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The Osli Formation – a Holocene lithostratigraphic unit in the Danube/Kisalföld Basin, eastern Austria and northwestern Hungary

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Abstract
In the course of field investigations and formalisation of Quaternary deposits in the Lake Neusiedl/Seewinkel and Hanság area the Osli Formation is designated as new formal lithostratigraphic unit. It covers an area of ~200 square kilometres and, in historic times, wetlands such as swamps and peat bogs extended from Waasen in the south-eastern Seewinkel Plain to the Hanság (Kisalföld). Due to missing stratigraphic data this formation cannot be formally divided into two members but into a lower and upper section instead. The lower section of the Osli Formation was cored in the Seewinkel Plain and consists of lacustrine deposits of up to 10 metres in thickness that were presumably deposited during Preboreal. Despite the draining of the Hanság over centuries and decades of peat mining, the upper section of the Osli Formation nowadays still consists of an at least one-meter-thick succession of peat intercalated with fluvio-lacustrine deposits. The investigated peat layers at Tétényi-Hany (~5 km north of Osli) were ^{14}C-dated, ranging in age from ~2,400 BC to 1,500 AD. ^{14}C ages of peat profiles at Osli-Tőzegbánya (Fövenyes-tó), located ~2,5 km northeast of Osli, even date back to ~4,000 BC. Hence the 10 to 12 m thick Osli Formation can be dated as Holocene. It is underlain by Quaternary deposits of the Illmitz Formation.

1. Introduction

At the beginning of the 20th century the Royal Hungarian Geologic Survey published a geological monography of Hungarian peat bogs (László and Emszt, 1916). This applied geologic monography also included the Hanság in Sopron- and Moson County where the newly studied peat profiles of Osli are situated (Figs 1, 2A). The geologists of the Danube Monarchy mapped the depth and size of peat deposits, analysed their chemical and physical composition, verified the calorific values and calculated the peat volume for heating. At that time applied bog-geology played an economic role all over Europe (Puchner, 1920; Bülow, 1928, 1929). Due to extensive drainage, in part due to the loss of peat's economic importance, the natural landscape of the Hanság fundamentally changed. Soil surveys from the 1960's were repeated in 2017, and Bidló et al. (2018) reported that even during this short period, the thickness of the peat layers diminished from several metres to 50–80 cm. When the Hanság groundwater level decreased by several metres during the millennium year, the Department of Environmental and Earth Sciences, Faculty of Forestry of the University of West Hungary in Sopron started a project to investigate soil profiles in the Hanság north of Osli (Figs 1, 2A, B).

To determine the actual thickness of the peat layers in 2004, a Pürckhauer soil auger was used for drilling one-meter-deep profiles in a raster of 559 points (Fig. 2C). At further 35 locations soil profiles were excavated with a caterpillar down to a depth of two meters and samples from paleo soil-horizons were taken for pedologic investigation. Due to a bilateral agreement between the Hungarian Department of Environmental and Earth Sciences and the Vienna Department of Environmental Geosciences, material from those samples was selected which were either taken from the top or base of the profiles or above and below silty to clayey beds. For the very first time this project offered the unique chance to date both paleo-soils and intercalated deposits of the Hanság. The outcome of the project results was used for establishing the Osli Formation as a new formal lithostratigraphic unit extending from the Hanság in Hungary towards the Waasen in Austria (Figs 1, 2). In order to better understand the shrinking and decomposition of these peat-deposits in the Waasen and Hanság, the transition from previous wetlands to present day cultural landscape is briefly described below.

Figure 1: Location of the study area of peat profiles in the Hanság north of Osli. Topography and river network were drawn using the Digital Elevation Model of the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer mission (ASTER; courtesy USGS).

1.1 The Hanság – from wetlands to cultural landscape

The former fen-area of the Little Hungarian Plain in western Hungary (Kisalföld) bordering Austria is termed Hanság. Literally, its German translation means "Waasen" (also Wasen) or wet meadow, a term derived from the old High German term "waso" (Kluge and Götze, 1953) that is used to describe the former continuation of the fen landscape to the north. In former times the flooded Waasen was part of Lake Neusiedl and nowadays it is part of the Seewinkel Plain, the Lake District with abundant salt ponds southeast of Lake Neusiedl (Fig. 1).

First simple cartographic maps of a swamp termed "Leit palus" or "Leyt palus" were drawn by Henricus Martellus Germanicus in 1490. In 1528 Lake Neusiedl was more accurately drawn, comprising the area of both the present Lake Neusiedl and the Hanság, at that time termed "Neusidler See Fertow" (Csaplovics, 2005). Also, the historic map of Wolfgang Lazius from 1561 documents the former continuation of southern Lake Neusiedl towards the Hanság during high water conditions. The Hungarian name for Lake Neusiedl is "Fertő tó" meaning swamp lake, which in historic times lived up to its name. For major flooding of this area up to the 116 m isoline in 1788 see Figure 3. Depending on seasonal precipitation, intensive draining and channelling since the 18th century greatly affected the size of Lake Neusiedl as well as the wetlands and fens of Hanság and Waasen.

The lake's drainage basin has an area of about 1,100 km². At a mean elevation of ~115.5 m (above Adriatic Sea) the depth of Lake Neusiedl reaches ~1.8 m and the lake covers an area of ~315 km² of which 240 km² is on the Austrian side and 75 km² on the Hungarian side (Wolfram et al., 2014). The Seewinkel Plain borders Lake Neusiedl to the southeast and the Parndorf Plateau to the north. Along a distance of 20 kilometres, the Seewinkel Plain declines from 120 m altitude (above Adriatic Sea) in the north to 117 m in the south. In 1850 there were about 120 saline ponds which, due to draining and lowering of the groundwater level, reduced in number and nowadays there are only 40 left. A Pannonian climate with a continental influence prevails in this region – low precipitation, hot summers, but only moderately cold winters. The mean annual precipitation is ~640 mm ranging from 400 to 900 mm, and during hot years precipitation of 400 mm equals evaporation and evapo-transpiration (Wolfram et al., 2014). The grassland of the Seewinkel Plain can be termed „Pannonian Steppe". The water volume of Lake Neusiedl depends ~80% on precipitation; smaller tributary rivers such as Wulka and Ikva only contribute ~20%. The lake is hardly charged by groundwater and due to water losses of 90% caused by evaporation and evapo-transpiration, as well as artificial channels, water management of the lake is difficult (Boroviczény et al., 1992). In historic times Lake Neusiedl periodically dried out, lastly from 1864–1870 (Csaplovics, 2005).

