STRATIGRAPHIC FRAMEWORK FOR THE CLASSIFICATION OF QUATERNARY DEPOSITS IN FINLAND

by

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Recent developments in geomorphological mapping and new concepts of sediment classification, as well as advances in geochronological methods, have led to a need to review the classification of Finnish Quaternary glacial (mainly Pleistocene) and non-glacial (mainly Holocene) deposits. The Quaternary Sub-Commission of the Stratigraphic Commission of Finland has conducted an overview study on the stratigraphic classification of Finnish Quaternary deposits and introduced the practices according to which these superficial deposits are classified in Finland. The stratigraphic practices for the classification have been dependent on the nature of basic or applied research foci and the availability and development of techniques and media to categorise different aspects of Quaternary sediment strata and their three-dimensional entities. The approaches used to classify Quaternary deposits have included litho-, bio-, and chronostratigraphic, morpho-lithogenetic and hydrostratigraphic, chemo- and pedostratigraphic, magneto- and seismostratigraphic, and sequence and allostratigraphic practices. In addition, absolute dating (e.g., radiocarbon, luminescence and cosmogenic nuclides), incremental dating (e.g., sedimentary varves and tree rings) and relative dating, such as dating based on paleomagnetic paleosecular variation (PSV) and tephras in Quaternary sediments, have been used for the age determination of glacial and interglacial sediment sequences and deposits. Morpho-lithogenetic classification offers perhaps the most comprehensive approach to map and classify Finnish Late Weichselian glacial and the Holocene non-glacial deposits on land. However, litho- and biostratigraphic and absolute dating methods aided by sequence and allostratigraphic approaches are most applicable for establishing a formal litho- and chronostratigraphy for Finnish Quaternary sediments.

Keywords: stratigraphy, geochronology, chronostratigraphy, sediments, deposition, landforms, soils, glacial environment, ice ages, Quaternary, Fennoscandian Shield, Finland

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1 INTRODUCTION

Stratigraphy is an integral part of geology. It is a scientific discipline concerned with the description of rock strata forming the crust of the Earth. Stratigraphy encompasses all the properties of rock strata, including their lithology, fossil content, organisation, correlation and age relationships, and categorises the rock strata into stratigraphic units. Furthermore, stratigraphic research is a prerequisite for interpreting the origin of rocks and sediments, their depositional conditions and sedimentary environments, as well as the evolution of life and geological history at large (e.g., Salvador 1994).

Several international geological organisations focus on organizing the world's rock strata, including the Quaternary strata. The International Union of Geological Sciences (IUGS) and the International Commission on Stratigraphy (ICS) with the Sub-Commission on Quaternary Stratigraphy (SQS), in partnership with the International Union for Quaternary Research (INQUA) Commission on Stratigraphy and Chronology (SACCOM), are responsible for managing and accepting the formal division of the Quaternary Period. The global chronostratigraphic units (eonothems, erathems, systems, series and stages) and equivalent geochronological units (eons, eras, periods, epochs and ages) ratified by the IUGS are presented in the International Chronostratigraphic Chart (https://stratigraphy.org/chart). Recommendations and guidelines concerning Finnish Quaternary stratigraphy are addressed by the Quaternary Stratigraphy Group of the Finnish Stratigraphy Committee, which operates under the Finnish National Committee of Geology (a member organisation of the IUGS).

Numerous international and national stratigraphic guides and codes have been published to clarify and dictate various concepts of formal (as well as informal) stratigraphic practices and procedures, such as Hedberg (1976), Salvador (1994), the ICS Stratigraphic Guide (ICS 2022), the North American Stratigraphic Code (NACSN 2021) for North America, Kumpulainen (2017) for Sweden and Nystuen (1989) for Norway. In these stratigraphic guides, the rules for establishing formal and informal litho-, bio- and chronostratigraphic units are explained. In some countries, there are also guides for allo-, magneto- and pedostratigraphic practices (e.g., NACSN 2021). The intent of these guides is to provide clear instructions on how stratigraphic terms are defined and what they are used for. However, stratigraphies such as chemo- and seismostratigraphy, as well as sequence stratigraphy, are approaches that analyse conformable successions of genetically related strata, which may lead to the definition of lithostratigraphic units or seismostratigraphic and allostratigraphic units.

Ultimately, the formal classification of Quaternary deposits in most Eurasian countries has traditionally been based on climatostratigraphy, where sedimentary sequences are divided into geological-climatic units based on litho- and biostratigraphically defined glacial and interglacial/-stadial stages and substages (Gibbard 2013). The formal stratigraphy is, however, challenging to apply to sediments deposited in formerly glaciated terrains, especially in areas adjacent to the centres of former ice sheets located, for example, in Fennoscandia and Canada (e.g., Lee 2018). This is mainly because glacial sedimentary sequences deposited in formerly glaciated areas are full of hiatuses (glacial erosion) and often void of organic-rich units, hampering regional stratigraphic correlation. Therefore, instead of applying formal stratigraphic procedures, there are many informal practices to classify the Finnish Quaternary deposits introduced in this review.

Recent developments in geomorphological mapping (e.g., Johnson et al. 2015, Ojala & Sarala 2017, Putkinen et al. 2017), new concepts of sediment and landform classification (e.g., Ojala et al. 2021, Rivers et al. 2023) and advances in geochronological methods (e.g., Sarala et al. 2022, Kalliokoski et al. 2023) have led to a need to review the classification of Finnish Quaternary sequences, both glacial (mainly Pleistocene) and non-glacial (mainly Holocene). In this review, the Quaternary Sub-Commission of the Stratigraphic Commission of

Finland provides a brief overview on the classification of Quaternary sedimentary sequences and introduces the practices by which the superficial Quaternary deposits are classified in Finland. The presented classification schemes introduce applicable approaches and practices by which different classifications are currently carried out to benefit both scientific interest and more applied research in Quaternary geology. **This review article is not a stratigraphic guide or a stratigraphic code**. Its purpose is merely to illustrate the most applicable methods to classify Quaternary sedimentary sequences and landforms in Finland, an area that has been covered by the Fennoscandian Ice Sheet (FIS) several times during the Quaternary Period, leaving behind complex Quaternary strata.

2 QUATERNARY DEPOSITS IN FINLAND AND THEIR CLASSIFICATION

2.1 Background

A general but fundamental point concerning geology and stratigraphy in the Finnish context is that practically the entire present territory of Finland consists of Precambrian crystalline rocks, the Fennoscandian Shield (e.g., Nilsson et al. 2022), upon which loose Quaternary sediments occur. “The Great Unconformity of Finnish Geology” (Nenonen 1995) between the bedrock and Quaternary strata represents a time gap amounting to more than a billion years. The Quaternary overburden in Finland is mostly glaciogenic, composed of diamicton (i.e., till), sand and gravel, as well as glaciolacustrine fine sediments (silt and clay). On the other hand, non-glacial sediments, mostly Holocene in age, consist of peat, organic-rich shallow brackish-water marine sediments, lake sediments, and fluvial and aeolian sands. The wide variety of siliciclastic and organic sediments form a spatially complex mosaic where sedimentary units are typically extremely discontinuous and their lateral extent is often limited. Therefore, the so-called ‘layer-cake’ stratigraphy common in sedimentary basin areas such as the Netherlands (Moscariello 2011) does not exist in Finland in a broad sense. However, the Baltic Sea Basin sediments in some parts of the coastal areas of Finland and in the current Baltic Sea basin are laterally more extensive, and the ‘layer-cake’ approach is applicable for the classification of these late- and postglacial basin sediments (e.g., Virtasalo et al. 2014).

2.2 Surface mapping of Quaternary deposits

The classification of Finnish Quaternary deposits has a long history (Palmu et al. 2021). The stratigraphic context of the Quaternary superficial sediments was already recognised well over one hundred years ago (Ramsay 1909). Quaternary geologists and geographers traditionally used geomorphology as the basis to identify and classify Quaternary deposits (e.g., Rainio 1996, Haavisto-Hyvärinen & Kutvonen 2007). The Geological Survey of Finland (GTK) and its predecessors were responsible for carrying out bedrock and Quaternary deposit mapping from the late nineteenth century. Quaternary mapping consisted of surface sediment (lithological maps) and geomorphological mapping at different scales ranging from 1:20 000 to 1:400 000 (Haavisto-Hyvärinen & Kutvonen 2007). Initially, both bedrock and superficial deposits were classified and presented on the same map sheet (e.g., Map Sheet Ekenäs, 1:200 000, printed in 1879), while the first Quaternary deposit map at the scale 1:400 000, covering the Mikkeli area, was published in 1900. The use of aerial photo(graphic) image interpretation in Quaternary mapping was initiated during the 1960s by Penttilä (1963) and Kujansuu (1967). Different mapping projects continued to produce printed maps on the lithological characteristics and distribution of Quaternary deposits and geomorphological features in different parts of Finland up until the late 20th century.

During the past two decades, developments in digitalization, data concepts and new remote sensing techniques, such as digital elevation models (DEMs) from modern airborne LiDAR (light detection and ranging), have enabled the classification, processing and mapping of Quaternary deposits and landforms in a more holistic manner than ever before (Johnson et al. 2015, Putkinen et al. 2017, Palmu et al. 2021). At present, the systematic mapping of Quaternary terrain by GTK is based on LiDAR DEMs (Palmu et al. 2021). The mapping and classification of Finnish Quaternary deposits is still largely dictated by superficial sediment lithology and geomorphology-driven practices. However, high-resolution LiDAR-based mapping of glacial and nonglacial features, such as subglacial lineations, striations, murtoos, meltwater corridors, ancient shorelines and De Geer moraines, has produced a vast amount of data that is presently stored in the geodatabase at GTK (Ojala 2016, Putkinen et al. 2017, Ojala et al. 2019b, Ahokangas et al. 2021, Palmu et al. 2021). Today, these data, when processed and integrated with data from boreholes and exposures, as well as seismic-acoustic and geochemical surveys, allow us to map, categorise and understand the three-dimensional nature, formation processes and chronological relationships of Finnish Quaternary deposits and sediments.

2.3 Stratigraphic logging of vertical sections

Logs of sedimentary sequences in exposures and boreholes, and their lithological and biological characteristics, are the most essential source of information in Quaternary stratigraphy. These data (below 1 m depth) were not integrated into Quaternary maps in Finland during the decades of the Finnish national mapping projects. Regional superficial mapping practices in Finland were dominated by a surface lithology-based approach before the recent LiDAR data revolution (Palmu et al. 2021). The systematic classification of Quaternary strata in sediment exposures or boreholes was not a common practice in Finland during the first part of the 20th century. Lithological sections were occasionally described, drawn and photographed from natural and excavated exposures (e.g., Sauramo 1923, 1929, Aurola 1949), but it was only in 1970s that sediment successions were systematically recorded in site-specific studies (e.g., Gibbard 1979) and in spatially extensive projects by GTK. In these activities, tests pits were dug, and exposures logged for sediment characteristics and sampled for grain size and heavy mineral fractions, mostly for gold prospecting purposes (e.g., Hirvas et al. 1977, Niemelä & Tynni 1979). In the 1980s, steps towards facies analysis (Miall 1978, Eyles et al. 1983) as the main method for recording sediment sections were taken. This approach formed the basis for attempts at establishing local and regional lithostratigraphic schemes of glacial and interglacial sequences in Finland (e.g., Bouchard et al. 1990, Hirvas et al. 1995).

The use of pollen analysis from lake and peat bog sediments to unravel the interglacial and interstadial vegetation history in Finland, and local biostratigraphy, often included lithological/lithostratigraphic sediment descriptions from the 1930s onwards. Palynology has remained the principal biostratigraphic method for defining the Quaternary climatostratigraphy and chronostratigraphy in Finland (e.g., Hirvas 1991, Nenonen 1995, Donner 1995, Pitkäranta 2013, Sarala 2005, and references therein). The analysis of fossil diatom flora has been an additional and important method in the recognition and division of the Baltic Sea phases, particularly in Finland and Sweden, since diatom assemblages indicate transitions between freshwater and brackish water phases in the basin history (e.g., Mölder & Tynni 1967, Tynni 1975).

The Quaternary history of Finland is, in essence, based on litho- and biostratigraphy supported by age determinations using geological dating methods suitable for dating the Pleistocene and Holocene sediments. In the Baltic Sea Basin, these data are combined with the allostratigraphic classification of sediment sequences and their spatial continuation, based on interpretations of seismic-acoustic sub-bottom profiles (e.g., Virtasalo et al. 2005). However, there are no formal or confirmed litho-, bio- or chronostratigraphic classifications for the Quaternary sediment units in Finland, although several schemes from key localities in different parts of Finland have been proposed (see section 3.1.2). In the following, we introduce the most common concepts to classify Finnish Quaternary sedimentary units, starting from litho-, bio- and chronostratigraphic classification schemes, followed by morpho-, magneto-, chemo-, pedo-, seismo-, sequence, allo- and hydrostratigraphic classification schemes. In addition, geochronological methods applicable to the dating of Finnish Quaternary sediments are also introduced.

3 LITHO-, BIO- AND CHRONOSTRATIGRAPHIC CONCEPTS TO CLASSIFY QUATERNARY SEQUENCES

3.1 Lithostratigraphy

3.1.1 Background

Lithostratigraphy in its broadest sense encompasses the description and classification of sediments from exposures and boreholes based on their lithological properties and their relative stratigraphic position in the strata (e.g., Hedberg 1976, Salvador 1994). No other criteria than these are considered when defining lithostratigraphic units, which are independent of the inferred geological history, mode of genesis and biological content. Their boundaries are in principle independent of time horizons, and most boundaries are time transgressive. However, the lower boundary of a unit formed by a sudden, brief event may be nearly synchronous throughout the area in which the unit boundary occurs.

In formal lithostratigraphy, lithostratigraphic classification is based on lithological variations in superimposed sediment strata. The formal lithostratigraphic classification of sediment strata requires distinct criteria to be fulfilled (Box 1). Conventional formal lithostratigraphy divides sediment strata into beds, formations (separated, if necessary, into members) and groups (Box 1). The concepts of supergroups, subgroups, lithostratigraphic complexes and lithohorizons are also used and defined in the formal lithostratigraphic classification. If lithostratigraphic units are not adequately described and defined, but they have been named, they should be considered as informal units.

It is typical that Quaternary glacial sediment strata in the central areas of the formerly glaciated terrains are often thin (or absent), and individual sediment units are limited in their lateral extent. This is also the case in Finland and more broadly in the Fennoscandian Shield area, where glacial sediment units constituting glacial landforms can be relatively thick, but their lateral extent is highly limited. In contrast, the Holocene Baltic Sea Basin sediments overlying the glacial strata are more widespread and continuous, occurring below the highest Holocene water level of the Baltic Sea Basin (e.g., Ojala et al. 2013). Despite the limitations in carrying out formal lithostratigraphy on glacial sediments, lithostratigraphic procedures to classify the Quaternary sediment strata, where warranted, should follow the basic lithostratigraphic classification rules where (i) each sediment unit is accurately described, (ii) the stratigraphic scheme has a hierarchical structure where formation is the central unit, (iii) the scheme has a clear nomenclature and (iv) the units are mappable.

The most common informal lithostratigraphic approach to study sediment sequences is based on lithofacies analysis, where sediment exposures and drill cores are divided into sediment units according to their lithology and structural characteristics (Fig. 1). A sediment unit (also termed beds or facies) differs from the unit below and above by its different textural and structural characteristics. Multiple lithofacies in vertical sections or drill core sediments may form so-called facies associations when

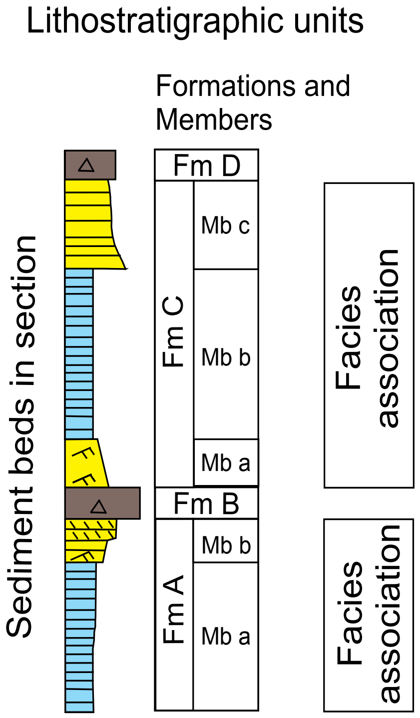


Fig. 1. Schematic presentation of a hypothetical sediment section in which the sediment beds of laminated silt and clay (blue), rippled, parallel and planar cross-bedded sand (yellow) and diamicton (grey) are lithostratigraphically divided into different formations (Fm) and members (Mb). The lithostratigraphic description and classification may lead to the definition of a facies association, which is not a stratigraphic term but a term indicating that multiple lithofacies are genetically related.

they are genetically related, and multiple stacked facies associations may form facies successions (Fig. 2). Facies associations normally constitute an architectural element or assemblages belonging to depositional systems and basin fill (e.g., Miall 1985, Pickering et al. 1995). This type of approach to classify Quaternary strata based on their hierarchy, bound to three-dimensional architectural elements and ultimately to depositional systems, has proven to be most applicable to categorising Quaternary glaciogenic and non-glaciogenic sediments.

