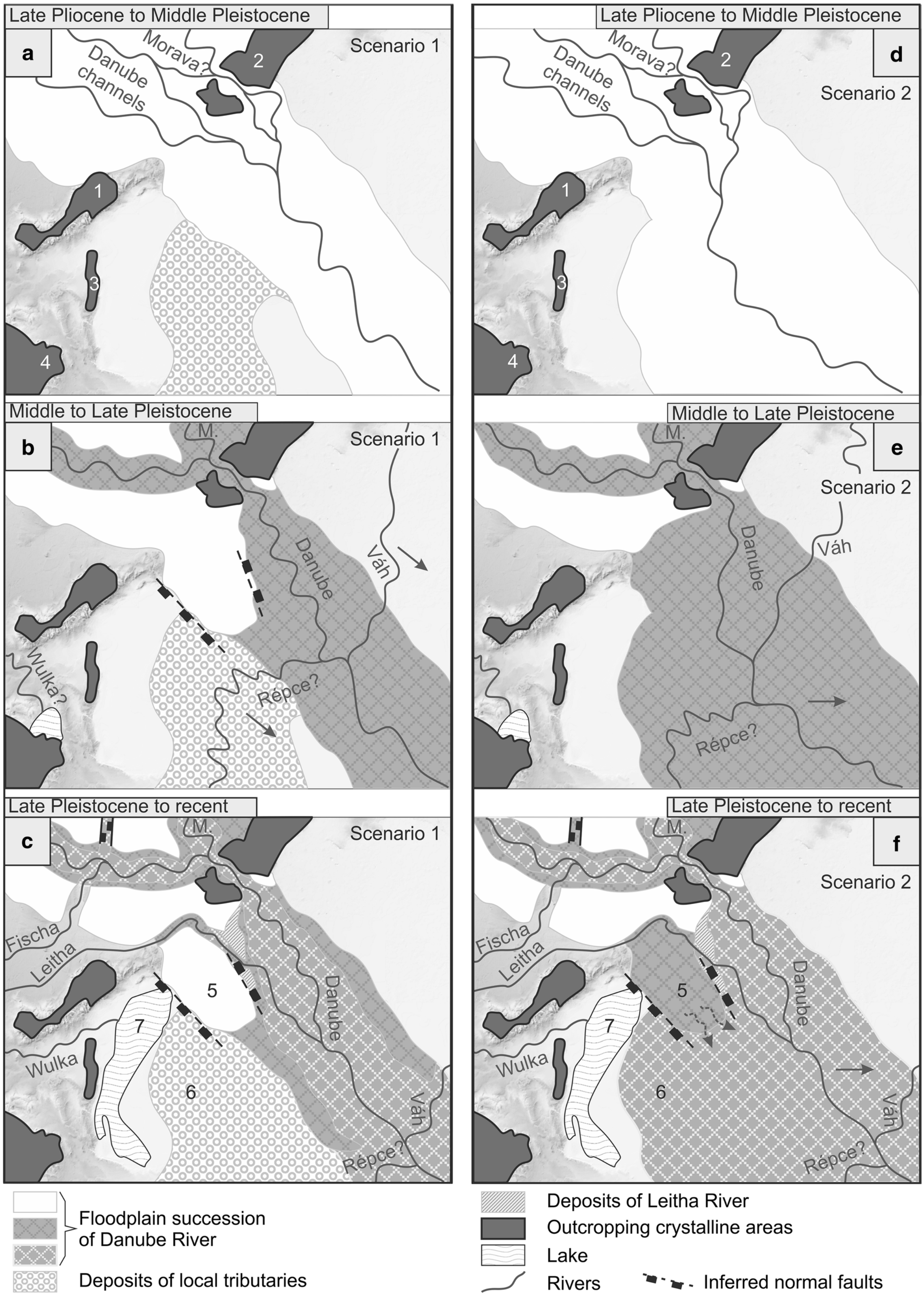
Upper Pannonian sediments directly below Lake Neusiedl show rather similar heavy mineral assemblages as the Upper Pannonian sediments from the Danube and sample NIC 1 from the Parndorf Plateau (Fig. 11c): They all have high amounts of garnet and staurolite, together with epidote and varying amounts of green hornblende and significant traces of kyanite and sillimanite. Green hornblende is significantly less abundant than staurolite, forcing almost all Pannonian samples to plot left of the zero-line. Pannonian sediments from the catchment of the Répce at Landsee, Drassmarkt and Bubendorf also show rather similar heavy mineral assemblages strongly dominated by garnet, but higher epidote percentages (Nebert et al. 1980; Schoklitsch 1962).