Due to former water level fluctuations, the ecosystem of Lake Neusiedl included different kinds of wetlands. A wetland is defined as distinct ecosystem that is regularly wet or flooded by water, either permanently or seasonally, where oxygen-free processes prevail (Aber et al., 2012). Marshes (Germ.: Marsch; Hung.: Mocsár) developed in the low lying areas close to the lake by sub-surface and surface water. Basically, these areas were frequently flooded. The marshes were nutrient-rich areas typically covered with reeds and grasses. In contrast to these marshes, the coastal swamps (Germ.: Sumpf; Hung.: Ingovány) were only flooded by high-water levels of the lake and therefore the previously accumulated organic matter converted into permanent humus. According to Aber et al. (2012), in Europe forested fens and reed (*Phragmites*) wetlands are called swamps. Swamps are waterlogged habitats varying from wet meadows to bogs (Germ.: Moor; Hung.: Tőzegláp) and provide a habitat for wooden plants such as shrubs and trees.

When the Hungarian peat bogs were mapped at the beginning of the 20th century, the definition comprised places where organic material naturally flooded and decayed, and where decomposition products accumulated (László and Emszt, 1916). According to Lájer (1998) and Borhidi (2003), a bog is characterised by a decaying vegetation that generates peat. This type of wetland is characterised by acidic water, low alkalinity, and low nutrient contents (Aber et al., 2012). Bogs are formed by accumulation of peat over a long period, filling up lakes. As most wetlands exist in topographic depressions, they tend to accumulate sediment through time (Aber et al., 2012). Peat bogs that developed in the Waasen and Hanság became typical areas for peat-mining. Between these areas, fens (Germ.: Moor; Hung.: Felláp) developed. These had a water level lower than that of the bogs and therefore not constantly covering the fen surface, although still saturating the upper soil layers most of the time. The flowing water allowed for a stronger plant cover and higher nutrient contents.

Due to regular floods that destroyed the arable fields and crops of the Hanság, there was a public interest in

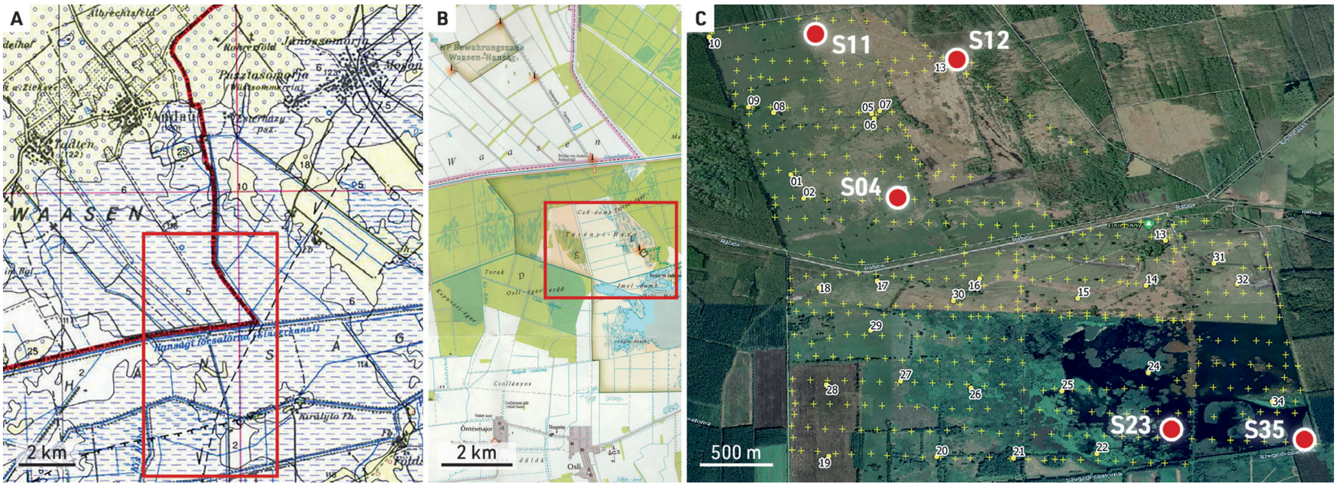

Figure 2: Map of the investigated wetlands in the Fertő-Hanság National Park. (A) Section of geological map of Burgenland 1:200,000 (Pascher, 1999; courtesy of Geological Survey of Austria). Yellow colour indicates Quaternary deposits of the Illmitz Formation (former "Seewinkel gravel beds") and horizontally blue dashed lines indicate swamp and peat bog. (B) Section of map Fertő-Hanság Nemzeti Park/Nationalpark Neusiedler See-Seewinkel 1:60,000 with the 2004 investigation site Tétényi-Hany located ~5 km north of Osli (Paulus, 2012; courtesy Paulus company) and (C) locations of dated peat profiles at Tétényi-Hany (e.g., S11; Google Earth).

its drainage (Kövér, 1930; Szekendi, 1938). In the 17th century first measures were taken under the reign of Maria Theresia in the form of laws regulating the maintaining of riverbeds, and Duke Pál Eszterházy ordered a north-south tending dam that was built from 1777–1780, spanning the depression between Pomogy (Pamhagen) and Eszterháza (near village Fertőd). This ~9 km long dam separated Lake Neusiedl in the northwest from the Hanság in the east. Lake Neusiedl was charged by rivulet Wulka from the northwest and the fragmented basins of the Hanság were charged by tributary rivulets such as Ikva and Répce from the south (Fig. 1). During high water conditions, Lake Neusiedl also charged the Hanság and together with water courses of Répce and Rába contributed to the Danube. During larger floods of the River Danube the excess water flowed up the Hanság Basin towards Lake Neusiedl while during low water conditons the whole water-system flowed in the other direction.

