Genesis and abiotic characteristics of three high-altitude peatlands in the Tien Shan Mountains (Kyrgyzstan), with focus on silty peatland substrates

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SUMMARY

Peatlands are scarce and threatened ecosystems in the semiarid region of Kyrgyzstan. Knowledge about the Kyrgyz peatlands is still poor and, especially, their genesis has hardly been investigated so far. Typically, the peatland substrates are characterised by the admixture of silt-sized particles in various quantities. In this work we report the abiotic properties and genesis of three peatlands within different altitudinal zones in southern Kyrgyzstan. We surveyed the stratification of the peatlands and their water chemistry. In addition, we investigated whether the silt found in the peatland substrates was deposited by wind, rivers or springs. The mineral constituents of the peatland substrates were analysed for particle size distribution and their elemental composition was compared with that of nearby loess, river and spring sediments using the immobile trace element titanium. One peatland shows a high abundance of different peatland substrates, indicating a frequent change of ecological conditions in the past. All three peatlands are fed by groundwater. Overgrazing and trampling by cattle has led to recent degradation of the upper peat layer. The resulting compaction of the peats prevents water from seeping into the substrates of the peatlands and subsequently changes their hydrology. Our results indicate that both wind and rivers have deposited silt in the peatlands, depending on their positions in the relief. Silts may also have been relocated by springs within the peatlands.

KEY WORDS: aeolian, fluvial, mire, particle size, X-ray fluorescence

INTRODUCTION

Peatlands are rare ecosystems in Kyrgyzstan, occupying only 0.3–0.4 % of the total Kyrgyz area (Družinin & Harakoz 1959, Aljes *et al.* 2014). The semiarid climate of this country provides an insufficient water supply for the formation of peat in most of its regions (Heinicke 1999). Being surrounded by dry environments, the peatlands fulfil important ecosystem services, such as the retention and filtration of water, storage of carbon and provision of habitats for organisms linked to wetlands (Aljes *et al.* 2014). These scarce ecosystems are currently declining. This is mainly caused by overgrazing, but also by drainage, peat mining and the transformation of peatlands into agricultural fields (Heinicke 1999, Heinicke 2003). Land users are often unaware of the benefits of intact peatland ecosystems and the need for effective protective measures. Indeed, there is little knowledge about the special characteristics and formation of Kyrgyz peatlands. The available studies on peatlands are mostly outdated (Isaev 1956, Isaev & Družinin 1958, Družinin & Harakoz 1959, Korovin 1962, Džoldošev 1970, Sobolev 1972), and in recent years only a few studies have been published (Zemmrich 1997, Heinicke 1999, Heinicke 2003, Heinicke 2004, Gottschling 2006, Aljes *et al.* 2014, Aljes *et al.* 2016). The only existing classification of Kyrgyz peatlands was introduced by Isaev (1956, 1958). He distinguishes peatlands *sensu stricto*, with peat deposits of more than 30 cm, and shallow peatlands (so-called "sazy") with peat deposits less than 30 cm thick. Due to the dry climatic conditions, Kyrgyz peatlands are solely minerotrophic (Isaev 1956, Isaev & Družinin 1958, Družinin & Harakoz 1959, Heinicke 1999). Therefore, the peats usually contain a considerable amount of mineral material, which can often prevail over the organic matter. In addition, the peats are sometimes interspaced with inorganic mineral layers, in which the majority of the mineral components are often made up of silt particles (Heinicke 1999, Heinicke 2003, Aljes *et al.* 2014). Although the large amount of silt in the substrates and its influence on the genesis of the Kyrgyz peatlands is apparent, the origin of such sediments is largely unknown. Heinicke (1999) assumes either a fluvial or an aeolian origin. Natural conditions in the mountains of central Asia trigger the continuous generation of moderate quantities of silt particles (Assalay *et al.* 1998, Smalley *et al.* 2014). This is traced back to physical and chemical weathering, relief and the influence of glaciers (Boulton 1978, Wright 2001, Owen *et al.* 2003). The silt is transported either by wind (depending on the vegetation cover) or by rivers (Dodonov 1991, Machalett *et al.* 2006, Youn *et al.* 2014); thus, both can be responsible for the deposition of silt in Kyrgyz peatlands.

Several attempts have been made to distinguish between fluvial and aeolian depositon of silt sediments. Muhs & Benedict (2006) assessed the aeolian origin of silt in the soils of the Colorado Front Range by analysing the elemental composition of the minerals. Kölbl (1931), Janik (1967, 1974) and Muhs & Benedict (2006) applied particle size analysis to clarify whether silt particles were deposited by wind or water. However, these techniques have never been applied to identify the transport media that deposited silt in peatlands.

In the study reported here, we investigated three peatlands in Kyrgyzstan. We focused on the following questions:

(1) What are the abiotic characteristics of the investigated peatlands?
(2) Which processes influenced the development of the peatlands over time?
(3) Which transport medium - water or wind - induced the deposition of silt in the peatlands?

Fluvial inputs could be either from rivers or from springs. If the silt was transported by wind, its elemental composition would be similar to that of nearby loess deposits. Additionally, it would resemble typical loess deposits in terms of particle size distribution. If the silt was transported by water, it would have similar particle size distribution to fluvial deposits. Furthermore, the elemental composition of the silt should resemble nearby spring sediments if it was deposited by springs or nearby floodplain sediments if it was deposited by rivers.

METHODS

Terms and concepts

There is still no conformity in international peatland terminology (Joosten & Clarke 2002). To avoid misunderstanding, crucial terms are defined here. A peatland is an area with a naturally accumulated peat layer at the surface (cf. Joosten & Clarke 2002). The thickness of the peat layer is of no importance. Thus, this term encompasses the shallow peatlands of Isaev's classification system (Isaev 1956, 1958). A mire is a peatland were peat is currently being formed (cf. Joosten & Clarke 2002). In the present context we prefer the term "peatland", as the state of peat formation is not clear for the investigated sites.

There is no proper substrate classification for Kyrgyz peatlands. Therefore, the classification of peatland substrates used in this article is based on the classification of Succow (1988), which is very detailed and thus allows comprehensive interpretation of the abiotic characteristics and genesis of the peatlands. Two types of peatland substrates are defined, namely 'peat' and 'organic-rich sediment' (ORS). Peat is sedentarily accumulated dead plant material with a mass fraction of at least 30 % of organic matter (dry mass). ORSs are sediments with a mass fraction of at least 5 % of organic matter (dry mass). The term designates sediments whose deposition is closely related with the development of the peatland. Such sediments are usually characterised by a reasonable amount of organic matter. ORSs are usually associated with gyttja, a lake deposit which often contains organic detritus or plant remains. Gyttja can develop in close spatial and temporal relationships with peat, but ORSs can also be fluvial or aeolian depositions into a mire environment. The high organic matter content of theses deposits can be the result of sedimentation in between already-existing mire plants.

All sediments with a mass fraction of organic matter below 5 % (dry mass) are not considered as peatland substrates and are referred to as mineral substrates in this article.

