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Holocene lake sediments as the parent material of soil

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Abstract

Holocene lake sediments, as specific formations deposited in freshwater reservoirs, rarely constitute soil parent material. Under natural conditions, the accumulation of lake sediments is most often followed by a peat-forming phase, which results in the development of peat soils that are underlain by lake deposits. However, in Poland, as well as in the young glacial zone of other European countries, intensive drainage works have taken place that have drained shallow water reservoirs, which in some cases have led to the exposure of lake sediments and the formation of specific soils. With the development (and subsequent editions) of the Polish Soil Classification (PSC) scheme, there was a need to develop detailed qualitative and quantitative criteria to recognise these sediments as soil parent material. These criteria were primarily intended to make a logical division of these materials as soil diagnostic materials in the context of their position within the PSC and to enable accurate identification of these sediments in the field. The aim of this work was to present selected lake sediment classification systems (including studies by von Post, Troels-Smith, Okruszko and Markowski), with particular emphasis on the terminology used, in relation to the division of these sediments (as proposed by Polish researchers). Classification of limnic materials used in PSC is presented. In addition, the genesis of lake sediments and the anthropogenic factors that have led to their exposure are discussed, and a part of this work also focuses on the issue of field identification of sediments and on the selected properties of the lake sediments and soils that they form.

1. Introduction

Holocene lake sediments are of interest to many scientific disciplines, such as limnology, geology, paleogeography, paleoecology, sedimentology, soil science, and geotechnics. However, this has led to the development of a multitude of terms, definitions and proposals on how to classify them (Table 1) (Horawski, 1971; Freytel and Verrecchia, 2002; Myślińska, 2003; Schnurrenberger et al., 2003; Więckowski, 2009; Vári et al., 2023; Vári and Sümegi, 2024). As such, the wide range in methodological approaches used to investigate those sediments have made it difficult to compare results across different studies (Myślińska, 2001; Borówka, 2007; Bartmiński et al., 2022). As Rzepecki (1983) stated, the terminological chaos with regard to lake sediments is partly justified by the fact that "lake sediments constitute a specific and extremely complex formation, both in terms of mineral, chemical and, above all, biological composition".

As a consequence of both natural and anthropogenic processes, lake sediments can appear on the land surface and form the parent material of the soil (Uggla, 1971; Dearing and Foster, 1986; Berglund, 1996; Marszelewski, 2005; Berglund and Berglund, 2010; Choiński et al., 2012; Kruczkowska et al., 2021). Processes that can expose lake sediments include:

- reduction of lake water levels due to natural hydrographic changes, such as deepening of watercourses, climate change, etc.;
- isostatic land uplift after glaciation associated with land elevation;
- drainage of lakes through water engineering;
- degradation (mineralisation) of shallow peat layers in drained lacustrine bogs.

It should be noted that as a result of glacio-isostatic land uplift, the central part of Scandinavia has risen by more than 250 m since the last glaciation, with many shallow sea bays and coastal lakes uplifted as a result (Dearing and Foster, 1986; Mokma et al., 2000). This has spurred considerable interest in Scandinavian countries in general, and in Sweden in particular, where the first scientific descriptions of such formations were published (von Post, 1862; Naumann, 1922; Lundquist, 1927; Wik-

Table 1
Selected definitions of lake sediments

Term	Definition	Source
Coprogenous earth	A material in some organic soils that contains at least 50% by volume of fecal pellets less than 0.5 mm in diameter.	Gregorich et al., 2002
Diatomaceous earth	Fine, grayish siliceous material composed chiefly or wholly of the remains of diatoms. It may occur as a powder or a porous material.	Gregorich et al., 2002
Dy	Finely divided, partly decomposed organic material accumulated in peat soils in the transition zone between the peat and the underlying mineral material. Dy peat also refers to amorphous material formed from humus soils that have settled in lake waters. Dy is poorer in nutrients that gyttja and is characterized by a high C : N ratio.	Gregorich et al., 2002
Gyttja	A nutrient-rich, sedimentary peat consisting mainly of plankton, other plant and animal residues, and mud. It is deposited in water in a finely divided condition.	Gregorich et al., 2002
Gyttja	A sedimentary peat consisting mainly of strongly decomposed plant and animal residues precipitated from standing water. An under-water humus form consisting of a mixture of organic and mineral particles, rich in nutrients, well aerated.	Canarache et al., 2006
Lacustrine deposit	A deposit settled out of bodies of still lake water, and later on exposed to the Earth's surface either by lowering of the water level or by elevation of the land. Lacustrine deposits, frequently as well as soils developed on such deposits, reveal a clear layering and banding, each corresponding to a different season of deposition. Lacustrine soil are formed on such deposits.	Canarache et al., 2006
Limnic material	A diagnostic soil material, containing both organic and inorganic materials that were either deposited in water by precipitation or through action of aquatic organisms, such as algae or diatoms; or derived from underwater and floating aquatic plants and aquatic animals. Limnic materials include coprogenous earth, diatomaceous earth and marl. This concept includes the gyttja concept, as used in Northern Europe.	Canarache et al., 2006
Mud	An unconsolidated rock of clay and/or silt grades with much water, e.g. as commonly deposited in estuaries, lakes, lagoons and at depths under the ocean. It may be partly consolidated in certain geological formations to form mudstone, resembling a soft shale, but non-plastic.	Clark, 1990
Mud; ooze; slime	A suspension of mineral and organic matter, the mineral particles being of clay, silt and fine sand size, present in river water or other kinds of water, or deposited, usually with a high moisture content, after removal of fooding, stagnant or runoff water. Mud is a common soil parent material in deltas and in lacustrine areas.	Canarache et al., 2006
Sapropel	A sediment rich in organic matter which has been formed under reducing conditions (an H_2S environment) in a stagnant water body.	Wasmund, 1930a
Sapropel	Sludge or mud which collects in swamps or shallow marine basins, rich in organic matter, formed by slow anaerobic decomposition of remains of small organisms, e.g. of diatoms and plankton, which, if compressed by accumulated sediments, may form petroleum compounds.	Clark, 1990
Sapropel	An unlithified, fine-grained, often laminated black organic-rich deposit containing mainly macrophytic (benthic) plant remains that have been decomposed anaerobically. The original definition (Wasmund, 1930a) refers to lacustrine environments where the bottom water contains dissolved H_2S and a benthic fauna is consequently absent. The term has subsequently been extended to include marine deposits that are olive-green, gray or brown in color and contain both planktonic as well as macrophytic organic material.	Calvert, 2005
Sapropel; fetid slime	A sedimentary peat, a general term for organic matter-rich mud, sludge or ooze of black colours, formed in the bottom of some freshwater swamps and shallow marine basins, lagoons or oxygen-deficient swamps. Some sapropels are considered as cat clay. An underwater humus form consisting of mainly organic limnic sediments, often with sulphates, rich in nutrients, poorly aerated.	Canarache et al., 2006
Sedimentary peat	A material composed of plant debris and fecal pellets less than a few tenths of a millimeter in diameter and having brown or gray-brown colors when dry. It has slightly viscous water suspensions, is slightly plastic but not sticky, and shrinks upon drying to form clods that are difficult to rewet. It has few or no plant fragments recognizable to the naked eye.	Gregorich et al., 2002

lander et al., 1950a, b). Due to the specific characteristics of lake sediments, the soils that subsequently develop exhibit a number of features that distinguish them from peat soils and, as such, should be classified separately.

Since most of the peatlands in the young glacial landscape are of lacustrine origin (i.e. developed as a result of lake terrestrialisation), their surface peat layers are lined with lake sediments. If the peat layers are shallow, the lake sediments can surface during drainage and peat mineralisation, whereupon they are exposed to present-day soil-forming processes (Uggla, 1967; Berglund, 1996; Chmieleski et al., 2004; Chmieleski, 2006; Chmieleski and Zeitz 2006; Saurette and Deragon, 2023).

The aim of this article was to trace how the terminology that describes Holocene lake sediments has evolved since the pioneering work by von Post (1862), as well as characterise such sediments as materials from which present-day soils have formed. The article is focused on the soil-based context of these sediments, with particular emphasis on Poland specifically, as well as the achievements of Polish soil scientists.

2. Origin of lake sediments

Lake sediment deposits began to form in the late Pleistocene (Younger Dryas) and the early Holocene (pre-Boreal period). In the young-glacial zone of Poland, Błaszkiewicz (2007) distinguished three morphogenetic groups of lake basins: (1) depressions where sedimentation began in the pre-Allerødian period; (2) depressions where sedimentation began in the Bölling-Allerød complex; and (3) depressions where sedimentation began in the pre-Boreal period. Sedimentation takes place entirely under water with the accumulation of various debris previously suspended in the water or brought in from the catchment area. The formation of lake sediments is closely related to the nature of the reservoir's catchment area (Uggla, 1964b; Róg, 1978; Ilnicki, 2002; Błaszkiewicz et al., 2015; Tokarz et al., 2015; Malkiewicz et al., 2016) but is also impacted by other factors. Climate plays a key role in this regard, especially the amount, intensity and distribution of precipitation, the ambient temperature and the prevailing wind direction (Kruczkowska, 2024).

Organic gyttja (detrital gyttja) is formed in closed lake basins that are fed by small amounts of nutrient-poor waters. It is formed when dead planktonic organisms (i.e. algae, exoskeletons of crustaceans, single diatom cells), small benthic fauna (that inhabit the bottom zone of a water reservoir) and metabolites of aquatic organisms fall to the bottom. Organic gyttja also comprises precipitates of chemical compounds, mainly calcium carbonate ($CaCO_3$), and mechanically deposited non-carbonate mineral particles of clay and silt, and to a lesser extent sand (Róg, 1978; Myślińska, 2001; Okupny, 2023). In lake waters that are rich in calcium bicarbonate ($Ca(HCO_3)_2$) dissolved in water, biological decalcification takes place, and calcareous gyttja is formed, most often in shallow reservoirs or lake bays. Precipitation of $CaCO_3$ may also occur with changes in water temperature and carbon dioxide content (Prusinkiewicz and Noryśkiewicz, 1975; Tobolski, 2000).

The sedimentation process is affected by the amount of organic matter produced in the water body and the external matter inflows. When the debris is brought into the lake by fluvial and aeolian translocation or originates from chemical/mechanical denudation of the catchment soils, the sediment formation process is considered to be allogenic in nature. Conversely, if the accumulating material is of *in situ* origin, the sedimentation is defined as an autogenic process (Wasmund, 1930b; Tobolski, 2000; Wójcicki, 2015; Okupny, 2023).