The entire wetlands encompassing Waasen and Hanság originally summed up to ~570 km², 230 km² of which were drained by 1900. The peat bogs of the Hansag are divided into two areas, a western of ~188 km² in size (a large section of which is visible in the geologic map of Fig. 2A) and another south of Mosonmagyaróvár of ~41 km² in size. Drilling of the western basin revealed thickness of peat ranging from 0.1 to 1 metre in an area of 94 km², between 1.1 and 2 metres in an area of 76 km² and exceeding 2 metres in an area of 18 km² (László and Emszt, 1916). In the 20th century several larger drainage channels and pumping stations were constructed. Most important was the first channel („Einser-Kanal", „Hanságifőcsatorna") that was constructed from 1895 to 1909, paralleling the present border between Austria and Hungary, as an outflow for high waters from Lake Neusiedl towards the River Danube. A second smaller channel („Zweier-Kanal") west of Pamhagen drained the majority of the Seewinkel saline ponds and another smaller channel drained the bogged area of the Waasen („Torfkanal"; Häusler, 2007). Present topographic maps reveal the dense net of ditches draining both the Seewinkel Plain and the Hanság (see Fig. 1). In contrast to the previous 60 km² of fen in the Waasen that was completely drained, the wetlands of the Hanság still flood up to an area of several hundreds of square kilometres during wet years. After the Second World War, drainage works continued until 1967 and another drainage system was constructed in the lowest depressions of the Hanság Basin for agricultural use of the lower situated areas. As a consequence, during more arid periods the groundwater level of higher parts of the Hanság decreased, in particular during the latest decades (Bendefy, 1969; Aujeszky et al., 1975). Before the construction of major channels for draining Lake Neusiedl and its fens and marshland, it was an endorheic lake with no evident outlet. Today the water level of Lake Neusiedl is controlled by a sluice on Hungarian territory near Fertőújlak southwest of Pamhagen.

Since 1982 Lake Neusiedl and its Lake District have enjoyed protection through the Ramsar Convention on Wetlands (Fischer, 1993). In 1998 this area was expanded to include the southern part of Lake Neusiedl. Since 2001 both the National Park "Neusiedler See-Seewinkel" in Austria and the National Park "Fertő-Hanság" in Hungary have been accepted together as a UNESCO World Heritage Site.

The long-lasting anthropogenic impact in the Hanság-Waasen region by draining the wetlands or occasionally flooded areas by ditches and channels significantly changed the hydrologic regime and caused lowering of the groundwater table, while the exploitation of peat significantly changed the landscape. From 1870 onwards the cutting of peat as burning material played an economic role, and about 80% of the peat has disappeared since 1915 (Dömsödi and Hajdu, 1978). Unfortunately, from 1945–1947 a peat-fire in the Hanság got out of control and large areas of peat were destroyed between Wallern im Burgenland, Tadten and Andau (Nelhiebl, 1980). In 1978 another 30 hectares of peat were destroyed by fire near Wallern im Burgenland (Löffler, 1982).

2. Environmental settings of the Seewinkel-Hanság region

This section introduces the geologic-hydrologic, geomorphologic and pedologic settings of the Lake Neusiedl-Seewinkel-Hanság region.

2.1 Geology and hydrology

The Danube/Kisalföld Basin is the north-western sub-basin of the Neogene Pannonian Basin System (Szantó et al., 2016). With the beginning of the late Pannonian, Lake Pannon retreated from the Vienna Basin and a fluvial system, which already developed during the early Pannonian, followed the receding shore. Stagnant lakes and swamp forests developed on the interdistributary areas (Harzhauser and Tempfer, 2004). Though belonging to the Central Paratethys, the Vienna Basin zonation of Papp (1953: Biozones A–H) is applied to deposits of Lake Pannon in the western Danube Basin. Fossiliferous marls of middle Pannonian age (Biozone E), upper Pannonian marls termed „Blue Series“ (Biozones F and G) as well as marls of the „Yellow Series“ (Biozone H) were drilled in the Seewinkel region (Tauber, 1959; Häusler, 2007). Quaternary deposits in the surroundings of Lake Neusiedl were lithostratigraphically defined by Häusler et al. (2021), comprising the Parndorf Formation and the Illmitz Formation. The Parndorf Formation was deposited during Günz- and Mindel Glaciation when Paleo-Danube diverted from Bruck Gate via Parndorf to the south. The Illmitz Formation (“Seewinkel Schotter” of Fuchs and Herrmann, 1985) had been deposited in the Seewinkel since the Riss Glaciation by a widely branched river system consisting of paleorivers Danube, Ikva and the Rába/Repce (Häusler et al., 2021). The flat landscape of the Seewinkel Plain with its former peat cover of the Waasen and its continuation to the bogged wetlands of the Hanság belongs to the youngest geologic deposits of this region. A recent overview on the geology of this area was compiled by Császár et al. (2000) in a surface geological map at 1:100,000 scale. In this map the borders of the previous peat area of the southeastern Seewinkel Plain, the Waasen, were drawn based on the geologic map of Fuchs and Hermann (1985) 1:50,000. Although the majority of this area had been undergoing drainage for centuries, a small area of ~1 km^2 had been preserved as a wetland in the Austrian National Park southeast of Tadten. In contrast, large areas of wetlands were preserved in the Győr-Moson-Sopron County (“National Park Bewahrungszone Waasen-Hanság”, Fertő-Hanság National Park; Fig. 2B).

Figure 3: Map of Sopron County (“Komitat Ödenburg”) designed by Johann Nepomuk Hegedüs in 1788 (courtesy of Széchenyi National Library, Budapest). Compared to recent topographic maps this historic map reveals that the landscape from “Lacus Fertő” or “Neisidler See” to the “Hanságh” was flooded up to an altitude of 116 m (above Adriatic Sea).