Study area and sites

The study area is located in the southern part of Kyrgyzstan, in the district Naryn, south-west of the town Naryn (Figure 1). This region is characterised by the Tien Shan, a large mountain range of mean height approximately 2750 m a.s.l. (Klotz 1990). The three peatlands investigated in this study are located around the At-Bašy mountain chain, in basins within three different altitudinal zones (Table 1). The basins are filled with cenozoic sediments, such as lake and river sediments, which cover the palaeozoic substratum (Franz 1973, Burbank *et al.* 1999). The slopes of the surrounding mountains (At-Bašy Range, Džamantau Range, Fergana Range) are partly covered by glaciers which play an important role in feeding mountain rivers and recharging groundwater, although they never blanketed the study basins themselves during the Weichselian glaciation and the Holocene (Koppes *et al.* 2008). Due to the location in the centre of Asia, the climate is continental, with low precipitation and high seasonal fluctuation in temperature (Franz 1973) (Figure 2). The southern mountain chains of central Asia (e.g. Himalayas)

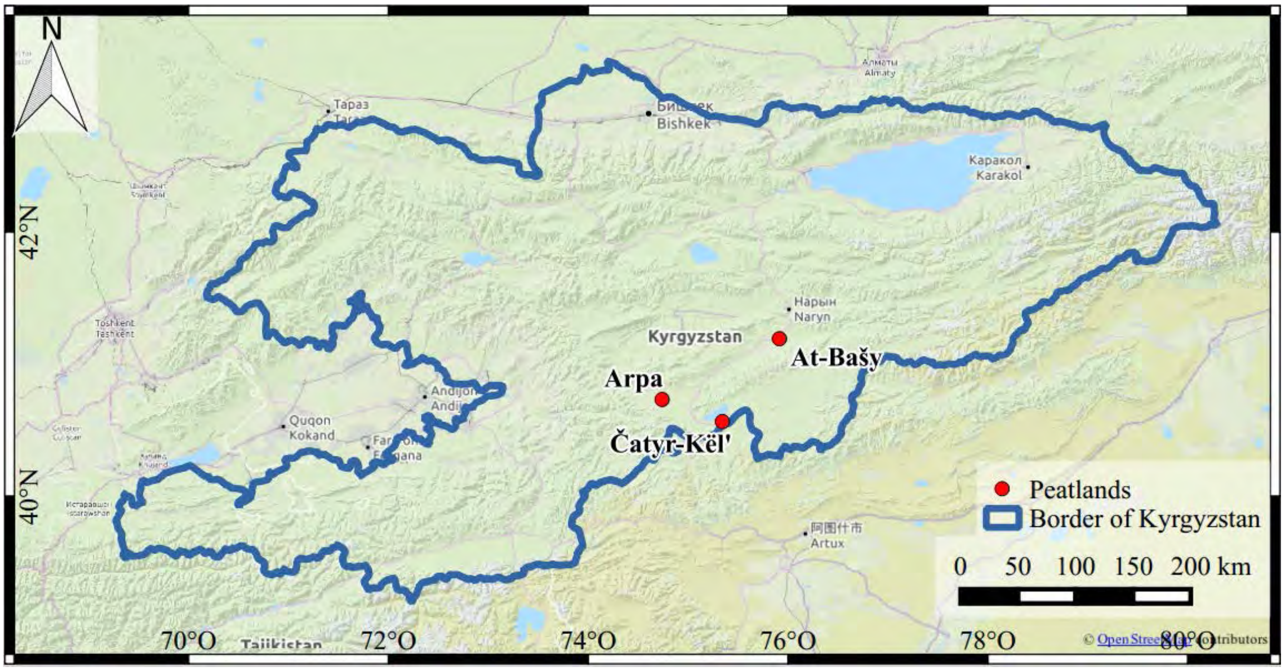

Figure 1. Location of the investigated peatlands in Kyrgyzstan. (coordinate reference system: EPSG:4326, Map data: © OpenStreetMap contributors, CC-BY-SA 2.0).

Table 1. Geographical location (coordinate reference system: EPSG:4326) and area of the peatlands.

Peatland	Area [ha]	Centroid		Altitude a.s.l. [m]
		East [dec]	North [dec]	
At-Bašy	81.1	75.9196896940	41.1981174691	2 250
Arpa	48.9	74.7438894936	40.7373064916	2 900
Čatyr-Këlʹ	46.0	75.3480936240	40.5695328626	3 550

intensify the aridity of the area by impeding further northward movement of the moist air mass of the monsoon (Weischet & Endlicher 2000). The average annual temperature is low (2.1 °C at At-Bašy) and declines with increasing altitude (Williams & Konovalov 2008).

The At-Bašy Peatland

The first study site, which we call the At-Bašy Peatland, is located in the At-Bašy Basin. It is situated on the edge of a fluvial terrace 35 m above the At-Bašy River. This river is a braided river, fed by water from glaciers and by snowmelt. The surface of the peatland has a gentle inclination and is covered by numerous hummocks with heights up to 30 cm. The vegetation is dominated by herbaceous plants (e.g. *Carex orbicularis, Carex divisa*) while woody plants are completely absent (Figure 3). The peatland is currently used as pasture, whereas the surrounding areas are mainly irrigated agricultural fields. Due to the low precipitation, semi-deserts and deserts have developed in several parts of the At-Bašy Basin. The vegetation period (average day temperature > 5 °C, as defined by DWD 2014) lasts from April until September.

The Arpa Peatland

The second study site, which we call the Arpa Peatland, is located in the Arpa Basin. It is situated on the lower edge of a huge shallow alluvial fan. The fan was formed by several rivers that originate in the nearby Fergana and Torugart Mountains. The most important of these streams is the Suek River which is, like the At-Bašy River, a braided river fed by water from glaciers and by snowmelt. Nowadays, the Suek flows approximately 600 m north-west of the

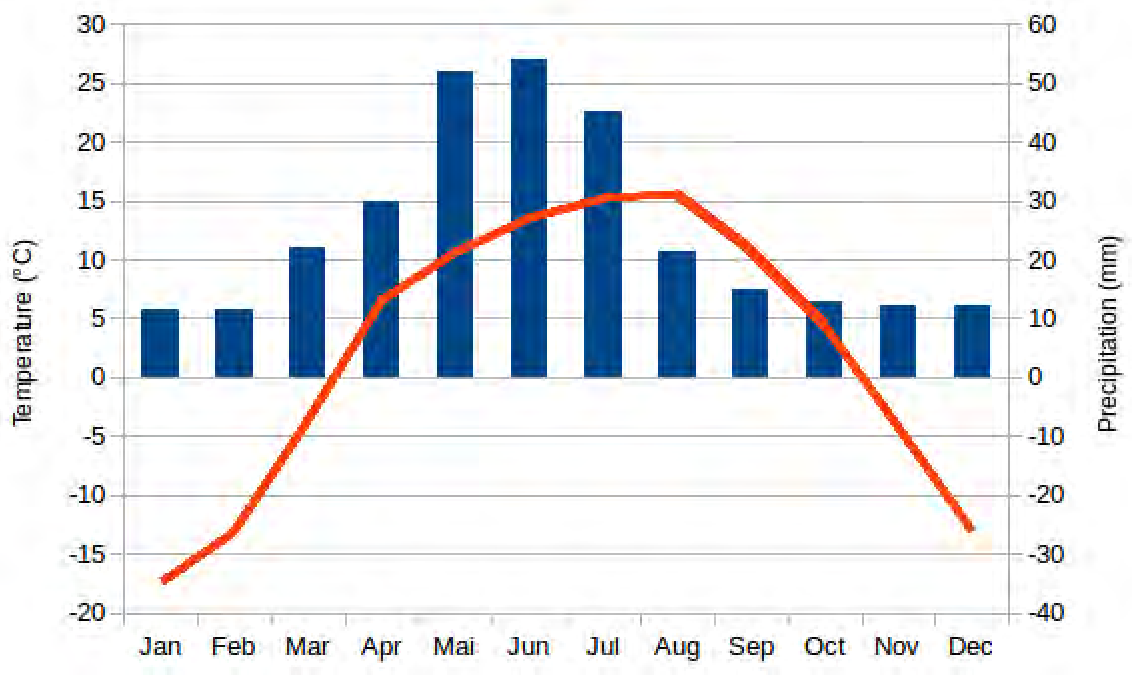

Figure 2. Climograph of weather station At-Bašy (75.80 °N, 41.20 °E), period: 1965–1994 (after Williams & Konovalov 2008).

