Lake Neusiedl Area: A Particular Lakescape at the Boundary Between Alps and Pannonian Basin

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Abstract

The Lake Neusiedl area is a unique lakescape, situated at the geodynamical and geomorphological boundary between the Alps, Carpathians and the Pannonian Basin, and therefore represents an important transition zone concerning terrain, climate, vegetation, fauna and cultures. We use geomorphological as well as geological data, topographical and historical maps plus historical charters to reconstruct the palaeohydrology of Lake Neusiedl and document dramatic landscape changes, especially in the last centuries. The present-day hydrological conditions of and processes at Lake Neusiedl are very different from those in the past. Virtually, all historical maps before 1780 show the Ikva River, Répce (Rabnitz) River and Kis-Rába River discharging into the connected Neusiedlersee/Hanság area that possessed a natural outlet, the Rábca River. The documented episodic variation of the water levels of Lake Neusiedl between desiccation and highest flood levels is c. 4.2 m, affecting enormous areas in this extremely low-relief region, with a huge impact on the landscape, fauna and vegetation, human settlement patterns, land use and communication routes—which should be considered in regional archaeological and historical interpretations. The numerous shallow lakes and presently dry basins in the Seewinkel originally formed as thermokarst lakes during early Lateglacial permafrost degradation after the end of the Late Glacial Maximum (LGM).

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13.1 Introduction

Lake Neusiedl (German: *Neusiedler See*, Hungarian: *Fertő-tó*) area (Fig. 13.1) is the westernmost extension of the Little Hungarian Plain (Hungarian: *Kisalföld*) and characterized by low-lying, low-relief landscapes, dominated by Quaternary fluvial and lacustrine sediments, deposited on top of upper Pannonian (=Tortonian, upper Miocene) sediments (Fuchs and Schreiber 1985). This region is situated at the geodynamical and geomorphological boundary between the Alps, Carpathians and the Pannonian Basin (Székely et al. 2009) and represents an important transition zone concerning terrain, climate, vegetation, fauna and culture (Oberleitner et al. 2006; Korner 2008; Fally and Kárpáti 2012; Molnár et al. 2012; Boros et al. 2013). Grounded on the region's unique landscape and natural importance, a part of this area was declared a transnational Neusiedler See-Seewinkel National Park in 1992 and UNESCO World Heritage Site in 2001 (Fally and Kárpáti 2012).

Visualization of high-resolution digital terrain models (DTM) with 1 × 1 m resolution, derived from airborne laser scanning (ALS) measured in April 2010, is essential for the geomorphological investigation of this low-relief area (Figs. 13.1 and 13.2) (Doneus and Briese 2006; Mandlburger et al. 2009). In this low-relief landscape, even moderate lake level variations impact large areas. Thus, they are well visible in historical maps, which, therefore, represent invaluable sources for hydrological reconstructions (Csaplovics 2005; Draganits et al. 2008). As elevation information in maps and documents is affected by the difference in the Austrian and Hungarian levelling system, the latter being

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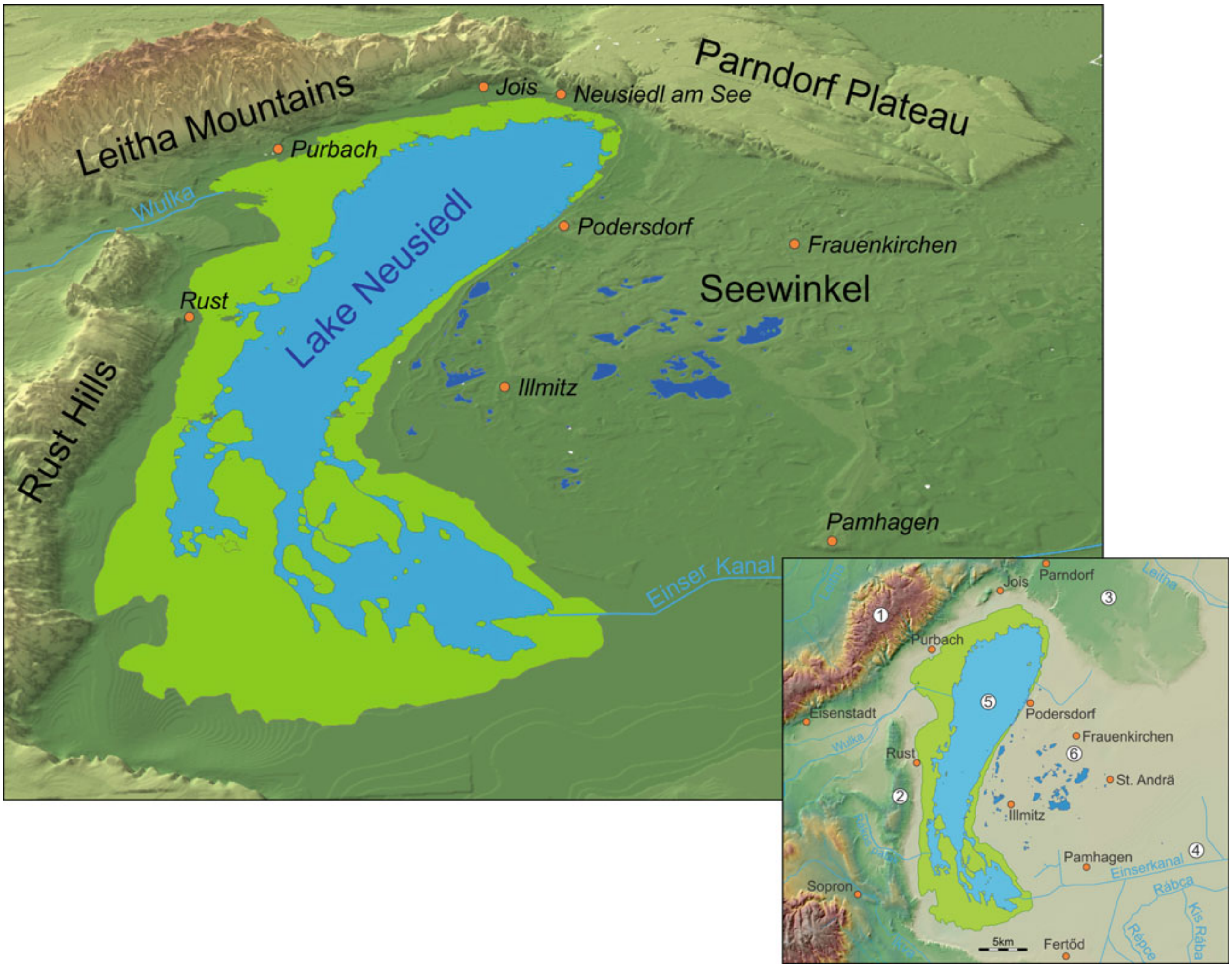

Fig. 13.1 Overview of the topography of the Lake Neusiedl area. Geomorphological elements are labelled in the order, they are mentioned in the text. Lake Neusiedl: light blue; reed area: light green; shallow lakes of the Seewinkel: blue. Oblique view is 8-times vertically exaggerated. Topographic data are a combination of 10 × 10 m DTM in the Austrian part and lower resolution data for the Hungarian portion

49.6–60.6 cm lower (Höggerl 2013), all altitude values were transformed to the Austrian system.