A major difference between the Upper Pannonian samples and the Quaternary samples from the Seewinkel Plain is that the latter have more abundant hornblende and fibrolithic sillimanite. This may indicate changing amounts of amphibolites within the source area, but may also be related to lower stability of hornblende during transport (Nebert et al. 1980; Mange and Maurer 1992). Note also that staurolite is present in all the sediments of the Danube terraces further downstream, in the Little Hungarian Plain (Csapó 1998). Based on these observations, a clear distinction can be made between Upper Pannonian and Quaternary strata, indicating a change in sediment transport and provenance since the Upper Pannonian.

The role of tectonics in shaping the topography of the Little Hungarian Plain

A regional uplift affecting the study area is indicated by staircase terrace formation and river incision (e.g., Starkel 2003; Salcher and Wagreich 2010). The incision rate at the eastern margin of the Little Hungarian Plain is in the order of 2.7 mm/a (Ruszkiczay-Rüdiger et al. 2005b), compared to only ca. 0.125 mm/a mean incision rate of the Mur River to the south of the study area (Wagner et al. 2010). Additionally to this regional uplift, local tectonics plays an important role in shaping the topography, as suggested by: (1) the elevation difference in the top of Pannonian between the Parndorf Plateau and the Seewinkel Plain (Figs. 3, 5), (2) the current position of older gravels on top of the Parndorf Plateau *versus* younger gravels in the Seewinkel Plain, (3) the linear elevated ridges in the Seewinkel Plain (Székely et al. 2009) (Fig. 4), (4) the remarkably straight scarps of the Parndorf Plateau with incised rivulets and dry valleys (Fig. 5) and (5) the constant thickness of the Quaternary gravel layer on the tilted Parndorf Plateau (Figs. 3, 12), indicating a post-Pannonian onset of tilting.

The top of the Pannonian (Upper Miocene) sediments in the lake area and the adjacent Seewinkel Plain is located at around 110 m a.s.l. In contrast, the top Pannonian of the Parndorf Plateau is up to 50 m higher and clearly tilted toward SE (Fig. 5). There was no river system capable of eroding the remarkably



straight southern scarp of the Parndorf Plateau or the areas around it. The minor role of fluvial erosion is also supported by the small catchment area of the Wulka River (Fig. 4) and, more importantly, by the lack of Quaternary fluvial sediments within Lake Neusiedl (Figs. 8, 9, 10). The lake seismic sections show indications of much older, Late Pannonian fluvial activity

◂**Fig. 13** Sketch maps of the two possible evolution models of the study area. The age constraint for the beginning of the first phase is derived from data on the filling up of the Lake Pannon (Kováč et al. 2006; Magyar et al. 2013). The onset of the second phase (ca. 640 Ka) is controlled by the northward migration of the Danube from the Gate of Bruck to the Gate of Devin (Halouzka and Minaříková 1977; Wessely 2006). The last phase is set to ca. 100 Ka due to the age of the gravel deposits in the Seewinkel Plain (this paper). The *gray arrows* indicate the migration of the river channels toward the east, toward the modern depocenter of the Little Hungarian Plain. River network is schematically drawn after Scharek et al. (2000a, b), Pišút (2002) and Petr et al. (2013). *1* Leitha Mountains, *2* Western Carpathians, *3* Rust Hills, *4* Sopron Hills, *5* Parndorf Plateau, *6* Seewinkel Plain, *7* Lake Neusiedl