Figure 3. Photograph of the At-Bašy Peatland (photo Thomas Heinicke).

peatland. The peatland's surface slopes gently and is characterised by little hummocks (mounds) at dryer spots. Some of the depressions between mounds have no plant cover and are subject to erosion. The vegetation is dominated by herbaceous plants like *Carex atrofusa* and *Eleocharis uniglumis*, while woody plants are absent (Figure 4). The whole Arpa Basin is characterised by steppe vegetation and is used for grazing of herded sheep, cattle and horses during summer. The vegetation period is quite short (June until August).

The Čatyr-Këlʹ Peatland

The third peatland, which we call the Čatyr-Kël' Peatland, is situated in the Čatyr-Kël' Basin, south of the corresponding lake. The peatland borders on two small lakes and a small river in the north and on several desiccated river channels in the south. The small lakes and the river drain to the nearby Čatyr-Kël' Lake, an endorheic lake without discharge. The slope of the surface of the Čatyr-Kël' Peatland is in general low, but at several points the inclination rises up to 12 %. Hummocks are usually very shallow, reaching heights of up to 55 cm at only a few points. The vegetation is made up by herbaceous plants (e.g. *Carex atrofusca*, *Carex melanantha*) and brown mosses (Figure 5). The Čatyr-Kël' Basin is covered by dry steppe and alpine meadow vegetation. The vegetation period lasts for only two months (July and August) and the basin is used extensively as a summer pasture for sheep, cattle and horses.

Fieldwork

The stratification of each peatland was investigated along one representative transect (with varying number of transect plots). A shallow pit of 30 cm depth was dug at each transect plot. If the peatland was deeper than 30 cm at the particular point, an instorf corer by Eijkelkamp was used to drill a hole to the mineral subsoil. Substrate materials in both the pit and the drill core were examined for colour, type of material, root penetration, reductimorphic features, carbonate content, and in the case of peat substrates also for humification (von Post 1922).

The type of material was assigned to one of three groups, namely: peat, ORS or mineral substrate (see

Figure 4. Photograph of the Arpa Peatland (photo Thomas Heinicke).

Figure 5. Photograph of the Čatyr-Këlʹ Peatland (photo Thomas Heinicke).

'terms and concepts'). Peats were subdivided into the types: *fine rhizome peat* (width of rhizomes < 1 mm), *coarse rhizome peat* (width of rhizomes = 1–4 mm), or *humified peat*; or, if the peat was dominated by plant remains that could be identified, the peat was named by a plant taxon. ORSs were grouped into the classes *detritus ORS* (organic matter > 30 %) and *mineral ORS* (organic matter 5–30 %). Mineral ORS was subdivided into *calcareous ORS* ($CaCO_3$ > 30 %) and *sandy ORS, silty ORS* or *clayey ORS* ($CaCO_3$ < 30 %). The properties of the material were determined according to the field methods proposed by AG Boden (2005).

The geographic position of the plots was determined with a handheld GPS. The relative altitudes of the plots within one transect were determined with a tube water level. The groundwater level, as well as the pH and electrical conductivity (EC) of the groundwater, was measured at every plot if the groundwater level was above 50 cm depth. Additionally, at every plot, the pH and EC of the surface water were measured in a small pond or in a nearby stream, if possible.

Peatland samples and comparison samples

Samples of peatland and mineral substrates were collected from layers that had been identified as being common for the peatland in question. Substrates from the pits were sampled with a coring sleeve (volume = 100 cm³). In the case of the drilled cores, the substrates were taken out of the peat sampler in lengths of 10 cm. The samples were always taken within the boundaries of one horizon and in one repetition. Afterwards, the samples were packed in plastic bags and moist mass was measured the same day. The samples were subsequently air-dried.

Additionally, three different types of mineral sediments that had been deposited close to each peatland by wind and water were sampled: (1) loess, (2) spring sediments and (3) floodplain sediments. These samples are referred to as "comparison samples". The loess material and the floodplain sediments were collected underneath the Ah horizon. The material of the spring sediment was taken from the channel. The samples were packaged in plastic bags and dried at air temperature.

In the laboratory, all samples were dried at 105 °C in a drying cabinet and the resulting dry mass was measured. Dry bulk density was determined as dry mass ÷ volume of coring sleeve.

A few of the samples were also used for further analysis. These samples were sieved (< 2 mm) and ground. Sieving of peats is complicated, as they consist mainly of dead plant remains that are larger than 2 mm. For this reason the dead plant material of the peats was rubbed through the sieve.

The homogenised samples were analysed for several properties:

(1) pH was determined in $CaCl_2$ solution, as proposed by Schofield & Taylor (1955). 20 ml of sample was added to 50 ml of 0.01 mol L^{-1} $CaCl_2$ solution and pH was measured with a pH meter after one hour.

(2) Calcium carbonate content was analysed volumetrically with a Scheibler apparatus (method: ISO 10693 (1995)). Mass fraction of inorganic carbon $\omega(C_{inorg})$ was then calculated as:

$$\omega\left(C_{inorg}\right) = \omega(CaCO_3)\frac{M(C)}{M(CaCO_3)} \qquad [1]$$

where M = molar mass and ω = mass fraction.

(3) The mass fractions of total carbon $\omega(C_t)$ and total nitrogen $\omega(N_t)$ were determined with a CNS analyser (Leco TruMac CNS) after dry combustion (method for carbon: ISO 10694 (1995), method for nitrogen: ISO 13878 (1997)). For samples with mass fraction of organic carbon below 25 %, the analyser was calibrated with a soil standard; otherwise a plant standard was used.

(4) The organic carbon content $\omega(C_{org})$ was calculated as ($\omega(C_t)$ - $\omega(C_{inorg})$). The mass fraction of organic matter was then estimated as ($\omega(C_{org}) \times 2$) for peats, and as ($\omega(C_{org}) \times 1.72$) for other substrates (AG Boden 2005).

(5) The trophic level of the peatland substrates was computed as ($\omega(C_{org}) \div \omega(N_t)$). This quotient gives the nutrient supply of peatland plants and was introduced by Succow & Stegmann (2001) for peatlands of Middle Europe. The method may not be appropriate for Kyrgyz peatland substrates due to different natural conditions, but is used here because there are no systems for determination of trophic levels that are specific to Kyrgyz peatland substrates (Heinicke 1999).

(6) The mass fraction of additional elements (Al, As, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Ti, Zn) was measured by inductively coupled plasma optical emission spectrometry (ICP-OES, device: Thermo Fisher ICP-OES Iris Radial Intrepid II XSP, method: ISO 11885 (2007)). The samples were prepared beforehand with aqua regia to extract the elements (method: ISO 11466 (1995)). In general, 0.5 g of the sample was analysed. If the mass fraction of $CaCO_3$ was above 30 %, only 0.3 g of the sample was used and 2 ml of ultrapure water was added. If the mass fraction of C_{org} was above 20 %, 0.2 g of the sample was analysed.

(7) The particle size distribution of part of each sample was analysed by the pipette method (as proposed by Köhn (1929), method: ISO 11277 (2009)). Because carbonates and organic matter were not removed before the measurements, only samples with a mass fraction of organic carbon below 10 % were used. The mass fractions of sand (63–2000 μm), coarse silt (20–63 μm), medium silt (6.3–20 μm), fine silt (2–6.3 μm) and clay (< 2 μm) were determined. The reported mass fraction is the average of two consecutive measurements.