Lake Neusiedl, located at the political border of Austria and Hungary, is the most prominent geomorphological element of this area and thus receives most attention in this context. The previous studies about the lake are summarized in Sauerzopf (1959a), Löffler (1974, 1979), Fally and Kárpáti (2012) and Wolfram et al. (2014).

13.2 Geodynamical Setting

The boundary between the Eastern Alps, Carpathians and the Pannonian Basin represents a complex deformation zone, which has been active since the Early Miocene (Székely et al. 2009; Zámolyi et al. 2016). The tectonic processes in this area result from the collision of the Adriatic and Eurasian plates and are dominated by lateral escape and extensional collapse. Geomorphologically, significant tectonic activity in this area is indicated by seismicity (Tóth et al. 2007; Häusler et al. 2010), linear features related to normal- and strike-slip faults (Székely et al. 2009; Zámolyi et al. 2016) as well as tectonically influenced river courses (Zámolyi et al. 2010).

In the low-relief Little Hungarian Plain, hydrology is strongly influenced by active vertical crustal movements with highest recent subsidence values around 1–2 mm/year at the depocentre at Győr (Joó 1992). Long-lasting subsidence in this area is indicated by >8000 m thick Neogene sediments and >600 m thick Quaternary sediments (Scharek 1991). This subsidence causes tilting of the Lake Neusiedl area towards the east, and consequently, the thickness of

Fig. 13.2 Aerial photo from south of Podersdorf towards south-southwest, showing (left to right) the lakescape of the Seewinkel, the shore-parallel ridge (*Seedamm*) with some tree cover, followed by the brownish reed area and finally the southern part of Lake Neusiedl towards the west; The largest shallow lake in the foreground is the Oberer Stinker See. Photo: A. Ziegler, 20.12.2014

Pannonian sediments increases from zero at the Leitha Mountains to >2000 m below the Hanság south of the Seewinkel (Fuchs and Schreiber 1985). Similarly, Quaternary sediments thicken from virtually zero at Lake Neusiedl to >20 m below the Hanság (Tauber 1959).

13.3 Geomorphological Units

13.3.1 Leitha Mountains

The Leitha Mountains (Fig. 13.1, No. 1) are a NE-SW trending hilly landscape, rising above the surrounding low-relief areas from around 118 to 484 m asl. Despite their relatively low altitude, they represent a considerable weather divide, contributing to lower precipitation in the Lake Neusiedl area. Geologically, the Leitha Mountains represent a tectonic horst comprising Lower Austroalpine schists, gneisses and amphibolites overlain by low-grade metamorphic Triassic quartzites and dolomites (Pistotnik et al. 1993; Spahić and Rundić 2015). At the rim of the Leitha Mountains, these metamorphic rocks are covered by Badenian to Sarmatian (=Langhium to Serravallium, Middle Miocene) clastic sediments and limestones (Pistotnik et al. 1993; Wiedl et al. 2014).

13.3.2 Rust Hills

The Rust Hills (Fig. 13.1, No. 2) form a narrow N-S trending ridge with altitudes between 118 and 283 m asl at the western margin of the Lake Neusiedl. 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). The Rust Hills are a tectonic horst, bordered by N-S trending normal faults, which affects both the Neogene cover and the basement rocks (Fuchs 1965; Spahić and Rundić 2015).

13.3.3 Parndorf Plateau

The Parndorf Plateau (Fig. 13.1, No. 3) represents a relatively even surface comprising Pannonian clastic sediments with a thin Pleistocene fluvial cover left by the Danube. It is elevated about 25–45 m above the surrounding lowland and its surface gently dips from northwest with around 184 m to some 144 m asl in the southeast. In the northwest, the Parndorf Plateau has a narrow connection with Danube terraces of the Vienna Basin, whilst in all other directions, it shows distinct slopes (Fig. 13.1). The Parndorf Plateau is dissected by dominantly northwest-southeast oriented dry valleys, which possibly represent periglacial features. Zámolyi et al. (2016) summarized arguments for a tectonic origin of the Parndorf Plateau.

13.3.4 Hanság/Waasen (Former) Wetlands

The Hanság depression (Fig. 13.1, No. 4) is an extremely flat area south of the Seewinkel Plain with an altitude below 117.5 m asl. Before drainage, this area was an extensive alder wetland (Fally and Kárpáti 2012) in the southeastern continuation of Lake Neusiedl. During episodic high water levels, this area formed a continuous L-shaped lake with Lake Neusiedl. In many places, a <0.5 m thin cover of peat is still preserved (Löffler 2000).

13.3.5 Seewinkel

The Seewinkel (Fig. 13.1, No. 6) is bordered by Lake Neusiedl in the west, the Parndorf Plateau in the northeast and the Hanság in the south. The name Seewinkel (*Winkel* = English: angle, corner) possibly originates from the former larger, L-shaped Lake Neusiedl with the Seewinkel in the corner of the 'L'. This roughly 300 km^2 large area is one of the flattest regions of Austria with less than 17 m relief variation. It contains the lowest area of Austria (c. 113 m asl), and its highest point is a small mound northwest of Frauenkirchen with the top at 130 m asl, which rises >4 m above the surrounding surface and is a (probably Iron Age) burial mound (Lindinger 1996).

13.4 Lake Neusiedl

The present-day (!) conditions of Lake Neusiedl are

(i) Largest lake of Austria: 321 km^2 (143 km^2 open water, 178 km^2 reed area; calculated for 116.50 m asl, Bácsatyai et al. 1997).
(ii) Exact lake level adjustment since 1965 (Wasserportal Burgenland 2016).
(iii) End of June 2016 lake level is 115.66 m asl (Wasserportal Burgenland 2016).
(iv) The average lake level of the last 10 years is 115.63 m asl, which is higher than in the period 1965–2006 (115.47 m asl) (Wasserportal Burgenland 2016).
(v) Average depth is only around 1.4 m (Heine et al. 2014).
(vi) Catchment area is 1120 km^2 (Herzig 2014).
(vii) On average, during the period 1965–2012, precipitation contributed 76% of the lake water and river inflow 24%; lake water is reduced by evaporation (89%) and drainage through the artificial outlet 'Einser Kanal' (Hungarian: *Hanság-főcsatorna*) (11%) (Maracek and Kubu 2014).
(viii) Chemically (Knie 1959), the lake belongs to subsaline lakes (Hammer 1986).
(ix) Lake Neusiedl is an endoreic lake and commonly called 'steppe lake' (Sauerzopf 1959a; Löffler 1974).

13.4.1 Origin of Lake Neusiedl

In contrast to most lakes in the Circum-Alpine area, which occupy glacially overdeepened valley floors, Lake Neusiedl lies outside the formerly glaciated areas (van Husen 1987), and therefore, other formation processes must have been involved. The lake is very shallow, and in contrast to deeper lakes, only less than 0.7 m thick lake sediments are deposited at the bottom (Heine et al. 2016), because even moderate wind generates waves that erode the lake floor.