2.2 Geomorphology

The depression of the Lake Neusiedl region is bound by several faults (Zámolyi et al., 2016). Those faults bordering the Rust Range to the west, the Leitha Mountains to the northwest and the Parndorf Plateau to the northeast are of geomorphological relevance. Due to the flat relief, Lake Neusiedl originally extended in the southeast to the marshlands of the Hanság and, until the middle of the 19th century, fishery was common from Pamhagen to Wallern in Burgenland (Häusler, 2007). In the entire region the 116 m isoline (above the Adriatic Sea) marks the historic shoreline of highwater conditions west and east of Lake Neusiedl (Fig. 3). Due to height differences between Austria and Hungary after 1945, the altitudes of the Osli site at Tétényi-Hany in Figure 4 refer to the zero level of Kronstadt Sea-Gauge of the Baltic Sea that was ~ 0.67 m higher than the mean Adriatic Sea level to which altitudes were referred to in Austria. At present the relief of the Hanság is slightly undulated and during the 2004 Osli-project local height differences of the land surface were measured ranging from ~112 to 118 m altitude above the Baltic Sea. At an area of 7 km^2 and within the drilling grid of 100 by 200 m the cumulative thickness of peat ranged from 0 to 124 cm which reveals an irregular undulated paleorelief of the Hanság with hilly areas up to an altitude of ~118 m above the Baltic Sea (Figs 5, 6).

2.3 Pedology

Mapping of semiterrestric soils in the Seewinkel for agricultural use dates back to 1976 (Nelhiebl, 1986). At that time, when the Waasen had already been drained for many decades, soil types were mapped as salty fen or as drained fen, which developed from altered peat. The peat originated as hydric soil in a permanently or seasonally flooded ecosystem that was filled up by fine-grained deposits. Many fast growing plants such as cattail (*Typha*) and reed (*Phragmites*) rooted in the soils of wetlands, and due to oxygen-free processes the organic substance amounted to 20 Mol-% organic carbon. Surface hollows were filled up with organic matters and intrazonal meadow fens developed where the groundwater-level did not sink below one meter. In the Hanság region the intrazonal fen-soils are dominant. Peat developed from the decaying organic materials and, on average, formed layers of up to one metre in thickness (László and Emszt, 1916). As a result of the drainage activity during the last centuries, the peat soils of the marshes have undergone a strong transformation. Accordingly, the Hungarian soil classification system discusses drained and compacted organic peat soils as separate soil types, in which human activity has caused such a profound and lasting change that their properties differ significantly from those of meadow soils. When the permanent water cover was eliminated by draining the bogs, the groundwater level decreased. The drying surface layers were mineralized and the fast-decaying organic material of the peat layers changed its color from dark to black due to humic substances. The light organic material in the top layer is called "kotu", a pedologic term which can be translated neither to German nor to English. Prolonged dehydration of layers containing many organic substances results in a significant reduction of its water storage- and swelling-capacity and therefore wind erosion of the kotu was significant. As a consequence, the conversion of meadow soils to arable farming systems fundamentally changed the original water and nutrient management of the soils. Such peat soil types already occur in most of the Hanság (Kárpáti and Fally, 2012).

In the Hanság both peaty and kotus meadow fens developed (Aujeszky et al., 1974, 1977). Figure 2C informs on the locations of peat samples selected for ^{14}C-dating north of Osli (Tab. 1). The western and southern border of the Fertő-Hanság Basin is defined by Fertőside-hills and the uplifted alluvial fan of the ancient Ikva River. This sharp border is also reflected in the soil conditions. While eroded Cambisols (brown European forest soils and rendzinas) can often be found on the edges, inside the basin hydromophic soils such as, e.g., Fluvisols (alluvial soils), Histosols (peat soils), Gleysols (meadow soils) and Solonchaks/Solonetz (alkali soils) prevail. In other terms, the primary soil types are confined to the poorly drained depressions. Soils of swamps and marshlands of the Waasen-Hanság region with shallow groundwater can be summarised as Histosols that comprise soils formed in organic material accumulating as groundwater peat (fen; International Union of Soil Sciences, Working Group World Reference Base for Soil Resources, 2015).

Table 1: ^{14}C- and $\delta^{13}C$-data of the samples from the Osli peat profiles at Tétényi-Hany (Häusler et al., 2017). For location of samples see Figure 2C.

Location	Coordinates (N, E)	Depth	Sample	Laboratory ID	$\delta^{13}C$ [‰]	^{14}C-age [yr BP]	Calibrated age
Osli-S04	47°41'04,62" 17°05'07,56"	35-56 cm	S04-210 peat	VERA-3746	-26.2 ± 0.6	475 ± 30	1,400 AD (95.4%) 1,460 AD
Osli-S04	47°41'04,62" 17°05'07,56"	35-56 cm	S04-210 peat, repeated	VERA-3746W	-28.8 ± 3.0	530 ± 30	1,310 AD (19.5%) 1,350 AD 1,390 AD (75.9%) 1,440 AD
Osli-S04	47°41'04,62" 17°05'07,56"	56-65 cm	S04-211 peat	VERA-3747	-26.9 ± 0.6	285 ± 35	1,490 AD (93.6%) 1,670 AD 1,780 AD (01.8%) 1,800 AD
Osli-S04	47°41'04,62" 17°05'07,56"	56-65 cm	S04-211 peat, repeated	VERA-3747W	-29.1 ± 2.4	585 ± 30	1,290 AD (66.1%) 1,370 AD 1,380 AD (29.3%) 1,420 AD
Osli-S04	47°41'04,62" 17°05'07,56"	93-100 cm	S04-213 degraded peat	VERA-3748A	-24.8 ± 0.6	2,065 ± 40	190 BC (95.4%) 20 AD
Osli-S04	47°41'04,62" 17°05'07,56"	93-100 cm	S04-213 charcoal	VERA-3748B	-23.8 ± 0.9	3,745 ± 35	2,280 BC (95.4%) 2,030 BC
Osli-S04	47°41'04,62" 17°05'07,56"	93-100 cm	S04-213 charcoal repeated	VERA-3748_1	-24.4 ± 0.7	3,915 ± 35	2,490 BC (95.4%) 2,290 BC
Osli-S04	47°41'04,62" 17°05'07,56"	93-100 cm	S04-213 degraded peat	VERA-3748_2	-29.5 ± 0.5	3,780 ± 30	2,300 BC (92.9%) 2,130 BC 2,090 BC (02.5%) 2,050 BC
Osli-S04	47°41'04,62" 17°05'07,56"	93-100 cm	S04-213 humic acids	VERA-3748_3	-25.8 ± 0.6	3,475 ± 30	1,890 BC (89.2%) 1,730 BC 1,720 BC (06.2%) 1,690 BC
Osli-S04	47°41'04,62" 17°05'07,56"	93-100 cm	S04-213 handpicked plant remains	VERA-6426	-27.8 ± 1.7	2,400 ± 35	750 BC (11.1%) 685 BC 670 BC (03.2%) 640 BC 555 BC (81.1%) 395 BC
Osli-S11	47°41'48,96" 17°04'43,98"	15-35 cm	S11-243 peat	VERA-3741	-26.9 ± 0.6	540 ± 30	1,310 AD (29.8%) 1,360 AD 1,380 AD (65.6%) 1,440 AD
Osli-S11	47°41'48,96" 17°04'43,98"	42-55 cm	S11-245 degraded peat	VERA-3742	-25.7 ± 0.5	1,685 ± 35	250 AD (95.4%) 430 AD
Osli-S12	47°41'41,94" 17°05'22,98"	60-90 cm	S12-251 degraded peat	VERA-3743	-25.1 ± 0.6	915 ± 30	1,030 AD (95.4%) 1,190 AD
Osli-S23	47°39'59,58" 17°06'22,56"	60-98 cm	S23-301 degraded peat	VERA-3744	-26.7 ± 0.6	955 ± 30	1,020 AD (95.4%) 1,160 AD
Osli-S35	47°39'56,88" 17°06'58,86"	26-28 cm	S35-359 peat	VERA-3745	-27.4 ± 0.5	675 ± 35	1,260 AD (55.2%) 1,330 AD 1,340 AD (40.2%) 1,400 AD