Core samples

The cores of one or two plots *per* transect were preserved for X-ray fluorescence (XRF) analysis. The length of each core was 50 cm and several cores were taken at plots with peat depth > 50 cm. The moist cores were put in polyvinyl chloride tubes and preserved with cellophane for transportation. In the laboratory, the top layers were removed from the still-moist cores, which were then covered with thin plastic film for measurements. Intensity of X-radiation (unit: counts per second, cps) as transmitted by the elements (Mg, Al, Si, Ca, Ti, Mn, Fe, Se, Sr, U, amongst others) of the cores was measured with an ITRAX XRF core scanner (method: Croudace *et al.* 2006). The resolution of the measurement was 5 mm.

RESULTS

The At-Bašy Peatland

Substrate properties

The At-Bašy Peatland shows a high abundance of different peatland substrates (Figure 6) and is also comparatively deep (maximum depth: 2.76 m). Peatlands in this altitudinal zone are usually much more shallow (Aljes *et al.* 2014). The peats are dominated by fine rhizomes and dead roots of vascular plants. Small layers of moss and *Schoenoplectus* peat as well as layers with dominantly coarse rhizomes (width 1–4 mm) are interstratified. Some peats contain small quantities of woody plant remains (partly *Salix*), charcoal, and shells of *Mollusca*. All peats are characterised by considerable amounts of minerals, primarily silt, and thus the mass fraction of organic matter of the peats

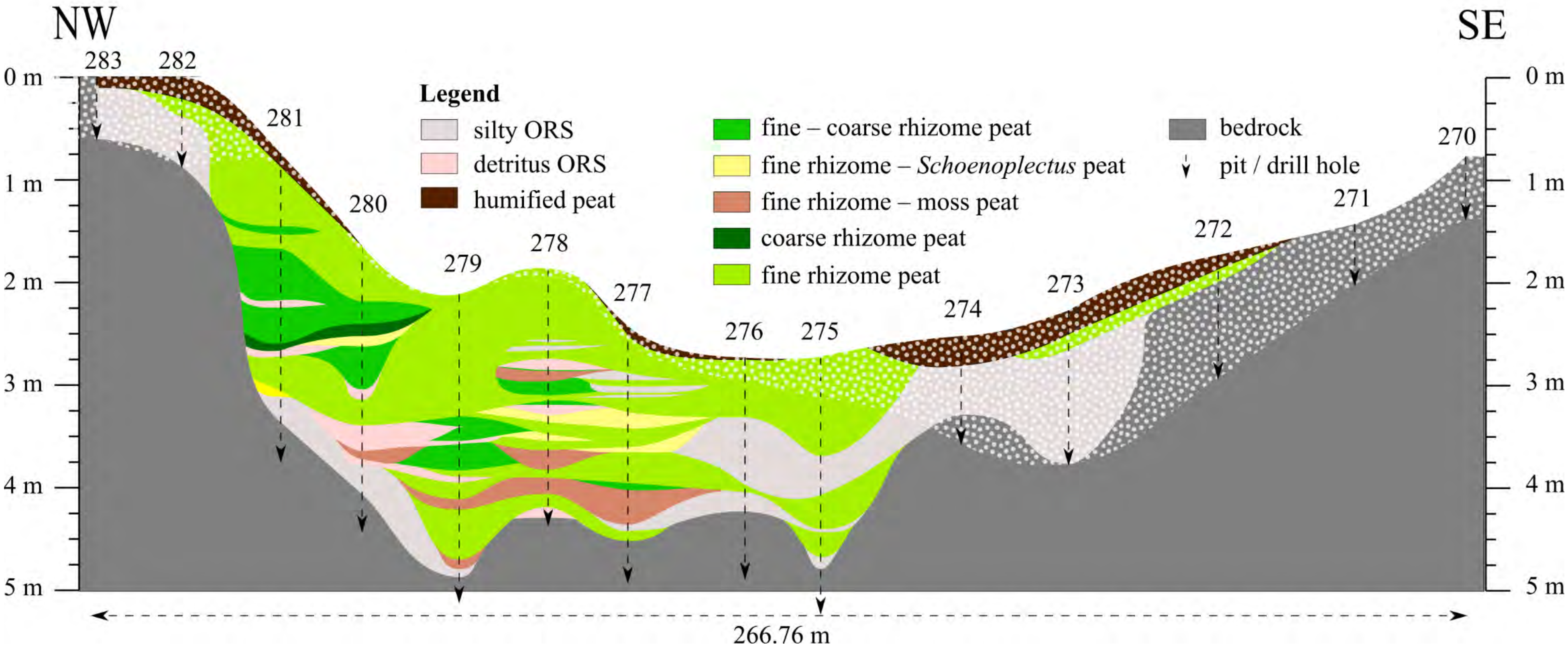

Figure 6. Stratification of the At-Bašy Peatland. White dots mark layers which contain carbonate.

ranges between 30 and 61 %. Peat humification varies between 5 and 8, while mean peat humification is 5.5. Some of the top layers of peat, especially hummocks and peat layers close to the edge of the peatland, are mineralised and pedogenetically modified up to a depth of 21 cm.

Silty ORSs are a very prominent substrate of the At-Bašy Peatland. These ORSs contain small rhizomes, dead roots, and at times small fractions of fine sand or clay (Figure 7). Small layers of detritus ORS are intercalated within the peatland substrates at several points. The substratum of the peatland is dominantly silty with small and varying quantities of sand and clay.

The top layers of the peatland as well as substrates close to its border are calcareous (up to 25 % of mass fraction), while the deeper layers in the centre of the peatland do not contain carbonates. The pH of the substrates is sub-neutral to alkaline (4.9–7.9) and the trophic level of all substrates is eutrophic (14–17).

Element geochemistry

Titanium is used to compare the geochemical composition of the peatland substrates and the comparison samples. Titanium is resistant to chemical weathering and, therefore, suitable as a