Tauber (1959) and Löffler (1979) discussed various hypotheses of the formation of Lake Neusiedl. Hassinger (1905) proposed that the depression of Lake Neusiedl was formed by erosion by the Danube. This hypothesis was rejected because of the lack of any substantial gravel on top of the Pannonian sediments at the lake bottom of Lake Neusiedl (Küpper 1957). Formation by deflation has already been rejected by Wiche (1951). Finally, Szádeczky-Kardoss (1938) as well as Küpper (1957) suggested a tectonic origin of Lake Neusiedl depression. Tectonic activity, probably in a Horst-Graben type deformation style (Spahić and Rundić 2015), has been supported in several recent studies (Székely et al. 2009; Häusler et al. 2010; Zámolyi et al. 2016; Loisl et al. 2018). The steep eastern side of Hackelsberg, next to Jois, is most probably a normal fault, juxtaposing metamorphic rocks in the west besides Holocene Lake sediments in the east (Fig. 13.3a).

13.4.2 Age of Lake Neusiedl

Surprisingly, the age of Lake Neusiedl is still uncertain. So far, no well-defined geochronological age exists, but an age estimate is between 12 and 14 000 years, based mainly on ostracods (e.g. Löffler 1990). The only areas with thicker lake sediments are in reed areas (Löffler 1990) and around the present lake in areas up to about 117.5 m asl (Szontagh

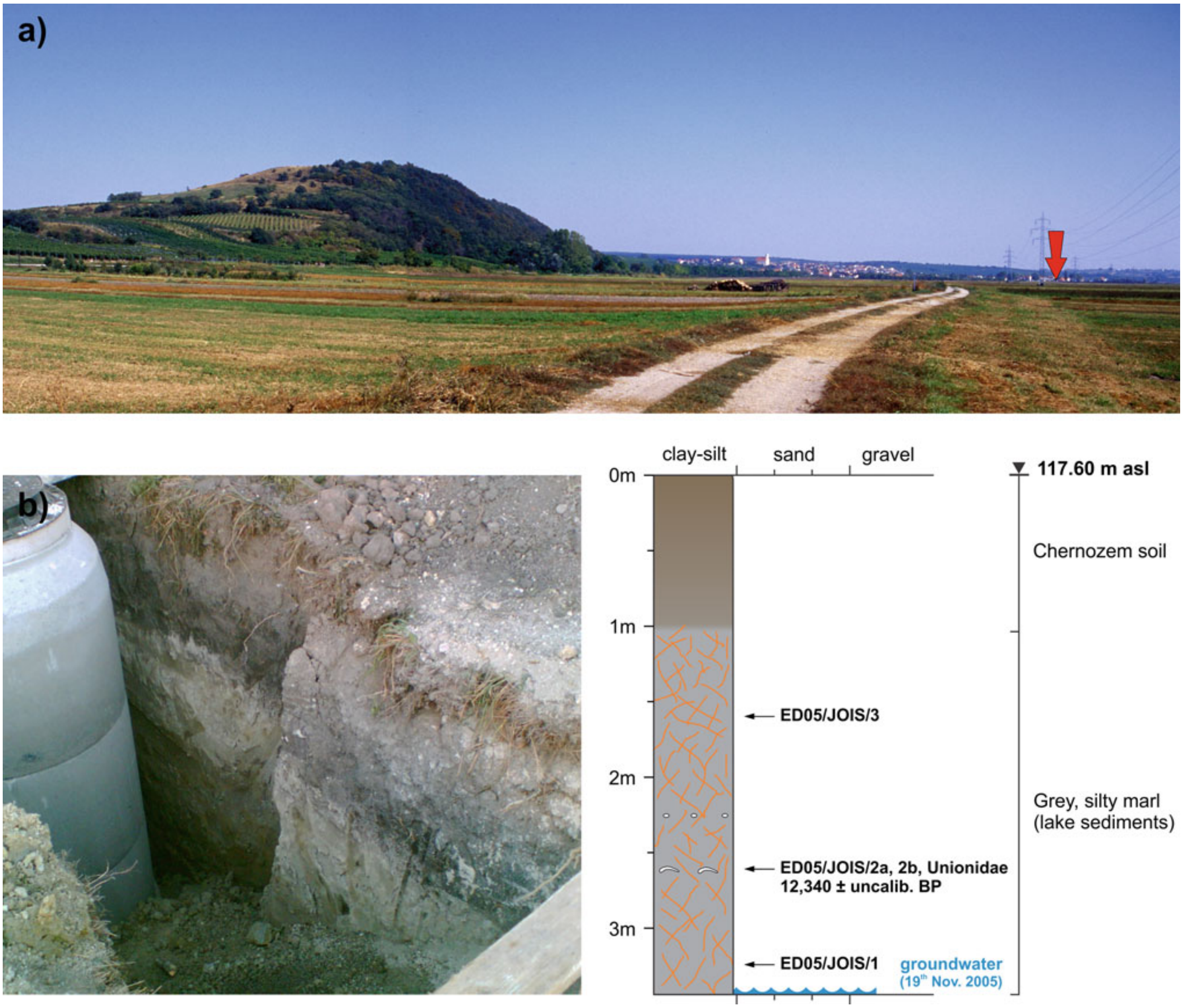

Fig. 13.3 **a** Steep eastern slope of Hackelsberg, probably representing a normal fault, juxtaposing Lower Austroalpine metamorphic rocks against Holocene lake sediments. Note the extreme flatness of the former inundation area of Lake Neusiedl up to more or less the fault scarp. Approximate location of profile in Fig. 13.3b is indicated by red arrow. Photo taken from northeast of Winden am See towards northeast: Photo: E. Draganits, 24.9. 2006. **b** Trench exposing 3.5 m lithostratigraphy above the ground water, east of Jois (N47°57′14.1″; E016°47′30.8″; ±5 m). Below **c** 1 m of Chernozem soil are silty lake marls with hardly any indication of bedding except for two horizons, one with quartz pebbles and another one with Unionidae shells. Photo: E. Draganits, 19.11.2005

1904; Draganits et al. 2007). There is lake water with high content of suspended sediment flooded the surrounding of the lake, and later, during slow lake level drop, sediment was trapped in the vegetation. A construction trench within the former lake east of Jois exposed two horizons with Unionidae shells (Fig. 13.3b). The shells have been radiocarbon dated and yield an uncalibrated age of 12,340 ± 70 years BP (1σ confidence interval) (Table 13.1). As the radiocarbon age is not calibrated and the investigated trench did not reach the base of the lake sediments, this age represents a minimum age.

13.4.3 Palaeohydrology of Lake Neusiedl

There are many detailed studies about the limnology of Lake Neusiedl, including climate variations, precipitation and evaporation measurements, etc., (Sauerzopf 1959a; Löffler 1979; Eitzinger et al. 2009; Soja et al. 2013; Wolfram et al. 2014). We use geological (e.g. lake sediments), geomorphological (e.g. ALS DTM, palaeo shorelines, ice-push ridges), topographical and historical maps as well as historical charters to evidence dramatic changes of the lake, especially in the last centuries.