(Fig. 9c, d). Székely et al. (2009) investigated the neotectonic origin of linear features in the Little Hungarian Plain that are oriented parallel to the scarps of the Parndorf Plateau (Fig. 4). In fact, NNE–SSW-trending grabens which were discovered in the Tertiary basement in a depth of more than 1500 m (Kilényi and Sefara 1989; Tari 1994) are parallel to the straight SE margin of the Parndorf Plateau. Evidence for neotectonic activity of basement features was provided by Zámolyi et al. (2010), who showed that planform channel geometries of the local tributaries of the Danube in the Little Hungarian Plain are affected by normal faulting. However, it has to be noted that, in contrast to other locations (e.g., the Lassee Fault in the Vienna Basin; Beidinger and Decker 2011), outcrop evidence of normal faults displacing the Quaternary sediments at the margins of the Parndorf Plateau has not been found. Fodor et al. (2005) report indications for deformation related to the latest Pliocene uplift of the basin flanks at the eastern margin of the Little Hungarian Plain (Vértes Hills, Transdanubian Range; Fig. 1), including steep scarps and fault reactivation along with burial of faults by Late Pleistocene loess. Compaction plays only a minor role for Quaternary strata (Tari 1994; Papp and Kalmár 1995). The present-day kinematics (Grenerczy et al. 2002) and observed reactivations of inherited structural elements (Fodor et al. 2005; Jarosinski et al. 2011; Minár et al. 2011) highlight the major influence of tectonic subsidence in the Little Hungarian Plain (Horváth and Cloetingh 1996) as well as in adjacent basins (e.g., Sachsenhofer et al. 1997). Thus, the overall dip of Upper Pannonian strata around 2° toward the east observed in the lake seismic and in industrial seismic sections (Figs. 4, 12) is interpreted to be the result of the undisturbed thermal subsidence phase between the post-Sarmatian basin inversion and the latest Pliocene compressional event (Horváth 1995, Horváth and Cloetingh 1996; Decker and Peresson 1996). The small-scale faulting confined to specific Upper Pannonian layers in certain seismic sections (Fig. 9a, b) is interpreted as slumping-related deformation that shows up very well due to the alternating sand and clay layers (compare Alsop and Shmuel 2011). The increase in slope also indicates ongoing subsidence during the Late Pannonian and Pliocene. The differences in elevations between the Parndorf Plateau and the Seewinkel Plain are most likely the result of local post-Pannonian to Pleistocene normal faulting.

Quaternary landscape evolution models

The recent configuration of the Lake Neusiedl region is mainly the result of processes related to regional uplift and local subsidence. Similar, but much smaller-scale configurations are known also in the northern Danube Basin (e.g., Petr et al. 2013). The influence of Quaternary climate in our study area remains speculative due to the lack of a more complete sedimentary record. Ages from the exposed, upper fluvial gravel layers of the Seewinkel Plain (e.g., FAU 1, KIR 1) exclusively fall into the early stages of the last glacial period. However, we cannot exclude reworking or the occurrence of older fluvial sediments beneath these upper layers. Ages and the stratigraphic context (i.e., lack of unconformities in the studied outcrops) suggest that the sedimentation of these upper layers of the Seewinkel Plain took place during a relatively short depositional phase. Such a distinctive and limited time period for deposition (i.e., few tens of thousands of years) is regionally uncommon for an active basin setting, where generally longer records of climatic and/or tectonically driven sequences are preserved (e.g., Decker et al. 2005; Salcher and Wagreich 2010). Remarkably, the deposits do not seem to reach the area of Lake Neusiedl hosting only much older, Upper Pannonian (Upper Miocene) sediments. The change in sediment distribution roughly coincides with the lake's eastern shore. In accordance, the thickening of the Quaternary fluvial sediments toward the east, on top of the tilted Pannonian sediments, highlights the progressive loss of accumulation space toward the west. The lack of significant gravel deposits beneath Lake Neusiedl cannot be explained by erosional processes, a view also shared by Tauber (1959a). The lack of a protective gravel layer, however, provides a surface that is sensitive to wind erosion, and this process may have contributed to the formation of the lake bed, since eolian erosion features are common in adjacent areas (Sebe et al. 2015). Furthermore, the thick loess deposits accumulated along the southern slope of the Parndorf Plateau (Fig. 7b) highlight the important role of wind during different periods of the Quaternary.

The fluvial gravels on the Parndorf Plateau are significantly older than the dated fluvial sediments of the Seewinkel Plain, and they are located approximately 45 m higher (measured from Top Pannonian/Base Quaternary). However, Quaternary sediments on the plateau are too old for an absolute age using the IRSL method. An interpretation of the Parndorf Plateau as Danube terrace can clearly be derived from sediment provenance and depositional geometry (Szádeczky-Kardoss 1938; Tauber 1959b). Ruszkiczay-Rüdiger et al. (2016) correlate the Parndorf Plateau with the >700 ka old terrace level tIV–VI at the eastern margin of the Little Hungarian Plain, just to the east of Győr (Fig. 1). They suggest an onset of terrace formation during the "mid-Pleistocene climate transition" (ca. 1.2–0.7 Ma) of Clark et al. (2006).