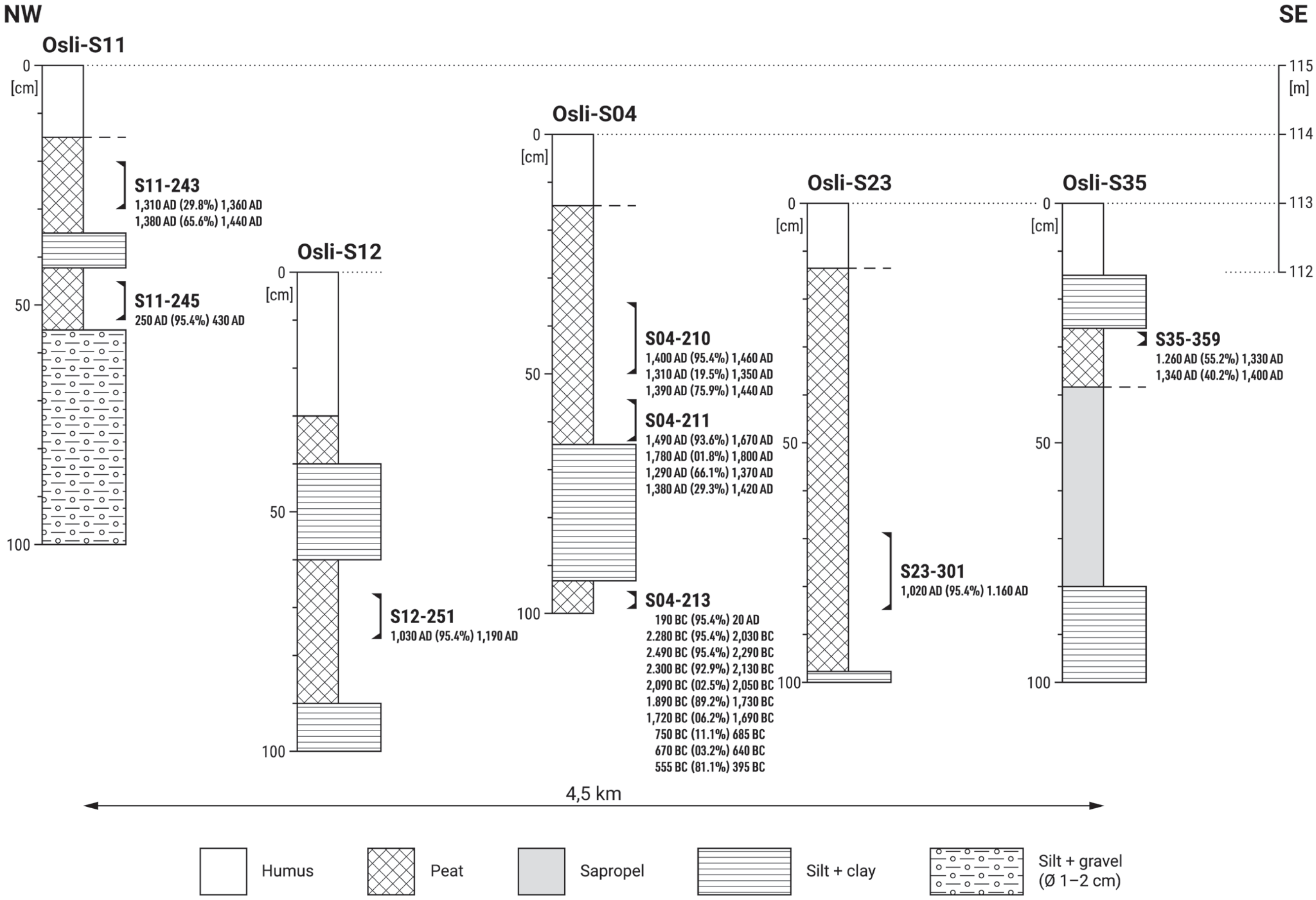

Figure 4: Peat profiles investigated at Tétényi-Hany, along with Osli sample-IDs and calibrated ^{14}C-ages of Table 1. Profile Osli-S04 was chosen as type-section and profile Osli-S11 as reference section of the upper section of the Osli Formation. Altitude of 112 m above Baltic Sea equals ~111.4 m above Adriatic Sea. For locations see Figure 2C.

3. Material and methods

In the wetlands at Tétényi-Hany, ~5 km north of Osli, in an area of ~7 km^2, 35 peat profiles were excavated down to a depth of two metres. Depending on the occurrence of peat layers intercalated with soft rocks, five profiles were chosen for further investigation. In order to date the youngest and oldest peat layers and therefore to indirectly date sedimentary deposits, 8 peat samples of profiles Osli-S04, Osli-S11, Osli-S12, Osli-S23 and Osli-S35 (Figs 2C, 4) were selected for ^{14}C-dating (Häusler et al., 2007, Häusler et al., 2017).