Table 13.1 Radiocarbon data from Unionidae shells from the lake section at Jois (Fig. 13.3b)

Sample	Laboratory number	$d^{13}C$*[‰]	^{14}C-age* [BP]
ED05/JOIS/2b[a]	LTL3911A	−5.5 ± 0.1	12,340 ± 70

[a] Unionidae bivalve shells (Fig 27_4); CEDAD radiocarbon facility in Brindisi

* 1σ confidence interval

Some major hydrologic interventions for flood control and reclamation of wetland areas are responsible for the present-day conditions of the lake. The earliest preserved record of intervention into the lake's hydrology is a charter from June 5th 1568 archived in the Austrian *Finanz-und Hofkammerarchiv* in Vienna, documenting a considerable reduction of the lake level caused by a diversion of the Rabnitz River (Anonymous 1568). Probably, the most important intervention was the building of a dam road between Pamhagen and Fertőd (Fig. 13.1), which was finished in 1780 (Fig. 13.4, Korabinszky 1804). At the beginning, there existed some passages for water, which were closed later, cutting off the lake from important tributaries including Ikva and Répce Rivers.

The so called 'Einser Kanal' was connected with the lake in 1909 (Hicke 1996) and used to drain water from the lake. Since 1965, the Einser Kanal is used to remove water only if necessary—thus raising the average lake level (Wasserportal Burgenland 2016).

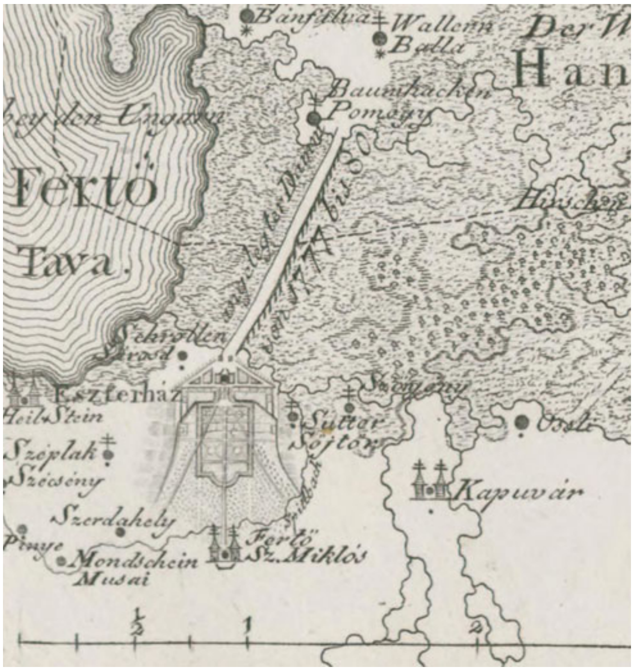

Fig. 13.4 Historical map showing the dam road between Pamhagen and Fertőd and the year of completion (Korabinszky 1804, Table XXIV; Digital Collections of the University Library Regensburg, W 02/8 5392)

Daily lake level measurements in Austria started in Neusiedl am See on June 1st 1930 (HDÖ 1938). Since then, the minimum lake level was 114.50 m asl (July 1949), the maximum value reached 116.08 m asl (May 1941) and the mean value is 115.57 m asl (Wasserportal Burgenland 2016). Lake levels before 1930 have been reconstructed mainly using maps and historical charters (Sauerzopf 1959b; Kopf 1963; Kiss 2009–2010). Kiss (2009, 2010) rightly questioned reconstructions based on terms like lake/river/bog in charters, leaving only few clear indications of the lake level before about 1784.

Larger lake extents than at present are clearly indicated by historical topographic maps (Fig. 13.5 and Csaplovics 2005) and lake deposits (Draganits et al. 2007). The investigated lake sediments east of Jois (Figs. 13.1 and 13.3b) comprise c. 3.5 m thick greyish, silty marl covered by Chernozem soil (Fig. 13.3b). Based on the content of characteristic authigenic carbonate minerals (Neuhuber et al. 2015), the silty marl unequivocally represents lake sediments. The investigated section is situated close to the western termination of an extremely flat area, in geomorphological continuity with the lake. Thus, the top of the section (117.65 m asl) is very close to the maximum inundation level of the lake during episodic flood events. What are the explanations for such high water levels of Lake Neusiedl (Figs. 5 and 6)? The lake's palaeohydrology cannot be understood based on its present conditions (e.g. Sauerzopf 1959a; Löffler 1979; Wasserportal Burgenland 2016), but only in the context of its entire palaeohydrological history. This includes its entire catchment prior to the construction of the dam road between Pamhagen and Fertőd in 1780 and the later closure of the dam's passages, its former natural outlet, the Rábca River, debouching into the Mosoni-Duna River at Győr (Fig. 13.7) (see Kopf 1963).

A combination of several factors may have contributed to episodically higher lake levels in the past (Fig. 13.6) including (i) climate variability (Eitzinger et al. 2009), (ii) less or no artificial drainage, (iii) changes in topography due to active vertical movements (Joó 1992) and (iv) the former larger catchment. It is important to remember that the maximum flood levels at the Rába gauge at Győr range between 115.85 and 115.96 m asl (altitude corrected for the difference in Austrian and Hungarian levelling systems) (http://www.edukovizig.hu/map/layout.html). Flooding in this area reportedly caused afflux of the Répce (Rabnitz) River and Kis-Rába River and consequently flooding of the Lake Neusiedl/Hanság lowland from the east (e.g. Kugler 1871). Virtually, all historical maps before 1780 show the Ikva River (383 km^2 additional catchment), Répce (Rabnitz) River (1268 km^2) and Kis-Rába River (6649 km^2) discharging into the connected Neusiedlersee/Hanság area

Fig. 13.5 Historical map from 1788 showing the intimate connection between Lake Neusiedl and the Hanság, shortly after the road between Pamhagen and Fertőd was completed (Hegedűs 1788, Országos Széchényi Könyvtár, TK 1614). Note that the Ikva, Répce and Kis Rába rivers drain into the connected Lake Neusiedl/Hanság system

(Fig. 13.7). Larger lake size and larger wetlands east of the lake may have also provided ideal habitats for malaria transmitting mosquitos (see Bruce-Chwatt and de Zulueta 1980; Wernsdorfer 2002).

Most historical maps show a natural outlet, the Rábca River (Fig. 13.5) (e.g. Zeller 1753; Hegedűs 1788), and consequently, Lake Neusiedl was unlikely an endoreic lake in most periods before 1780. Even in the period 1965–2012, when the Wulka River was its only major tributary, on average 11% of the lake's water was drained by the artificial Einser Kanal (Maracek and Kubu 2014). The much larger palaeohydrological catchment before c. 1780 also suggests a lower salt content of Lake Neusiedl compared to modern values, especially during flood periods. In this context, it is worth reconsidering the limnological basis for the categorization of Lake Neusiedl as 'steppe lake', a category lacking conclusive definition.

During 1865–1870, the lake has been more or less dry (Sauerzopf 1959b). Although there is a lot of evidence for exceptionally low precipitation before and during this period (ZAMG 2016), the maps of the second and third Military Survey of Austria, 1845–1846 and 1872–1881, respectively, already show a network of drainage channels tapping Lake Neusiedl. Therefore and based on the palaeohydrological reconstructions above, it seems very unlikely that Lake Neusiedl had '*about 100–200 dry periods since the lake came into existence*' as stated by Löffler (1990).