It is essential to understand that the classification of lithostratigraphic units should be based on physical characteristics obtained from sediment sections and drill cores. Architectural elements, depositional systems and system tracts, on the other hand, are interpretive characterisations of sediment features based on bounding surfaces, facies, scale and geometry (e.g., Pickering et al. 1995), and may or may not be completely unrelated to eventual formal lithostratigraphic boundaries.

Quaternary deposits are distinctive landforms, often limited in their lateral extent, and normally composed of distinct packages of sediments. In a glaciogenic context, the landforms, such as drumlins, flutings, ribbed moraines, or bottom-, fore- and topset elements in Gilbert-type glaciofluvial deltas, can be understood as three-dimensional accumulations (or erosional remnants) composed of facies associations. Lithological properties for defining units, their hierarchical lithostratigraphic structure and the naming of stratotypes of sediment sequences in the central areas of formerly glaciated terrains are normally adequately met to fulfil the requirements of formal lithostratigraphy. However, the relations between described sediment sequences from one locality to another and their mappability often remains elusive if facies and element analyses are not used.

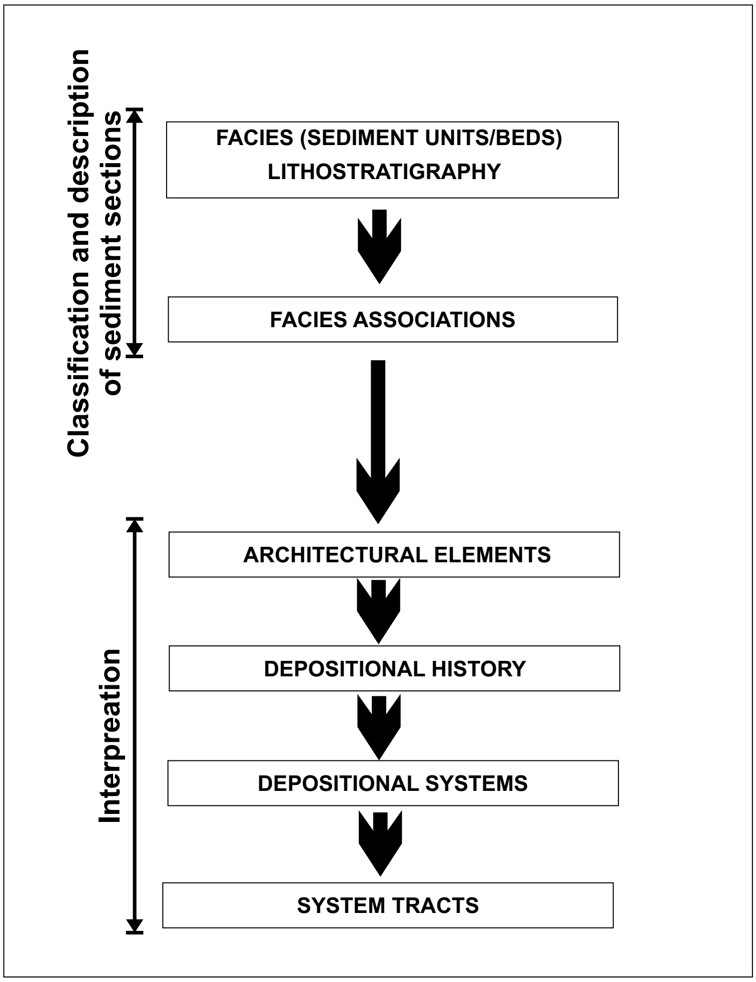


Fig. 2. Hierarchy to unravel depositional systems and system tracts. The lithostratigraphic description of sediment beds forming facies associations is the most important data for the interpretation of architectural elements and finally depositional systems and their evolution (highstand, lowstand and transgressive tracts). Modified after Walker (1992).

3.1.2 Lithostratigraphy of Finnish Quaternary sequences

Numerous studies have focused on the description of Finnish Pleistocene lithostratigraphic units (e.g., Gibbard 1979, Aario & Forsström 1979, Hirvas & Nenonen 1987, Bouchard et al. 1990, Hirvas 1991, Nenonen 1995, Lunkka et al. 2004, Sarala 2005, Salonen et al. 2008, Johansson et al. 2011, Pitkäranta 2013, Lunkka et al. 2015). These investigations have included several local and regional stratigraphic schemes that have been introduced for different parts of Finland. Finnish Pleistocene lithostratigraphy is still heavily based on till stratigraphy, where separate till units in sections, often superimposed on and interbedded with non-glacial sediments, are correlated between different localities. The most comprehensive examples of this type of lithostratigraphic approach, with designated reference sections, have been presented by Hirvas (1991) and Nenonen (1995), who established regional lithostratigraphic schemes for Finnish Lapland and southern and western Finland, respectively. However, the correlation of till units across wide areas can be challenging (e.g., Lunkka et al. 2015) due to a lack of dating and spatially diverse glacial dynamics in the area covered by the FIS during the Late Pleistocene. Therefore, the long-distance correlation of different till units based solely on the physical characteristics of till units (e.g., grain size, colour, lithological composition or till clast fabric) can lead to erroneous correlations.

The need to classify Finnish Quaternary deposits following internationally accepted principles was widely recognised in the 1990s by the Finnish Quaternary community. Gibbard (1992) discussed the stratigraphic aspects and provided recommendations related to the formal stratigraphic procedures to subdivide Finnish Pleistocene sediments. Even at that time, the recommendations encouraged the following of internationally accepted principles and procedures in (litho)stratigraphy and carefully selecting stratotypes for wider lithostratigraphic correlation (see ICS 2022). Based on these principles, Palmu et al. (2021) listed possible key locations upon which a wider stratigraphic classification of Finnish Quaternary sequences could be based (Fig. 3).

Fig. 3. Suggested key locations where the stratigraphic record of Quaternary deposits in Finland is well represented, after Palmu et al. (2021). Locations: Kela and Lommila (Bouchard et al. 1990); Vuosaari (Hirvas et al. 1995); Sallila, Horonkylä, Haapalankangas, Eteläkylä, Kaasila, Pampalo, Ruotanen, Vesiperä, Mertuanoja, Vuojalankangas (Nenonen 1995); Risåsen, Penttilänkangas, Karhukangas, Harrinkangas (Pitkäranta 2013); Hitura (Salonen et al. 2008); Ruunaa (Lunkka et al. 2008); Vammavaara, Petäjävaara, Sihtuuna, Korttelivaara, (Sarala 2005); Saarenkylä (Sutinen 1992); Rautuvaara (Lunkka et al. 2015); Hannukainen (Salonen et al. 2014); Sokli (Helmens et al. 2015); Koivusaarenneva (Lunkka et al. 2016); Kaarreoja (Sarala et al. 2016) and Äältövittikot (Putkinen et al. 2020). Basemap data © National Land Survey of Finland.

BOX 1

TERMINOLOGY USED IN FORMAL LITHOSTRATIGRAPHY

(modified after the ICS Stratigraphic Guide)

(Finnish terms in parentheses)

DEFINITIONS (applicable in the context of Finnish Quaternary geology)

LITHOSTRATIGRAPHY AND LITHOSTRATIGRAPHIC CLASSIFICATION *(litostratigrafia ja litostratigrafinen luokittelu)* – A field of stratigraphy that includes the description and nomenclature of superficial Quaternary sediments based on their lithology and stratigraphic relations.

LITHOSTRATIGRAPHIC UNITS *(litostratigrafiset yksiköt)* – Bodies of sediments, bedded or un-bedded, that are defined and characterised according to their lithological properties and stratigraphic relations. Lithostratigraphic units are the basic units of geological mapping, and their extent is entirely controlled by the continuity and extent of their diagnostic lithological features.

HIERARCHY OF FORMAL LITHOSTRATIGRAPHIC UNITS

- **Bed** (*kerros*) – named distinctive sediment layer in a member or formation
- **Member** (*jäsen*) – named lithological subdivision in a formation
- **Formation** (*muodostuma*) – primary unit of formal lithostratigraphy
- **Group** (*ryhmä*) – two or more formations (**Subgroup** (*alaryhmä*) – a group may be divided into subgroups that include formations)
- **Supergroup** (*superryhmä*) – may be used for several associated groups or for associated groups and formations with significant lithological properties in common

In addition to these terms, **lithostratigraphic horizon** (*litostratigrafinen horisontti*) can be used to formally distinguish a lithologically distinctive boundary or marker bed in sediment strata (the surface of the lower boundary of a sediment unit or a marker bed within a sediment unit).

ESTABLISHING FORMAL LITHOSTRATIGRAPHIC UNITS

Stratotype (*tyyppileikkaus eli stratotyyppi*) and **type locality** (*tyyppipaikka*) – a formal lithostratigraphic unit should have 1) a clear and precise definition or characterization, 2) a stratotype section (*tyyppileikkaus*) and 3) an assigned type locality (*tyyppipaikka*). Auxiliary reference sections or additional type localities may be used to supplement the definition of a lithostratigraphic unit.

Terminology: 1) **Holostratotype** (*holostratotyyppi*) – the original stratotype designated by the original author. 2) **Parastratotype** (*parastratotyyppi*) – a supplementary stratotype used in the original definition to illustrate the heterogeneity of the stratigraphic unit. 3) **Lectostratotype** (*lektostratotyyppi*) – a stratotype for a previously described stratigraphic unit selected later in the absence of an adequately designated original stratotype. 4) **Neostratotype** (*neostratotyyppi*) – a new stratotype selected to replace the older one which has been destroyed, covered or otherwise made inaccessible. 5) **Hypostratotype, also called reference section** (*hypostratotyyppi*) – a stratotype proposed after the original designation of the holostratotype (and parastratotype).

Note – Holostratotypes and parastratotypes are generally situated in the type area / region (*tyyppialue*). Neostratotypes and lectostratotypes are preferably chosen within the limits of the original type area. Hypostratotypes may be chosen beyond the limits of the original type area.

Lithostratigraphic unit boundaries (*litostratigrafisten yksiköiden rajat*) – unit boundaries should be placed at positions of lithological change or arbitrarily within zones of vertical or lateral lithological gradation.

Note – 1) Lithostratigraphic unit boundaries commonly cut across time surfaces and across the boundaries of any other type of stratigraphic unit. 2) Lithostratigraphic sequences of similar lithological composition that are separated by regional unconformities or major hiatuses should be mapped as separate lithostratigraphic units. 3) Local or minor hiatuses, disconformities or unconformities within a sequence of similar lithological composition should not be a reason to establish more than one lithostratigraphic unit.

LITHOSTRATIGRAPHIC CORRELATION
A lithostratigraphic unit and its boundaries are extended away from the type section or type locality as far as the lithological properties on which the unit is based remain similar. In the case of poor or no outcrops or exposures, where lithology is difficult to determine, a lithostratigraphic unit and its boundaries may be identified and correlated using indirect evidence, such as geomorphological expression and/or geophysical reflection data. The top or the base of a marker bed may be used as a boundary for a formal lithostratigraphic unit where the marker bed occurs at or near a recognizable vertical change in lithology.

NAMING OF LITHOSTRATIGRAPHIC UNITS
The naming of lithostratigraphic units follows the general rules for naming stratigraphic units, i.e., the name is formed from a local geographical feature with the appropriate unit term indicating its rank. The name of lithostratigraphic units normally consists of a geographic component and a lithological component, e.g., Kela (geographic location) Till Formation (lithological component and rank) (see Bouchard et al. 1990). In Finnish, the geographical location is written with a capital letter while the lithostratigraphic unit is separated with a hyphen and written in lower case, e.g., Kela-moreenimuodostuma.

3.2 Biostratigraphy

3.2.1 Background

Biostratigraphy is used for the organization and classification of sedimentary and rock strata based on their fossil content. The principle of biostratigraphy is that biozones (basic unit) can be identified based on their distinctive fossil content compared to the over- and underlying zones (Lucas 2021). The formation of biozones is enabled by the evolution and range shifts of different organisms. As species evolve and become extinct or change their geographical range, they form distinctive fossil assemblages that can be defined within sedimentary strata (Lucas 2021). Biostratigraphy has enabled the global correlation of lithostratigraphic units and chronostratigraphic correlation (SQS 2023). In general, five biozones can be identified: range zones (stratigraphic range of certain taxa), interval zones (boundary strata between two biostratigraphic zones), lineage zones (evolutionary zones), assemblage zones (certain combinations of several fossils) and abundance zones (abundance of certain fossils or fossil assemblages) (SQS 2023). Prior to defining biogeographical zones, it is essential to identify the environment in which the fossil taxa lived. Especially useful fossil assemblages are those that have a wide geographical range, lived for only a relatively short time in a particular region and have distinctive evolutionary features that can be identified (Lucas 2021). In Quaternary research, marine and lake sediments, together with peat archives, are commonly used to define biostratigraphic zones, as fossils such as pollen and spores, macrofossils, dinoflagellates, foraminifera, diatoms, chironomids and molluscs are well preserved in these archives.

In the early 1800s, biostratigraphy developed when the stratigraphic order of rock strata with a similar fossil content across a large area was noted, for example, by William Smith in England and Georges Cuvier and Alexandre Brongniart in France (Lucas 2021). In addition, the biostratigraphic definition of organic deposits was first recorded in the early 1800s, when stratified peat layers were visually identified from peat excavations by H. Dau in Zealand, Denmark (Dau 1829). In Europe, a widely occurring peat layer was named by Weber (1926) as ‘Grenzhorizonte’. A few decades later, the geologist Lennart von Post, who is considered as the founder of modern palynology (Manten 1966), combined palynological data with peat stratigraphy and paleoecology, and a scientific discipline was born. Consequently, fossil pollen records have been widely used as basis for the identification of biostratigraphic units, especially in Europe and also in Finland. Sediment dating methods were not fully established in the 1800s and early 1900s, but immediately after the radiocarbon method enabled the dating of organic sediment remnants from 1949 onwards (Arnold & Libby 1949), it became possible to rather reliably date biostratigraphic units and shed light on paleoecological and paleoclimatological development in different areas during the past 40 000 yrs.

Historically, the Holocene was divided into postglacial climate phases in northern Europe based on distinctive biostratigraphic zones defined by pollen spectra from peat and lake sediments, the so called Blytt–Sernander classification (Blytt 1876, Sernander 1908). The phases (Blytt–Sernander units) were named as Preboreal (warming temperatures immediately after deglaciation), Boreal (cool and dry), Atlantic (warm, moist, maximum temperature) and the Late Holocene phases Subboreal and Subatlantic (Mangerud et al. 1974). However, this classification is less commonly used at present, as the postglacial vegetation succession was time-transgressive, meaning that the phases did not simultaneously occurr all over Europe, but there was a delay driven by various factors such as the withdrawal of the glacial front. Moreover, a very tightly constrained way to classify vegetation succession patterns based on, for instance, pollen alone appeared meaningless, and it was relatively soon noted that changes in microfossil assemblages were not necessarily correlative with other proxy data, such as plant macrofossils or peat stratigraphy in general. No universally accepted replacement for the Blytt–Sernander units has been proposed. However, the chronostratigraphic division of the Holocene Epoch into the Early (Greenlandian), Middle (Northgrippian) and Late (Meghalayan) Ages is relatively commonly used at present in paleoecological and paleoclimatological studies to indicate the time period in question rather than to describe the climate phases.

Gradually, qualitative paleoecological classification based on pollen proportions and concentrations gave way to quantitative reconstructions, and major developments occurred during the 1980s by Cajo ter Braak and John B. Birks, among others (Smol et al. 2012). Quantitative pollen analyses to reconstruct not only the vegetation history but also the past climate was established as a standard biostratigraphic method in the 1970s (Webb & Bryson 1972, Birks & Gordon 1985, Birks 1995, Birks & Seppä 2004), and the practice of using modern calibration sets and the transfer function approach was introduced to biostratigraphic studies. Currently, scientists can exploit continental-wide pollen databases, which include modern surface samples, within the Neotoma Paleoecology Database (http://www.neotomadb.org). In addition to pollen data, this database stores data from diverse sources, such as vertebrates, independent paleoclimatic records, genetic and macroecological data, and records of human activity and influence (Edwards et al. 2017).