Lakes are classified based on the abundance of nutrients in their waters. The basic division distinguishes oligotrophic, eutrophic and dystrophic lakes (Wasmund, 1930b). Dystrophic lakes occupy relatively deep depressions among limeless, sandy podzolic soils covered with coniferous forests (Fig. 1). They occur in Northern Europe, especially in the boreal zone, but are relatively rare in Poland (e.g. Augustowska Primeval Forest, Piska Primeval Forest, Wigry National Park). Humic compounds dissolved in water and held in iron (Fe) complexes penetrate into the basin of dystrophic lakes, where they form a colloidal semi-liquid mass. In von Post's (1862) classification, these types of sediments are referred to as *dy*. The vegetation cover that encroaches onto the surface of a lake begins to form a floating mat. Over time, the thickness of the mat increases and covers the entire surface of the lake, which enters the phase of a transitional bog (quaking bog) and ultimately becomes a raised bog (Wetzel and Likens, 1991). Dead plant fragments break off from the floating mat and fall to the bottom of the lake where they mix with the sediments that have accumulated there and create sedimentary peat (Fig. 1). The thickness of the layers of transitional and raised bogs in terrestrialised dystrophic lakes may reach several meters, and in some instances, a so-called water lens may develop in the lower parts of the basin. Therefore, the occurrence of dy-like sediments on the surface or within the soil profile (1.5 m) in Polish conditions is unlikely.

Eutrophic lakes, numerous in the Polish lowlands, are very diverse in terms of the nature of the lake basins and fertility of the waters. The evolution of eutrophic lakes depends on the abundance of nutrients in the catchment soils, including $CaCO_3$, as well as the lake bottom configuration, the water inflow in the streams and the intensity of denudation processes that take place in the catchment. The evolution of eutrophic lakes leads to the formation of post-lacustrine low peatland (fen). At the start, lacustrine clay is usually deposited at the bottom of the lake (Fig. 1) where it fills the lowest parts of the basin due to its ability to "flow" – move along the bottom (Wasmund, 1930b; Uggla, 1971). At the end of the Pleistocene and the beginning of the Holocene, clay accumulation took place mainly when the prevailing cold climate induced intense frost weathering, and a lack of dense vegetation cover favoured denudation. At that time, the lakes were low in nutrients, so development of plankton was poor and the proportion of organic matter in the lake clay was small.

As biological life in the catchment developed, the amount of nutrients in the lake increased and planktonic algae reproduced continuously. Their dead remnants formed deposits of detrital gyttja that usually lay on the lacustrine clay. In the case of a catchment rich in $CaCO_3$, calcareous gyttja and lacustrine

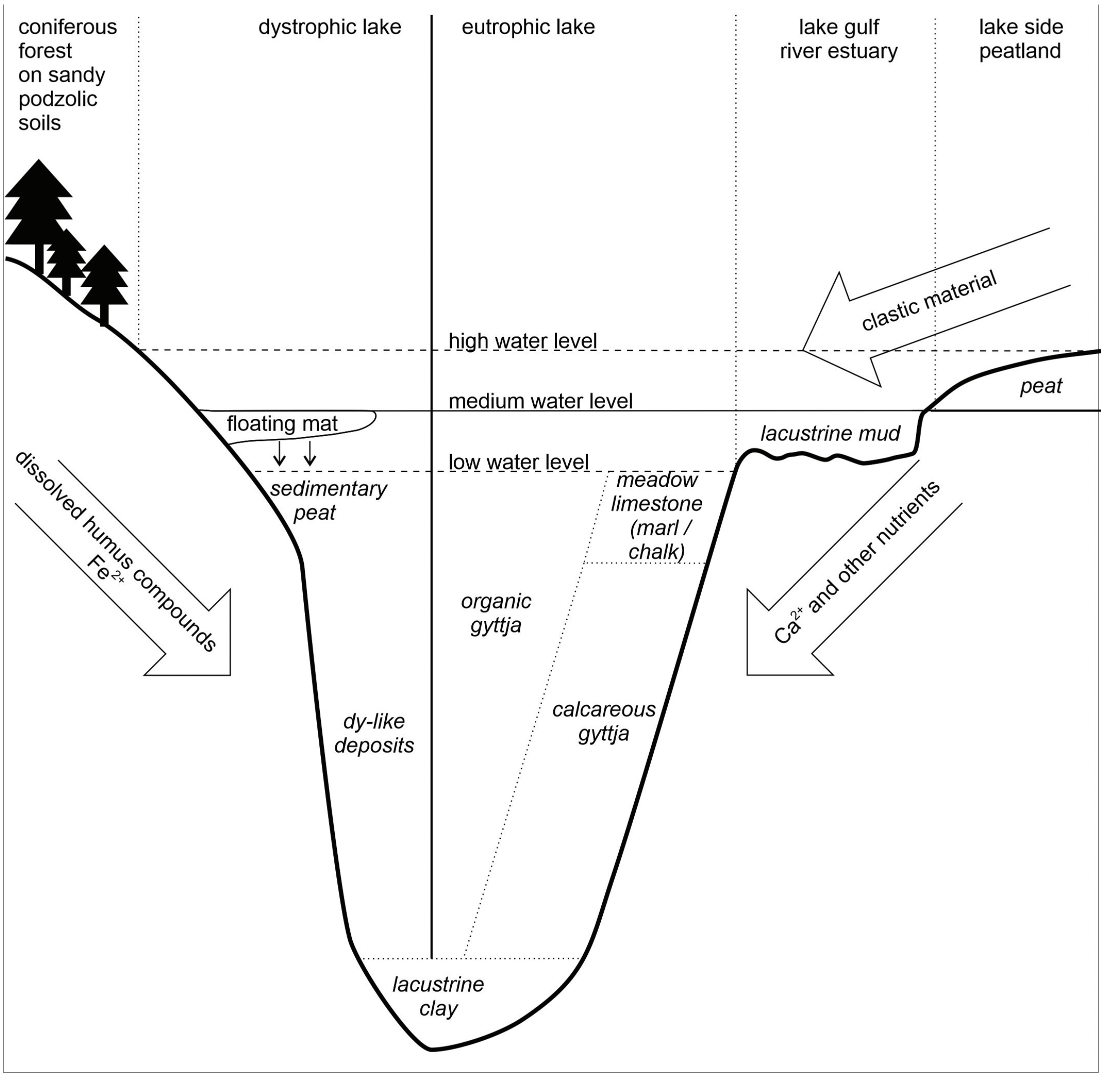

Fig. 1. Accumulation of organic and mineral components in the lake basin

limestone (marl) accumulated in the lake basin. In special cases (e.g. in shallow bays, at the shores of lakes), the $CaCO_3$ content in the sediments may exceed 80% and such a deposit is termed lacustrine chalk.

In the final phase of terrestrialisation of a eutrophic lake, when a significant part of the lake basin is filled with lake sediments, vascular plants with floating leaves (*Potamogeton* sp., *Nymphaeaceae*) develop extensively on the water surface, and rush (e.g. *Phragmites australis*, *Carex* sp.) species enter from the shore. The remnants of vascular plants that have fallen to the bottom of the lake are fragmented and are mixed with gyttja as detritus, thereby creating fine detrital and coarse detrital gyttja. Hence, they usually occur in the upper layers of lake deposits. Depending on the proportion of plant detritus, some classifications (e.g. Soil Taxonomy, Soil Survey Staff, 2022) distinguish sedimentary peat. It should be emphasised that lakes are dynamic sites of biogenic accumulation that change in space and time, hence mixed formations with intermediate features are often found (Rzepecki, 1983; Tobolski, 2000; Kostka, 2023). For example, sedimentary peat is referred to as *peaty gyttja* by Okruszko (1976).

The origin of limnetic mud is also associated with eutrophic lakes. Such formations accumulate in shallow bays and estuaries of rivers, in the zone of water level oscillations and related changes in water oxygenation (Fig. 1). Under these conditions, the remnants of vascular plants mix with materials from the catchment area (humus and fine-grained mineral materials) to create an amorphous black formation that does not contain significant amounts of plankton (algae) or show the typical elasticity of gyttja.

3. Anthropogenic transformation of lakes

The disappearance of lakes is a natural process in their evolution. It occurs when the water level is changed due to a reduction in water inflow and/or when sediments brought from the catchment area infill the lake basin. The rate at which this process occurs is conditioned by the type of lake, the geological structure of the catchment, the evolution of the hydrological network, the climate and the vegetation (Okupny, 2023; Kruczkows-

Fig. 2. Water pump station located on gyttja land at Gązwa, NE Poland. Note: the ditch drains water from the former lake, which is then transferred via an underground water pipe to the lower lying Juno lake. The edge of the former lake corresponds to the location of the road. The left map: Stamma lake on the "Map of East Prussia and Prussian Lithuania by F. L. von Schroetter" (1803); the right map: Gązwa gyttja land on contemporary topographic map. Red dot indicates the pump station

ka, 2024). However, human activity can also be a very important and direct driver of water body transformation (Marszelewski, 2005; Choiński et al., 2012).

In the second half of the 19th century and the early 20th century, the territory of former East Prussia (today the Warmia and Mazury region of Poland) experienced intensive hydrotechnical works that led to lake drainage (Srokowski, 1930). The interventions consisted of widening and deepening of riverbeds, as well as the construction of canals, drainage ditches and pump stations (Fig. 2). This caused a significant drop in the water level in the region, in some areas by several metres. In addition, these works caused a decrease in the area of some lakes and the complete disappearances of others. During this time, drained lake basins and the peatlands that surrounded the lakes were converted into farmland (grassland) (Olkowski, 1971; Uggla, 1971).