13.4.4 Geomorphological Features Related to Lake Neusiedl

Geomorphological features contribute considerably to our understanding of the palaeohydrology of the lake. Palaeo shorelines are well developed, especially in its northern and northwestern part. They are easily recognized in ASL digital terrain data, but many of them are also visible on the ground, for instance the palaeo shoreline north of Purbach (Fig. 13.8).

One of the most noticeable geomorphological features of Lake Neusiedl is a ridge (German: '*Seedamm*') that runs more than 22 km parallel to its eastern shore, closely

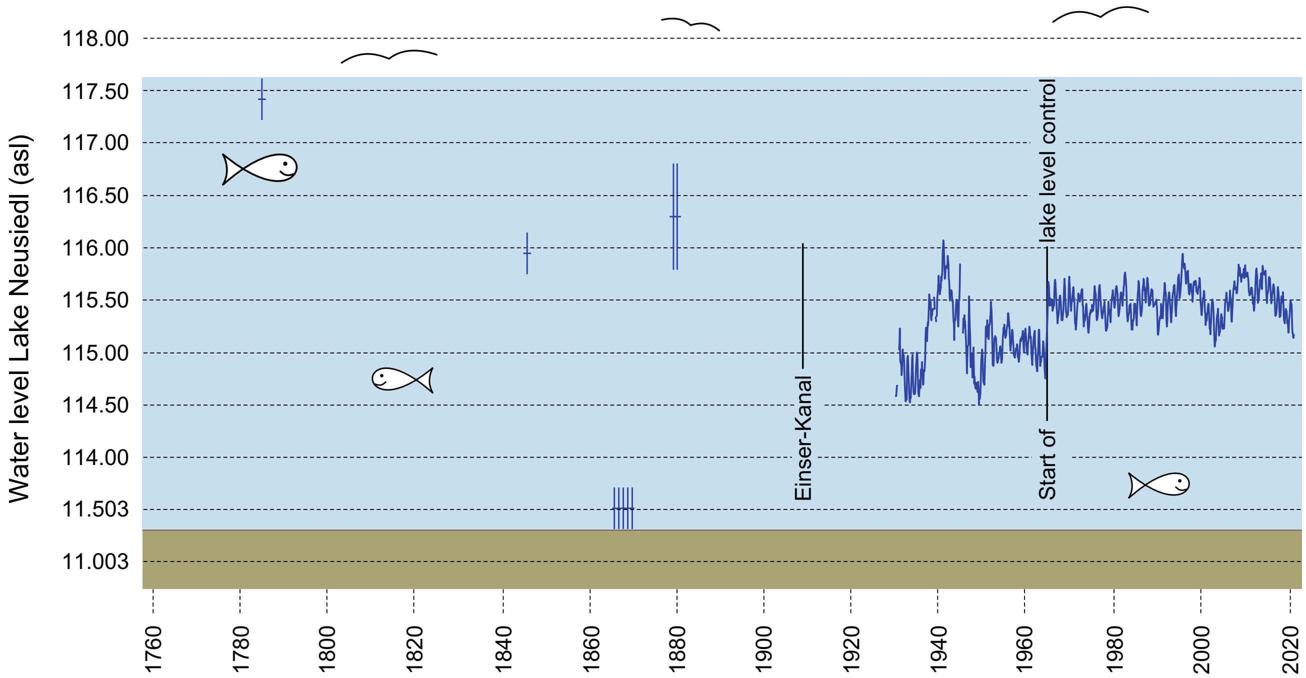

Fig. 13.6 Lake level variations reconstructed from the first Austrian land survey (1784), second Austrian land survey (1845/1846), historical sources (1865–1870) and third Austrian land survey (1872/1873). Modern daily water level measurement started in the Austrian part on June 1st 1930, exact lake level adjustment in 1965 (Wasserportal Burgenland 2016). Diagram is based on monthly values. Lowest lake bottom altitude from Heine et al. (2014)

following its outline (Figs. 13.9 and 13.10) (Bernhauser 1962). The structure comprises pebbly sand and is usually 100–150 m wide and 2.0–2.5 m high. It is generally accepted (e.g. Löffler 1974) that the ridge has been formed by ice-push (compare with Kelletat 1995 and Mahoney et al. 2004), which can occur when the lake is frozen and the dominant north-western winds push ice far onshore (Fig. 13.9a). Profiles across the structure indicate that this feature also formed at slightly higher lake levels than present. Already Bernhauser (1962) noticed the existence of at least one more similar ridge to the east. They are very well visible in the high-resolution ALS data (Fig. 13.10); however, their relationship with each other and with former lake levels is not completely clear and definitely deserves more research. Altitude data concerning palaeo lake levels and geomorphological features should be interpreted with care; active vertical crustal movements in this area are in the order of c. 1 mm/year (=1 m/millennium) (Joó 1992; Ruess and Mitterschiffthaler 2015), which may modify their altitude and spatial relationships, especially in this very low-relief landscape.

13.5 Seewinkel Lakescape

The Seewinkel is one of the flattest areas of Austria. Similar to the Parndorf Plateau, the Seewinkel is characterized by <25 m thick fluvial gravel and sand on top of Pannonian sediments (Tauber 1959; Häusler 2007). In some parts, thin layers of aeolian deposits have been described (Husz 1965). At present, the area is covered by anthropogenic steppe vegetation (Hungarian: *Puszta*), but originally, it most likely showed forest steppe conditions (Wendelberger 1950, 1955, 1987; Molnár et al. 2012).

The geomorphologically and ecologically most prominent elements of the Seewinkel are the numerous shallow lakes (Fig. 13.1) creating a particular lakescape (Fig. 13.2) of great beauty and importance (Löffler 1982). At present, only some 40 shallow lakes are preserved (Löffler 2000) but they were much more abundant in the past. Mid nineteenth century cadastral maps showed c. 150 shallow lakes in this area (Dick et al. 1994; Löffler 2000), which vanished due to artificial drainage and excessive extraction of groundwater.