^{14}C dating of the collected samples was performed at the VERA (Vienna Environmental Research Accelerator) laboratory of the University of Vienna. Part of the samples comprised well preserved plant remains. However, other peat samples consisted of degraded material from which an isolation of plant macrofossils was not possible. In order to avoid material-inherent age offsets ("old wood" or reservoir effects) it is advisable to select short-lived terrestrial plant remains for ^{14}C dating. *Sphagnum* is frequently described as suitable material for ^{14}C dating of peat (see, e.g., Piotrowska et al., 2011). For the Osli peat no identification of the plant remains selected for ^{14}C dating was performed, but it can be assumed that the used material consisted of short-lived, above-ground remains. The $^{14}C/^{12}C$ ratio of above-ground remains of short-lived terrestrial plants should reflect very closely the atmospheric value at the time of growing. The plant remains were chemically pre-treated with the standard ABA (acid-base-acid) method used at VERA (see, e.g., Wild et al., 2008). Also, bulk samples of the degraded peat were treated with the ABA method (see Mook and Streurman, 1983) as well as charcoal pieces and plant remains isolated from the degraded Osli-sample 04-213 (see below). When larger amounts of carbonate were expected the first HCl step was repeated. Humic acids from Osli-sample S04-213 were extracted with NaOH solution, which was then acidified with HCl to precipitate the humic acids (Wild et al., 2013). The further processing and measurement of the pre-treated samples is described in Wild et al. (2008) and Steier et al. (2004). The applicability of the ABA method for bulk peat samples is discussed, e.g., in Blaauw et al. (2004). Nevertheless, it has to be considered that the ABA-treated bulk samples may contain plant remains that could originate from different time periods (Kilian et al., 1995), and also carbon that is not removed during sample processing, e.g., clay-bound carbon or carbon originating from earlier fire events. The presence of significant amounts of such fractions may affect the determined ^{14}C ages. In order to check if such effects have to be taken into account in the interpretation of the dating results, several tests have been performed with the Osli-sample S04-213. Two independent age determinations (VERA-3748A and VERA-3748_2) of ABA-treated bulk material were performed to check for reproducibility. Furthermore, humic acids (VERA-3748_3), extracted from the bulk material as well as small pieces of charcoal (VERA-3748B and VERA-3748_1) and plant remains (VERA-6426), which were obtained by handpicking from the bulk material, were also dated. A test for reproducibility was also performed for the two peat samples S04-210 and S04-211, which both consisted of well-preserved plant remains.

The results of the investigation are listed in Table 1. Given uncertainties of the $\delta^{13}C$ values and the ^{14}C ages are 1σ-values. The calibration of the ^{14}C ages was performed with the calibration program OxCal 4.2 and the IntCal13 calibration curve (Ramsey, 1995, 2009; Reimer et al., 2013). The calendar time ranges correspond to a 95.4% probability. The $\delta^{13}C$-values were determined with the accelerator mass spectrometry (AMS) system. The altitude differences of the peat profiles in Figure 4 indicate the present relief at the Osli investigation site Tétényi-Hany, varying by three metres.

4. Results of dating and discussion

Despite differing results of dating the basal organic material of Osli-sample S04-213, three sets of peat generations can be distinguished: the oldest around ~2,400 to 2,300 BC, the youngest around 1,400 AD (S04-211, S11-243, S12-251 and S35-359) and a generation in between "(S11-245: 250 AD - 430 AD)." In profile Osli-S04 a 30 cm thick silty bed separates the oldest peat bed (S04-213), the charcoal of which was dated ~2,250 BC, from a hanging wall peat bed (S04-210) dated ~1,310 to 1,460 AD (Tab. 1).

The peat horizons in the upper part of the profile Osli-S04 (S04-210 and S04-211) reveal calibrated ^{14}C ages that are younger than the ^{14}C results obtained for several subsamples of S04-213, which is located at a lower position in the profile. Therefore, we assume that dating of the peat accumulation of the Osli site of Figure 2C is quite reasonable, although some problems with the reproducibility of the data occurred. Whereas the two dating results of the sample S04-210 agree within 2σ, the results determined for S04-211 are divergent. Also, the tests performed with subsamples S04-213 indicate the inhomogeneity of the peat samples. This lowermost peat layer of profile Osli-S04 was confined by dm-thick soft rock and dated older than 2,000 years BC. Two samples of small charcoal pieces were dated ~2,500 to ~2,030 BC. Two subsamples of degraded peat from the same sample significantly differed by ~2,000 years whereas the calibrated age of humic acids ranged from ~1,900 to 1,700 BC. As the peat profiles can no longer be accessed, it has to be left open if the detected inhomogeneity is due to the nature of the sample itself or has been contaminated during sampling of the peat profiles. It should be noted that the samples were not taken for the determination of a precise deposition chronology but in the course of a melioration project in the Hanság region. The ^{14}C measurements were performed to gain only a rough age estimate of the deposition history of the Osli peat deposits at Tétényi-Hany. The results of dating these one-meter deep Osli peat profiles reveal a rapid lateral and vertical change of fluvial deposits and varying thickness of intercalated peat beds during a time span of ~3,500 years. To this end, the dated peat layers of profiles studied at Tétényi-Hany give an insight into the youngest history of landscape development of the Lake Neusiedl-Hanság region which is documented by swamp deposits that were occasionally flooded by Paleolake Neusiedl and Paleoriver Répce (Fig. 3). Due to the unique accessability of these peat profiles in the Fertő-Hanság National Park in 2004 it was worth documenting their importance for dating the youngest geologic deposits by establishing a new formal lithostratigraphic unit.

5. Formal description of the Osli Formation

The Osli Formation is defined for the Hanság and Waasen, the former wetland that extended in the Danube Basin from the Seewinkel Plain in south-eastern Austria to the Kisalföld in western Hungary. Due to missing stratigraphic data this formation is not formally divided into members but into a lower and upper section instead.