3.2.2 Biostratigraphy in Finland

In Finland, biostratigraphic units have traditionally been used for stratigraphic correlation and as an indication of the age of a certain stratigraphic layer. Biostratigraphic correlation is often based on palynological records, and most records are focused on the Holocene biostratigraphy. However, biostratigraphic units have also been dated to the preceding Eem interglacial (ca. 130 000–116 000 yr BP). Such strata exist in northern Finland from Sokli (Salonen et al. 2018) and Tepsakumpu and Paloseljänoja (Hirvas 1991, Saarnisto et al. 1999) and in west-central Finland from Mertuanoja (Eriksson 1993, Eriksson et al. 1999) and Muhos (Eskola & Lunkka 2022). Moreover, combined with lithostratigraphy, numerous local biostratigraphic sections representing various Weichselian interstadials have been reported from northern Finland, namely a) Sokli (Helmens et al. 2000, 2012), b) Petäjäselkä (Sarala & Eskola 2011) and c) Kaarreoja (Sarala et al. 2016), from west-central Finland, namely d) Oulainen (Forsström 1982, 1988, Jungner 1987, Nenonen 1995), e) Marjamurto (Peltoniemi et al. 1989, Lunkka et al. 2016), f) Hitura (Salonen et al. 2008), g) Muhos (Eskola & Lunkka 2022) and h) Horonkylä, Teuva (Nenonen 1995, Grönlund & Ikonen 1996), and from eastern Finland, at h) Ruunaa (Lunkka et al. 2008) (Fig. 3).

The biostratigraphic zonation of the Holocene emerged in the 1970s based on palynological records presented by Donner (1963, 1971), Alhonen (1967, 1971), Hyvärinen (1972, 1975) and Tolonen & Ruuhijärvi (1976), among others. Based on stratigraphic records published in 1975, Hyvärinen presented a correlation between the Finnish and NW European Late Pleistocene and Holocene pollen stratigraphic schemes. In his main work in 1975 (Hyvärinen 1975), he already defined the postglacial vegetation and forest succession patterns, namely the Younger Dryas tundra phase and Early Holocene domination of birch, followed by the birch–pine phase. The Mid-Holocene temperate forest phase in southern Finland included taxa such as oak, ash, lime, elm and hazel (Fig. 4). The Late Holocene phase (Meghalayan, from 4200 yrs BP) is characterised by the decline of temperate taxa and immigration of spruce, an important and indicative taxon for Late Holocene climate change toward cooler and moister conditions (Hyvärinen 1975). However, these phases are spatially and temporally divergent, depending on the region. An example of the use of biostratigraphic zones for age correlation and of the spatially and temporally divergent biostratigraphic zones is the occurrence of spruce pollen in the palynological records in Finland. The establishment of spruce across Finland from east to west circa 6500—2000 years BP has been well dated by radiocarbon dating (e.g., Tallantire 1972, Tolonen & Ruuhijärvi 1976, Donner 1971, Giesecke & Bennet 2004, Latalowa & van der Knaap 2006, Seppä et al. 2009, Kuosmanen et al. 2016), allowing the use of spruce establishment as a chronological control of stratigraphic zones. Overall, biostratigraphic research based on palynology has remained a strong scientific discipline in Finland, as also elsewhere in Europe, being an integral part of Quaternary geology.

In addition to terrestrial pollen records, diatoms and molluscs have been utilized in reconstructing the postglacial history of the Baltic Sea basin, its uplifting coastline following ice withdrawal, and its freshwater and brackish water phases (Tynni 1975, Miettinen 2002). Baltic Sea sediments have also provided an important source of information in investigating anthropogenic pressure on coastal ecosystems, particularly eutrophication (Vaalgamaa 2004, Weckström 2005). Moreover, plant macrofossils have been used as stratigraphic indicators of climatic phases. For example, the findings of fossil fruits of water chestnuts (*Trapa natans*) (Alhonen 1964) and hazel (*Corylus avellana*) (Tallantire 1981, Eriksson et al. 1991, Seppä et al. 2015), as well as macrofossils of hornwort (*Ceratophyllum*) (Helmens et al. 2020), have been considered as good indicators of higher summer temperatures than at present.

As the development of chronological control methods has rendered the most traditional use

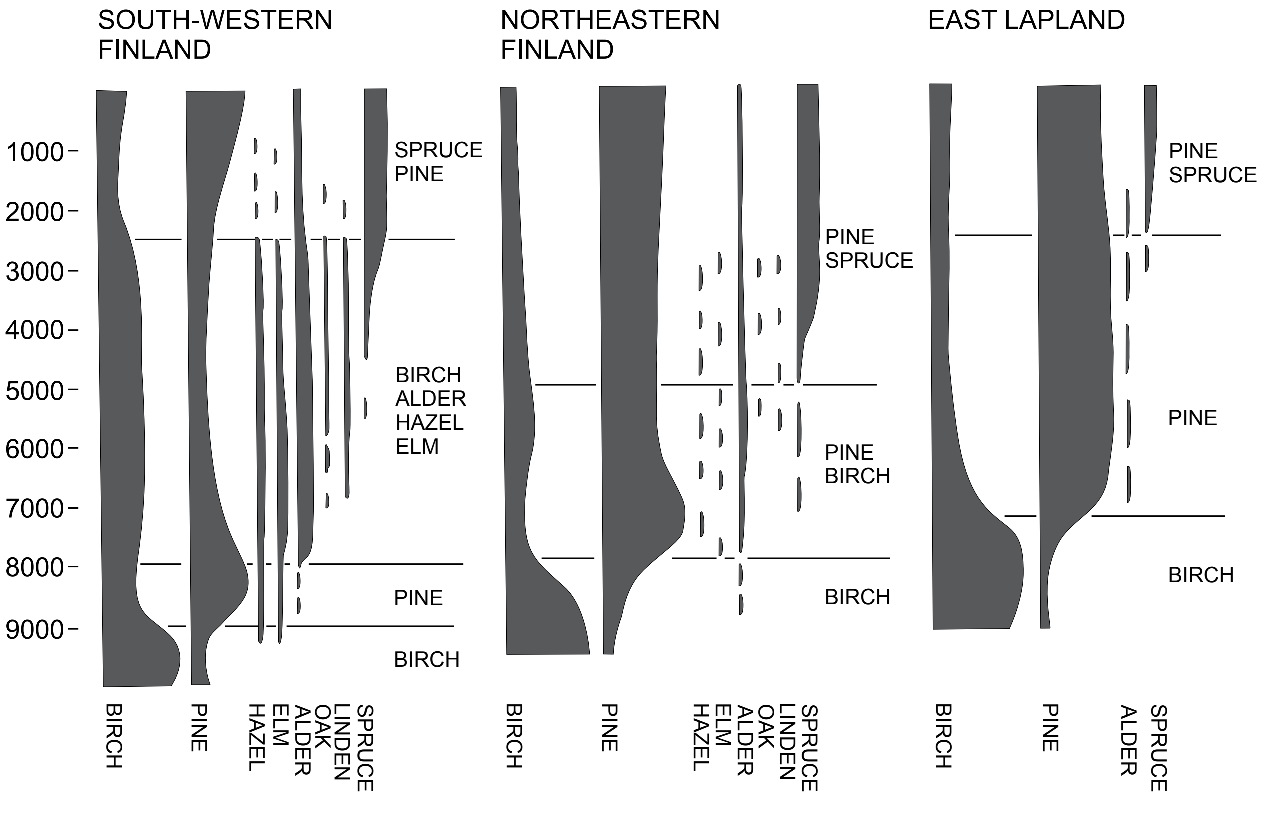


Fig. 4. Pollen stratigraphic biozones of southwestern Finland, northeastern Finland and eastern Lapland, and chronology from radiocarbon ages, modified after Hyvärinen (1986, according to Donner (1971) and Hyvärinen (1972)).

of biostratigraphic information as a stratigraphic constraint, new avenues have emerged, initiating new research questions. For example, a significant postglacial stratigraphic event in Finland is the so-called fen–bog transition, a peatland-scale regime shift where the entire hydrological system changes. This quasi time-transgressive process involves drastic changes in vegetation and carbon dynamics. However, the underlying driving factors of these changes remain unresolved at present. Moreover, the determination of this stratigraphic regime shift is not established, either, and the fen–bog transition zonation line, often easily detectable, cannot be considered as a reference surface for any climate event, as was earlier thought (Tolonen 1967, Tahvanainen 2011, Väliranta et al. 2017 and references therein, Piilo et al. 2020, Kolari & Tahvanainen 2023). The traditional toolbox of proxies, largely reconstructing local rather than regional conditions, includes visible peat stratigraphy, peat plant macrofossils, charcoal, pollen, non-pollen palynomorphs, testate amoebae, beetles, mites, chironomids, diatoms, various biomarkers and stable isotopes (Chambers et al. 2012). A network of surface-moisture reconstructions is offering a detailed and geographically wide perspective on past hydroclimate variability in many regions (Zhang et al. 2022).

BOX 2

TERMINOLOGY USED IN FORMAL BIOSTRATIGRAPHY

(modified after the ICS Stratigraphic Guide)

(Finnish terms in parentheses)

DEFINITIONS (applicable in the context of Finnish Quaternary geology)

BIOSTRATIGRAPHY (biostratigrafia) – A field of stratigraphy that includes the description and nomenclature of stratigraphic strata based on their fossil content.

BIOSTRATIGRAPHIC UNITS (biostratigrafiset yksiköt) – Biostratigraphic units (biozones) are bodies of strata that are defined or characterized based on their contained fossils. Therefore, their recognition and organization of the stratigraphic section depends on the identification of either their defining or characterizing attributes.

BIOSTRATIGRAPHIC ZONE (biozooni) – A general term for any kind of biostratigraphic unit regardless of thickness or geographic extent. Five main biostratigraphic zones are generally used: range zones, interval zones, assemblage zones, abundance zones and lineage zones.

BIOSTRATIGRAPHIC HORIZON (biostratigrafinen horisontti) – A stratigraphic boundary, surface or interface across which there is a significant change in biostratigraphic character.

TYPES OF BIOSTRATIGRAPHIC UNITS AND HIERARCY

- **Range zones** (*esiintymisbiozooni/-vyöhyke*) – represent the known stratigraphic and geographic range of occurrence of a particular taxon or combination of two taxa of any rank.
- **Interval zones** (*intervallibiozooni/-vyöhyke*) – the body of fossiliferous strata between two specified biohorizons.
- **Assemblage zones** (*koostumusbiozooni/-vyöhyke*) – the body of strata characterized by an assemblage of three or more fossil taxa that, taken together, distinguishes it in biostratigraphic character from adjacent strata.
- **Abundance zones** (*runsausbiozooni/-vyöhyke*) – the body of strata in which the abundance of a particular taxon or specified group of taxa is significantly greater than is usual in the adjacent parts of the section.
- **Lineage zones** (*polveutumisbiozooni/-vyöhyke*) – the body of strata containing specimens representing a specific segment of an evolutionary lineage.

The different types of biostratigraphic units (biozones) described above have no hierarchical significance, except in the case of subzones and superzones, where the prefix indicates the position in a hierarchy.

ESTABLISHING FORMAL BIOSTRATIGRAPHIC UNITS

It is recommended that the definition or characterization of a biostratigraphic unit includes the designation of one or more specific reference sections that demonstrate the stratigraphic context of the taxon or taxa diagnostic of the unit.

BIOSTRATIGRAPHIC CORRELATION

Biostratigraphic units are extended away from the areas where they were defined or from their reference sections by biostratigraphic correlation. In theory, any fossil can be used to make physical correlations between stratigraphic horizons and help in establishing correspondence in biostratigraphic character and position between geographically separated sections or outcrops. Fossils utilized for biostratigraphic correlation are termed 'index' fossils. Biostratigraphic correlation is not necessarily time correlation. It may approximate time correlation, or it may be the identification of the same biofacies, which may be diachronous.

NAMING OF BIOSTRATIGRAPHIC UNITS

The formal name of a biostratigraphic unit should be formed from the names of one, or no more than two, appropriate fossils combined with the appropriate term for the type of unit in question. The function of a name is to provide a unique designation for the biozone. The name of the taxon chosen to designate a biozone should include the entire name of the taxon. In Finnish, biostratigraphic units are named accordingly, either naming the taxon in Latin, e.g., *Betula nana* -esiintymisvyöhyke, or in Finnish, e.g., vaivaiskoivun esiintymisvyöhyke.

3.3 Chronostratigraphy and climatostratigraphy

3.3.1 Background

Chronostratigraphy ('time-rock stratigraphy') is the "element of stratigraphy that deals with the age of strata and their time relations," and the chronostratigraphic classification represent "the organization of rock strata into units on the basis of their age or time of origin" (Hedberg 1976, Salvador 1994). As chronostratigraphy deals with the relative time relations of sediment (or rock) units, the chronostratigraphic units represent sediments (or rocks) formed during a specific geological time interval (e.g., Salvador 1994).

The basic principles for defining and naming the formal Quaternary chronostratigraphic units are the same as those for other Phanerozoic chronostratigraphic units (Box 3). In formal chronostratigraphy, the Quaternary System, encompassing both the Pleistocene and Holocene Series, is defined by the Global Boundary Stratotype Section and Point (GSSP) at Monte San Nicola, Sicily, Italy (Gibbard & Head 2010). This stratigraphic boundary also serves as the base of the Pleistocene Series. The Pleistocene, in turn, is divided into the Lower, Middle and Upper Pleistocene subseries and their associated stages, the Gelasian (*Gela-vaihe*) and Calabrian (*Calabria-vaihe*), Chibanian (*Chiba-vaihe*) and Upper Pleistocene Stages. The formal units of the Geological Time Scale are defined at their base by GSSPs, of which six have currently been ratified within the last 2.58 million years (the GSSP for the Upper Pleistocene and its associated stage is pending at present). The Holocene Series begins at 11 700 ± 99 yrs before CE 2000 (yrs b2k), i.e., 11650 ± 99 cal. yr BP, and is divided into the Greenlandian (*Grönlanti-vaihe*), Northgrippian (*Northgrip-vaihe*) and Meghalayan (*Meghalaya-vaihe*) Stages. The Holocene Greenlandian GSSP (11 700 yrs 2bk) and Northgrippian GSSP (8236 yrs b2k) chronostratigraphic stages are defined from the Greenland ice core record, while the base of the Meghalayan Stage (4250 yrs b2k) is defined from cave speleothems in Mawmluh Cave, India (Walker et al. 2018).

Although almost all pre-Quaternary rock strata are primarily divided into different systems, series, subseries and stages based on their fossil content, paleomagnetic characteristics and absolute age determinations, the chronostratigraphic units of the Pleistocene Series are divided into stages primarily based on climatic proxies, which are often closely aligned with magnetic reversal stratigraphy. The lower boundary of the Gelasian Stage (2.58 Ma) approximates the Gauss–Matuyama Chron boundary, whereas the lower boundary the Chibanian Stage (~774 ka) approximates the Matuyama–Brunhes Chron boundary (~773 ka) (Head 2019). In formerly glaciated terrains, an informal climatostratigraphic approach for glacial and interglacial stages was historically applied to terrestrial sequences of the Alps, NW Europe, NW Russia and North America (Penck & Bruckner 1909, Woldstedt 1958, Flint 1957). In these areas, the theory of four glacial stages and intervening interglacials was established. The terrestrial strata were divided into climatostratigraphic units for practical lithostratigraphic mapping reasons based on the occurrence of tills and glacifluvial sediments, indicating glaciations, and the interbedded paleosols and/or organic-rich sediments, which indicate interglacials. This four-fold glaciation scheme, combined with data on climatic indicators such as pluvial and non-pluvial stages and paleosols from non-glaciated areas, led to the accepted model of four major glacial periods.

Later, particularly in the late 20th and early 21st century, the four-fold glaciation model became much more refined and better understood as data from international ocean drilling programmes provided more complete strata to unravel the Quaternary climate fluctuations (Lisiecki & Raymo 2005). Based on marine oxygen isotope data from benthic foraminifera, stratigraphy based on marine oxygen-isotope stages was developed, and the marine isotope stage (MIS) system is at present the widely used standard for the chrono- and climatostratigraphy of the Quaternary and beyond (Lisiecki & Raymo 2005). The chronostratigraphic correlation between terrestrial and marine stratigraphy has been established using magnetostratigraphic and climatic proxy data. The Gelasian Stage GSSP level is within the MIS 103, the Calabrian Stage GSSP level coincides with the transition from MIS 64 to MIS 65, the Chibanian Stage GSSP level occurs immediately below the top of MIS Substage 19c, and the base of the Late Pleistocene (GSSP not yet formally defined) corresponds with MIS Substage 5e.

BOX 3

TERMINOLOGY USED IN FORMAL CHRONOSTRATIGRAPHY

(modified after the ICS Stratigraphic Guide)

(Finnish terms in parentheses)

DEFINITIONS (applicable in the context of Finnish Quaternary geology)

CHRONOSTRATIGRAPHY AND CHRONOSTRATIGRAPHIC CLASSIFICATION *(kronostratigrafia ja kronostratigrafinen luokittelu)* – Chronostratigraphy is the element of stratigraphy that deals with the relation between rock bodies and the relative measurement of geological time. The purpose of chronostratigraphic classification is to systematically organize the rocks forming the Earth's crust into named units (chronostratigraphic units) that represent intervals of geological time (geochronological units) to serve as references in narratives about Earth's history, including the evolution of life.