In German, the shallow water bodies of the Seewinkel are either called '*See*' (lake) or '*Lacke*' (pond) (Löffler 2000, 2004). Similar water bodies have been called ephemeral lake, dry lake, playa, playa lake, saline lake, sabkha, salar, salina, salt flat, salt/clay pan perennial/seasonal astatic lake and soda lake (e.g. Briere 2000). However, neither playa, playa lake nor sabkha of Briere's (2000) definition are suitable because of the lack of arid climate conditions (e.g. Löffler 1957). Additionally, the lakes in the Seewinkel—except during very dry periods—have comparatively low salt contents (Krachler et al. 2012; Boros et al. 2013) and thus many of them classify as subsaline, only some as

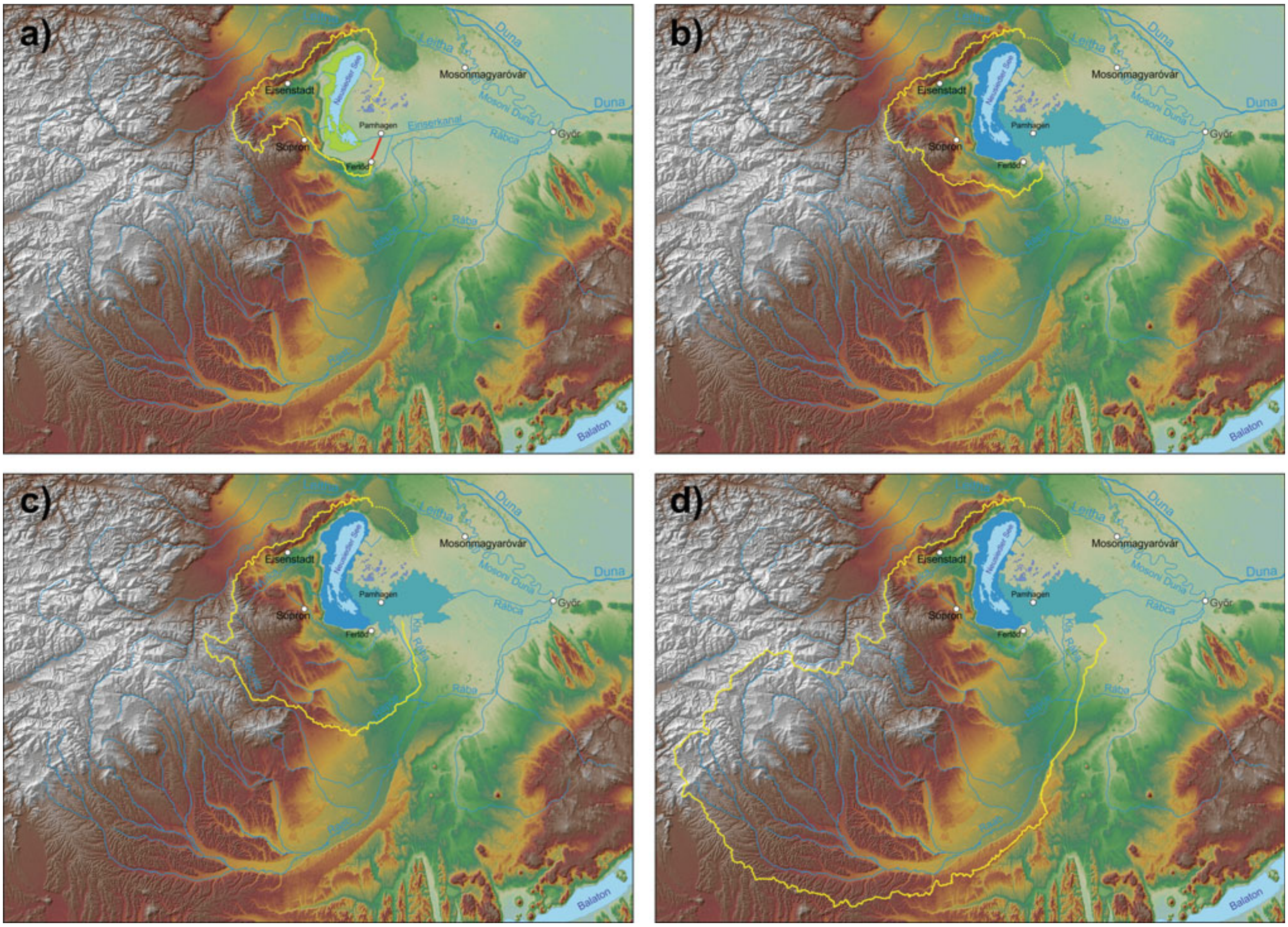

Fig. 13.7 Different watersheds (in yellow) of Lake Neusiedl; background DTM is height coloured (histogram equalize) with a 50% transparent hillshade (315° azimuth; 45° elevation). **a** Present-day catchment including only the Wulka River and some very small rivers in the Leitha Mountains (c. 1120 km^2). Current reduced catchment size results from the construction of the dam road between Pamhagen and Fertöd, drawn in red. Rivers draining into the lake as shown in historical maps increase the catchment of Lake Neusiedl additionally by **b** c. 383 km^2 (Ikva River), **c** c. 1268 km^2 (Répce River) and **d** c. 6649 km^2 by the Kis-Rába. Catchment areas calculated with SRTM 30 m DTM (http://earthexplorer.usgs.gov)

hyposaline lakes (e.g. Hammer 1986; Pinti 2011). Alkalinity and concentrations of specific anions are highly variable; pH-values are between 7.5 and 10.2 (Krachler et al. 2012; Boros et al. 2013). For all these reasons, we use the general term ‘shallow lake’ for the water bodies of the Seewinkel (see also Löffler 2004).

The largest of them measures 2 km in length (Fig. 13.10), but most are considerably smaller and even the largest are less than 1 m deep (Boros et al. 2013). The shallow lakes hardly have natural outlets, and one of their very characteristic features is an elevated salt content of the water, generally dominated by sodium carbonate (Na_2CO_3) (Krachler et al. 2012; Boros et al. 2014); many of them show perennial/seasonal astatic behaviour. The origin of the salt is a matter of long and still ongoing debate in the literature (Löffler 1957; Husz 1965; Krachler et al. 2000; Häusler 2007; Boros et al. 2013). Salt contents and compositions vary between the lakes and seasonally (Krachler et al. 2012), mainly depending on the amount of rain, groundwater influence, mineral precipitation and microbial activity (Löffler 1959; Krachler et al. 2000). Based on the hydrological properties, the shallow lakes can be divided into lakes completely depending on precipitation and surface runoff, lakes controlled by groundwater influx and mixed types (Steiner 2006). In all cases, permeability of the subsurface sediments is very important (Krachler et al. 2000; Steiner 2006).

13.5.1 Formation of the Shallow Lakes and Enclosed Depressions

One of the most important results of the ALS study was the discovery of more than 370 enclosed depressions in the

Fig. 13.8 Palaeo shoreline north of Purbach; photo taken towards west-northwest. The change in slope in this low-relief area is only gentle, and its visibility is enhanced by vineyard rows. The upper slope break is situated at 126 m asl, whilst the lower one is between 117.5 and 118 m asl, i.e. at the maximum flood levels of Lake Neusiedl. Photo: E. Draganits, 24.9.2006