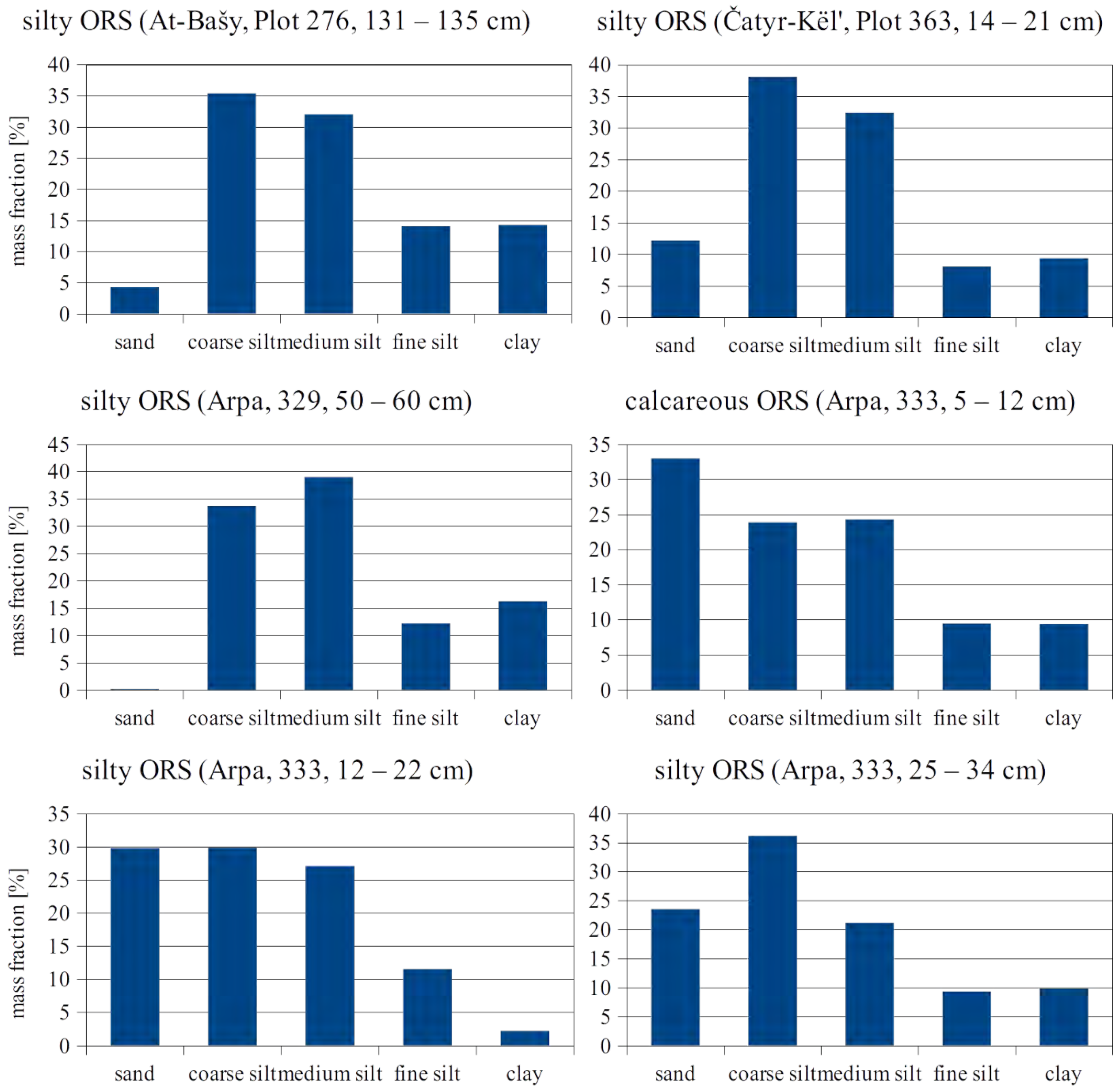

Figure 7. Histograms showing relative proportions of particle size classes of ORSs of all peatlands. In brackets: peatland, plot number and depth of substrate layer. (For overview samples of all peatlands are depicted).

basis for studying similarities and differences in element compositions between samples (Dixon 1989Muhs & Benedict 2006). The titanium content of peatland substrates is similar to that of the nearby loess deposit, but much lower than in the floodplain sediment of the At-Bašy River (Figure 8).

Core samples from Plot 276 were preserved for XRF analysis and detailed examination of element geochemistry. The upper silty ORS has higher contents of selenium and uranium, as well as a higher titanium/silicon (Ti/Si) quotient, than the lower silty ORS (Figure 9). In terms of its selenium and uranium contents, as well as Ti/Si quotient, the lower silty ORS resembles the substratum.

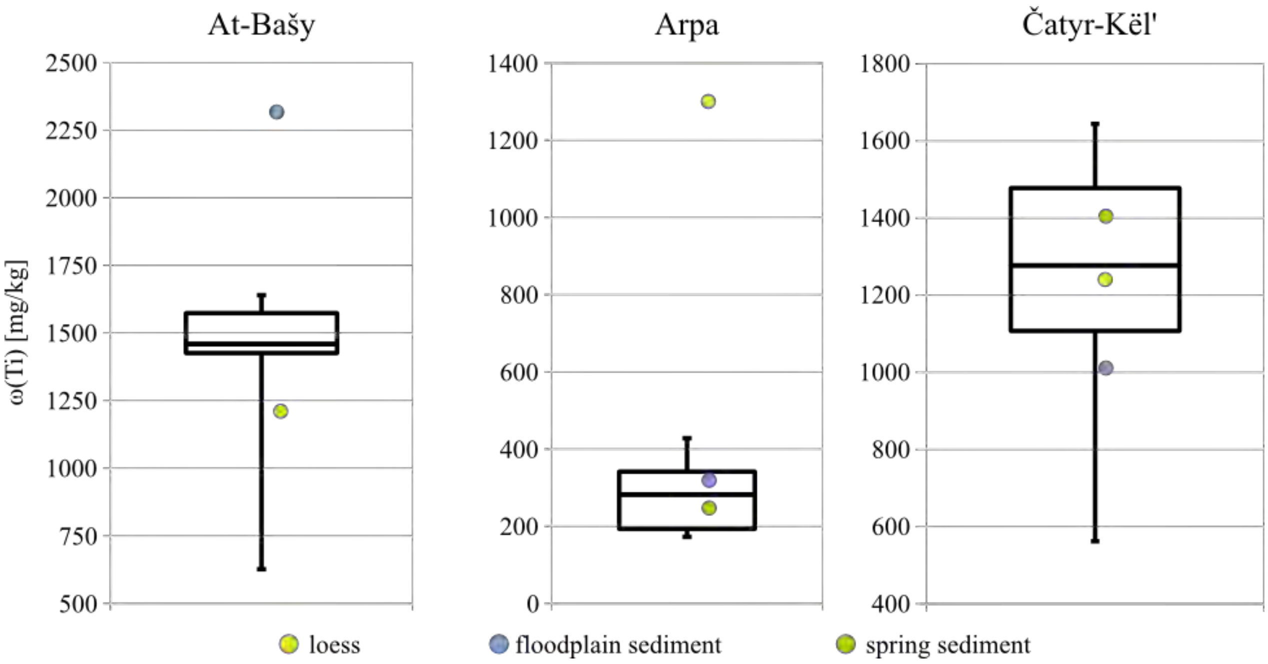

Figure 8. Mass fraction of titanium of the peatland substrate samples and the comparison samples. The box plots represent the values of the peatland substrate samples of the peatlands. The upper and the lower whiskers represent, respectively, the highest and lowest measured values. The circles represent the values for the comparison samples. To provide an overview, samples from all peatlands are depicted.

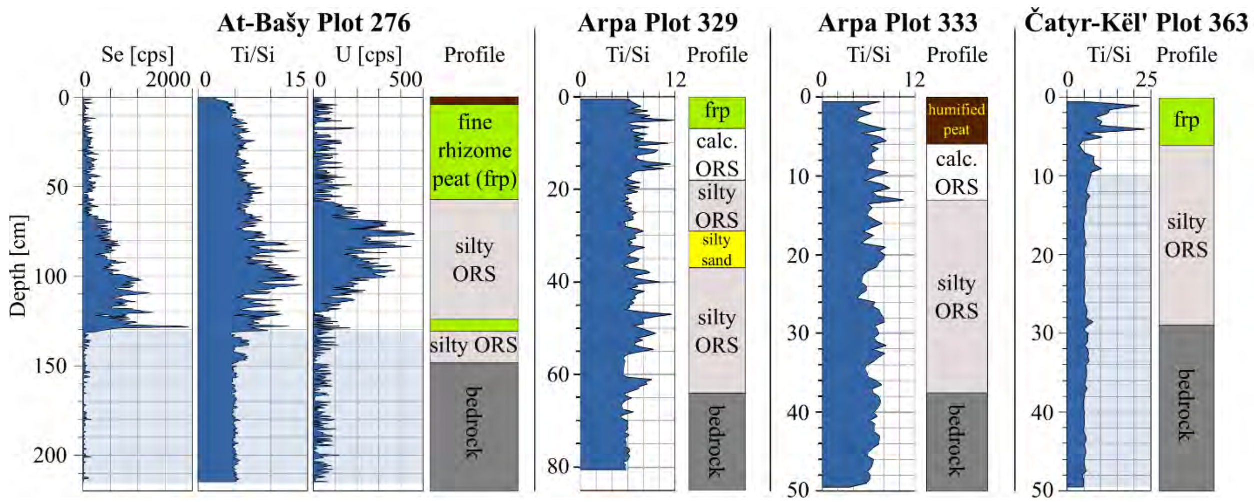

Figure 9. Vertical distribution of the mass fraction of selenium and uranium as well as the titanium/silicon ratio in the peatland cores. The stratification of each plot is displayed on the right side. To provide an overview, cores from all three peatlands are depicted.