CHRONOSTRATIGRAPHIC UNITS *(kronostratigrafiset yksiköt)* – A body of rocks, layered or unlayered, that includes all rocks representative of a specific interval of geological time, and only this time span. Chronostratigraphic units are bounded by isochronous horizons that mark specific moments of geological time. The rank and relative magnitude of the units in the chronostratigraphic hierarchy are a function of the durations they represent.

HIERARCHY OF FORMAL CHRONOSTRATIGRAPHIC UNIT TERMS

Chronostratigraphy *(kronostratigrafia)*	**Geochronology** *(geokronologia)*
Eonothem (*eonoteemi*) – e.g., Phanerozoic Eonothem (*fanerotsooinen eonoteemi*)	**Eon** (*eoni*) – e.g., Phanerozoic Eon (*fanerotsooinen eoni*)
Erathem (*erateemi*) – e.g., Cenozoic Erathem (*kenotsooinen erateemi*)	**Era** (*maailmankausi*) – e.g., Cenozoic Era (*kenotsooinen maailmankausi*)
System (*systeemi*) – e.g., Quaternary System (*kvartäärisysteemi*)	**Period** (*kausi*) – e.g., Quaternary Period (*kvartäärikausi*)
Series (*sarja*) – e.g., Pleistocene Series (*pleistoseenisarja*)	**Epoch** (*epookki*) – e.g., Pleistocene Epoch (*pleistoseeniepookki*)
Stage (*vaihe*) – e.g., Greenlandian Stage (*Grönlanti-vaihe*)	**Age** (*aika*) – e.g., Greenlandian Age (*Grönlanti-aika*)

Chronostratigraphic horizon (**Chronohorizon,** *kronohorisontti*) is a stratigraphic surface or interface that is isochronous, representing everywhere the same moment in time (i.e., they are of the same age).
Note – Series for several systems have been formally named with the adjectives "Lower" (*ala-*), "Middle" (*keski-*) and "Upper" (*ylä-*), derived from their position within a system.

ESTABLISHING FORMAL CHRONOSTRATIGRAPHIC UNITS

Boundary stratotypes – The boundaries of a chronostratigraphic unit of any rank are defined by two designated reference points in the rock sequence, the lower and upper boundary stratotypes of the unit. The two points are located in the boundary stratotypes of the chronostratigraphic unit, which need not be part of a single section. Both, however, should be chosen in sequences of essentially continuous deposition.
Global Boundary Stratotype Sections and Points (GSSPs) are reference points on stratigraphic sections of rock that define the lower boundaries of stages on the International Chronostratigraphic Chart. Since 1977, the ICS has maintained the international GSSP register.

CHRONOCORRELATION *(Time correlation)*

Chronostratigraphic units can be referred to as time-stratigraphic units. Chronostratigraphic correlation is focused on the correlation of time planes, defined by the bases of chronostratigraphic units. These boundaries are time significant, *i.e.*, they are synchronous horizons across the globe.

NAMING OF CHRONOSTRATIGRAPHIC UNITS

A formal chronostratigraphic unit is given a binomial designation – a proper name plus a term word – and the initial letters of both are capitalised. Its geochronologic equivalent uses the same proper name combined with the equivalent geochronological term, e.g., Cretaceous System – Cretaceous Period. The names of chronostratigraphic/geochronological units are written with a lower case in Finnish (e.g., fanerotsooinen eonoteemi/eoni, paleotsooinen erateemi/maailmankausi, jurasysteemi/-kausi, holoseenisarja/-epookki, Meghalaya-vaihe/-aika). However, when combined with a proper noun, the geographical name is capitalised (e.g., Guadalupe-sarja, Messina-vaihe). Adjectives such as Lower (*ala-*), Middle (*keski-*) and Upper (*ylä*) may be used for formal and informal chronostratigraphic units (e.g., alajurasarja). The qualifiers in English are capitalised when referring to a formal unit but written in lower case when used more loosely and referring to informal units. Note that the adjectives Early (*varhais-*) and Late (*myöhäis-*) should only be used for geochronology.

The Standard Global Chronostratigraphic (Geochronologic) Scale can be found in the International Chronostratigraphic Chart (https://stratigraphy.org/chart).

3.3.2 Climatostratigraphic classification of Finnish terrestrial sequences

The division of the Quaternary chronostratigraphic sequences into geological–climatic units remains the cornerstone of the Quaternary chronostratigraphic system. Based on climate proxy data determined from ice cores and sediment units, boundaries in the strata are to be defined and placed commonly at midpoints between interpreted temperature maxima and minima (as is also the case in defining ocean sediment sequence boundaries). In terrestrial strata, the terms interglacial and glacial are commonly used for cold climate and warm climate stages, respectively. Litho- and biostratigraphic units are used for this distinction. In formerly glaciated areas, for example, tills and glaciofluvial/-lacustrine units refer cold climate modes (glacial) and peat and organic-rich units to warm climate modes (interglacials and interstadials). The definition of an interglacial in any particular area in Europe, including Finland, is based on the comparison of the past climate with the climatic optimum of the present interglacial (Holocene) in the same area. The term interstadial indicates a warmer time than glacial, but compared with the interglacial phase, an interstadial is too short or normally too cold to have developed temperate broadleaf forests or equivalent vegetation for the same area, while a stadial is a cooler phase between two interstadials or between an interglacial and an interstadial.

In Finland, as in many other formerly glaciated terrestrial areas in Europe, glacial sediments, such as tills and glaciofluvial and glaciolacustrine sediments, indicate colder glacial phases, while organic-rich sand, silt and clay, as well as peat and gyttja sediments interbedded between till units, are at many sites thought to have been deposited during warmer interglacials or interstadials. However, correlation is often not straightforward, since interstadial and interglacial sediments in multiple till sequences are often partially or almost completely eroded, glacially tectonized and/or reworked during subsequent glaciations. Nevertheless, when there is solid litho- and biostratigraphic evidence and independent dating (geochronology) from sediment sequences to support local and regional correlation, the climatostratigraphic units can be correlated with other climato- and isotope stratigraphic units in the framework of chronostratigraphy. Here, the subdivision and correlation of glacial/interglacial/interstadial stages and substages between northwestern Europe, the British Isles, the Russian Plains and North America are of high importance for interpretations of global climate change (see Global chronostratigraphic correlation table for the last 2.7 million years at https://stratigraphy.org/).

During the past decades, it has also become more common and even predominant in Finnish Quaternary geology to correlate local terrestrial stratigraphic units with global marine and ice-core records (e.g., Petit et al. 1999, Lisiecki & Raymo 2005). Although climate-based MIS and ice-core stratigraphies in a broader sense provide a valuable framework for global-scale climate changes, caution should be exercised when correlating terrestrial sediment successions with marine and ice-core sequences because of the complicated global climate system and leads and lags between different paleoclimate records. It is also desirable that advanced geochronological methods (e.g., luminescence and C-14 dating methods) should be used together with bio- and lithostratigraphy when correlating Finnish Quaternary units with International Quaternary chronostratigraphy. It is generally agreed that Finnish Quaternary sediments can be chronostratigraphically correlated with the Holocene Epoch and NW European Weichselian, Eemian and Saalian glacial and interglacial phases (e.g., Donner 1995, Johansson et al. 2011), approximately corresponding with MIS 1–6, respectively.

4 MORPHOSTRATIGRAPHY AND MORPHO-LITHOGENETIC UNITS

4.1 Background

The diversity of glacial and non-glacial Quaternary deposits and landforms has promoted geomorphological approaches to be included in the mapping and subdivision of Quaternary units and erosional sequences of these deposits in Finland. This approach, where units are developed upon sediment bodies or on bedrock, requires the use of relative chronologies based on the law of superposition in many regions. Typical examples include ice-marginal landforms, glaciofluvial deltas and sandurs, dunes, and ancient shorelines. These are often related to and build upon each other (see also Chapter 9: Allostratigraphy).

In each of these cases, the so-called morphostratigraphic unit is used to denote a body of sediment that is identified primarily from the surface topography (Frye & Willman 1962). Central to the recognition of such units is that they include both landform and lithology in their definition (Bowen 1978). Clearly, these units are not directly comparable to standard lithostratigraphic units, where vertical and lateral changes, as well as relationships with other units, can generally be observed unambiguously. Morphostratigraphic units should, therefore, only be given an informal status (Richmond 1959). However, in some Quaternary environments, particularly in recently deglaciated areas, extensive ice-marginal formations that span over considerable distances are often afforded virtually a formal status, e.g., the Salpausselkä ice-marginal complexes in southern Finland. Similarly, ancient shorelines and glaciofluvial delta levels, either raised or submerged, have been used for stratigraphic comparison in some regions (e.g., Lunkka 2023). It should be noted, however, that even a simple morphometry of a landform may in some cases mask significant complexities in sediment composition and architecture. This is why it should never be regarded as a substitute for, or a short-hand way of referring to, other more precise types of stratigraphic unit descriptions, such as lithostratigraphy.

4.2 Morpho-lithogenetic units (MLG units)

4.2.1 Background

During recent years, the Geological Survey of Finland (GTK) has adopted a morpho-lithogenetic approach to classify the Finnish superficial Quaternary deposits. This classification scheme was originally developed by the British Geological Survey (BGS) (e.g., McMillan 2005, Lee & Booth 2006). The morpho-lithogenetic (MLG) classification is related to morphostratigraphy via terrain lithology, genesis and morphology, the latter being an essential part of the MLG approach. It should be noted, however, that morphostratigraphy and MLG units are not synonyms, because in the MLG approach, there is also equal importance for lithology and the interpretation of genetic processes, whereas in the morphostratigraphic approach, a genetic interpretation is not a part of the definition. The basic idea of the MLG approach is not new in Finland, and the concept was already a part of GTK's earlier superficial deposits mapping programme (Virkkala 1972). The combination of geomorphological, lithological (grain size) and genetic aspects also formed an underlying context for GTK's 1:20 000 Quaternary mapping programme (1972–2007), in which grain-size classes were used to describe superficial sediments and geomorphology to interpret glacial landforms.

Currently, the MLG approach (e.g., McMillan 2005) has become the principal method to categorise and map Quaternary units in Finland (Putkinen et al. 2017, Palmu et al. 2021). The reason for this is that the available high-resolution LiDAR DEM data have enabled detailed observations on Quaternary geomorphology in the entire area of Finland (e.g., Johnson et al. 2015, Ojala & Sarala 2017). The MLG mapping and interpretation process allows a flexible combination and utilisation (process flow) of different data sets, such as existing maps of superficial Quaternary deposits (lithology and deposit type), structural mapping data on landforms and surface features (e.g., lineaments, striations, dunes), and data obtained from vertical sections of subsurface data sets, such as borehole logs, excavation exposures, well records, test pits and various geophysical interpretative data sets (e.g., ground penetrating radar (GPR), refraction and reflection seismic and gravimetric profiling). In the interpretation process, extensive use is also made of current and older topographic mapping data and aerial imagery.

All MLG units are based on interpretation. According to Lee & Booth (2006), "The combination of landform morphology, lithology and formation process leads to interpreted morpho-lithogenetic units, which are mappable units that provide the basis for establishing a local stratigraphy." With sufficient data, the next step forward would be to include the local MLG model into a wider regional stratigraphic context involving geochronology and lithostratigraphy (Figs. 5 and 6). These elements contribute to the evolution of the conceptual model towards a completed map or 3D model.

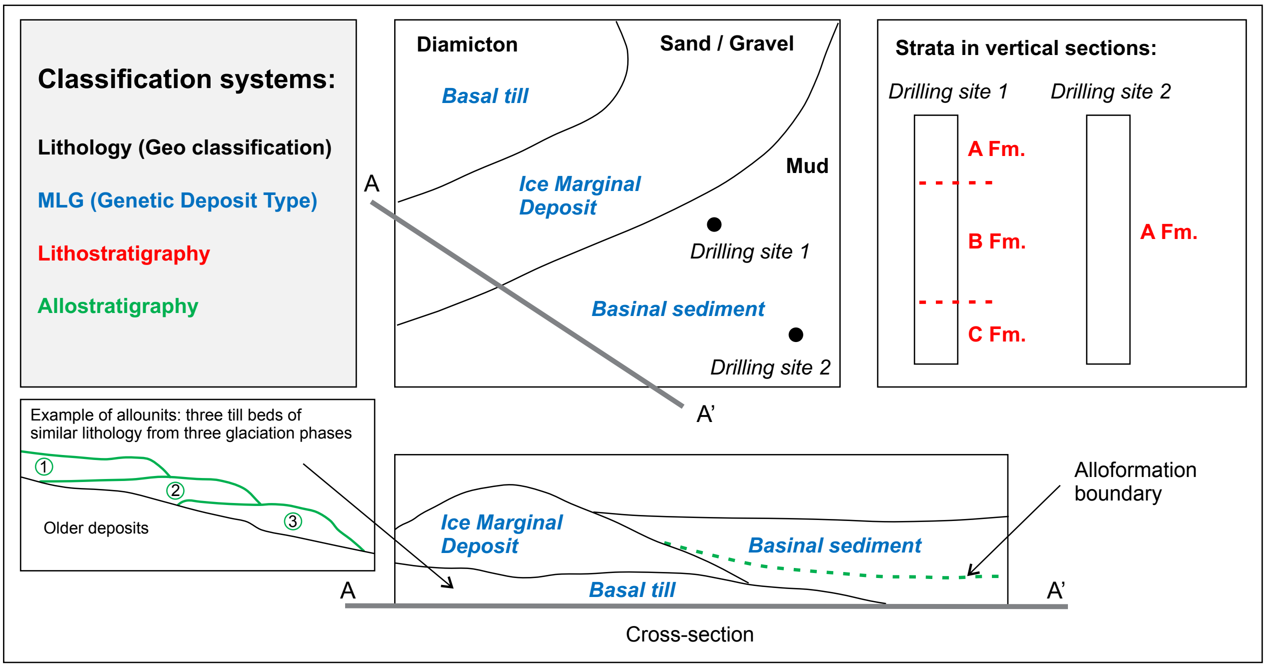


Fig. 5. Schematic illustration addressing the connections of different classification systems applied to the map view (top centre), vertical strata (top right) and geological cross-section (bottom centre). Note the colour coding (top left) for the classification systems.

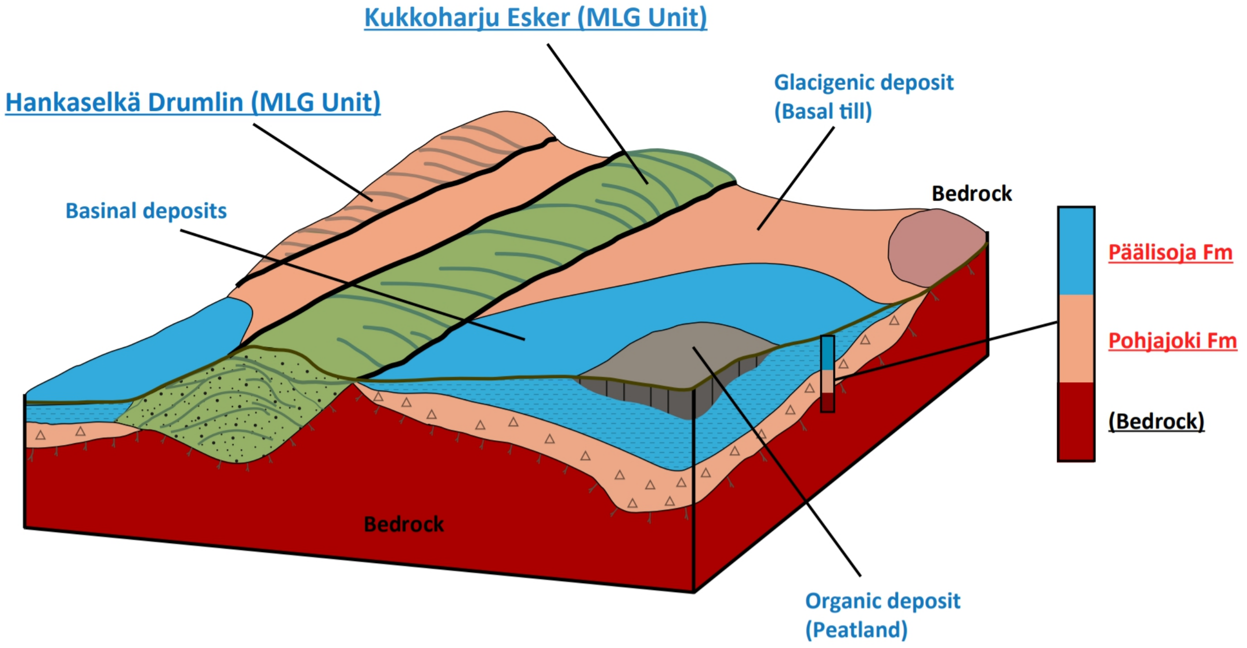


Fig. 6. Map units (top surface) classified by 'genetic deposit type' (blue text; see also Table 1) and their relationships with lithostratigraphic units (red text). The underlined geological units (see Table 2) will be included in the FinstratiMP lexicon database.