Derivation of name: After the village Osli (N 47°38"16.4", E 17°04'33.41"), located 7 km northeast of Kapuvár.

Geographic distribution: The upper section of the Osli Formation consists of peat that in recent times covers about 100 km² extending from the south-eastern Seewinkel Plain to the Hanság in western Hungary. Another 100 square kilometres of peat north of River Répce stretch towards Mosonmagyaróvár (Császár et al., 2000). The lower section of the Osli Formation was drilled in the Seewinkel Plain.

Type Section: The pedologic/lithologic profile Osli-S04 in the centre of the peat-investigation area Tétényi-Hany, is located ~5 km north of Osli (N 47°41'04,62", E 17°05'07,56"; Fig. 5A). It was chosen as type section because sediment layers could clearly be identified within a younger profile (Fig. 3). Due to dating fine-grained silt and clay beds within an older profile, the nearby profile Osli-S11 (Fig. 5B) was chosen as reference section (Fig. 3; for locations see Fig. 2C).

Lithology: The upper section of the Osli Formation consists of centimetre to decimetre thick beds of grey silt and clay as well as pebbly mudstone that are intercalated with decimetre- to metre-thick brownish peat layers. Lithology of the excavated sections of of ~1 m thickness rapidly varies at distances of several hundreds of metres. The lower section of the Osli Formation consists of grey silt and clay.

Thickness: The type section Osli-S04 is a half metre thick peat layer overlying a dm-thick layer of silt and clay. Cm-thick bright ellipses of plant relics with a central hole

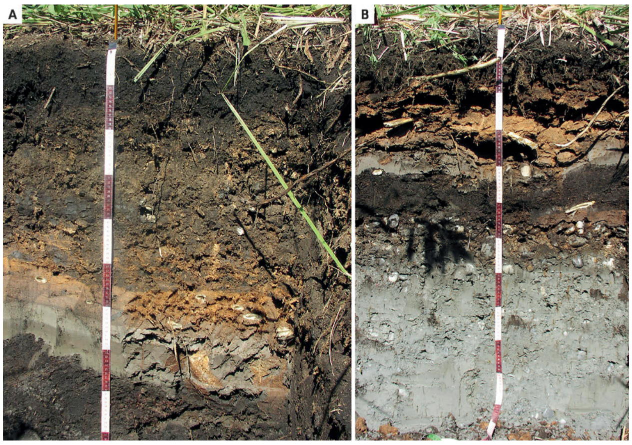

Figure 5: (A) The pedologic-lithologic profile Osli-S04 is type section and (B) profile Osli-S11 is reference section of the upper section of the Osli Formation at Tétényi-Hany. Photos taken by Gábor Kovács in September 2003. For location of profiles see Figure 2C.

indicate cross sections of recent reed. Due to decomposition of the youngest peat horizon, the horizon below the reed turned to a black, humus-rich kotu soil layer. The reference section of Osli-S11 contains a thin layer of silt and clay overlain and underlain by thin peat layers and with a pebbly mudstone at its base. Depending on the primary relief of the Hanság region, peat of the upper section of the Osli Formation forms a layer of, in average, one to a maximum of two metres in thickness (Fig, 6). In the Seewinkel Plain the fine-grained deposits of the lower section of the Osli Formation were drilled to a depth of ~10 m (Löffler, 1972). Summing up, a total thickness of at least 10-12 m can be attributed to the Osli Formation.

The altitude differences of peat profiles varying by three metres given in Fig. 4 and the isopach map of peat deposits shown in Figure 6 clearly reveal an undulated relief of the Quaternary landscape before the Hanság was flooded. According to the map of László and Emszt (1916, plate VI) such undulated geomorphology was typical for peat deposits within Quaternary deposits of the Hanság region.

Depositional environment: According to Löffler (1972), silt and clay deposits of the lower section of the Osli Formation, which are rich in ostracodes, are interpreted as lacustrine sediments. Fine-grained deposits of the upper section of the Osli Formation can only be interpreted from the photos taken during excavation (Figs 5A, B). Beds of the upper section of the Osli Formation, consisting of silt and clay (Fig. 5A) that are intercalated with peat, indicate a succession from a lacustrine, fluvial or floodplain environment to a swamp environment. The pebbly mudstone of the reference profile of the upper section of the Osli Formation (Fig. 5B) indicates occasional flooding by a fluvial regime.

Age: The upper section of the studied Osli Formation at Tétényi-Hany comprises ^{14}C-dated peat layers ranging from ~2,500 BC to ~1,500 AD. A fine-grained layer of the type section Osli-S11 (Fig. 3) was dated older than ~1,400 AD and is underlain by a peat layer dated ~300 AD. A fine-grained layer of the reference section Osli-S04 was also dated older than ~1,400 AD and is underlain by a peaty layer, where the age of the fibres ranges from ~2,500 BC to ~190 BC. The occurrence of older peat layers in the neighbouring location Osli-Tőzegbánya (Fövenyes-tó, ~2.5 km northeast of Osli) is discussed below. The deposits of the lower section of the Osli Formation were investigated in the Seewinkel Plain. Löffler (1972) reported that the ostracodes *Cytherissa lacustris* and *Limnocythere sancti-patricii*, identified in many of several hundreds of cores, indicate lake development during a colder climate. Due to pollen analysis, but without providing any evidence, Löffler (1982) dated these lacustrine deposits as Preboreal (Early Holocene).

Underlying formation: In the southeastern Seewinkel Plain the Osli Formation is underlain by Quaternary deposits (Nelhiebl, 1980, p. 44f.). According to László and Emszt (1916, p. 138), grey sandy gravel deposits overlain by yellow clayey sand not only underly the „Hansag-Terrain" but also form small hills within the peat-bogs. Between Csorna and Mosonmagyaróvár the peaty wetlands of the Hanság are underlain by clayey and sandy deposits (Császár et al., 2000) that presumably belong to the "Hanság Formation" (see Scharek, 1991, Fig. 2). As discussed below, in the Hanság the new formally defined Osli Formation is underlain by the „Ásványráró Gravel Formation $^{á}Q_2$" and the „Mosonmagyaróvár Gravel Formation" (Császár, 1997).