Disruption of the natural water body evolution resulted in the formation of gyttja lands – a unique type of wetland with exposed gyttja sediments (Uggla, 1971; Ilnicki, 2002; Chmieleski et al., 2004; Łachacz et al., 2009). The maintenance of these areas for agricultural purposes was often difficult due to the limited technical capabilities of the landowners at that time. The peculiar features of gyttja and the changes in hydration caused shrinkage, subsidence and crack formation, or alternatively – expansion, uplift and clogging of drains (Uggla, 1971; Uggla and Róg, 1976). Organic gyttja, which is a highly hydrated colloid, filled the ditches and slowed the operation of the drainage systems. For this reason, some gyttja lands had to be reclaimed repeatedly. In many cases, attempts to drain certain water bodies proved unsuccessful, and some drained lakes re-filled with water after a few years. Attempts to transform gyttja lands into grasslands most often failed to produce the expected results. Established meadows eventually evolved into wetlands as a result of re-swamping. In places where the drainage systems were not maintained, the once-drained water bodies re-emerged with open-water hydrophilic vegetation and reed vegetation around the periphery. Today, most gyttja lands are not utilised for agricultural production as they are extremely difficult to cultivate. However, they are known for their considerable natural beauty and some are under legal protection (Łachacz et al., 2009).

4. Classifications of lake sediments

The literature offers many classification systems for lake sediments, which can be based on their genesis, their morphological features or their physical and chemical properties. These can generally be divided into genetic and non-genetic (descriptive) systems (Tobolski, 2000). The most common classifications of lake sediments are those based on genesis and lithology (Grosse-Brauckmann, 1961; Horawski, 1971; Myślińska, 2001, 2003; Schnurrenberger et al., 2003; Borówka, 2007; Więckowski, 2009).

The first person to draw attention to lake sediments was the Swedish scholar Hampus Adolf von Post (1822–1911), who introduced the Swedish words "gyttja" and "dy" into scientific terminology (von Post, 1862). He defined gyttja as a "light coloured coprogenic formation consisting of plankton particles, exoskeletons of molluscs, chitinous debris of insects, pollen and spores of vascular plants and mineral particles, formed in eutrophic reservoirs" (Myślińska, 2001). The term "gyttja" (from Swedish – mud) proposed by von Post is still widely used to describe the sediment that forms on the bed of water bodies where dead plankton of plant and animal origin is mixed with the inorganic aggregate that settled at the bottom. Plant and animal remnants (tissues) are partially decomposed by bacteria under the anaerobic conditions typical of lake bottoms, which results in a structureless, jelly-like mass that contain fats, waxes and proteins (Larsson, 1990; Cieślewicz, 2007; Stankeviča, 2020).

It should be noted that some Swedish researchers (Wiklander et al., 1950b; Larsson, 1990; Berglund, 1996) have considered gyttja as a kind of lake sediments and also as a component of lake sediments and soils. They have treated the organic matter related to algae remnants as gyttja. For example, in addition to organic matter content, Wiklander et al. (1950b) took into account "the relative content of gyttja as estimated by the fluorescence method". Larsson (1990) used the term "gyttja-bearing soils", while Berglund (1996) also considered gyttja as a soil component: "...even a very small gyttja fraction has a great influence on the physical properties of soils." This author also stated that the specific properties of soils that contain gyttja "...can be at least partly explained if both the biogenic silica content and the organic matter content are combined in determining the gyttja content."

The classification presented by von Post (1862) distinguished between carbonate, clay and sandy gyttja (according to composition), and between lake, pond, river and spring gyttja (according to the place of origin). According to von Post, the term dy (from Swedish – mud, sludge) denoted organic lake sediment, which in addition to autogenic components (specific to gyttja), contains colloidal humus derived from catchment soils (allochthonous deposit). The Swedish researcher Larsson (1990) pointed out that dy (in addition to dy matter) also contains peat or gyttja matter and mineral particles and stated that "pure dy is seldom seen". The exact meaning of the word gyttja and other related terms that describe organic lake sediments were reviewed by Grosse-Brauckmann (1961) (Table 2 and 3).

When specifying the terms gyttja and dy, the Danish researcher Hansen (1959) claimed that gyttja, unlike dy, is never brown in its fresh state. He posited a threshold organic carbon content to differentiate between gyttja and dy – a formation with <50% organic carbon content in the humus (determined as loss-on-ignition) would be classified as a gyttja, whereas a formation with >50% organic carbon content in the humus would be dy or peat (the latter if plant remains were present). Hansen (1959) further specified that gyttja has a C:N ratio <10 and dy has a C:N ratio >10. He emphasised that dy is a gyttja mixed with colloidal brown humus, and that there are transitional formations between gyttja and dy.

Lauterborn (1901) introduced the term "sapropel" (from Greek – putrefying mud) into science in order to describe sediments with characteristic hydrogen sulphide odour. This term was popularised by Potonié (1904, 1906) who expanded its scope. Nowadays, the term sapropel is often used in post-Soviet states. In the definition of sapropel, it is emphasised that it is formed in very fertile waters with an oxygen-depleted bottom layer (as a result of reduction processes) (Wasmund, 1930a). Although the terms gyttja and sapropel are often treated as synonymous (Rzepecki, 1983; Stankevica et al., 2016; Stankeviča, 2020), some researchers have emphasised their distinctiveness (Table 1). The term sapropel is usually considered to be broader than gyttja. For example, it is used to describe deep-water marine sediments, also for oil source rocks. Thus, gyttja is formed under changing redox conditions and sapropel is formed in anoxic conditions. The latter is defined as black in colour and having a sticky, greasy (fatty) consistency. The evolution of the term sapropel and its various meanings were presented by Lüttig (1996). Given the long tradition in Polish soil science of treating gyttja soils as a separate entity, it would certainly appear that the term gyttja has found a permanent place in scientific terminology. Hence, there is no need to use the redundant term sapropel, which has a similar but broader meaning.

When the most common terms for lake sediment are analysed (gyttja, dy and sapropel) from a soil science standpoint, it should be noted that dy-type sediments are unique as parent material of soils. They may occur in the deeper layers of post-lacustrine soils due to their accumulation in small dystrophic (polyhumus) lakes with a moss floating mat on the surface (so-called quagmires). In fact, the origin of humus in such lakes is both autogenic (from the floating mat) and allogenic (leached from the mineral podsolised soils that surround the lake). Rzepecki (1983) classified dy sediments as humic gyttja among a class of organic gyttja sediments (organic matter content > 50%). Myślińska (2003) concluded that "in practice, dy is usually included within gyttja or strongly decomposed peats". In some cases, dy is treated as dopplerite sapropel, but the relationship between dy and dopplerite is not entirely clear (Tobolski, 2000). In other classifications, dy is referred to as tyrfopel (Naumann, 1922, 1929, 1930), while Okruszko (1976) did not distinguish dy in his division of soil materials. In soil science, sediments with the characteristics of gyttja, but with a greater share of colloidal allochthonous humus, can be treated as a sub-type of organic gyttja. Of course, this does not preclude the use of the term dy in limnology or paleoecology.

The classifications proposed by Lundquist (1927) and von Bülow (1929), while still drawing on the percentage composition of the main sediment constituents, also took into account biotic elements (Tobolski, 2000). The Swedish scientist Lundquist used microscopic methods to link lake sediment type to the biology and fertility of the lakes. Another definition was proposed by a German peatland researcher, Weber (1908), who referred to lake sediments as "mudde" (pl. mudden), which he considered to be synonymous with gyttja and sapropel. The term "mudde" is related to the German words "mud" – swamp, morass, mud, and "muddig" – swampy, muddy. Another term used in German is "Lebermudde", meaning "liver gyttja", because fresh detrital gyttja (especially algal gyttja) resembles liver in consistency.

In 1955, the Danish geologist Troels-Smith (1955) published an original methodology to describe and classify peat and lake sediments (known as the TS system), in which he identified fine (<0.1 mm) components of lake sediments as *limus*. The cited work lists the following components of lake sediments: *limus detrituosus* (detritus), *limus siliceus organocenes* (silica), *limus calcareus* (limestone), and *limus ferrugineus* (ferruginous). The TS system includes the following as main classification criteria for lake sediments: colour, humus content, elasticity, structure, content of iron compounds or $CaCO_3$, and the presence of remnants of aquatic organisms. The Troels-Smith (1955) equivalent of a gyttja is a *limus detrituosus*, a "mudlike, homogenous, non-plastic, deposit, consisting of particles or colloids <0.1 mm …" composed of decayed and decomposed microorganisms and higher plants. This system was later modified by Aaby and Berglund (1986). Kershaw (1997) proposed another modification replacing English terms for Latin and dropping the binominal architecture. The Troels-Smith (1955) system find widespread application, mostly among paleoecologists (Tobolski, 2000; Schnurrenberger et al., 2003).

In Soil Taxonomy (Soil Survey Staff, 2022), coprogenous earth, diatomaceous earth, and marl are considered limnic materials. Coprogenous earth, also referred to as sedimentary peat, roughly corresponds to the term organic gyttja used in Poland, with a plant remnant (peat) admixture. The World Reference Base (WRB) system (IUSS Working Group WRB 2022) distinguishes the following limnic diagnostic materials: coprogenous earth or sedimentary peat, diatomaceous earth, marl and gyttja.

Table 2
Comparison of gyttja, dy, and peat according to von Post (1862), after Grosse-Brauckmann (1961), modified

Specification	Colour	Components							Way of formation: from vascular plants		Colour of water	Presence of humus compounds in water
		excreta of animals (coprolites)		animal remnants		diatoms	plant remnants		forming plant cover	submerged		
		occurrence	origin	occurrence	origin	occurrence	occurrence	origin				
Gyttja	white or gray to light brown	dominant	aquatic animals	relatively low	lower (small) crustaceans	very frequent	relatively low	lakeside (littoral) and telmatic	no	yes	clear, colourless	no
Dy	brown or dark brown	dominant	aquatic animals	very frequent	lower (small) crustaceans, also mites (*Acari*)	relatively low	very rare	telmatic	no	yes	brown	yes
Peat	various shades of brown	rare	–	rare	solely insects	rare	dominant	mosses and sedges	yes	yes	brown	yes

Table 3
Forms (varieties) of gyttja and dy, according to von Post (1862), after Grosse-Brauckmann (1961), modified

Gyttja
Based on content of inorganic (mineral) components:
Sandy gyttja – (Sandgyttja)
Clay gyttja – (Tongyttja – Lergyttja)
Calcareous gyttja – (Kalkreich Gyttja)
Based on character of aquatic environment:
Spring gyttja – (Källgyttja) – in spring areas
Pond gyttja – (Dammgyttja) – contains large amounts of humus carried by water
River gyttja – (Flodgyttja) – occurring at still parts in water courses
Based on the depth of water:
Lake gyttja – (Sjögyttja) – formed in deeper parts of water bodies; occur intermediate forms to dy
Lakeside (coastal, rush) gyttja – (Strandgyttja) – in water bodies with water depth less than 3 m; contains remnants of vascular plants of rush vegetation
Mixed (intermediate) forms of gyttja
Peat gyttja – (Torfgyttja) – contains remnants of plants from younger peat layers overlying gyttja
Dy gyttja – (Dygyttja) – intermediate form between dy and gyttja
Dy
Lake dy – (Sjödy) – without remnants of vascular plants of rush vegetation
Rush dy (lakeside) – (Stranddy) – with remnants of vascular plants of rush vegetation
Peaty dy – (Torfdy) – with admixture of plant remnants of younger peat layers overlying older (fossil) layers of dy

In this classification, the main differences between coprogenous earth (sedimentary peat) and gyttja comprise the following:

(a) organic carbon content (C_{org}): coprogenous earth is an organic soil material, thus contains ≥ 20% C_{org}, and gyttja can be either organic or mineral with ≥ 0.5% C_{org};
(b) colour: coprogenous earth has a Munsell value of ≤4 when moist; gyttja has a Munsell hue of 5Y, GY, G when moist;
(c) admixtures: in coprogenous earth – peat residues; in gyttja – mineral admixtures, predominantly < 0.05 mm.