Fluvial sediments now on top of the Parndorf Plateau might not have reached the area of modern Lake Neusiedl. In fact, outcrops at or near the scarp's slope (e.g., at Edmundshof and Mönchhof) suggest no or only very minor (few dm thick) coverage of fluvial sediments (Fig. 7a, b) unconformably resting on top of Pannonian strata. The former floodplain of the Danube might therefore not have been extensive enough to cover the area of the modern lake. This view is supported by the lack of a continuous Quaternary gravel layer within the northern part of the lake. The seismic data show channel features in the Upper Pannonian strata within the lake (Fig. 9c, d). Similar features were also mentioned by Hodits (2006). However, the age of these features is unclear. Uhrin and Sztanó (2012) used seismic data to infer a rather constant lake level excluding major lake-level drops or major transgressions prior to 6 Ma constraining the formation of the channel features.

The age of scarp formation and tectonic separation of the Parndorf Plateau from the surrounding lower areas remains vague. A paleosol complex interbedded with thick loess deposits that crops out along the scarp slope may suggest an age that clearly exceeds the Late Pleistocene (Fig. 7b). Seismic activity at the western limit of the Parndorf Plateau indicates still ongoing normal faulting in this area (Lenhardt 2000).

While the provenance of the fluvial deposits on the Parndorf Plateau can clearly be attributed to the catchment of the Danube, the provenance of the younger sediments in the Seewinkel Plain is less clear. There are two possible scenarios for the deposition of the Quaternary sediments on the Parndorf Plateau and the Seewinkel Plain, suggesting either (1) an origin from the south (e.g., Répce) or (2) an origin from the north, the Danube (Fig. 13). The two scenarios are deliberately shown as sketch maps due to the focus on timing and mechanism of key events in the landscape evolution of the study area.

Scenario (1): The Danube deposited its sediments on the area of the recent Parndorf Plateau and shifted toward the north (Szádeczky-Kardoss 1937; Halouzka and Minaríková 1977; Wessely 2006 and citations therein) (Fig. 13a, b). The northward shift of the Danube into the Gate of Devin (Fig. 13b) can be explained by a major incision phase, probably linked to the uplift of the Western Carpathians and the Leitha Mountains (Wessely 1961, 2006). Due to subsequent post-Pannonian normal faulting and subsidence, the Parndorf Plateau formed an elevated region, probably at the time of the deposition of the gravels in the Seewinkel Plain (Fig. 13b). In this scenario, it is assumed that local tributaries from the south (similar to the modern Ikva or Répce rivers) deposited and/or reworked the gravel layer of the Seewinkel Plain (Fig. 13a–c). Distribution was already limited by the Parndorf Plateau in the north, but also the absence of accumulation space in the west. Fuchs (1974) states that the composition and depositional geometry of gravels within the Seewinkel Plain point toward an origin from the south, which would fit with the occurrence of staurolite (this study), gravel components from the Wechsel unit (this study) and the fact that the quartz of the Seewinkel sediments is not suitable for OSL dating, in contrast to samples from Danube River sediments. During the Late Pleistocene, during deepening of the depocenter around Győr (Joó 1992, Gábris and Nádor 2007, Lovász 2007) (Fig. 1), the main channels of the tributaries migrated toward the east, to their current positions (Fig. 13c, see also Lovász 2007) and the distinct orientation of the modern drainage pattern evolved. Cold or cool climate plays an important role in triggering physical erosion in the hinterland (e.g., Salcher and Wagreich et al. 2010) increasing the sediment supply of the streams. A higher sediment supply might have caused the excessive fill of accumulation space created through subsidence forming a distributive fluvial system (i.e., alluvial or fluvial fan; Weissmann et al. 2010). Consequently, a switch to a distributive fluvial system would provide a (much) larger potential for local spatial accumulation within a given period of time. The derived ages from the Seewinkel sediments may then reflect the youngest depositional (or reworking) event. In turn, last glacial maximum or later fan activity may not have been extensive enough to reach the area of the Seewinkel Plain. A rather small catchment size is also indicated by a low ZTR ratio, suggesting short transportation distances.

Scenario (2): The Danube developed a wide floodplain spreading across the whole Seewinkel Plain and on the area of the not yet elevated Parndorf Plateau (Fig. 13d) up to the Late Pleistocene. Thus, in this scenario, some younger gravel deposits (i.e., 300 ka) might have existed on the Parndorf Plateau, before they were (partly) eroded (Fig. 13f). This scenario is based on foreset orientations and component analysis of Szádeczky-Kardoss (1938), Tauber (1959b) and Husz (1965). Szádeczky-Kardoss´s (1938) measurements indicate a WSW–SE-directed paleocurrent. The formation of the Parndorf Plateau through normal faulting occurred much later compared to scenario (1), taking place during or even after the deposition of the fluvial gravels in the Seewinkel Plain in the Late Pleistocene (100 ka). Gully erosion may then have removed most of this young and thin fluvial cover resting on top of the older (>300 ka) fluvial remnants (Fig. 13f).