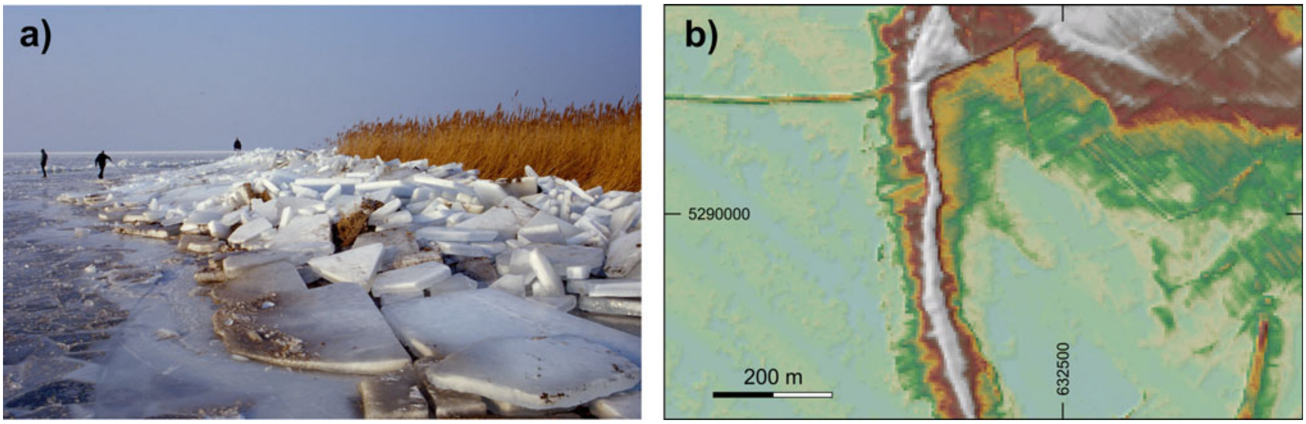

Fig. 13.9 Ice-push processes. **a** Ice-push northwest of Podersdorf; even frozen soil on the lake shore is pushed by the wind forces; view towards northwest. Photo: E. Draganits, 28.1.2006. **b** Ice-push ridge west of Illmitz is c. 150 m wide and up to 2.5 m high; digital terrain model based on 10 × 10 m ALS DTM; visualization of colour-coded elevation (histogram equalize) (115.7–119.2 m) and 50% hillshade (315° azimuth; 45° elevation) above

Seewinkel and that these features are not restricted to the Seewinkel, but also exist in several other regions, including c. 25 in the Austrian part of the Hanság, in areas south and east of the Parndorf Plateau and even c. 13 on the plateau itself (Fig. 13.10). In Austria, a few more are found west of Lake Neusiedl near St. Margarethen, even more on a terrace between the Danube and Leitha Rivers and on a Danube terrace in the Northern Vienna Basin. Therefore, any

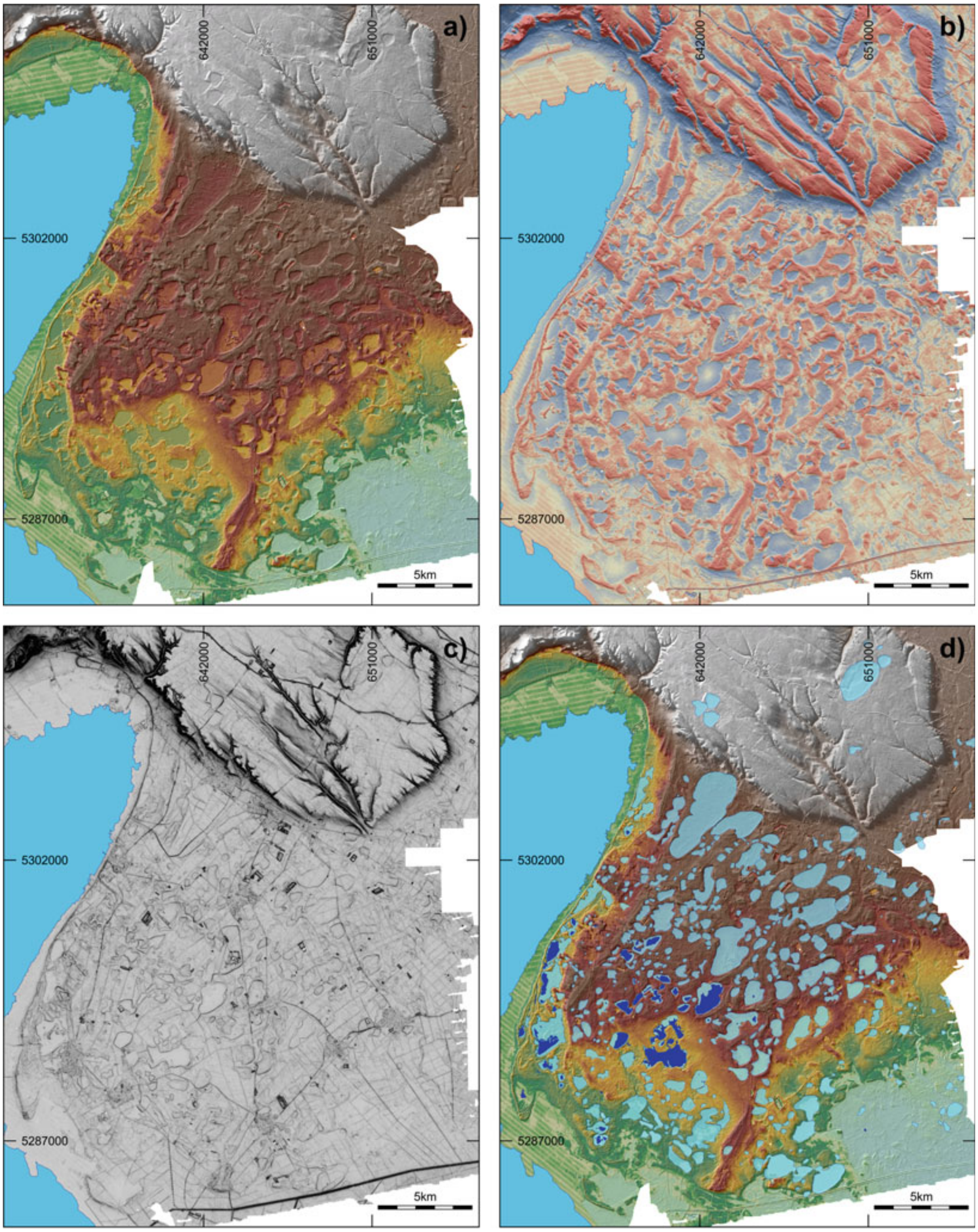

Fig. 13.10 Different visualizations of the digital elevation model (10 × 10 m ALS DTM), showing part of Lake Neusiedl, Parndorf Plateau and Seewinkel with the present-day extent of Lake Neusiedl. **a** Colour-coded elevation (histogram equalize) and 50% transparent hillshade (per cent clip) above. **b** Local relief model (LRM) (Hesse 2010) (1200 m kernel size, histogram equalize) 50% transparent above hillshade (315° azimuth; 45° elevation, histogram equalize) considerably increases the visibility of the shallow lakes. **c** Openness visualization (Doneus 2013) (900 m search radius) 50% transparent above slope map clearly showing the outline of the shallow lakes. **d** DTM visualization of Fig. 13.10a with interpreted mapping of shallow basins based on the previous visualizations in light blue and the presently existing lakes of the Seewinkel in blue. Note that the thermokarst basins are not restricted to the Seewinkel, but also occur southeast and on top of the Parndorf Plateau

explanation of the formation of these shallow basins (see also Boros et al. 2013) should also explain their distribution over different geomorphological units.

Riedl (1965) described several periglacial features from the Seewinkel, including ice-wedge pseudomorphs and deformed sediments, indicating a continuous permafrost regime. A recent review about permafrost extent during LGM shows the Lake Neusiedl area well within the continuous permafrost zone (Fábián et al. 2014; Vandenberghe et al. 2014).