4.2.2 Map units: definition of genetic deposit type

The step to define a genetic deposit type is a prerequisite in MLG mapping. The accurate determination of a deposit type evolves through detailed geomorphological mapping combined with field observations and laboratory work. These observations enable the genesis of landforms, their sediments and depositional environments within a mapping area to be defined. A well-established glacial depositional context is a critical requirement for a uniform 'mapping result' and has led to the establishment of glacial dynamic provinces and regions in Finland (Palmu et al. 2021). For a genetic deposit type (Table 1), the current MLG classification system in Finland also incorporates basinal fine sediment deposits (postglacial glaciolacustrine deposits and other basin fill deposits combined) and littoral deposits as separate classes, as well as coarse fluvial deposits as one map unit type (mainly occurring in northern Finland). Organic deposits include peatlands but also other organic-rich sediments, while aeolian deposits are displayed on maps as polygons.

4.2.3 Establishment of morpho-lithogenetic geological units

The FinstratiMP, a planned lexicon database of Finnish Quaternary geological units maintained by GTK, is designed in a way that the overlapping and simultaneous use of different classification methods is possible (Palmu et al. 2021) (Fig. 5). For example, MLG interpretation may be complemented by a lithostratigraphic approach. The key components of the approach are the map units defined by the interpreted genetic deposit type and the named MLG geological units characterised by a set of attributes (Table 1). Using the landform and lithology elements, the process (the mode of origin) can be interpreted. In practice, the map units are identified and formed in geological analysis based on the overall depositional context, landforms, existing mapping knowledge of lithology and, finally, the assumed depositional and/or erosional process (Fig. 6). The resulting map unit is classified according to the genetic deposit type, and the classification used is presented in Table 1.

The concluding step of the MLG process is the establishment of named, site-specific morpho-lithogenetic units (MLG units). The boundaries of the prominent geomorphological features/properties are relatively easy to identify, and the resulting units are locally mappable entities based on landforms with an interpreted (or inferred) depositional process. In most cases, lithological information is available to support the interpretation. The units are given by their characteristics using attributes and classified according to the MLG type (see Table 2). The key attribute of MLG units is the genetic deposit type, which is directly reflected in MLG unit types (Table 2). The MLG unit types can also be seen as a subdivision or incremental component of the genetic deposit types. In FinstratiMP, the characterization of named MLG units is planned to include the following features (i–iii) and corresponding attributes: (i) Landform (morphology, geomorphology) (Observed), (ii) Genetic deposit type (Interpreted), (iii) Lithology (material of the deposit) (Observed / Interpreted / Inferred / Not known). The number of attributes has not been limited to these, but additional features and descriptions, such as age, stratigraphy or lithofacies (Miall 1985), or the more detailed depositional environment or process, may be included. Key references to original research papers are also important.

Finally, the named MLG unit is named by combining the locality name, e.g., 'Pielisjärvi' or landform name 'Salpausselkä' with the MLG unit type given in Table 2. Here are some examples: Second Salpausselkä (FLDIL part) Ice-Marginal System, Vesivehmaankangas Delta Complex, Pielisjärvi Ice-Marginal System, Hämeenkoski-Kangasala-Pyynikki-Ylöjärvi Esker System, Asikkala-Joutsa Esker System, Pieksämäki Drumlin Field, Paltamäki Drumlin, Kalvola-Renko Hummocky Moraine Field, Karhulammi-Tähilammi Hummocky Moraine. It is pointed out that MLG units are currently used for the glaciofluvial and moraine deposit types, which have a distinctive positive geomorphological form. It is suggested that the definition and naming of units (and their storage in FinstratiMP) would be restricted to prominent, well-known and studied cases; the establishment of a new geological unit is only appropriate in cases where it substantially aids the overall usefulness of data. It is also noted that the map features corresponding to MLG units can be either polygons or polylines. For example, the Pieksämäki drumlin field refers to all the drumlins of the Pieksämäki region mapped as polygons or polylines if these symbolize the drumlins.

Table 1. Genetic deposit types used in the GTK's MLG map unit classification.

GTK classification Level 1	Level 2	Level 3
Glacigenic deposits, **G**	**Glacial deposits, GT**	**Till, basal** – includes lineations (drumlins etc.), **GTb**
		Hummocky moraines (with various subtypes), **GTh**
		Diamicton-dominated ice-marginal deposits, De Geer and other recessional moraines (also in groups of ridges), **GTi**m
	Glaciofluvial deposits, GF	**Eskers, GFe**
		Ice-marginal glaciofluvial deposits (sandurs, deltas, subaqueous fan deposits), **GFim**
		Other glaciofluvial deposits (extramarginal, other), **GFex**
Basinal deposits, B	Marine sediments, **BM** Lacustrine sediments, **BL**	
	Glaciolacustrine and -marine sediments, **BG**	
Littoral deposits, **L**	Littoral deposits on the higher hillslopes, berms, bars, spits Littoral deposits covering lower hillslopes and valleys	
Fluvial deposits, F	Coarse-grained fluvial deposits, **Fc** Fluvial deposits of variable grain size, **Fv**	Deltas, **Fvd**
Aeolian deposits, E		
Organic deposits (peatlands), **P**	Minerotrophic peatlands, fens, **PCt** Ombrotrophic peatlands, bogs, **PSt**	
Mass movement deposits, **M**	Mass movement deposits of fine-grained sediments Mass movement deposits produced by seismic activity Solifluction deposits Talus	
Frost action deposits, **FR**		
Anthropogenic deposits, **A**		

Table 2. Hierarchy of the named morpho-lithogenetic unit types for the planned FinstratiMP database. Map data are already included in the map database, Glacial features.

MLG geological unit type	Genetic Deposit Type	Main Lithology[*]	Typical Landform characteristics
Ice-marginal system	GFim	S, G, (D)	An ice-marginal system of delta complexes and other related deposits, with delta plateaus, ice-marginal ridges
>Delta complex	GFim	S, G, (D)	Plateaus, often with the below-mentioned parts
>>Delta (Sandur Delta)	GFimd	G, S, mS, fS	Plateaus
>>Sandur	GFims	G, S	Plateaus, with meltwater channels
>>Proximal ice contact zone unit	GFimpic	G, S, (D)	See below, often overridden, kettle holes
>>Ice-marginal ridge	GFimpm	G, S, (D)	Ridge on top of the plateau (delineates the proximal part)
>Ice-marginal ridge	GFimr	S, G, (D)	A separate ridge
Esker system	GFe	S, G	The complete "train"
>Esker	GFeb	S, G	Esker main and linked branches
>>Esker ridge	GFer	G, S	Ridge, also a ridge delineated by kettle holes, with lateral depositional elements (see below)
>>Esker sand (splay)	GFes	S (G)	Esker lateral (and distal) depositional elements
>>Esker delta	GFed	G, cS, mS, fS	Delta component of an esker system (code GFimd)
Other glaciofluvial deposit, incl. extramarginal deposits	GFex	G, cS, mS, fS	
Till system	GTb	D	
>Basal till	GTbb	D	Veneer or blanket
>Drumlin (lineation[**]) field	GTblf	D	Lineation fields
>>Drumlin/lineation[**]	GTbl	D	Linear ridges (now polylines), normally not used as a unit
Hummocky moraine	GTh	D	Hummocky terrains and fields
>Subglacial hummocky moraine	GThb		"
>>Ribbed moraines	GThbr	D, (S, G)	", Ribbed moraine geomorphology
>>Murtoo moraines	GThbm	D, G, S	", Murtoo moraine geomorphology
>Ice contact (passive, partly supraglacial) unit	GThp	D, S, (G)	"
End moraines (diamicton-dominated)	GTim	D, (S)	
>End-moraine ridge (Reunamoreeni-muodostuma) (can be part of an ice-marginal delta complex) (Notice the material difference compared to GFimr and GFimpm)	GTimr	D, (S)	Ridge form, may be multiple combined ridges, mainly in conjunction with the ice marginal systems
>Recessional moraines, small ridges (field)	GTimsr	D, (S)	
>>De Geer moraine field	GTimsrDG	D (S)	De Geer ridges in fields
>> Minor recessional moraine field	GTimsrr	D, (S)	Usually supra-aquatic or shallow water deposition
Dune field	E	fS	Dune ridge field

[*] GEO classification, in English, typical examples: S = Sand, fS = Fine sand, mS = Medium sand, cS = Coarse sand, G = Gravel, D = Diamicton,

[**] For drumlin/lineation: See text

4.2.4 Major named MLG units in Finland

Several examples of large and prominent landforms in Finland are already included in the FinstratiMP that represent MLG units with given names (see Palmu et al. 2021):

- Large glaciofluvial systems, which consist of (Fig. 8 in Palmu et al. 2021):
  - Large ice-marginal deposit systems (‘formations’), also known as the Salpausselkäs and the Central Finland Ice-Marginal Formation.
  - Large interlobate deposits (esker systems), such as the Pitkäkangas Esker System and the Hämeenkangas Esker System
  - Major intralobe deposits (esker systems), such as the Pori-Virtaankangas-Somero Esker System
- Large moraine fields, which consist of (Fig. 2 in Appendix 2 in Palmu et al. 2021):
  - Hummocky moraine terrains, such as the Kemijärvi Ribbed Moraine Field (Sarala 2005)
  - Recessional De Geer moraine fields, such as the Ridasjärvi De Geer Moraine Field (Ojala et al. 2015, Ojala 2016)
  - Large drumlin fields, which are also related to the main till deposit units, such as the Pieksämäki Drumlin Field (Glückert 1973)

The named MLG units have a hierarchy ranging from smaller to larger and from depositional complexes to systems (Palmu et al. 2021). For example, the Vesivehmaankangas Delta Complex consists of delta, proximal ice-contact parts and a push moraine ridge element and forms a deposit complex in the system of ice-marginal deposits of the Second Salpausselkä of the Finnish Lake District ice-lobe province (Palmu et al. 2021). Likewise, a major esker forms a system whose elements are the esker ridges, adjoining glaciofluvial sediment deposits and, if practical, esker deltas have also been delineated (Palmu et al. 2021). Similarly, esker systems and hummocky moraine areas in the central area of the Finnish Lake District ice-lobe province (FLDIL) are presented in Palmu et al. (2021). The esker systems consist of MLG units (the ridges, sometimes esker deltas, and adjacent areas of glaciofluvial deposition). In Palmu et al. (2021), the various types of glacial lineations (e.g., drumlins, megaflutings, flutings) are also shown, as are the hummocky moraine fields.

5 MAGNETOSTRATIGRAPHY

5.1 Background

Magnetostratigraphy is the sub-discipline of stratigraphy that divides the records of polarity reversals, rapid magnetic excursions and secular variation of the Earth’s magnetic field in sedimentary sequences and/or volcanic rocks (Jacobs 1994, Salvador 1994, Channell et al. 2020, Muttoni 2021). The basic unit is the magnetozone, i.e., a zone having the same magnetization, especially one between geomagnetic polarity reversals. Magnetostratigraphy generally focuses on the polarity reversals of the Earth’s magnetic field, where the stratigraphic record is divided into intervals of homogeneous magnetic polarity (normal or reversed), which are globally isochronous on geological time scales and therefore an essential component of sediment correlation (Jacobs 1994, Ogg & Smith 2004, Ogg 2020) (Fig. 7). These intervals are named as magnetostratigraphic polarity units according to the International Stratigraphic Guide (Salvador 1994) and as magnetopolarity units according to the North American Stratigraphic Code (NACSN 2021). The current magnetostratigraphic polarity unit is called the Brunhes Polarity Zone (normal polarity), which has a chronostratigraphic equivalent, the Brunhes Chronozone, and a geochronological equivalent, the Brunhes Chron. It was preceded by Matuyama (reversal polarity) and Gaus Chrons (normal polarity). Magnetostratigraphic polarity-reversal horizons, on the other hand, are surfaces or thin transition intervals across which the magnetic polarity reverses (Salvador 1994).

In the Late Pleistocene to Holocene timescales, there are two additional and essential elements involved in changes in the Earth’s magnetic field: secular variations and rapid geomagnetic excursions (Stoner & St. Onge 2007). Both can vary during constant polarities and at the boundaries of polarity changes.

The decadal to centennial variability of the Earth's magnetic field is known as secular variation (Thompson & Oldfield 1986, Jacobs 1994). Secular variation, which is due to the dipole and non-dipole behaviour of the magnetic field, occurs with field direction and strength changes at the rate of 1° per every few decades and several percent per century, respectively (Olsson et al. 2002). For the most recent times, information on secular variation is gained through geomagnetic observatories and satellite missions, as well as historical records since the 16th century (e.g., Olson et al. 2002). More extended records of past geomagnetic secular variations can be recovered from archeological artefacts, volcanic rocks and lacustrine/marine sedimentary records. In this respect, the information is referred to as paleosecular variation (PSV) of the Earth's magnetic field (e.g., Thompson & Oldfield 1986). Since Turner & Thompson (1981) reconstructed a Holocene paleomagnetic secular variation master curve for the United Kingdom, more recent studies on lake and marine sediments have continued to improve our understanding of regional changes in the direction and intensity of the past geomagnetic field (e.g., Vigliotti 2006, Snowball et al. 2007, Reilly et al. 2018). These studies have generated sets of independently dated records of PSV and relative paleointensity (RPI), thus establishing regional reference curves ('master curves') for the Late Pleistocene and Holocene. Of these, the FENNOSTACK and FENNOPRIS master curves (Snowball et al. 2007), obtained by stacking paleomagnetic data from varved lake sediments (Snowball & Sandgren 2002, Ojala & Tiljander 2003, Zillén 2003), provide the most important chronostratigraphic time markers of PSV and RPI characteristics in and around the Fennoscandian and Baltic countries for the Holocene Epoch (Fig. 7).

Paleomagnetic studies have also revealed that the Earth's magnetic field has undergone more significant and spatially and temporally wider range variability than the prehistoric paleomagnetic secular variation (e.g., Verosub & Banerjee 1977, Lund et al. 2006). PSV studies indicate the occurrence of rapid geomagnetic excursions (geomagnetic 'jerks'), in which the intensity and direction of the geomagnetic field varies considerably for a short time interval (typically 500–3000 years) (Laj et al. 2004, Korte et al. 2019b). An empirical definition for an excursion is a large, local movement of the virtual geomagnetic pole (VGP) from the geographic pole and a short duration of the altered polarity (Gubbins 1999). Detailed studies have identified 17 excursions with significant changes in the direction or/and intensity of the geomagnetic field during the Brunhes Chron (the last 780 ka), six of which are well dated and globally established (Jacobs 1994, Langereis et al. 1997, Lund et al. 1998, 2006). Of these, sedimentary records of the Mono Lake (~33 ka), Laschamp (~41 ka), Blake (~115 ka), Iceland Basin (~188 ka) and Pringle Falls (205–225 ka) excursions are numerous and widespread and provide the most important chronostratigraphic time markers for the last glacial-interglacial cycles (Lund et al. 2006, Korte et al. 2019b, Chanell et al. 2020) (Fig. 7).

5.2 Magnetic components and remanent magnetization

There are three components in the Earth's magnetic field (Thomson & Oldfield 1986). Declination and inclination are directional components, which respectively refer to the angle between magnetic north and geographic north, and the dip angle of the magnetic vector below the horizontal plane. The third component is intensity, which is the strength of the Earth's magnetic field. Geological rocks and sediments that contain magnetic minerals can acquire remanent magnetization during their formation or/and deposition. This is called natural remanent magnetization (NRM), which can be further divided, for example, into chemical remanent magnetization (CRM), thermoremanent magnetization (TRM) and detrital remanent magnetization (DRM), depending on the formation environment (Thomson & Oldfield 1986). The processes of NRM acquisition, details of mineral magnetic properties and their behaviour, and various applications of environmental magnetism are described in Thomson & Oldfield (1986), Walden et al. (1999) and Sandgren & Snowball (2002).