Conclusions

Based on the integration of new geophysical, sedimentological and geochronological data, we presented a Quaternary landscape evolution model of the complex tectonic and depositional history of the western margin of the Little Hungarian Plain.

The western margin of the Little Hungarian Plain is dominated by Pannonian marine to brackish clastic sediments that are covered by fluvial, coarse-grained sediments to the north and east of Lake Neusiedl on the Parndorf Plateau and the Seewinkel Plain. Infrared-stimulated luminescence dating of the fluvial cover of the Pannonian sediments of the Parndorf Plateau indicates an age in excess of the IRSL method (>300 ka). Samples from the uppermost layers of the fluvial sediments from the Seewinkel Plain show much younger, Late Pleistocene, potassium-feldspar IRSL ages.

This age relationship may indicate the onset of the tectonic displacement between both areas before the latest Pleistocene. Normal faulting between the Parndorf Plateau and the surrounding Seewinkel Plain is not only indicated by sediment deposition ages and the degree of weathering, but also by geomorphological features (i.e., straight scarps, highly incised rivulets) and active seismicity. The present-day morphology of the western margin of the Little Hungarian Plain is controlled by Latest Pliocene–Quaternary tectonic subsidence. Quaternary fluvial sediments in the Seewinkel Plain are thickening toward the east, following the overall trend of subsidence. In contrast, the Quaternary sediments on the Parndorf Plateau follow the overall tilt of the plateau.

While the Quaternary sediments from the Parndorf Plateau can be attributed to the Danube, the provenance of the Late Pleistocene sediments in the Seewinkel Plain remains ambiguous even though the heavy mineral assemblages from the Seewinkel Plain differ in specific minerals from the assemblage from the Parndorf Plateau. However, the low ZTR (zircon, tourmaline, rutile) ratio of all samples indicates a short transportation distance of the Pleistocene sediments of the study area.

Shallow-lake seismic data and up to 3-m-deep drill cores from the area of the modern Lake Neusiedl show the lack of fluvial, coarse-grained Quaternary deposits and the presence of only very thin layers of recent lake sediments, underlain by highly compacted Upper Pannonian clays to sands. These truncated and tilted Upper Pannonian sediments are cut by numerous small-scale normal faults indicating Late Pannonian faulting. The major NE–SW-striking fault postulated in earlier literature could not be verified in the shallow-lake seismic data covering the uppermost ~20 m of Upper Pannonian strata.

We conclude that the absence of Quaternary fluvial, coarse-grained sediments above the Upper Pannonian marine to brackish strata was a major factor for lake formation and indicates relatively young subsidence of this area. The sediment-starved basin of Lake Neusiedl developed in an interplay between tectonic subsidence triggering eastward river channel migration and local normal faulting creating the elevated Parndorf Plateau that impeded rivers (e.g., Danube, Leitha) from flowing into this area.

Our study reveals that the Little Hungarian Plain represented a balanced basin at least up to the Late Pleistocene. Although age data and stratigraphic observations are indicative, it is not fully clear whether the fluvial cover of the Seewinkel Plain developed from a short-lived depositional event (i.e., only some 10 ka) or fluvial reworking did repeatedly occur. Considering the IRSL ages form the Seewinkel Plain referring to the onset of the last glacial period, strong sediment pulses associated with very cold periods as regionally observed may not have played a significant role. The impact of climate in providing abundant sediment remains unclear and awaits further clarification.

Acknowledgments This study was supported by the Austrian Science Fund (FWF projects P20092-N10 and V151-N22) and University project FA 536001 [Karpatian Tectonics II]. Field work of the lake drillings and shallow-lake seismics was kindly supported by the Biologische Station (Alois Herzig), UWITEC, and students of the University of Vienna, Eötvös Loránd University, Budapest, and the University of Leeds. Many thanks to Maria Heinrich for the access to the counterflush data in the drill core archive of the Austrian Geological Survey and to OMV Austria Exploration and Production GmbH for the permission to use seismic lines in the Seewinkel area. The authors thank Franz Neubauer very much for the petrographic review of outcrop samples, Mathias Harzhauser for the paleontological investigation of the lake drill cores, Zsófia Ruszkiczay-Rüdiger for extensive discussions on the role of eolian erosion, Magda Bottig for heavy mineral counting, Markus Schwab for logistic support with coring and Hugh Rice for improving content and style. The improvements by Michal Kováč and an anonymous reviewer are highly appreciated.

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