5. Classifications of lake sediments in Poland

The first classification of lake sediments in Polish literature was presented by Stangenberg (1938), who distinguished between silicate sediments, organic sediments, sediments rich in $CaCO_3$ and mixed sediments. Decades later, a division of lake sediments (referred to as bottom sediments of peatlands) was proposed by Horawski (1971) where he separated 14 types of such sediments based on the ash content determined in the laboratory and the content of some components (e.g. clay, Fe compounds, $CaCO_3$).

Most of the contemporary soil-science divisions of lake sediments used in Poland are based on the distinction of its three main components: organic matter content (defined by mass loss after ashing; loss-on-ignition – LOI), the $CaCO_3$ fraction and the non-calcareous mineral fraction (called ash). The separation of mineral parts into $CaCO_3$ and non-carbonate parts in these divisions is caused by the important role played by "free", non-petrified, unconsolidated $CaCO_3$. It is very reactive and affects the physical and chemical properties of the material. Moreover, lake sediments can consist of almost 100% mineral matter, without any organic matter, and $CaCO_3$ content can reach 99% of the total mass. Such divisions were proposed in Poland by Marcinek (1976), Okruszko (1976), Markowski (1980) and Ilnicki (2002) with the non-genetic (descriptive) nature of the soil as the unifying thread among the four studies. The introduction of three main classification parameters led to the tripartite structure common to all schemes derived from Lundquist's classification (Lundquist, 1927; Rzepecki, 1983).

The classification of gyttja developed by Markowski (1980) is often used in Poland and draws on the division of sedimentary carbonate rocks. It is also used in a modified form to classify limnic materials in the current version of the PSC scheme (Kabała et al., 2019). This division allows the classification of lake sediments based on field organoleptic observations, followed by simple laboratory tests. This approach distinguishes between three main types of limnic materials: organic gyttja, calcareous gyttja and meadow limestone. Also, lacustrine clay is placed in the upper part of the triangle (Fig. 3) as it originated in lakes, but is considered as fluvic material in the PSC (2019). The rationale behind this particular delineation is provided in Łachacz and Nitkiewicz (2021). In the PSC (2019), lacustrine clay is classified as fluvic material rather than as limnic material as its sedimentary genesis proceeded with no significant contribution from living organisms, which is evidenced by a low organic matter content (<12% C_{org}) and its non-coprogenous character. It is usually older than limnic material and forms mixed (transitional) formations with coarse-grained mineral materials on the edge of the lake basin (Kostka, 2023). The division, constructed in this way and visualised in a triangle (Fig. 3), contains all the lake sediments that are common in Poland. The inclusion of lacustrine clay (as fluvic material) means that all fields in the triangle are filled and described.

The division of limnic materials is comprised of three principal divisions (Fig. 3), such as organic gyttja, calcareous gyttja and meadow limestone (or marl), which are then sub-divided into specific types. Organic gyttja contains ≥12% C_{org} and <20% $CaCO_3$, calcareous gyttja contains ≥12% C_{org} and ≥20% $CaCO_3$, meadow limestone (marl) contains <12% C_{org} and ≥20% $CaCO_3$. The latter, based on the $CaCO_3$ content, is further divided into lacustrine/meadow marl, proper lacustrine limestone/meadow limestone (marl) and lacustrine chalk (Kabała et al., 2019). Therefore, it is possible to distinguish facies that are formed in an aquatic environment (lake) from those developed in a terrestrial environment (meadow), although in many cases the identification is difficult unless specific tests are performed (Prusinkiewicz and Noryśkiewicz, 1975; Tobolski, 2000; Freytel and Verrecchia, 2002).

Markowski (1980) also included diatom-clay gyttja in his system, but found that it was an infrequently encountered formation, stating that: "The spread of diatom-clay gyttja is concentrated only in the Oder River valley." The question arises, then, whether this type of lake sediment is actually the parent material of soils in Poland, especially given that this kind of lake sediment is absent from the other soil science-derived divisions of such materials (Marcinek, 1976; Okruszko, 1976; Ilnicki, 2002). In contrast, WRB 2022 (IUSS Working Group WRB, 2022) lists diatomaceous earth among the limnic materials, as does the previous edition of the PSC (2011). Diatomaceous earth has also been included in limnic materials by the Canadian System of Soil Classification (Saurette and Deragon, 2023). The formation referred to as Diatomeenmudde (diatom mud) is distinguished as a separate entity in Germany, where freshwater diatoms are said to have been predominantly deposited in interglacial periods as unlaminated carbonate-poor muds (Maczey and Chmieleski, 2003; Schulz et al., 2019). Kaiser (2002), who examined 147 palynologically-dated lake profiles from NE Germany, stated that "silicate gyttjas are the typical sediments of the Late-Glacial period. Organic and calcareous gyttjas, as well as peats, are the typical sediments of the Holocene". Concerning the occurrence of gyttja types nearby surface in Germany, Chmieleski and Zeitz (2008) stated "while carbonate gyttja occur with high frequency, other types such as diatomeous earth (kieselguhr) as well as organic gyttja are rare".

The natural sequence of sediment accumulation in lakes involves the initial deposition of mineral sediments (mainly clay), then calcareous deposition (if $CaCO_3$ is present in the catchment area), and finally organic deposition (Fig. 4) (Uggla, 1971; Róg, 1978; Rzepecki, 1983; Tobolski, 2000). Given that diatoms occur mainly in cold waters (Timoney et al., 1997), it follows that lake sediments with a greater content of diatom shells (exoskeletons) are unlikely to be found in the surface layers (topsoil). Of course, diatom exoskeletons do occur in lake sediments – examined as

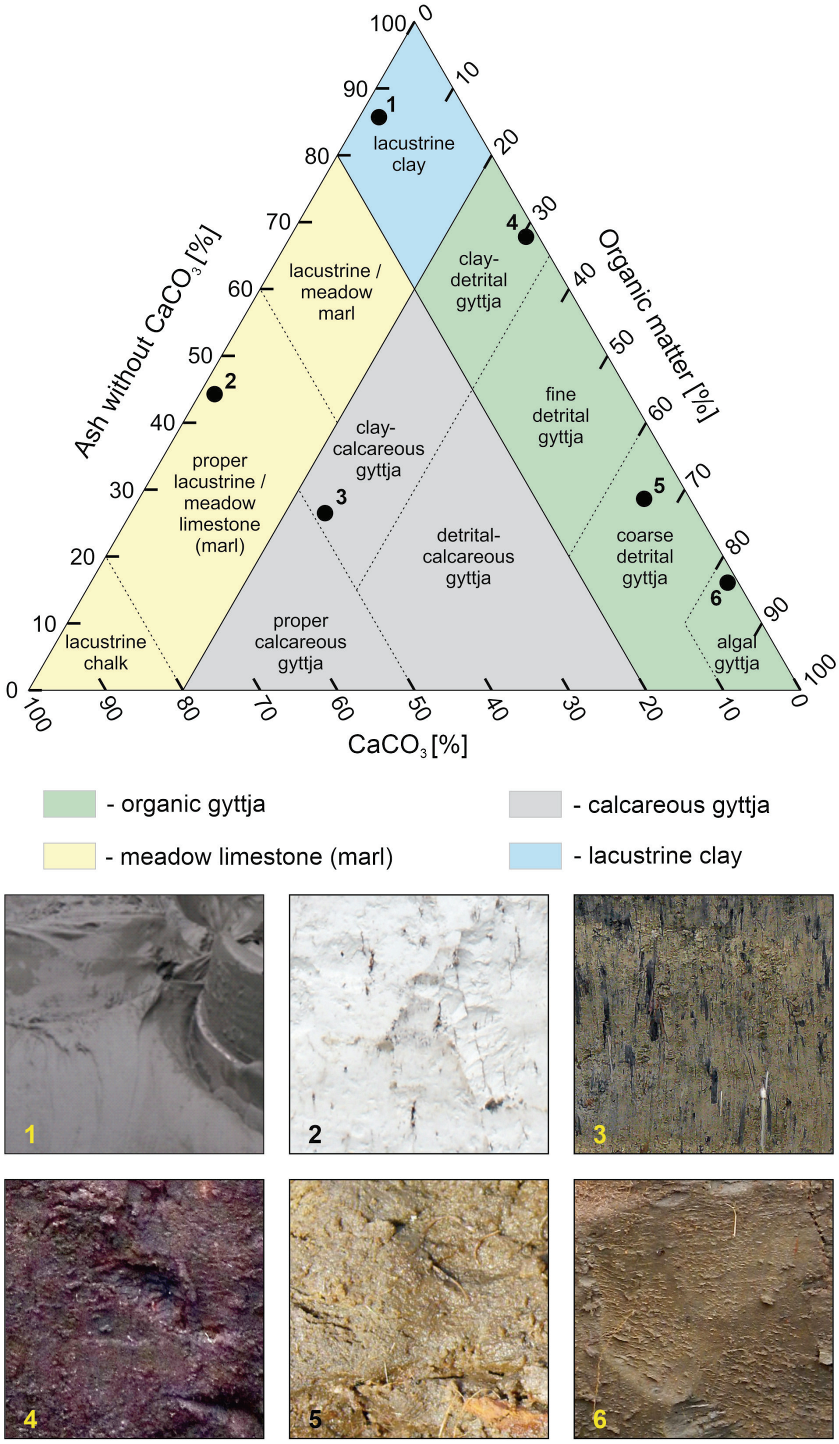

Fig. 3. Division of lake sediments with selected examples of different lake sediments. Note that according to the Polish Soil Classification (2019) organic gyttja, calcareous gyttja and meadow lacustrine are *limnic materials*, and lacustrine clay belongs to *fluvic materials*

part of diatomological analyses and quantitatively defined as biogenic silica (Battarbee, 1986; Tobolski, 2000) – but they are not a primary constituent.