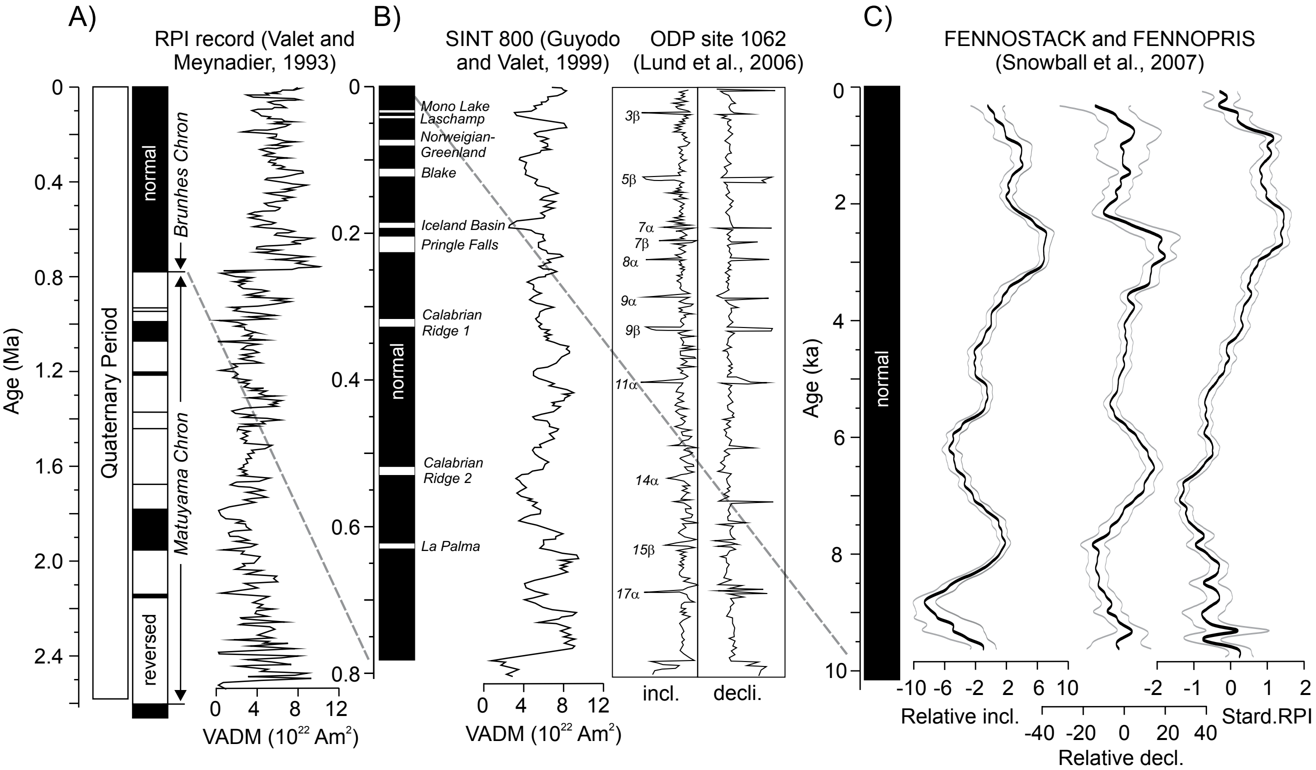


Fig. 7. Records of magnetic polarity A), geomagnetic excursions B) and paleosecular variation C) during the Quaternary Period. The Quaternary Period is characterized by the normal Brunhes and the reversed Matuyama chrons. Variations in Earth's magnetic axial dipole moment (VADM) are based on Valet and Meynadier (1993) and Guyedo and Valet (1999). Most magnetic excursions, labelled as 3β to 17α, are characterized by anomalously low inclinations and southerly pointing declinations, and occur during intervals of low relative paleointensity (Lund et al. 2006). The stacked records of the Holocene (FENNOSTACK and FENNOSPRIS) by Snowball et al. (2007) are based on multiple varved sites in Finland and Sweden and have been established as paleomagnetic secular variation (PSV) and standardized relative paleointensity (RPI) master curves for the Fennoscandian area.

Magnetostratigraphic investigations of rock or sediment cores can be based on discrete samples, typically 7–10 cm^3 cylinders or sample cubes, or U-channels that represent up to several-metres-long core sections (King & Peck 2002, Ojala & Saarinen 2002). According to Nowaczyk et al. (2021), high-resolution discrete sampling should be preferred when studying rapid geomagnetic field variations, such as reversals and excursions, from sedimentary records. Presently, two devices are commonly used to investigate remanent magnetization, the cryogenic SQUID magnetometer and the spinner magnetometer, both of which can detect and sensitively measure remanent magnetization (e.g., King & Peck 2002, Sandgren & Snowball 2002).

5.3 Applications of mineral and paleomagnetism

In Fennoscandia, paleosecular variation (PSV) and magnetostratigraphic studies have mostly been conducted on Late Pleistocene and Holocene marine/lacustrine sediments (clay, gyttja) that contain magnetic minerals, preferably fine-grained magnetite of biogenic or terrestrial origin (e.g., Snowball et al. 2007). The methods could also be applied to investigate PSV characteristics and magnetic excursions from interglacial and interstadial sediments, but the authors are unaware of published records of such sequences from areas covered by the Fennoscandian Ice Sheet (Batchelor et al. 2019). Magnetostratigraphic studies on deep-sea sediments in the Arctic Ocean and North Atlantic region, which are beyond the maximum extension of the Fennoscandian Ice Sheet and other Northern Hemispheric ice sheets (e.g., Batchelor et al. 2019), provide records of continuous sedimentation and thereby potentially reveal rapid magnetic excursions of the Brunhes Chron (e.g., Laj et al. 2004, Lund et al. 2022).

Both the International Stratigraphic Guide (Salvador 1994) and the North American Stratigraphic Code (NACSN 2021) only consider magnetic polarity reversals as a stratigraphic tool (magnetopolarity units). In these publications, guidelines for defining magnetostratigraphic units are provided. Intervals in sedimentary records identified by changes in paleosecular variation (PSV) and relative paleointensity (RPI) are referred to as magnetosecularity units, although these are not formally defined. They represent regionally correlatable shifts and/or rapid excursions of PSV and RPI (e.g., Thomson & Oldfield 1986, Lund et al. 2006, Snowball et al. 2007). By definition, a magnetosecularity unit is a body of sediment defined by its record of regionally correlatable patterns of PSV (inclination and/or declination) and/or RPI and distinguished from adjacent bodies of sediment that record different PSV and/or RPI patterns (Fig. 8). The upper and lower limits of a magnetosecularity unit are defined by distinct and regionally correlatable features of PSV and RPI, typically representing distinctive inflexions (turning points), maximum and minimum values or culminations in their patterns, or any combination of these.

Even though PSV, RPI and magnetostratigraphic studies are well established for correlation and age determination (dating) of lacustrine and marine sedimentary sequences in Fennoscandia (e.g., Valpola & Ojala 2006, Hutri et al. 2007, Virtasalo et al. 2007, Alenius et al. 2008, 2017, Haltia-Hovi et al. 2011) and elsewhere (e.g., Korte et al. 2019a), no definitions of stratigraphic units based solely on paleosecular variation have been presented. The magnetosecularity information is rather presented as regional PSV and RPI master curves and associated with lithofacies information (e.g., Snowball et al. 2007). As such, paleosecular direction and intensity patterns are regionally consistent, and the future will show their significance as a stratigraphic tool.

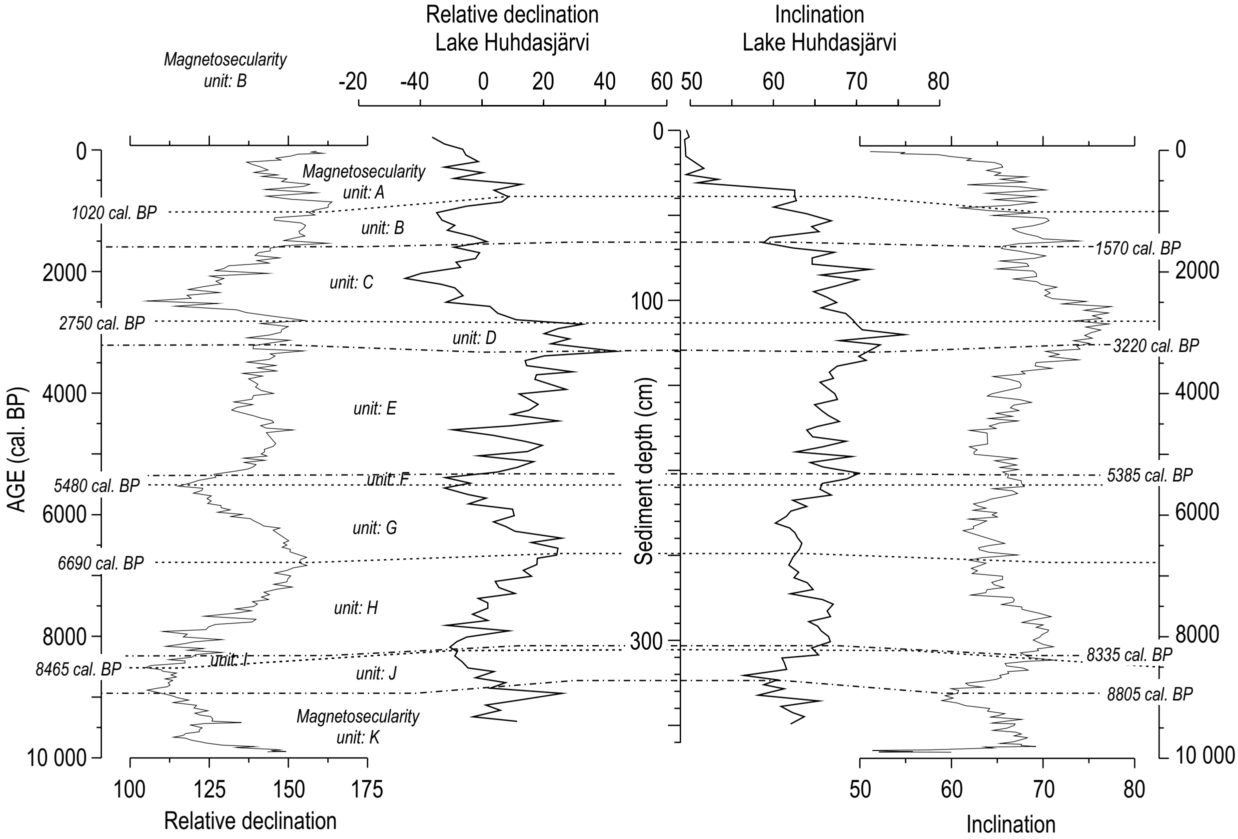


Fig. 8. A hypothetical example of magnetosecularity units A to K correlated between the accurately dated Lake Nautajärvi varved sequence from SW Finland (Ojala & Saarinen 2002) and the Lake Huhdasjärvi sediment core FID 60 A, SE Finland (Alenius et al. 2017). Subhorizontal lines indicate the paleosecular variation (PSV) of inclination and declination features that are used for defining the magnetosecularity unit boundaries (chain line for inclination and dashed line for declination). Note that the units and their boundaries can be defined by declination or inclination characteristics, or by their combination. This type of approach has been applied in a number of sedimentary sites in Finland for dating purposes (e.g., Valpola & Ojala 2006, Alenius et al. 2008, Mäkinen & Ojala 2013, Ojala et al. 2019a).

6 CHEMO- AND PEDOSTRATIGRAPHY

6.1 Chemostratigraphy

Chemostratigraphy, also known as chemical stratigraphy, is the study of the chemical variations within sedimentary sequences to determine stratigraphic relationships. Chemostratigraphy uses chemical fingerprints stored in sediments and sedimentary rocks for stratigraphic correlation (Weissert et al. 2008, Sial et al. 2018), and can determine the age of sedimentary strata through the analysis of trace elements and isotopic ratios (https://www.yourdictionary.com/chemostratigraphy). The use of this stratigraphic method is closely connected to the methodological advances in element analysis of geological materials.

Main and trace element analyses using, for example, X-ray fluorescence (XRF) started in the 1950s and 1960s, but chemostratigraphy came into a common usage in the early 1980s with the development of atomic absorption analytical techniques. However, the basic idea of chemostratigraphy is nearly as old as stratigraphy itself; distinct chemical signatures can be as useful as distinct fossil assemblages or distinct lithography to establish stratigraphic relationships between different rock layers. The chemostratigraphic signals in the rocks and sediments can display distinct stratigraphic patterns that can be observed in other sediment sequences, allowing correlation. If one of the correlated sequences has a geochronological age control, the ages of the correlative chemostratigraphic patterns can be determined. Stable isotope signatures in sedimentary inorganic and organic matter are among the most powerful proxies used in chemostratigraphy. The stable isotope signatures used for stratigraphic purposes particularly focus on the use of oxygen and carbon isotope geochemistry (Weissert et al. 2008). Although the use of oxygen isotope variability in the calcium carbonate shells of foraminifera is a proxy for past ocean temperatures and the global ice volume (MIS), it is in fact the basis of Quaternary chronostratigraphy.

Chemostratigraphy generally provides two useful types of information to a wider geological community. First, chemostratigraphy can be used to investigate environmental change at local, regional and global levels by relating variations in rock and sediment chemistry to changes in the environment in which the sediment was deposited. This is based on sediment characterisation and correlation using subtle variations in the elemental compositions of the sediments studied. The technique relies upon the fact that even apparently homogeneous sediments show changes in their chemical composition. These changes reflect minor fluctuations in variables such as sediment source, facies, paleoenvironment, paleoclimate and diagenesis. For example, in glaciated terrains, geochemistry can be used in addition to mineralogy to distinguish between till units and estimate provenance areas for each layer (e.g., Aario & Peuraniemi 1992, Ojala et al. 2011) (Fig. 9). A similar type of provenance estimation can also be conducted for fluvial, lacustrine and marine sediments.

In addition, chemostratigraphy is especially useful when applied in conjunction with other stratigraphic techniques. In most cases, chemostratigraphy is not tied to chronostratigraphy and should therefore be considered as a rock characterisation tool that can be linked to sequence stratigraphy, the paleoclimate and provenance when employed at a regional scale, with the chemostratigraphic interpretations constrained by biostratigraphy, magnetostratigraphy and/or isotopic chronostratigraphy.

6.2 Pedostratigraphy

Pedostratigraphy (i.e., soil stratigraphy) can be defined as the study of the stratigraphic and spatial relationships and implications of surface and buried soils. In other words, it is the study of different soil associations formed in an area during past periods of varied soil-forming conditions (Catt 1990). This encompasses the identification of soil-forming processes of paleosols found in sedimentary sequences. Past landscapes and their soils can be interpreted by analysing their formation environments, together with other stratigraphic indicators such as morphology, geochemistry and lithology. In addition, organic materials with micro and macro fossils are key indicators for interpreting paleoenvironments, particularly in Quaternary sediment deposits. However, it is often difficult to interpret

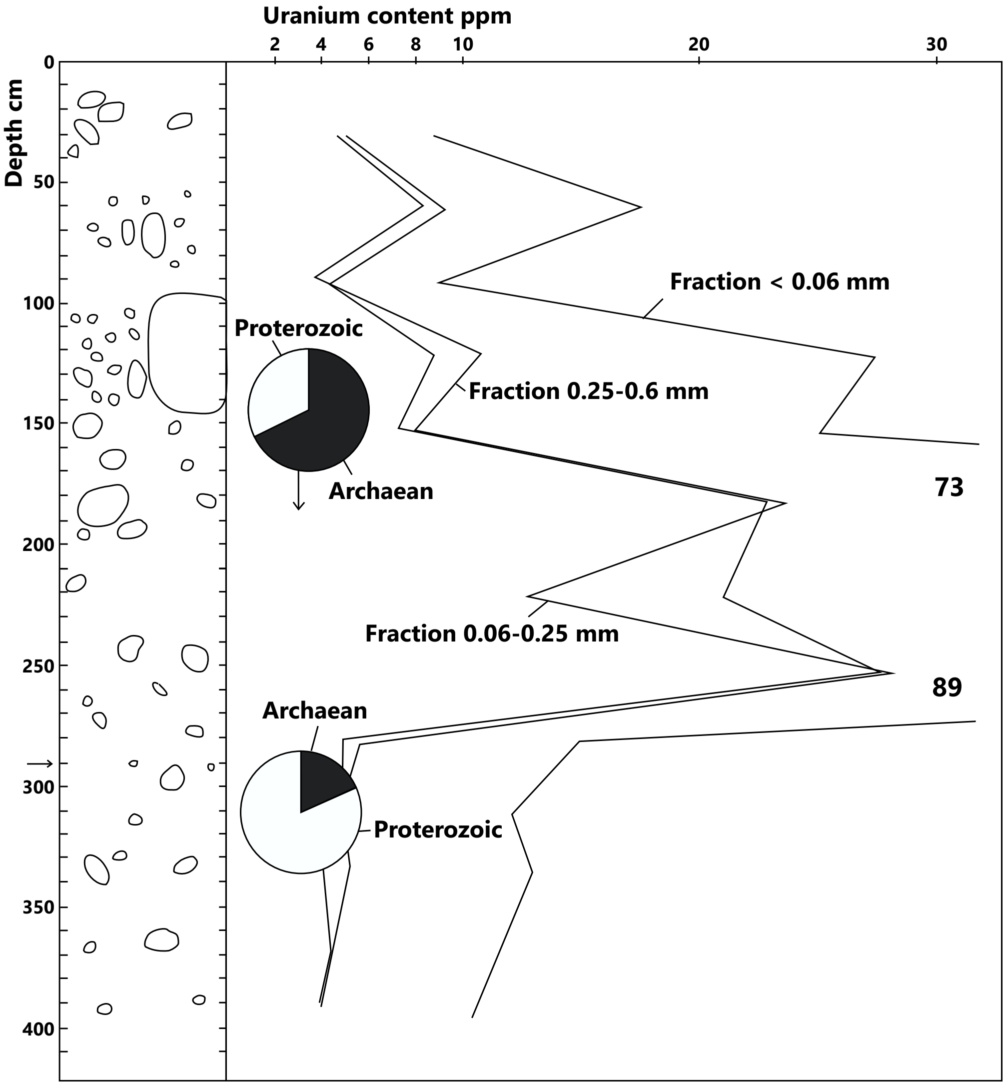


Fig. 9. An example of the use of chemostratigraphy to characterize different till units in southern Finnish Lapland. High uranium concentrations in the upper part of a till section indicate a much shorter transport distance and origin of till material compared to the lower part of the section. After Aario & Peuraniemi (1992).

post-depositional changes that have taken place after initial sediment deposition (Nettleton et al. 2000, Elias 2007).