Riedl (1965) suggested that the shallow lakes in the Seewinkel originally formed as pingos during glacial periods, a model hardly challenged in the past 50 years and still widely accepted (e.g. Löffler 2000). However, in recent reviews by French (2007) and Yoshikawa (2013), pingos are usually less than 0.6 km in diameter and are typically solitary features or appear in groups of only a few.

Both properties are in contrast with the up to 2.2 km long, and more than 370 basins in the Seewinkel (Fig. 13.10) visible in the high-resolution ASL survey. The basins are round to oval/kidney shaped with northeast-southwest oriented major axis. In some cases, smaller depressions seem to have merged—for example, south of Gols—to larger ones with sizes up to 2.2 km (Fig. 13.10). Several of the basins are surrounded by <3 m high ridges at their southeastern outline (Fig. 13.10), which probably formed by ice-push during northwestern winds, similar to the shore-parallel ridge (*Seedamm*) east of Lake Neusiedl. The appearance and properties of the basins closely resemble thermokarst lakes that develop by permafrost degradation and are very common in Arctic Canada and Northern Siberia (Bird 1967; Grosse et al. 2013; for comparison, see the area around the Kolyma River in Siberia: 69°00′00″N, 158°00′00″E). Already Székely et al. (2009) suggested that the basins of the Seewinkel may represent relict latest Pleistocene thermokarst lakes. High-resolution ALS DTM data proved extremely helpful for the interpretation of the enclosed depressions, which was more difficult in the past (see French and Demitroff 2001).

In contrast to pingos, which contain a core of relatively pure ice (Yoshikawa 2013), thermokarst lakes develop by thawing of pore ice of clastic sediments (French 2007; Grosse et al. 2013). Small, scattered natural depressions accumulate small amounts of water during warming periods. In these areas, the local ground thermal regime is disturbed by the high specific heat capacity of water, and consequently, a talik (unfrozen ground) forms underneath the water (Grosse et al. 2013). The positive feedback between lake growth and permafrost thawing results in basin growth; neighbouring basins may join to larger ones. Burn and Smith (1990) measured mean growth rates of 16 thermokarst lakes in the Yukon Territory of 0.7 m/year along their major axis, 0.5 m/year along their minor axis, and the maximum rate was 1.2 m/year. According to Edwards et al. (2016), even much lower growth rates are documented. The largest single thermokarst lake in the Seewinkel is more than 1.5 km long (Fig. 13.10), its growth, according to these data, may have taken a few millennia.

Another feature that the shallow depressions in the Lake Neusiedl area have in common with thermokarst lakes in permafrost areas in Northern Canada, and Siberia is the probable aeolian influence on their shape and growth. Recently, Sebe et al. (2015) presented evidence for strong northwestern winds impacting Eastern Austria during the Pleistocene. Modern observations in Northern Canada and Siberia indicate that thermokarst lakes are shaped by wind-generated waves and currents, which produce oval to kidney shaped lakes with their major axis perpendicular to the dominant wind direction (Fig. 13.10).

The thermokarst lakes in central and Eastern Europe probably developed by permafrost degradation during temperature increase at the end of the last glacial period. The thin cover of fine-grained overbank deposits and aeolian sediments in many parts of the Seewinkel area (Husz 1965) are very suitable for the formation of thermokarst lakes. The preservation of these features is probably linked to vertical tectonic movements leaving elevated areas with thermokarst features out of reach of subsequent fluvial destruction. In the case of Seewinkel, active subsidence of the Little Hungarian Plain around Győr (Joó 1992; Ruess and Mitterschiffthaler 2015) gradually shifted the Répce and Rába Rivers to the east (Scharek 1993), preserving these latest Pleistocene features until today.

So far, thermokarst lakes have been described almost exclusively from Arctic or high Alpine areas (Kääb and Haeberli 2001; Grosse et al. 2013). When the shallow lake basins formed by thermokarst degradation, these basins from Eastern Austria represent one of the first latest Pleistocene thermokarst lakes documented in central Europe.

Some basins visible in the ALS DTM are situated in the flooding zone of Lake Neusiedl (Fig. 13.10), for instance in the Hanság, but also east of the shore-parallel ridge (*Seedamm*). They resemble the other shallow basins in the Northern Seewinkel and Parndorf Plateau. Their relationship with the lake indicates that these basins are slightly older than Lake Neusiedl, as already concluded by Löffler (2000). Löffler (2000) divided the shallow lakes in the Seewinkel into (i) shallow lakes dammed by the ridge east of the lake, (ii) shallow lakes in the area of the Hanság and (iii) shallow lakes of central Seewinkel. Based on this study, this can be simplified by concluding that all of them formed as thermokarst lakes shortly before Lake Neusiedl started to exist—at least in its present extent. Later, some of the basins in the southern part were flooded episodically by the lake and some of them in the western part of the Seewinkel became adjacent to the later formed ridge (*Seedamm*) (Fig. 13.10). When the shallow lake basins formed by thermokarst processes during early Lateglacial permafrost degradation and before Lake Neusiedl came into existence (as shown by superimposition in the ALS data), their age is constrained between the end of the LGM at c. 19 000 years ago (van Husen 2011, Wirsig et al. 2016) and the formation of Lake Neusiedl around 12–14 000 years ago (Löffler 1990, this study).

13.6 Conclusions

The present-day conditions and processes of Lake Neusiedl strongly differ from conditions in the past. The earliest preserved record of modification of the lake's hydrological conditions is from 1568, followed by increasing drainage efforts and the building of a dam road between Pamhagen and Fertőd, finished in 1780, which subsequently cut off the lake from its most important tributaries and fundamentally changed its palaeohydrology.

Virtually, all historical maps before 1780 show the Ikva River, Répce (Rabnitz) River and Kis-Rába River discharging into the connected Neusiedlersee/Hanság area that possessed a natural outlet, the Rábca River. This palaeohydrological reconstruction of Lake Neusiedl and Hanság also implies a lower salt content of the water compared to modern values, especially during flood periods.

Therefore, it is not useful to compare the hydrological situation of Lake Neusiedl before 1780 (or even 1568) and after. Consequently, it is unlikely that Lake Neusiedl was an endoreic lake in most periods before 1780 and it is very unlikely that the lake had 'about 100–200 dry periods since the lake came into existence'.

The documented variation of the water level of Lake Neusiedl between desiccation and highest flood level is around 4.2 m. These variations affected enormous areas in this low-relief region, with a huge impact on the landscape, fauna, vegetation, human settlement patterns, land use, communication routes and even possible occurrence of malaria—which should be considered in regional archaeological, historical and biological interpretations. The dating of specific lake levels is an important challenge left for the future.

The numerous shallow lakes and presently dry basins in the Seewinkel originally formed as thermokarst lakes during permafrost degradation after the end of the LGM (after 19,000 years ago), and at least, some of them are slightly older than Lake Neusiedl as revealed by superimposition observed in the ALS DTM, which shows more than 370 enclosed depressions in the Seewinkel itself. The depressions of Eastern Austria represent one of the first latest Pleistocene thermokarst lakes documented in central Europe.

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