The formation known as diatomaceous earth occurs very rarely in the lower layers of peat bogs in the Polish Lowland, and is associated with accumulation in the final phase of the Vistulian glaciation and at the beginning of the Holocene. However, the classification developed by Rzepecki (1983) includes diatomaceous gyttja (containing 10–50% of the mass of diatom shells). This author stated that it was not possible to identify this type of gyttja in the field and that identification of diatoms under a microscope is required. Schulz et al. (2019) held a similar opinion. Sediment that contains >50% of diatom remnants is called diatomaceous earth (in German: Kieselgur). Without prior determination and scientific documentation of the presence of such formations within the soil profile (up to 150 cm), the inclusion of both diatomaceous-clay gyttja and diatomaceous earth as distinct soil materials in Poland does not appear justified. Of course, such a formation may occur in sediments formed in other geographical (climatic) areas around the world.

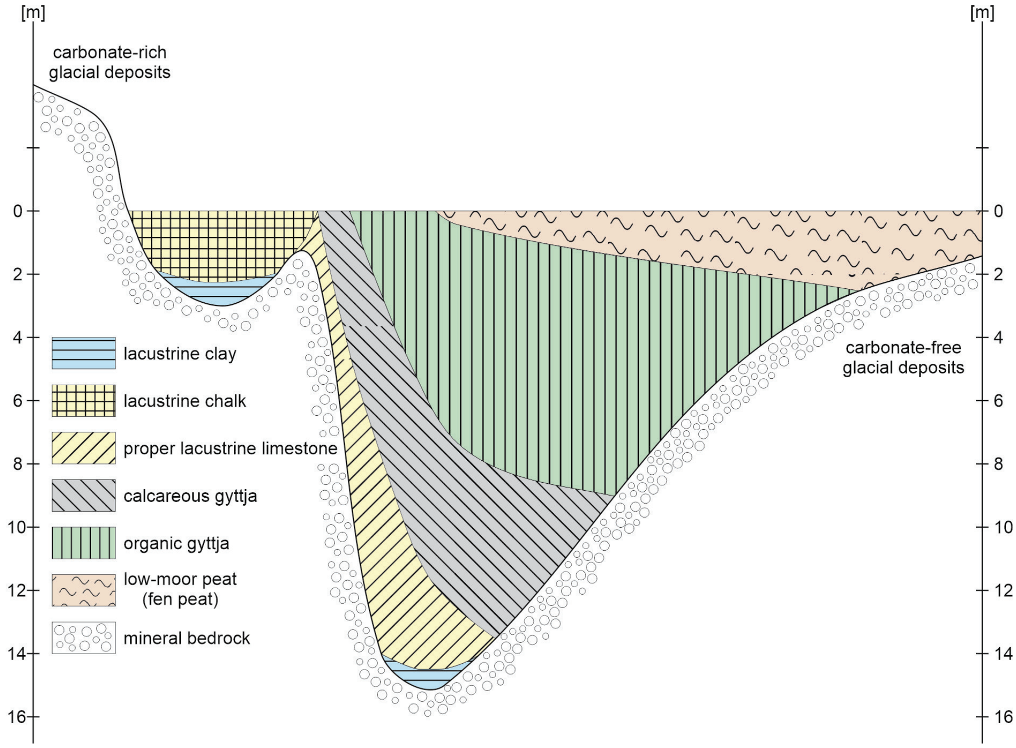

Fig. 4. Cross-section of terrestralised lake filled in by lake sediments and partly covered by peat

6. Lake sediments considered as soil diagnostic materials with the Polish Soil Classification scheme (2019)

Within the current edition of the PSC (2019), lake sediments are treated as diagnostic soil materials (limnic materials) (Łachacz et al., 2024). They are defined as organic or mineral materials formed in the processes of sedimentation, accumulation of aquatic organism remains, accumulation of aquatic plant (mainly planktonic) debris and its further transformation by aquatic animals, sedimentation of transported, allochthonous (exogenic) organic matter or from the chemical precipitation of carbonates in an aquatic environment. The list of limnic soil materials includes organic gyttja, calcareous gyttja, meadow limestone (marl), lacustrine mud and telmatic mud (Kabała et al., 2019).

Organic gyttja is a limnic coprogenic sediment that has accumulated in a still (or with gentle water movement) water body. It contains at least 12% C_{org}, and at the same time, <20% $CaCO_3$. It is resilient in a moist or fresh state, but is prone to cracking during drying to form a platy structure. Four varieties of organic gyttja are distinguished, mainly by the organic carbon content: algal gyttja (≥40% C_{org}, <10% $CaCO_3$), coarse detrital gyttja (30–40% C_{org}, fine detrital gyttja (20–30% C_{org}) and clay-detrital gyttja (12–20% C_{org} , <20% $CaCO_3$, 45–80% non-carbonate mineral matter, dominated by the clay and silt fractions). Coarse detrital gyttja contains substantial amounts of vascular plant remnants and may be a transitional formation to low-peat (fen). Coarse detrital gyttja contains plant remnants of diameter >1.0 mm, while fine detritus has a diameter of 0.1–1.0 mm. Determination of algal gyttja derives from the specificity of this formation (i.e. algae content), which has been mentioned above.

Calcareous gyttja is also defined as a limnic coprogenic sediment, but contains more $CaCO_3$ than organic gyttja. Thus, the criteria for its indication are: ≥12% C_{org}, >20% $CaCO_3$. Similarly to organic gyttja, it forms a platy structure while drying, although is much less resilient in the natural (fresh) state and is rather massive with a tendency to break under pressure, especially when it contains large amounts of $CaCO_3$. Three varieties of calcareous gyttja can be distinguished: proper calcareous gyttja (≥50% $CaCO_3$), detrital-calcareous gyttja (20–50% $CaCO_3$, >21% C_{org}) and clay-calcareous gyttja (20–50% $CaCO_3$, and 12–20% C_{org}, with non-calcareous mineral component dominated by the clay and silt fractions).

Meadow limestone (marl) is a mineral or mineral-organic, strongly calcareous, quaternary limnic sediment that develops from chemical or biochemical precipitation of $CaCO_3$ in an aquatic environment, and/or from the accumulation of snail and mussel shells (as well as the remains of other aquatic organisms), or due to the precipitation of $CaCO_3$ in a telmatic environment. Meadow limestone contains <12% C_{org} and ≥20% $CaCO_3$. Depending on the $CaCO_3$ content three varieties of meadow limestone have been listed: lacustrine chalk (containing ≥80% $CaCO_3$), proper lacustrine/meadow limestone (≥40–80% $CaCO_3$) and lacustrine/meadow marl (≥20–40% $CaCO_3$).

Limnetic mud is a non-coprogenic organic sediment that has accumulated in shallow water bodies fed with oxygen-rich water. This soil diagnostic material is found in depressions, filling (or co-filling) basins of former lakes, abandoned channel lakes (oxbow lakes) and other shallow water bodies, e.g. lake gulfs, estuaries, ponds. It contains ≥12% C_{org} and fulfils the criteria of sapric peat in terms of the degree of decomposition but could be interlayered with less decomposed plant debris. The main characteristic that distinguishes it from gyttja is the lack of resilience. Also, the admixture of mineral fractions in the soil mass or in the form of thin layers is a common feature of this soil material.

The final limnic diagnostic soil material – telmatic mud – is a non-coprogenic organic sediment that develops at the bottom of river valleys and depressions that are regularly flooded with oxygen-rich waters. Telmatic mud is found on river terraces and in the depressions that are flooded every year, or almost every year. It contains 12–25% C_{org}, fulfils the criterion of the degree of decomposition for sapric peat, and the amorphous mud mass is characterised by values of ≤2 and chroma ≤2 in the moist state, according to the Munsell Soil Colour Charts (Munsell Color Company, 1994). Critically, it does not exhibit the resilience (elasticity) that is typical of gyttja.

Mud could be considered as an intermediate formation between peats (strongly decomposed fen peats) and gyttja sediments. Both types of muds are similar from a morphological point of view. The main difference is related to the place of accumulation and the greater mineral fraction content in the case of telmatic muds. Note that definition of mud provided by Canarache et al. (2006) (Table 1) is close to the Polish understanding of this term. In the Soil Taxonomy (Soil Survey Staff, 2022) and WRB classification system (IUSS Working Group WRB, 2022), materials similar to muds are included as a sedimentary peat, but PSC (2019) emphasises their non-coprogenic character and substantial addition of fine-grained mineral particles.

7. Field identification of gyttja

Since the pioneering study by von Post (1862), the characterisation of lake sediments has focused on the presence of coprolites (in German: Koprogene Ablagerungen). The second organic component of gyttja is detritus, i.e. disintegrated (crushed) remains of vascular plants. A significant proportion of the organic matter may be amorphous in form, which further complicates organoleptic identification of the individual constituents. Identification of coprolites in lake sediments is difficult, both because they are hydrated and because benthic animals are generally smaller than those living in terrestrial humus. It should also be noted that terrestrial humus coprolites were formed from the tissues of vascular plants, which are different in structure and chemical composition to plankton. The organic fraction in the mineral and mixed lake sediments is limited; meaning that they also contain less coprolites. As such, field identification of coprolites using a magnifying glass (10×) may prove ineffective. The photos published by Lundquist (1927) and Uggla et al. (1972) provide some idea as to the size of the coprolites in gyttja under the microscope. Similarly, laboratory identification of plankton-derived pigments can be of limited use and may only provide tentative data. This is because the various groups of planktonic organisms (and aquatic organisms in general) exhibit different colours and do not retain their pigmentation in a consistent manner (Gorham and Sanger, 1975; Sanger, 1988; Wetzel and Likens, 1991). In addition, some types of gyttja rapidly change their colour after extraction from the deposit (Markowski, 1980; Waleńczak, 1987; Chmieleski, 2006). However, these considerations do not negate the critical importance of colour in field identification of gyttja (Markowski, 1980; Schnurrenberger et al., 2003; Chmieleski, 2006; Schulz et al., 2019).