The Arpa Peatland

Substrate properties

The Arpa Peatland is shallow (maximum depth 87 cm) and shows a low abundance of peatland substrates (Figure 10). The peats are characterised by fine rhizomes and dead roots. Coarse rhizomes, as well as silt, are frequent additives. Fine sand, moss remains and shells of *Mollusca* are found in only a small number of peat layers. Mean peat humification is about 6, varying between 4 and 8. Some of the top layers of peat, especially hummocks and peat layers close to the edge of the peatland, are mineralised and pedogenetically modified up to a depth of 13 cm.

Silty ORSs are prominent amongst the substrates of the Arpa Peatland. These ORSs often contain a considerable amount of sand and particles are less well sorted (Figure 7). An exception to that rule is a silty ORS found on Plot 329 which contains only a small portion of sand and is very well sorted. In addition to the silty ORSs, several calcareous ORSs, with a high content of carbonates, are embedded in the top layers of the Arpa Peatland. All ORSs contain small quantities of rhizomes and roots.

The substratum of the peatland is predominantly silty with changing portions of fine sand. At some plots, the substratum also contains small fractions of medium and coarse sand as well as gravel.

Almost all substrates contain carbonates (up to 49.8 % mass fraction) and the mass fraction of carbonates declines with increasing depth. Noticeably, some non-calcareous layers are intercalated with calcareous layers (Figure 10). The pH (6.8–8.0) of the substrates is neutral to alkaline and its trophic level (11 – 13) is eutrophic.

Element geochemistry

The titanium contents of the peatland substrates are similar to those of the spring sediment and the floodplain sediment of the Suek River (Figure 8). However, the titanium content of the nearby loess deposit is far higher than that of the peatland substrates.

At two of the Arpa Peatland plots, core samples were preserved. XRF analysis of these cores does not show a difference in Ti/Si ratio between the peatland substrates and the underlying mineral material (Figure 9).

The Čatyr-Këlʹ Peatland

Substrate properties

The Čatyr-Këlʹ Peatland is the shallowest of the investigated peatlands (46 cm). The peats are dominated by fine rhizomes and, frequently, coarse rhizomes. Silt particles and/or brown mosses are added in lower proportions (Figure 11). The humification of these peats varies between 5 and 6. At a few plots the peats consist solely of dead brown moss remains with humification between 2 and 5. The top layers of the peats are at some points mineralised and pedogenetically modified, especially in hummocks and areas close to the edge of the peatland.

Silty ORSs are an important part of the peatland substrates of the Čatyr-Këlʹ Peatland. These ORSs contain often small quantities of sand or clay (Figure 7). Additionally, sandy ORSs were found at two plots. All ORSs contain small proportions of rhizomes and roots.

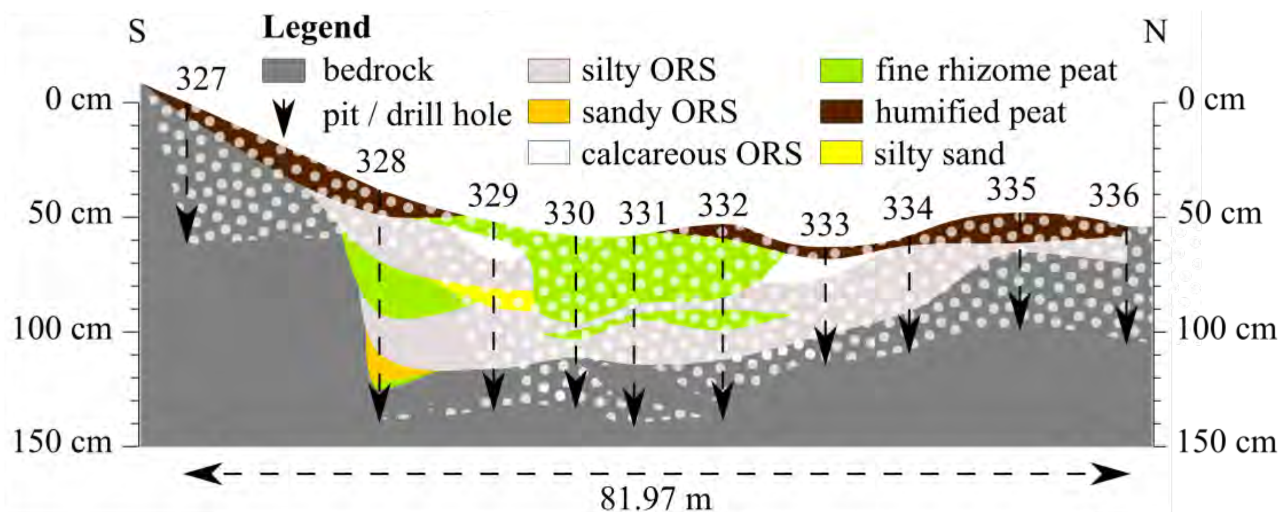

Figure 10. Stratification of the Arpa Peatland. White dots mark layers which contain carbonate.