A pedostratigraphic unit can be identified as a geological unit that represents a single consolidated or non-consolidated pedological horizon in sediment strata (Tandarich et al. 2002). It is a buried, traceable, three-dimensional body of rock or sediment that consists of one or more differentiated pedological horizons (NACSN 2021). In addition, the units can be classified into three types: buried, exhumed and relict, based on the alteration of paleosols during and/or after burial (Nettleton et al. 2000). Paleopedology and pedostratigraphy are devoted to the use of buried and relict soils to interpret the record of environmental conditions that are different from the present ones. It indicates metastability in landscapes when the rates of erosion and accumulation are slow. As such, paleosols may be used in models that aim at predicting future Earth system reactions to changing environmental conditions. Dated paleosols are an important part of the natural heritage, can be used as regional stratigraphic markers for Quaternary stratigraphy and sedimentary environments and should be protected (Costantini 2018).

Paleosols are widely used in Quaternary stratigraphy as stratigraphic markers. They are very important in loess sequences, such as those in China (e.g., Chen & Li 2011), and in coastal and aeolian areas, such as in the Curonian Spit in Lithuania (Sergeev et al. 2015). PaIeosols have also been recognised, described and used for stratigraphic correlation in many Finnish Pre- and Late Weichselian sediment sequences, particularly in the Pohjanmaa region, western Finland. Here, the Early Weichselian Ostrobothnian geosol is widespread and well established (Kujansuu et al. 1991, Kujansuu 1992, Pitkäranta 2013). In northern Finland, inter-till sediment sequences including both minerogenic and organic paleosol horizons have been used to date and correlate the Middle Weichselian deposits (e.g., Sarala 2005, Sarala & Eskola 2011, Sarala et al. 2016).

It is important, however, to understand that fossil soils do not need to be chronostratigraphic units, because they may have boundaries that are time-transgressive and may cut across sediment sequences of differing ages (Holliday et al. 2016). Fossil soils are also easily deformed and eroded during or just after their formation when they occur in the upper part of a sediment deposit. Good examples of this are, for example, the erosion of paleosols after forest burning and the re-activation of sand movement in dune fields (e.g., Hart & Peterson 2007, Gaigalas & Pazdur 2008) (Fig. 10).

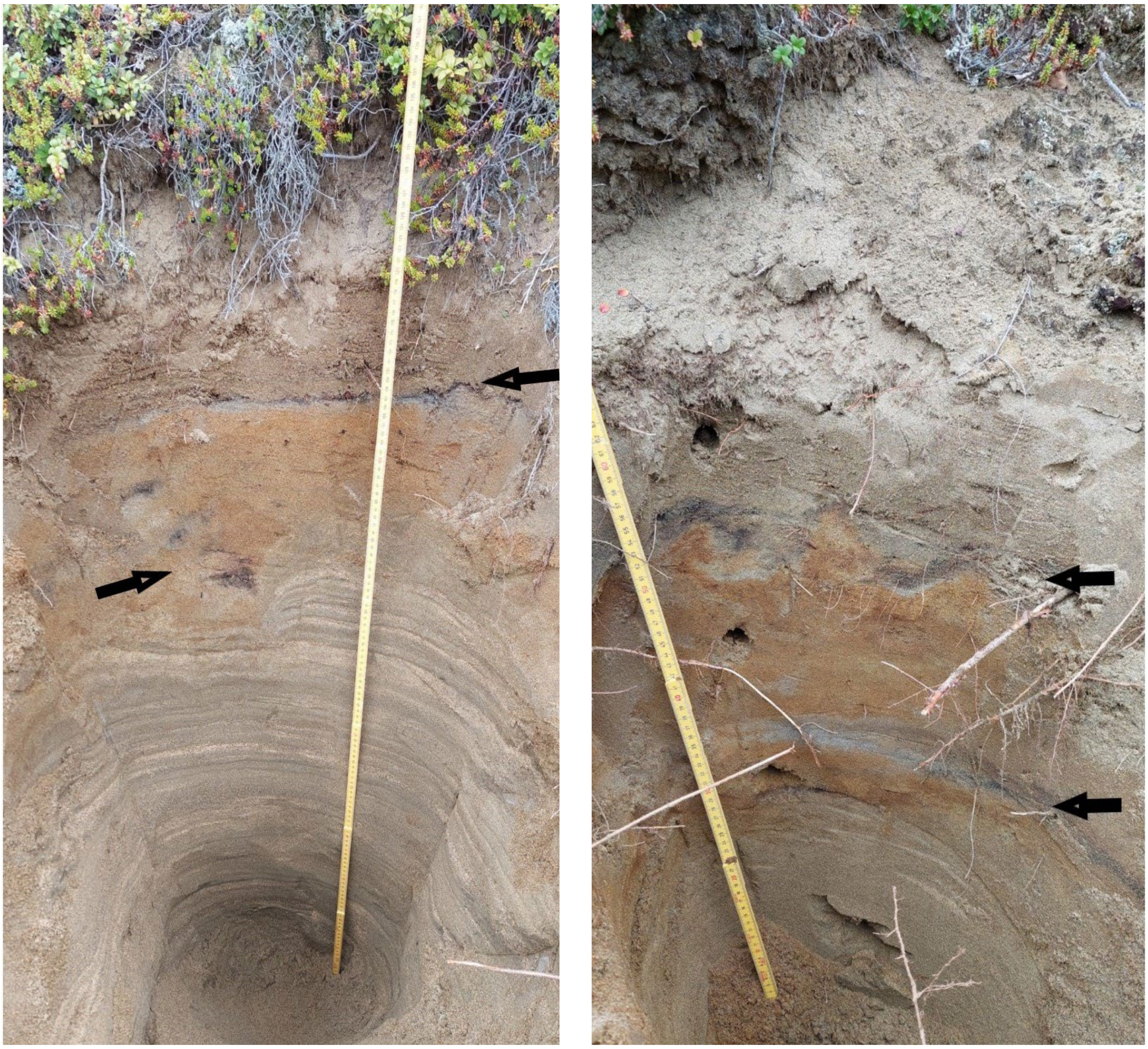


Fig. 10. Paleosols after forest burning (several black, organic-rich layers with underlying Podzol soil profiles, marked with black arrows) in dunes in the Kaamanen area, northern Finland (Photographs: P. Sarala, Oulu Mining School).

7 SEISMOSTRATIGRAPHY

7.1 Background

Seismic stratigraphy is a method to study and correlate subsurface sedimentary strata and to reveal unconformity-bounded sedimentary (seismic) units for the analysis of regional geological history (Sheriff & Sheriff 1980). Seismic stratigraphy is based on a variety of geophysical techniques employed in subsurface investigations, often divided into seismic reflection and seismic refraction (e.g., Neal 2004). Seismic profiles consist of the records of waves that are generated by explosions, vibrators or airguns at sea and on land, which then reflect and refract from bedding planes at which the wave velocity (material density) sharply changes, thus resulting in cross-section profiles of density and composition differences in sediments and rocks (Neal 2004). Seismic stratigraphic techniques have become an important routine, and the interpretation of seismic data sets to form seismostratigraphic units is a necessary approach towards three-dimensional geological modelling (Veeken & van Moerkerken 2013). Seismostratigraphy is often closely related to allo- and sequence stratigraphies (Chapters 8 and 9), as well as to lithostratigraphy (Chapter 3.1).

Because seismic reflection and refraction profiles do not meet the resolution helpful for practical shallow subsurface investigations, the ground penetrating radar (GPR) technique can be used to subdivide glacial and glacifluvial sediment strata (e.g., Mäkinen et al. 2018). GPR profiles provide a basis for radar stratigraphy. These profiles are based on electrical discontinuities in subsurface sediments (typically <50 m) detected by the generation, transmission, propagation, reflection and reception of discrete pulses of high-frequency electromagnetic energy with a typical range of 100–400 MHz. It is noteworthy that subsurface profiles obtained by GPR and seismic methods are not directly intercomparable, because the methods record different properties of sedimentary sequences. However, significant unconformities are typically well expressed in both GPR and seismic profiles (an abrupt change in water content and acoustic impedance), and GPR data can therefore be used together with the seismostratigraphic method for correlation following the allostratigraphic approach (Virtasalo et al. 2019).

7.2 Application: Terrestrial surveys with ground penetrating radar (GPR)

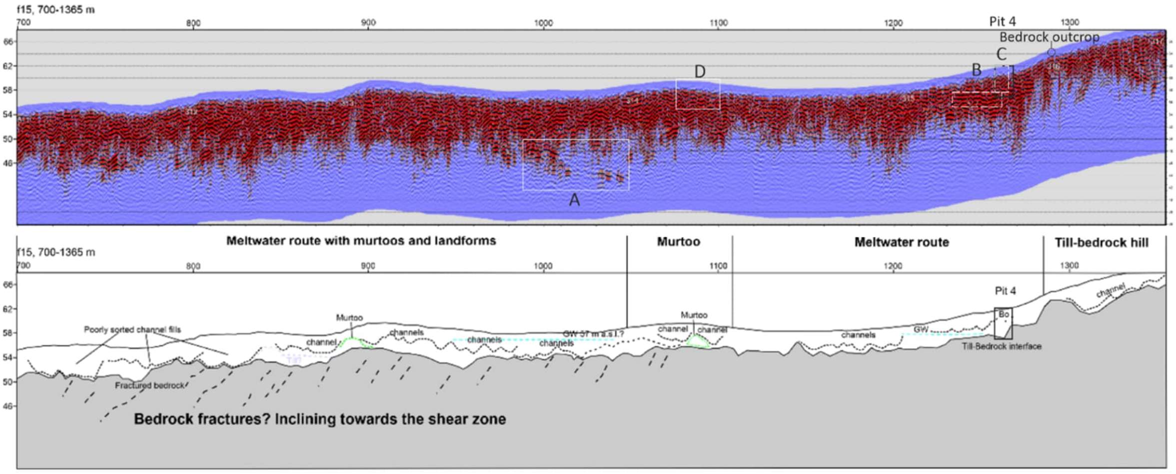
In Finland, the GPR and radar stratigraphy approach is commonly applied in the form of reconnaissance surveys (a continuous method), using a common-offset antenna configuration, where the separation of the transmitter and receiver antennae remains the same and the antennae are towed by foot, car, motor sledge or all-terrain vehicle. In the recently glaciated terrains, radar stratigraphy has been used to reconstruct sediment thicknesses and characteristics, as well as sedimentary processes, in a variety of environmental settings, including till-covered glaciofluvial deposits and glaciotectonic deformation (Pasanen 2009). As clay (and fine silt) and most till deposits considerably impede signal penetration, stratigraphically the best results and the deepest penetration can be obtained from glaciofluvial landforms, including covering littoral, fluvial or aeolian sediments, and from large ice-marginal complexes dominated by glaciofluvial sediments.

The penetration depth of GPR is controlled by the antenna frequency, and in ideal conditions, large-scale bedding or architectural elements can be detected down to 30–50 m by using 40–50 MHz antennas. If better resolution for the shallower subsurface (<15–25 m) sediment characterisation is needed, higher frequency (100–200 MHz) antennae are used. Generally, depending on the scale and purpose of the study, single antenna surveys usually apply a 100 MHz antenna, which is the best, most cost-effective compromise between the depth of penetration and resolution of sedimentary structures and bedding characteristics. These studies are often targeted at hydrogeological investigations and groundwater reservoir characterisation, thus providing information for assessment, flow modelling and management of groundwater regimes or aggregate resources. The informativeness of GPR surveys can be enhanced by constructing semi-3D fence diagrams from a wider area or, in some cases, ‘true’ 3D representations with dense and systematic profile configurations limited to a smaller area.

The basic principles of seismic stratigraphy are also applied to GPR data interpretation, including the recognition of radar surfaces (boundaries), radar packages (geometries) and radar facies (bed assemblages) (Neal et al. 2004). Radar facies are described based on reflection properties, the including amplitude, continuity, form or shape, attitude and dip of reflections, as well as the relationships between reflections and the presence of diffraction hyperbolas from large clasts or steeply inclining surfaces such as faults. Depending on the survey environment, interfering reflections (e.g., groundwater table, ringing), diffraction hyperbolas from internal and external sources may exist. Facies determination may also become obscured by limited signal penetration and attenuation. Ultimately, radar facies are constructed from radar reflections, which arise from the behaviour of electromagnetic waves when they penetrate in and reflect from the substratum. This behaviour is dependent on vertical and lateral variations in the local sediment composition, its sedimentary architecture and structures, and on bedrock characteristics (e.g., the state of weathering and fractures), as well as on the water content, which is regulated by climate conditions. This means that the compilation of a uniform atlas of radar facies for different depositional environments is not, to some extent, a straightforward task. Furthermore, facies analysis is also influenced by the selected data-processing procedure. Therefore, the availability of proper on-site reference data and understanding of the geomorphological setting are crucial factors for the interpretation of GPR data to avoid pitfalls. Moreover, the application of topographic correction and consideration of dip corrections are important for successful interpretation.

An example of using a combination of geomorphological mapping, lithostratigraphy and seismostratigraphy to investigate the ice-contact deltas of Salpausselkäs I and II is given by Kurjański et al. (2021). They investigated sediment architectural elements of ice-contact deltas identified from section outcrops and juxtaposed against GPR reflection patterns observed from geophysical profiles, thus providing GPR facies for each typical lithofacies association in this environment.

Subglacial meltwater routes from different glaciodynamic settings in Finland, containing murtoos and murtoo-related landforms, have been recently studied in GPR surveys (100 and 200 MHz antennae) supported by machine-dug test pits (Ahokangas et al. 2021, Ojala et al. 2021, Mäkinen et al. 2023) (Fig. 11). These studies revealed that GPR signals normally penetrate deeper (down to bedrock) in poorly sorted and till-resembling diamictons with low amounts of boulders and fine-grained sediments compared to more massive subglacial tills deposited in various other subglacial landform settings. Therefore, in areas where poorly sorted and till-resembling diamictons with low amounts of boulders and fine-grained sediments occur, it is possible to detect different subglacial till beds, meltwater route deposits and glacigenic landforms, and to define the elements of a subglacial land system and local glacial lithostratigraphy (Fig. 11).