As Markowski (1980) noted, lake sediment classification cannot be based on colour alone. Nevertheless, it is one of the primary indicators of sediment type. It is recommended that colour should be determined initially with the gyttja that is freshly extracted from the deposit, again after its exposure to air, and finally when it is air-dry. Although organic gyttja is classified in the PSC (2019) as having most frequently a hue of 2.5Y and 5Y, and a value <5 (moist) according to Munsell colour charts, some varieties may have different colours. For example, Marcinek (1976), who examined a wide variety of samples of coarse detrital gyttja and algal gyttja (non-calcareous, <1% $CaCO_3$) reported the following hues: 5YR, 7.5YR, 10YR, 2.5Y, 5Y, 7.5Y. Markowski (1980) stated that the colour of fresh gyttja can range from light red, red-brown, brown to brown-green, but darkens strongly in contact with air, then turns lighter again after drying. The red colouration of some gyttja varieties comes from the high proportion of cyanobacteria (*Cyanophyta*) within the sample. This specific coloration was described from the Montreal area (Canada) as "burgundy coloured" (Saurette and Deragon, 2023). Coarse-detrital gyttja is brown, brown-green, and olive in colour, darkens strongly in contact with air, and becomes lighter after drying. Gyttja that contains a greater proportion of $CaCO_3$ (calcareous gyttja) exhibits colour that ranges from white-yellow, yellow-green, yellow-grey, yellow-brown, grey-green to grey. They also darken in contact with air, but less strongly than algal gyttja, and turn lighter when completely dry. Lacustrine chalk is whitish or whitish-yellow in colour, turning white in contact with air and during drying. Finally, lacustrine clay has a grey-green to grey-blue colour that becomes greyer upon contact with air and upon drying.

Identification of gyttja in the field is based partly on its presence in the basins of former lakes, which is usually not a controversial criterion. The most important organoleptic features to be considered relate to the cohesive traits (consistency test) of the sediment, such as elasticity, plasticity and degree of cloddiness (Okruszko, 1976; Markowski, 1980). Algal gyttja exhibits a telltale set of features, marked by a preponderance of planktonic algae. The material is very elastic (most elastic of all limnic material types) and shrinks substantially when dried. Organic gyttja does not dirty the hands, which differentiates it from the other lake sediments. Many researchers point to elasticity as an important benchmark for the identification of limnic materials in the field. In the PSC (2019), a test is recommended whereby a block (approx. 2–3 cm) is cut out from the tested material and is then squeezed between the fingers (Fig. 5). When moist or fresh, gyttja shows characteristic resilience, i.e. it returns to its original shape after the force has been removed. In contrast, wet gyttja deposited in deeper layers disperses in the fingers, whereas fresh or semi-dried gyttja behaves like rubber (Chmieleski and Zeitz, 2008). This feature is conditioned by the colloidal organic matter content, which includes planktonic matter

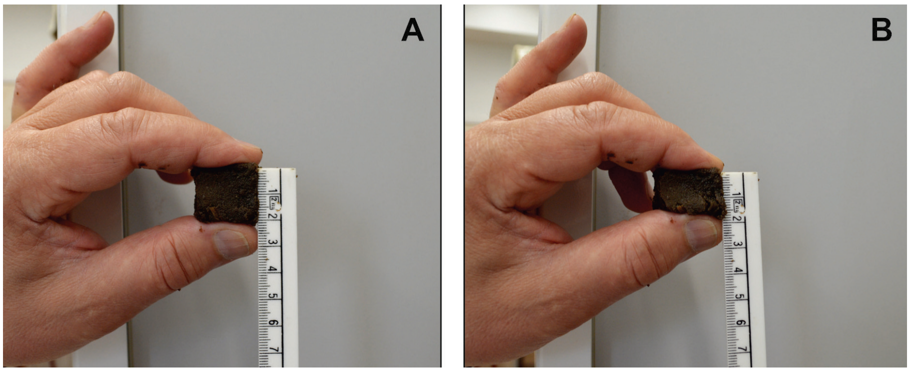

Fig. 5. Elasticity test for coarse detrital gyttja (50–70 cm, 72.3% SOM): A – sample before squeezing; B – sample during squeezing

in particular, and is affected by the moisture status and by the addition of a mineral fraction. Certain limnic materials (especially those with a greater clay content) are malleable (plastic), i.e. the mass succumbs to force and is permanently deformed. Cloddiness becomes visible under the influence of force, when the mass is fragmented and crumbles into aggregates.

The presence of a mineral fraction, including $CaCO_3$ (HCl-test), should also be considered during field identification. The presence of amorphous humus, plant detritus, as well as plant and animal macroremains, provides additional information as to the origin and nature of the sediment. Therefore, a 10× magnifying glass is needed for the field examination of lake sediments, though microscopic specimens (100× or more) may need to be prepared for coprolite identification. However, the use of a 440× microscope is recommended for diatom identification (IUSS Working Group WRB, 2022).

These changes to dehydrated gyttja, such as the darkening of organic gyttja in contact with atmospheric oxygen, are not the only factors that influence the morphology of the soils that they form. Secondary pedogenic transformations that result from long-term drainage also have a pronounced impact on the correct field identification of lake sediments (Markiewicz et al., 2016; Mendyk et al., 2015, 2016; Markiewicz et al., 2017). The most common of these transformations includes secondary precipitation of Fe oxides and $CaCO_3$ from capillary rise, compression of these sediments under the pressure of the mineral sediments that lie above them, and the formation of wedges upon the rapid shrinkage of dried-out gyttja (Fig. 6).

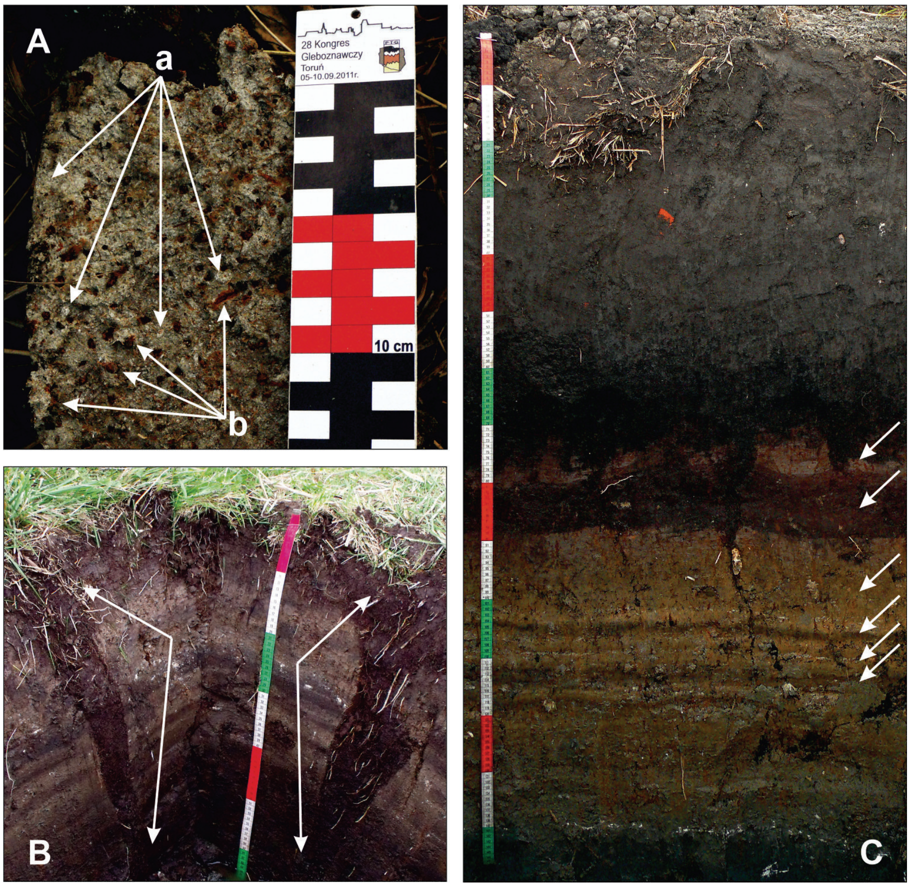

Fig. 6. Secondary pedogenetic transformation of limnic deposits and its influence on soil morphology: A – secondary calcium carbonate (a) and iron oxide (b) precipitations, B – deep wedges caused by rapid shrinkage of organic gyttja, and C – compaction of limnic sediments caused by the pressure of the mineral material (e.g. colluvium)

8. Features of gyttja soils

The unique characteristics of gyttja soils stem from the co-occurrence of carbonate and non-carbonate (silicate) minerals and organic matter, most of which show colloidal fragmentation. The organic matter can occur in many forms, ranging from organic substances in the pore water to aggregates formed of organic and mineral matter, and remnants of plants and animals of different degrees of decomposition and size (Larsson, 1990). Each of these forms affect the characteristics and properties of the sediment in a specific way. Fresh (fully watered) gyttja is a gel, a semi-liquid gelatinous mass (Żurek-Pysz, 1992). As it dries, gyttja, and organic gyttja especially, shrinks irreversibly (Uggla, 1964a). This in turn results in the subsidence of gyttja deposits and the formation of cracks and polygonal micro-relief (Uggla and Róg, 1976). As the organic gyttja dries, it separates into plate and lamellar aggregates (Fig. 7A, B), and becomes extremely hydrophobic, which negatively affects the air-water status of the soils (Fig. 7C) (Papierowska et al., 2009).