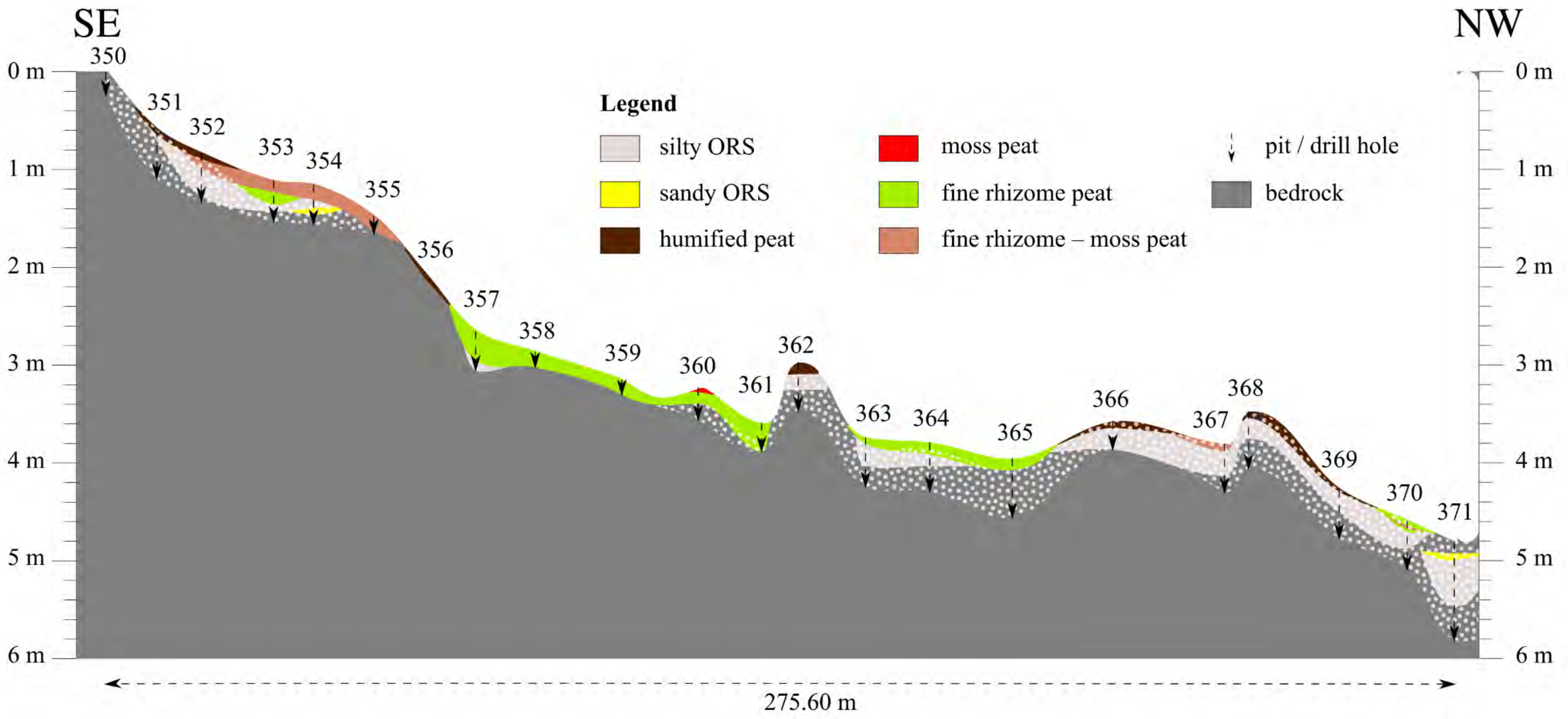

Figure 11. Stratification of the Čatyr-Kël' Peatland. White dots mark layers which contain carbonate.

In general, the substratum of the peatland is characterised by sandy or clayey silt. Only a small part in the middle of the peatland (between Points 353 and 359, Figure 11) is made up of gravel and rocks.

The substratum, the lower strata of the peatland, and substrates close to its edges contain carbonate, while the rest of the peatland substrates are free of carbonate. The pH (5.6–7.2) of the substrates is sub-neutral to alkaline and its trophic level (13–19) is eutrophic.

Element geochemistry

The titanium contents of all comparison samples are similar to those of the peatland substrates (Figure 8).

At Plot 363 a core sample was preserved for XRF analysis. The Ti/Si-ratio shows high fluctuations between 4 and 23 within the peat strata and between 4 and 10 in the upper layer of the silty ORS, but only small oscillations in the lower layer of the silty ORS and the substratum (Figure 9).

Water conditions

All of the investigated peatlands are fed by groundwater which percolates through the whole peat body. The silty substrata prevent discharge through the bottoms of the peatlands and the modest inclination induces a flow of water. Simultaneously, water flows over the surfaces of the peatlands. This is caused partly by the high abundance of silty particles in the substrates. The silt reduces the amount of coarse pores and, thus, the saturated hydraulic conductivity. At the At-Bašy and Arpa Peatlands this effect is intensified by the mineralisation of the upper peat layers. At the Čatyr-Kël' Peatland the higher inclination as well as the shallow peat layer cause the water to flow above the surface. Additionally, several small springs can be found within the peatlands' boundaries. The groundwater level of the At-Bašy and Arpa Peatlands was usually at least 5 cm beneath the surface at the time of fieldwork. It was at the surface only at some points. At the Čatyr-Kël' Peatland, the groundwater level was always close to or coincident with the ground level.

The pH (7.0–9.0) of the groundwater and surface water is neutral to alkaline. At the At-Bašy and Arpa Peatlands, the EC of the water is generally lower in the groundwater (48.8–87.7 mS m^{-1}) than in the hollows on the surface (79.7 – 274.0 mS m^{-1}). This corresponds with the higher carbonate content of the surface layers. In contrast, the EC of water at the Čatyr-Kël' Peatland is very low (26.9–62.6 mS m^{-1}). This corresponds with the absence of carbonate from the upper strata of the peatland.

DISCUSSION

Hydrogenetic mire types

The peatlands can be classified as several coexisting hydrogenetic types (Succow 1988, as modified by Joosten & Clarke 2002) based on the hydrological conditions and their positions in the relief. The At-Bašy and Arpa Peatlands are in general percolation mires, but are in a transition stage to surface-flow mires due to degradation of their top peat layers by cattle grazing. The compact mineralised peats force the groundwater to flow above the surface of the peatland instead of percolating through the pores of the substrates, and thus permanently change the flow path of the groundwater. This hydrogenetic mire type transition, caused by cattle grazing, was discovered in Kyrgyz peatlands by Heinicke (1999) and later reported in Tibetan peatlands by Joosten & Schumann (2007). The Čatyr-Kêl' Peatland is a sloping mire due to the comparatively high inclination, the shallow peat layer and the consequently high overland flow. At all three peatlands, spring mires are locally embedded where groundwater leaks from the mineral substratum.

Genesis of the peatlands

The peatlands probably started to develop after the end of the Weichselian glaciation. Although glaciers did not cover the basins themselves but only the surrounding mountains during that time (Koppes *et al.* 2008), the temperature was not high enough for plants to grow and thus for the formation of peat. Mel'nikova & Alešinskaâ (1990) provide an indication about the beginning of peatland development in the region by determining the age of a peat found in the Arabel' Basin at 4,890 (± 70) years. By this time at the latest, temperatures in the At-Bašy and Arpa basins must have been high enough for the development of peat because they are located at a far lower altitude than Arabel'.

The decrease of mean annual temperature with increasing height influences the peatlands in several ways. First of all, it results in shorter vegetation periods and, consequently, lower peat accumulation rates and shallower peatlands (Aljes *et al.* 2014). Secondly, the fraction of brown mosses in the vegetation rises (Heinicke 1999); thus, more brown moss peat can be found in the Čatyr-Kël' Peatland.

At the At-Bašy Peatland ecological conditions for plants changed frequently over the course of time, as indicated by the numerous alterations of peatland substrates. Several small standing water bodies existed in the past, where detritus ORSs (detritus gyttja) emerged. In contrast, the peatland probably also underwent repeated dry phases. This is indicated by the woody roots (such as *Salix* species) found in several layers. Except for dwarf shrubs of *Salix coesia* on high-altitude sloping fens, shrubs and trees do not grow on intact peatlands in Kyrgyzstan but may colonise degraded peatlands if the groundwater level drops considerably below the surface (Heinicke 1999, Heinicke 2004, Aljes *et al.* 2014). Additionally, fire has passed over the peatlands from the surrounding steppes in the past and burned the woody vegetation, as shown by the presence of charcoal.

At the Arpa Peatland lime is prominent in the peatland substrates. The origin of the lime, as well as the development of the calcareous layers (calcareous ORSs), could not be determined in this study. Two processes could have resulted in high lime content of the peatland's substrates. First, groundwater could have transported Ca^{2+} and HCO_3^- ions into the peatland, the ions being precipitated as $CaCO_3$ either directly from the groundwater or in springs or small standing water bodies within the peatland. The substrates with high $CaCO_3$ content (i.e. the calcareous ORSs) are similar to tufa, a typical substrate of spring mires. Secondly, lime could have been deposited as part of the sediments during the development of the peatland. A combination of both processes may also have occurred, which makes discrimination of their roles in mire genesis difficult.