Discussion: The peat deposits of the Hanság were dated late Holocene by Scharek (1991). The 1.2 m deep peat profile at Osli-Tőzegbánya, Fövenyes-tó, was dated by geoarcheologist Pál Sümegi from the Department of Geology and Paleontology of University of Szeged. On the basis of pollen spectra and radiocarbon data, he reconstructed the vegetation history from the 4th millennium BC onwards (pers. comm., 2018). Despite the

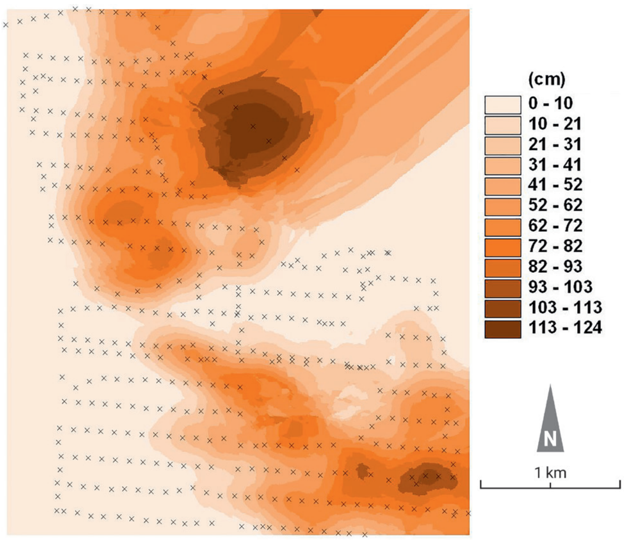

Figure 6: Isopach map of peat deposits of the upper section of the Osli Formation at Tétényi-Hany. In depressions north and southeast of the Osli investigation site, peat was drilled to a thickness of up to 120 cm. For location see Figure 2C.

time gap between the lower section of the Osli Formation dated to the early Holocene and the peat layers of the upper section of the Osli Formation that were dated ranging from 4,000 BC to 1,500 AD, it can be concluded that the Osli Formation covers the entire Holocene.

Obviously, the term "Osli Formation" for the peat succession of the Hanság resembles the term "Osli Peat Formation" used in literature. According to Császár (1997, p. 33) Frigyes Franyó, member of the Quaternary Subcommission of the Stratigraphic Commission of Hungary, described the "Osli Peat Formation $^{o}Q_2$" in the Kisalföld as: „Immature, brownish moor-peat of fibrous texture. Containing a large amount of decayed plant material". Due to the lack of principle characteristics for the introduction of a lithostratigraphic unit, Franyó´s „Osli Peat Formation", which he dated Holocene (Jámbor, 2012, Fig. 4.1), can only be termed an informal unit. In conclusion, the former „Osli Peat Formation" can be now compared to the upper section of the formally defined Osli Formation.

In the composite geologic profile of the Kisalföld (Scharek, 1991, Fig. 2) in general two formations underlie Franyó´s „Osli Peat Formation": the „Ásványráró Gravel Formation $^{\acute{a}}Q_2$" and the „Mosonmagyaróvár Gravel Formation." Comparable to the „Osli Peat Formation", the „Ásványráró Gravel Formation $^{\acute{a}}Q_2$" is also dated Holocene (Scharek, 1991, Fig. 2). Frigyes Franyó described this Holocene gravel formation as: "A light colored fluvial sequence consisting of the alternation of small grained gravel (mostly with a diameter of 2 to 4 cm) and, less frequently, coarser grained gravel, and to a smaller extent sand" (Császár, 1997). Both "Osli Peat Formation" and „Ásványráró Gravel Formation $^{\acute{a}}Q_2$" are underlain by the Upper Pleistocene „Mosonmagyaróvár Gravel Formation". Frigyes Franyó described this Upper Pleistocene gravel formation of the Kisalföld as: "Fine and coarser grained fluvial gravel of great thickness, here and there with thin sand intercalations. Rarely discolored by limonite" (Császár, 1997).

At this stage of comparing Upper Pleistocene to Holocene formations of the Seewinkel Plain and the Hanság it cannot be excluded that the Quaternary deposits of the Illmitz Formation can be compared to the „Ásványráró Gravel Formation $^{\acute{a}}Q_2$" as well as to the „Mosonmagyaróvár Gravel Formation". Furthermore, the term „Hanság Formation" is used in the literature for deposits underlying the peat succession of the Hanság region that originally were dated late Pannonian by Gábor Szurkos (Scharek, 1991, Fig. 2). The "Hanság Formation $^{h}Pa_2$" of the Kisalföld is described as follows: "Consists of a frequent alternation of fluvial or lacustrine grey and variegated calcareous, sandy clay and sand beds, with lignite strings, basalt veins, tuff traces and gravel beds to be found in some places." (Németh *in* Császár, 1997). In their paper on the latest Pannonian and Quaternary evolution at the transition between the Eastern Alps and the Pannonian Basin, Zámolyi et al. (2016, Fig. 2) proposed the Hanság Formation (probably including the informal "Tapolcai Bazalt Formation" of Scharek, 1991) as Pliocene, overlying upper Pannonian (Pontian) deposits. Taking a Pliocene age into account, the Hanság Formation could be correlated with the Pliocene Kolárovo Formation of the Malé Karpaty Mountains (Šujan et al., 2021, Fig. 8) that represents erosive remnants on the basin margins, but continuous depositional record in the central depression of the Danube/Kisalföld Basin. The Kolárovo Formation is considered an Upper Pliocene alluvial sequence that occurs below Quaternary deposits, however, due to missing outcrops, it is poorly defined (Šujan et al., 2018).

To this end we recall that during the last centuries, environmental processes in the Waasen and Hanság (such as decrease of the groundwater table, dehydration of layers rich in organic substances and the resulting increased wind erosion of altered peat) caused significant changes to the ecosystem. Except for the very small National Park protection area "Waasen-Hanság" in Austria south of Andau, the wetlands of the Waasen have changed to cultural landscape that no longer contain any peat-bogs. Hence, the photos of peat profiles taken at the Tétényi-Hany investigation site in 2004 (Figs 5A, B) represent snap-shots of the upper section of the Osli Formation at its type locality.

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