In Poland, gyttja soils occur mainly in the northern part of the country, which (due to the young-glacial nature of the terrain) was, and still is, rich in lakes. The number of lakes drained in the Warmia and Mazury region has been estimated at over 189, and the area of gyttja lands at approximately 8,000 ha (Olkowski, 1971). Furthermore, these estimates only include the "open" lake deposits, and exclude gyttja deposits that are covered by a peat layer and cultivated gyttja soils. Therefore, it is likely that the area of gyttja soils, with surface peat layers < 30 cm thick, is much larger. In Poland, the most common are gyttja soils that are formed from organic gyttja. They are of little agricultural value and are usually classified as rangelands (Olkowski, 1971; Łachacz et al., 2009). Calcareous gyttja deposits are less common and appear in the form of so-called lacustrine chalk or lacustrine/meadow limestone, forming specific soils called lacustrine rendzinas or Quaternary rendzinas (Uggla, 1976; Meller, 2006; Lemkowska and Sowiński, 2018; Jarnuszewski and Meller, 2018, 2019; Jarnuszewski et al., 2023; Sowiński et al., 2023).

After reclamation, the lake sediments are exposed to the influence of the atmosphere and the biosphere, and are subject to soil-forming processes that transform them into sub-aerial soils (Uggla, 1962, 1971; Okruszko, 1976). As with all other soil materials that have accumulated in anoxic conditions, organic and calcareous gyttja is subject to the mursh-forming process after dehydration (Uggla, 1962, 1967, 1969a; Okruszko, 1976; Łachacz et al., 2023).

Organic gyttja is rich in nitrogen (N), a natural consequence of its origin, since zoo- and phyto-plankton are particularly rich in proteins, and therefore N (Waleńczak, 1987; Punning and Tõugu, 2000; Cieúlewicz, 2007; Stankeviča, 2020). Organic gyttja may contain as much as 5% total N (Maciak, 1965; Uggla, 1971). Therefore, the C:N ratio range is narrow, often falling within 5–10, while Uggla (1968) reported that the C:N ratio in gyttja ranged from 6.5 to 9.2 at the Gązwa site in northern Poland. The C:N ratio in lacustrine algae is narrow (ca. 4–10) (Cieślewicz, 2007). According to Cieślewicz (2007), the value of this ratio (ranges between 13–14 in lake sediments) is indicative of a mixture with similar proportions of detritus from vascular plants and from algae. This is due to the fact that the C:N ratio is >15 in vascular plants (depending on the species) (Meyers and Lallier-Vergès, 1999; Punning and Tõugu, 2000).

Uggla (1968), who examined gyttja from the Gązwa site, found a significant fraction of sugars and hemicelluloses (up to 11.8% in total), as well as cellulose and protein (up to 9.9% in total). As gyttja also contains various bioactive substances, such as vitamins and enzymes, attempts were undertaken in post-Soviet states to use organic gyttja as an animal forage (Lukashev et al., 1991; Stankevica et al., 2016).

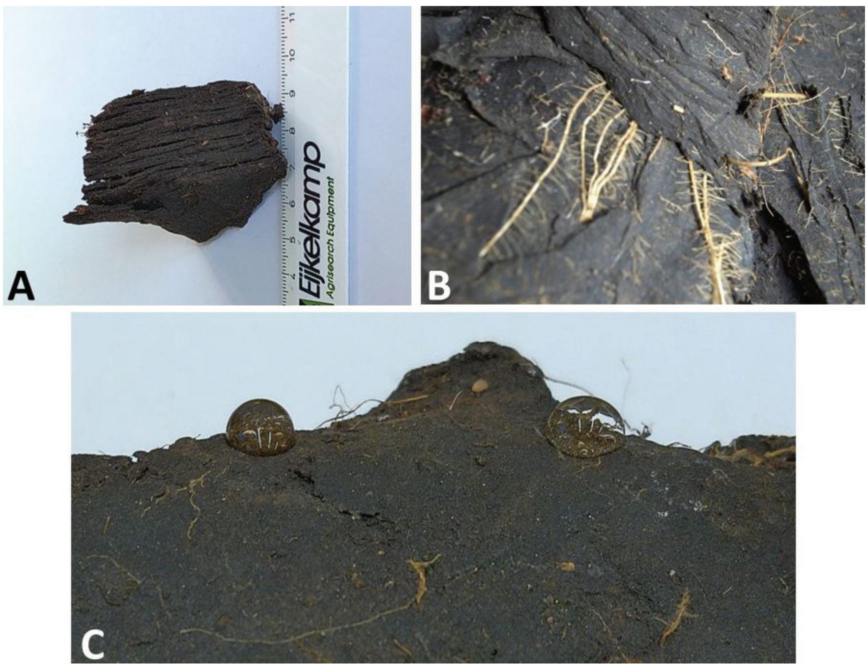

Fig. 7. Mursh developed from algal gyttja (10–15 cm, 84.5% SOM): A – visible laminar structure (lamellae or thin platy aggregates 1–3 mm in thickness); B – roots penetrate horizontally spaces between layers; C – extreme hydrophobicity (Water Drop Penetration Time): water droplets resist infiltration into soil

Gyttja soils are relatively rich in sulphur (S) (Uggla, 1971). Due to their biotic origin and accumulation under anaerobic conditions, the total S content and its reduced forms (mainly Fe sulphides) is an important measure in gyttja soils. The total S content in gyttja from the Gązwa site was found to be in the range of 0.72–1.45%, which is half that found in gyttja soils in Sweden (Wiklander et al., 1950a; Uggla, 1968). This is understandable since Swedish gyttja often develops in marine or coastal environments. Detrital gyttja usually contains more S than other types of gyttja, and the deeper layers of gyttja deposits contain more S than the surface layers. Conversely, the content of sulphate S was greater in the surface layers of gyttja soil (Uggla, 1969b). Oxidation of reduced S compounds leads to the formation of sulfuric acid (VI) and acidification of soils.

9. Features of mud soils

The concept of mud soils was introduced by Tomaszewski (1938), who aside from distinguishing peat soils, also classified mud soils (which he termed in Polish: gleby mułowo-błotne). He stated that such soils occur in river valleys and other water courses in agricultural areas. A further division of mud soils by Tomaszewski (1938) took into account the characteristics of the mineral soil component, and also distinguished between sandy mud soils (in Polish: gleby mułowo-błotne piaszczyste), silty mud soils (in Polish: gleby mułowo-błotne pyłowe) and clay mud soils (in Polish: gleby mułowo-błotne ilaste). In general, soils developed from telmatic mud are formed in river valleys that are in the so-called mud stage of development (groundwater level fluctuations are 0.7–1.5 m) (Okruszko, 1969, 1990). The scheme (Fig. 8) presents the accumulation of organic and mineral matter in relation to the distance along the river course and to its gradient for the typical medium-sized river within East European Plain with a snowy, fully humid climate with warm summer according to the Köppen-Geiger climate classification (Kottek et al., 2006).

Telmatic muds are formed in lowest places of the floodplain (flood terrace) and in their immediate vicinity (Fig. 9). The higher parts of the floodplain are occupied by alluvial soils, while the lower parts are occupied by mud soils (Okruszko, 1969; Oświt, 1977; Okruszko et al., 1997; Banaszuk, 2000; Banaszuk and Roj-Rojewski, 2004; Kalisz and Łachacz, 2008; Roj-Rojewski, 2009). The accumulation of mud is possible through decomposition and humification of aquatic and telmatic vegetation remnants (*Typha* sp., *Glyceria* sp., *Phalaris* sp., *Carex* sp.) under aerobic conditions (Gałka and Kalisz, 2008). Mud accumulation is slow, between 0. 062–0.132 mm per year (Kalisz and Łachacz, 2008). Mud soils are typical for many lowland rivers, but in most cases they occupy small areas. The Biebrza valley is especially rich in mud soils, which cover in the Lower Biebrza Basin the area around 3 thousand ha (14.5% of the whole area of organic soils) (Roj-Rojewski, 2009). Mud soils occur in complexes with peat soils and alluvial soils (Kalisz and Łachacz 2008; Roj-Rojewski and Banaszuk, 2004; Kabała, 2022).

Mud formations accumulate in a specific environment where the mud-forming process can alternate with the peat-forming process, depending on oxygen availability. This results in the formation of heterogeneous, layered deposits (Wójcicki,

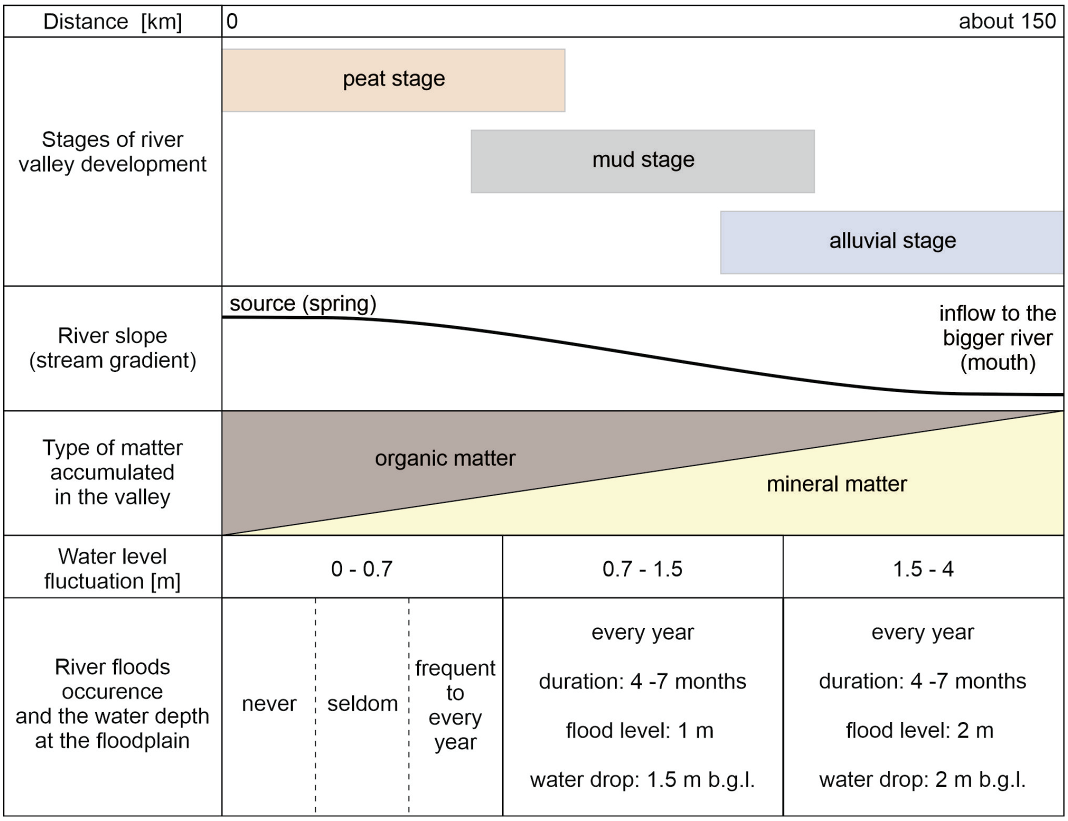

Fig. 8. Longitudinal profile of lowland (East European Plain) medium-sized river with natural flow regime