Peatland degradation

At the At-Bašy and Arpa Peatlands we consider overgrazing to be the major reason for the recent degradation and mineralisation of the top peat layers. The transition of both of these peatlands from percolation mires to surface-flow mires leads to stronger water level fluctuations. This triggers stronger decomposition of the top peat layers. Heinicke (1999) and Aljes *et al.* (2016) suggest that an additional process accelerates the degradation of Kyrgyz peatlands - the grazing animals trample deep hollows into the peatlands' surface. This displaces the substrates and triggers a relative rise of the hummocks. Subsequently, the tops of the hummocks are cut off from the water supply and start to mineralise slowly. Eventually the peaks of the hummocks become strongly humified. Additionally, high-intensity-grazing will reduce the vegetation cover in depressions and cause soil erosion by wind and water. This theory is supported by research on peatlands of the Alabash-Konurolen Valley, where Heinicke (1999) could relate increasing height of hummocks to rising livestock density.

The hypothesis is challenged by the fact that peat hummocks also occur naturally in alpine peatlands which are seasonally exposed to strong frost. The genesis of cryogenic mounds in general is mainly traced back to differential frost heave, although several other theories do exist (Grab 2005). In Fennoscandia, hummocks (called pounus) are common features of shallow peatlands, but can also be found on mineral ground. The development of pounus consisting mainly of peat is supposed to be initiated by randomly scattered hummock-forming plants. During the colder season, frost will penetrate the mounds more easily due to their thinner snow cover. Differential frost penetration will trigger injection of unfrozen substrate (Van Vliet-Lanoë & Seppälä 2002, Grab 2005). In semi-arid high-altitude regions, frost induced hummocks are restricted to wetland areas (Grab 2005). Soil moisture in these regions may be not high enough for hummock growth outside the wetlands' boundaries. Grab (1998) states that a low snow cover, as occurring in semi-arid regions, is a prerequisite for the formation of cryogenic mounds outwith permafrost areas.

Nevertheless, high grazing intensity can lead to a complete loss of shallow peatland areas and, in the end, small mineral hills - residues of the mineral-rich peatland mounds - will be left. At At-Bašy and Arpa these mineral hills surround both peatlands and thus give a hint of their original extent. The recent rhizomes of *Phragmites australis* found in the At-Bašy Peatland may also be an indicator of this kind of anthropic peat degradation. Fossil rhizomes of *Phragmites australis* are absent from peatlands of the foothill zone and higher altitudes in Kyrgyzstan, but fossil rhizomes or *Phragmites* peat can be found in the peatlands of the plains (below 1,000 m a.s.l.), for instance in the Čuj River Basin near Tokmok (Heinicke 1999, Aljes *et al.* 2014). *Phragmites australis* is most vital in the plains and lower altitudes, but reaches its vertical distribution limit in the foothill zone of Kyrgyzstan at about 2,000 m a.s.l. (Korovin 1962). At this distribution limit *Phragmites* grows only in combination with wet sedge vegetation, if the former pure sedge vegetation cover and soil surface are disturbed by overgrazing and trampling (Heinicke unpublished).

At the Čatyr-Kël' Peatland a natural change of groundwater level may be the most important factor in peat degradation. The fluctuating water table of the endorheic Čatyr-Kël' Lake probably triggers fluctuations in the groundwater level of the peatland. Cattle grazing is not a noticeable factor in peat degradation, as the Čatyr-Kël' Peatland is rarely used for this purpose.

Origin of silt

Our results indicate that both water and wind can cause silt deposition in the studied peatlands.

At the At-Bašy Peatland, silts were probably primarily sedimented by wind. Deposition of silt by the At-Bašy River has not been possible in the recent past because the peatland is located on a fluvial terrace outside the present floodplain. Moreover, the stratification of the peatland indicates that the At-Bašy River never played a major role during its genesis. Braided rivers like the At-Bašy River usually deposit coarse particles (sand or gravel) and only small layers of silt in restricted areas. At the At-Bašy Peatland, gravel is missing and sand is found only in small proportions in the lower strata which are close to the substratum. The elemental composition of a nearby loess deposit provides an additional indication of the aeolian origin of the silt: the titanium content of the peatland substrates is similar to that of this loess, while the titanium content of the nearby floodplain sediment is much higher (Figure 8). Although weathering-resistant elements like titanium are suitable for the comparison of different substrates, the findings suffer from two methodological problems: (1) only one sample was taken from the loess and river deposits, thus the variation in titanium content between the river and windborne sediments is not known; and (2) usually, *ratios* of weathering resistant elements are used for substrate comparison (Muhs & Benedict 2006, Thomson *et al.* 2006). This technique could not be applied in this study, as titanium was the only weathering resistant element that was determined with ICP-OES.

At the At-Bašy Basin, the semi-desert and desert areas close to the peatland are a possible source of the aeolian silt. In recent years, farmers created additional sources by establishing numerous fields and degrading meadows and pastures. This led to serious anthropic decline in the vegetation cover of the basin and stimulated erosion.

After aeolian deposition of silts on the peatland, these silts may be secondarily relocated by springs. This is once again suggested by the stratification of the At-Bašy Peatland. At some points, fairly thick layers of silty ORSs have been deposited, which are restricted to small areas. These spatially restricted deposits suggest point spring influence. In contrast, windborne sediments usually cover a wide area.

The mineral components of the lower layers of the peatland, which lie directly above the mineral substratum, were probably deposited before the formation of the peatland and share the same genetic process as the substratum itself. This is suggested by the XRF core data, which show similar elemental compositions of the lower layers of the peatland substrates and its substratum. In contrast, the composition of the upper silty ORS of the peatland is clearly different. The still high content of organic carbon of the lower layers of the peatland originates from the ingrowth of plant roots, as admixed macrofossils prove.

At the Arpa Peatland, silts were probably primarily deposited by water. The particle size distribution of almost all of the peatland substrates resembles the size spectrum of fluvial deposits - the substrates contain high quantities of sand and are less well sorted (Figure 7). In addition, elemental analyses suggest a close relationship between waterborne sediments and peatland substrates, the titanium content of the peatland substrates being very similar to the content in nearby spring sediments and floodplain sediments of the Suek River, while the content of a nearby loess sample is significantly higher (Figure 8). Furthermore, XRF core data do not show a difference in elemental composition between the peatland substrates and the underlying substratum, which is known to have been deposited by the Suek River. Thus, similar minerals in the peatland substrates probably have the same source. The Suek River provides enough silt-sized particles because it is (a) fed by silt-rich water from glaciers, and (b) a braided river with considerable slope and thus producing silt particles during the transportation process. The inclination of the Arpa Peatland is low enough for silt particles transported by water to settle.

However, differentiation between spring and river transport of silt is complicated by the fact that springs relocate only sediments that were previously deposited by the Suek River. This makes discrimination by elemental or particle size analyses impossible.

At the Čatyr-Kël' Peatland the prevalent medium that deposited silt in the peatland could not be determined. The method of comparing the content of titanium could not be applied because the comparison samples had similar titanium contents. As at the At-Bašy Peatland, the mineral components of the lower layers of the Čatyr-Kël' Peatland had probably already been deposited before development of the peatland began. This is once again indicated by XRF core data, which show that the mineral components of the substratum and the lower strata of the peatland have similar elemental composition, while the composition of the upper silty ORS and the upper peat is differerent. After deposition of the lower layers, development of the peatland began and the substrates were penetrated by plant roots whose fossil remains can be found in these strata today.

For precise discrimination of the transport media of silt particles, additional measurements that need to be made on peatland substrate samples in future research are: (1) particle size analysis with high resolution; and (2) analysis of several immobile trace elements like niobium, zirconium, cerium, and yttrium.

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