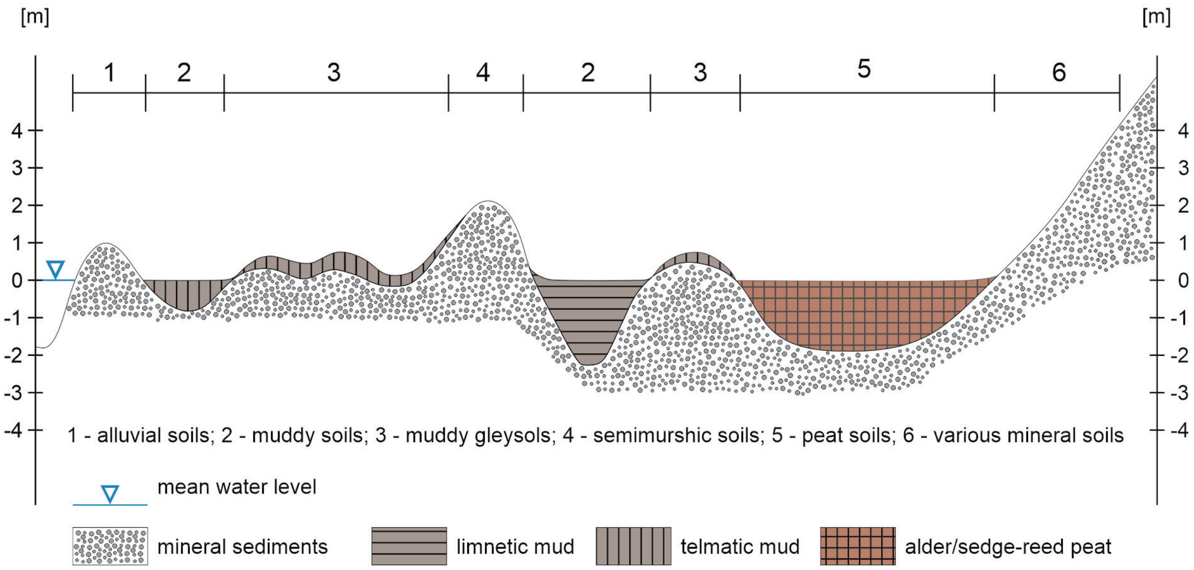

Fig. 9. Cross-section through the river valley in the mud stage of development; systematic position of the soils within the valley is given acc. to the Polish Soil Classification (2019)

2022). Work has shown that in river valleys in Europe, there is a simultaneous accumulation of fine-grained mineral particles and well-humified organic matter (Devesa-Rey and Barral, 2012; González et al., 2014; Graf-Rosenfeller et al., 2016; Bruno et al., 2017; Koster et al., 2018; Rossi et al., 2021).

Mud soils are shallow, with a mud horizon up to 60 cm thick in telmatic muds and more so in lacustrine muds (Fig. 10). Typically, mud soils contain from 20% to 50–60% of soil organic matter (SOM), which is strongly humified and does not contain plant fibres. A significant mineral fraction content affects the physicochemical properties of mud soils. The characteristic feature of mud soils is the presence of allochthonous mineral matter that originates from the river waters (Gałka and Kalisz, 2008; Kalisz and Łachacz, 2008; Długosz et al., 2018). The mud itself is brown, dark rusty or grey-brown in colour. It contains ferruginous concretions, clay particles and peat intercalations. Bulk density values of mud soils range from 0.5–0.9 g cm^{-3}, and the total porosity is ca. 60–80%. The permeability of mud soils is low (filtration coefficient is 0.23 m/day) and is less than strongly decomposed alder peats. The volume of mesopores in mud soils is in the range of 12–15%, less than in peat soils, while the volume of micropores and macropores is greater (Kalisz and Łachacz, 2009a; Roj-Rojewski, 2003).

Tomaszewski (1938, 1956) stated that mud soils are more agriculturally useful than typical peat soils, which he attributed to the beneficial effect of the mineral components in the former, which can contain significant amounts of phosphorus (P) and potassium (K) from river waters and from biological accumulation. The P content is closely related to the content of Fe, which is usually high (Kalisz and Łachacz, 2009a). In some instances, Fe oxides and vivianite accumulate in the zone between the mud layer in the contact zone and the underlying sandy layer. Copper (Cu) and zinc (Zn) content may also be greater than in peat soils, while total N content in mud deposits is greater than in

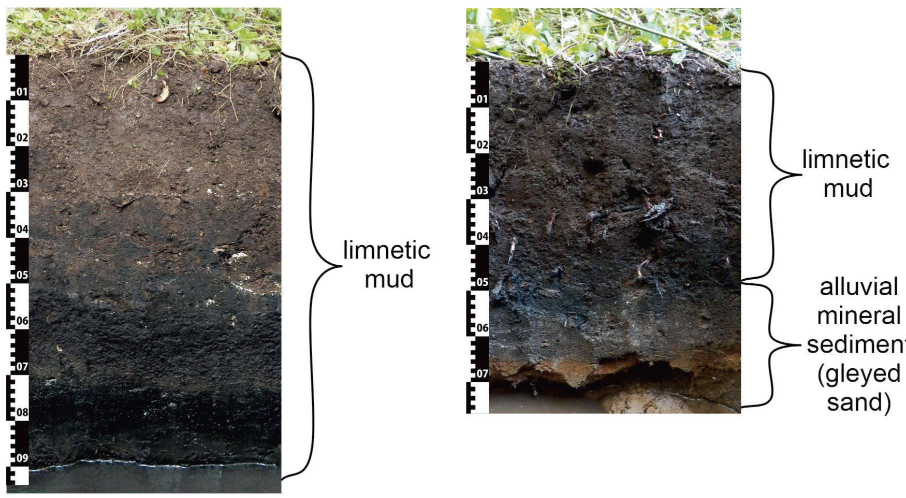

Fig. 10. Examples of muddy soils (PSC, 2019) developed from limnetic mud

peats with similar SOM content, which is connected to its greater humification rate. Roj-Rojewski (2003) found significant differences in the chemical composition of telmatic and limnetic muds, and also between those mud soils that contain various admixtures of mineral matter. Limnetic muds contain more N, calcium (Ca), Fe and P than telmatic muds.

After drainage, mud soils (similarly to peat soils), undergo a mursh-forming process (Łachacz et al., 2023), which is related to SOM mineralisation, and that eventually leads to the development of a mollic horizon typical of black earths (Łabaz and Kabała, 2016). Mud soils contain humus-clay complexes that (after drainage) protect the organic matter from rapid microbiological decomposition (Graf-Rosenfeller et al., 2016). Thus, mud soils are considered fertile and suitable for plant cultivation, as well as for the establishment of grasslands (Kalisz and Łachacz 2009a, b).

10. Conclusions

1. Soils that have developed from lake sediments cover a relatively small area of Poland. However, they are an interesting element of the environment and have attracted the attention of specialists from various scientific disciplines.
2. Soils that have developed from lake sediments exhibit a number of specific features that distinguish them from peat soils. The specificity of soils formed from lake sediments should be taken into account when they are classified and utilised.
3. Some soils that have developed from lake sediments (lacustrine chalk, lacustrine limestone, lacustrine marl, lacustrine and telmatic mud) have potentially high productivity and may constitute valuable agricultural areas. Soils developed from organic gyttja and some types of calcareous gyttja are not suitable for agricultural use due to specific physical properties, but may constitute important sites for nature conservation.
4. Further research on the properties of lake sediments and the soils that they form is needed. The distribution of soils formed from lake sediments and the areas covered by them requires further research. Collaboration between specialists from a wide range of scientific disciplines is needed to better understand lake sediments in Poland.

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Holoceńskie osady jeziorne jako materiał macierzysty gleb

Słowa kluczowe

Materiały limniczne
Gytia
Muł limnetyczny i telmatyczny
Identyfikacja gytii
Gleby gytiowe i mułowe
Systematyka gleb Polski

Streszczenie

Osady jeziorne jako specyficzne utwory powstające w słodkowodnych zbiornikach wodnych stosunkowo rzadko stanowią skałę macierzystą gleb. W warunkach naturalnych, po akumulacji osadów jeziornych następuje najczęściej faza torfotwórcza, wobec czego powstają gleby torfowe głęboko podścielone osadami jeziornymi. Na obszarze Polski, jak również w strefie młodoglacjalnej innych krajów Europy, miały jednak miejsce intensywne prace melioracyjne polegające na osuszaniu płytkich zbiorników wodnych, które w niektórych przypadkach doprowadziły do odsłonięcia osadów jeziornych i powstania z nich specyficznych gleb. Wraz z rozwojem i kolejnymi edycjami Systematyki gleb Polski zaistniała więc potrzeba opracowania szczegółowych kryteriów jakościowych oraz ilościowych dla tych osadów rozpatrywanych jako skała macierzysta gleb. Kryteria te mają na celu przede wszystkim dokonanie logicznego podziału tych materiałów w kontekście ich pozycji w obrębie Systematyki gleb Polski jako glebowych materiałów diagnostycznych oraz umożliwienie właściwej identyfikacji tych osadów w terenie. Celem niniejszej pracy jest prezentacja wybranych systemów klasyfikacji osadów jeziornych (m.in. opracowania von Posta, Troels-Smith'a, Okruszki, Markowskiego), ze szczególnym naciskiem na stosowaną terminologię, w relacji do podziału tych utworów zaproponowanych przez polskich badaczy oraz do rozwiązania zastosowanego w ramach obecnie obowiązującej Systematyki gleb Polski (2019). Ponadto omówiono genezę osadów jeziornych oraz czynniki antropogeniczne, które doprowadziły do ich odsłonięcia. W dalszej części pracy przedyskutowane zostało zagadnienie terenowej identyfikacji omawianych osadów oraz wybrane właściwości osadów jeziornych i powstających z nich gleb.