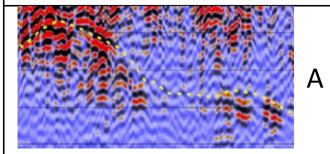
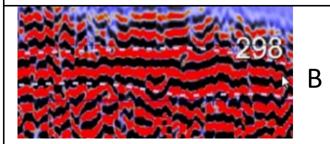
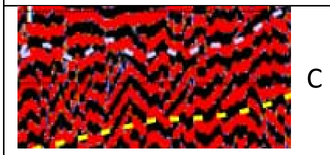
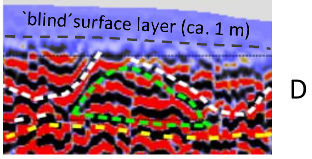
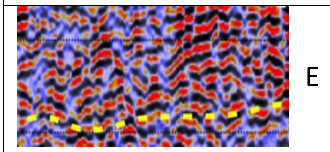
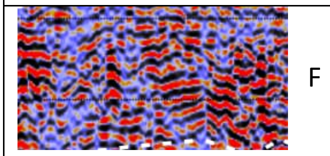
Radar facies	Characteristics	Lithology	Interpretation
 (100 MHz)	Medium to high amplitude semi-continuous and undulating reflection (dashed line) within chaotic and downwards attenuated reflections containing numerous diffraction hyperbolas.	Crystalline bedrock, granodiorite or quartzdiorite	Bedrock with a major fracture (dashed line)
 (100 MHz)	Strong, high amplitude, horizontal and continuous reflections (between radar surfaces by dashed lines). Best preserved on the margins of the subglacial meltwater route. Lower boundary with bedrock.	Diamicton, silty, fine-grained	Subglacial till (silty bluish/grey till), formed prior to the Salpausselkä stage.
 (100 MHz)	High amplitude undulating or inclined reflections, at times chaotic appearance with diffraction hyperbolas (between radar surfaces by dashed lines). Lower boundary to silty till or bedrock (yellow dashed line).	Diamicton, sandy with large boulders up to 2 m	Subglacial till (grey/brown sandy till), formed at the Salpausselkä stage.
 (100 MHz)	Cupola-shaped, stratified feature (green dashed line) with flanking trough-shaped/stratified reflection packages (white dashed lines). Lower boundary to subglacial till or bedrock (yellow dashed line).	Diamictons (silt-gravel) intercalated with sorted sediments (mostly silty sands in cupola-shaped unit)	Part of the subglacial meltwater route containing murtoo with flanking meltwater channels.
 (200 MHz)	Medium amplitude undulating and inclining, discontinuous reflections with calm appearance. Lower boundary to subglacial till or bedrock (yellow dashed line).	Diamicton, coarse-grained	Glacial lineation (drumlin).
 (200 MHz)	Medium amplitude horizontal to inclined (undulating) reflections, varies from discontinuous/chaotic to stratified. Lower boundary to subglacial till or bedrock surface (white dashed line).	Diamicton, coarse-grained with sorted sediments	Ribbed moraine.

Fig. 11. Radar (GPR) facies (100 and 200 MHz antennae) for the description and interpretation of lithostratigraphy and a subglacial land system, including subglacial meltwater route sediments in the Sääksjärvi area, western Finland. The GPR profile (100 MHz) represents a cross-section across a subglacial meltwater route, showing the true position of radar facies samples A and D, and examples similar to radar facies B and C at the margin of the route confirmed by the exposed sediments on bedrock in Pit 4. The grey area of the profile refers to till-covered bedrock and the white area to meltwater route sediments with poorly preserved sandy diamicton (radar facies C). GPR profiles by the Geological Survey of Finland and text/interpretations by Elina Ahokangas and Joni Mäkinen, University of Turku.

7.3 Application: Marine seismic surveys

Marine seismic surveys have been instrumental to improving our understanding of the geometry and lateral extent of glacial, postglacial and recently deposited sediment units in Finnish offshore areas (e.g., Winterhalter 1972, Ignatius et al. 1980). Aboard GTK's research vessel Geomari, seismic surveys are conducted using three seismic systems simultaneously. These three systems operate using different frequency ranges (typically 28 kHz, 3.5–8 kHz, 0.250–1.3 kHz). The higher frequency systems provide high resolution data from the upper few metres of the subsurface, but their vertical extent is limited compared to deeper penetrating lower frequency systems, which, on the other hand, are hampered by lower resolution. In addition to mapping the external form of sediment bodies, seismic sub-bottom profiles also reveal the internal reflector structure of the deposits and the nature of termination of the internal reflectors against the underlying surface (toplap, offlap, onlap and downlap). The internal reflector configuration is informative of the dominant depositional process of a sediment unit. It enables distinguishing between, for example, sediments deposited during the lacustrine phases of the Baltic Sea Basin, which were deposited as a drape of uniform thickness on the underlying topography, and softer asymmetric brackish water sediment drifts, whose deposition was controlled by near-bottom currents and waves (Virtasalo et al. 2007, 2014). Because many of the prominent reflectors observed in marine seismic surveys are interpreted as unconformities, these boundaries can be used to define allostratigraphic units (alloformations), which can be subdivided into smaller allounits (allomembers) and lithostratigraphic units, following the combined allostratigraphic and lithostratigraphic (CUAL) approach (Räsänen et al. 2009, Virtasalo et al. 2014).

8 SEQUENCE STRATIGRAPHY

8.1 Background

Sequence stratigraphy is a branch of stratigraphy that studies stratal stacking patterns and their stratigraphic relations (Catuneanu et al. 2010, 2011, Catuneanu 2017). It combines sedimentological and geophysical data sets with stratigraphic disciplines such as litho-, bio- and chronostratigraphy. One of its key concepts is accommodation, which defines the space available for sediments to accumulate (Jervey 1988) (see Fig. 12 and Table 3 for terminology). The changes in accommodation space through time, coupled with sedimentation, control depositional trends. Adjacent sedimentary units with contrasting stacking patterns are bounded by sequence stratigraphic surfaces, which divide sedimentary successions into systems tracts and ultimately into sequences (Table 3). Such data provide the framework for the genetic, process-based interpretation and classification of sedimentary successions (Catuneanu 2017).

Sequence stratigraphy was originally developed in marine basins after the recognition that unconformities can be used to divide sedimentary successions into depositional units. Since then, its concepts have been refined and extended to non-marine environments, including fluvial, lacustrine and even glacial systems (e.g., Posamentier et al. 1992, Wright & Marriott 1993, Brookfield & Martini 1999, Powell & Cooper 2002, Posamentier & Walker 2006, Catuneanu et al. 2010, 2011, Pedersen 2012, Catuneanu 2017). In essence, the basic building blocks of sequence stratigraphic models are allostratigraphic units (see Chapter 9: Allostratigraphy). Presently, sequence stratigraphic methodologies are applied at virtually all scales to all types of sedimentary rocks.

Sequence stratigraphy as a discipline has not been presented in the North American Stratigraphic Code (NACSN 2021) or the International Stratigraphic Guides (Salvador 1994, ICS 2022). The formalization process has been complicated by different schools of thought and a plethora of methodological approaches (see SEPM 2024, website for the debate). However, the current ISSC Task Group on Sequence Stratigraphy has published recommendations for sequence stratigraphic nomenclature and methodology in a separate journal publication (Catuneanu et al. 2011). The reader is also advised to follow future versions of the Code and Guide (see also Catuneanu 2017, 2019), and bear in mind that particularly the non-marine approaches are still developing.

The recommended model-independent workflow starts with the documentation of facies, contacts and stratal terminations, which is followed by the construction of a sequence stratigraphic framework defined by specific stratal stacking patterns and bounding surfaces (Catuneanu 2017 and references therein). The selected sequence boundary can be any sequence stratigraphic surface that separates units with contrasting stacking and is best expressed in the available data (Catuneanu et al. 2011). Whatever model-dependent sequence stratigraphic approach is subsequently applied, observations should not be force-fitted into idealized models.

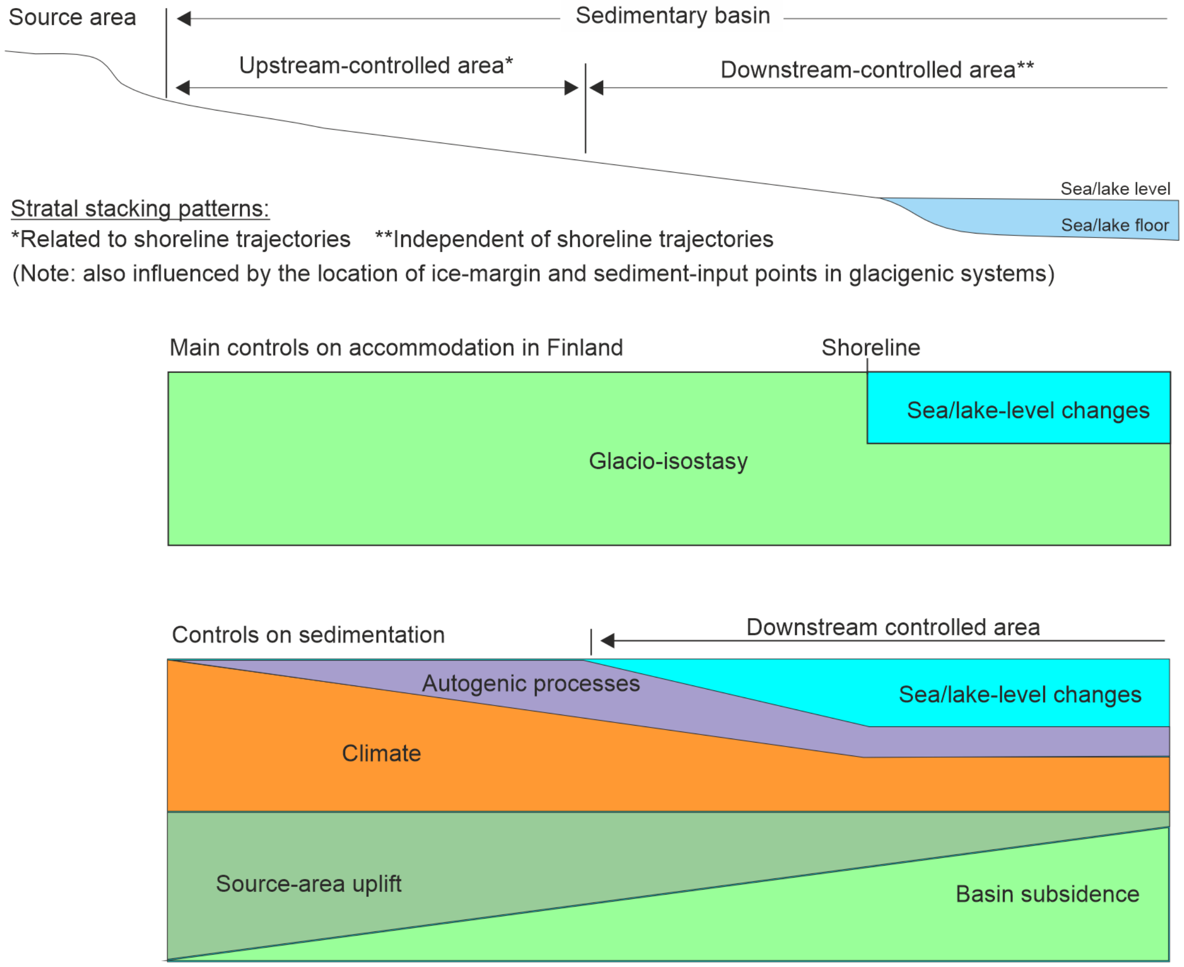


Fig. 12. Controlling factors of accommodation and sedimentation (modified from Catuneanu 2017; not to scale). Relative contributions of these controls may vary with the tectonic and depositional settings. In the Quaternary sedimentary systems of Finland, accommodation is mainly controlled by glacioisostasy and sea/lake-level changes. The downstream-controlled area includes marine/lacustrine and nearshore systems, which are affected by changes in relative sea/lake level. The upstream controlled area includes continental systems, which are beyond the influence of relative sea/lake-level changes. Autogenic processes include factors such as channel avulsion and delta-lobe switching. It should be noted that stratal stacking patterns are also influenced by the location of ice-margin and sediment-input points in ice-marginal systems (Brookfield & Martini 1999). For instance, sediment-point sources located under the glacier margin do not respond to changes in accommodation space and lake level in the same way as those in non-glaciogenic settings.

Table 3. Examples of sequence stratigraphic concepts mentioned in the text and notes regarding their applicability to Quaternary deposits in Finland. Definitions are adapted from Catuneanu et al. (2011) and Catuneanu (2017).

Term/concept	Definition	Quaternary depositional environments in Finland
Accommodation space *(kerrostumistila)*	The space available for sediments to fill. Primary controls are tectonism, glacio-isostatic adjustment and sea/lake-level changes. In fluvial systems beyond the influence of eustacy, factors such as climate and source area are also important.	• Accommodation space has been controlled by glacial loading, isostatic rebound, lake level changes and eustasy in marine environments. • Climate and intra-basinal factors, such as lacustrine outflow ridge height, have been significant controls in inland settings.
Flooding Surface (FS) *(tulvimispinta)*	A surface showing evidence of an abrupt increase in water depth.	• Potentially observable in any lacustrine and marine succession. • For instance, mid-Holocene eustatic sea-level rise generated a flooding surface in the Baltic Sea Basin. • In areas dominated by strong glacio-isostatic uplift, the flooding surface is not strictly caused by the relative sea-level rise. The rapid change from a post-glacial lake to salinity-stratified brackish water sea, caused by the flooding, resulted in significant erosion due to changed current patterns.
Forced regression (FR) *(pakotettu regressio)*	Stacking pattern of strata that shows a combination of progradation and downstepping. FR is driven by relative sea/lake-level fall (negative accommodation). In comparison, normal regression takes place when the sedimentation rate outpaces the relative sea/lake-level fall rise.	• FR can be caused by sudden ice-lake drainage and gradual glacio-isostatic uplift. • Due to current isostatic uplift and FR in Finland, sediments are being eroded and transported from land to sea.
Sequence *(sekvenssi)*	A sequence is a full cycle of change in stratal stacking patterns, which starts and ends with the same type of sequence stratigraphic surface.	• Sequences of low hierarchical rank are potentially present in sediment successions. • In the Baltic Sea Basin, sequences are expected to be asymmetric due to the strong isostatic uplift. • Glacial advance and retreat sequences may be applicable.
Sequence boundary (SB) *(sekvenssin raja)*	Any sequence stratigraphic surface that separates units with different stacking can be selected as a sequence boundary.	• The choice depends on local conditions, such as development and preservation. • For instance, subaerial unconformities are common and can form a candidate for SB in many onshore localities.
Systems tract *(kerrostumissysteemien alue)*	A systems tract is defined by specific stratal stacking patterns. Each systems tract corresponds to a specific phase of the relative sea-level (i.e., accommodation) cycle in marine basins.	• Systems tracts are primarily sedimentological cycles formed by laminae, beds and bed sets. • Glacial systems tracts can include (informally) glacial maximum, - retreat, - minimum and - advance systems tracts (Powell & Cooper 2002).
Subaerial unconformity (SU) *(ilmanalainen epäjatkuvuus)*	An erosional surface that forms under subaerial conditions as a result of fluvial and other processes, most commonly during periods of negative accommodation (Catuneanu 2017)	• A major SU separates the regolith topped bedrock and the Quaternary succession in Lapland. • Several SUs of various hierarchies are present within the Quaternary sediment series and are potentially useful for both sequence stratigraphic and allostratigraphic classifications.

8.2 Application of sequence stratigraphy to Quaternary deposits in Finland

The Quaternary strata of Finland host several characteristics that pose limitations to the use of sequence stratigraphic approaches. First, the deposits are dominantly non-marine, glacial to glacially influenced sediments, which are exposed in fragmented and limited outcrops that normally cannot be correlated over long distances. Secondly, chrono- and biostratigraphic challenges are common, and most outcrops or stratigraphic surfaces cannot be accurately dated at present. Nevertheless, bearing these limitations in mind, sequence stratigraphy can provide a useful means to understand and classify local changes in accommodation and facies stacking patterns, and in some cases even basin wide events, depositional trends and glacial cycles.

The Pleistocene and Holocene Epochs were characterised by prominent eustatic sea level oscillations that were mainly driven by changes in ice sheet volumes (e.g., interglacial vs. interstadial). Together with glacio-isostasy, eustatic sea-level fluctuations have been among the primary controls of accommodation in marine and coastal areas in Finland, particularly during the Eemian and modern brackish water sea phases in the Baltic Sea Basin. For instance, the mid-Holocene eustatic sea-level rise is recorded in both seismoacoustic and sedimentological data sets, and it can be mapped regionally as an erosional flooding surface in coastal areas and as a conformable succession with a sharp and possibly erosional basal flooding surface in offshore settings (Virtasalo et al. 2016).

Glacio-isostatic uplift has had a significant impact on accommodation during past deglaciation phases, particularly in western Finland and the Gulf of Bothnia. During deglaciations, isostatic rebound has typically outpaced eustatic sea-level rise, causing sea-level fall and consequent forced regression (Table 3). Examples of sedimentary responses to this process include the rapid shallowing of the Eemian sea (e.g., Eriksson et al. 1999), as well as incising river valleys and the development of subaerial unconformity over exposed Baltic Sea sediments in the present-day landscape in coastal Finland.

In non-marine locations beyond the influence of sea-level changes, accommodation and sedimentation have been more strongly influenced by climate and intra-basinal factors such as the elevation of outflow ridges in ice-lake systems (Catuneanu 2017). Prominent examples include the sudden drainage of the Baltic Ice Lake, which generated a rapid lake-level fall and forced regression, as recorded in successive delta levels along the Second Salpausselkä zone (e.g., Lunkka 2023 and the refences therein).

Finally, glacial sequence stratigraphy offers a promising means to classify and reconstruct glacial advance-and-retreat cycles (glacial systems tracts; Powell & Cooper 2002, Pedersen 2012). Such an approach has been used in subsurface Baltic Sea Basin sediments and local outcrop data (e.g., Virtasalo et al. 2014, Räsänen et al. 2015). The wider application of the method on land requires improvement in the stratigraphic control of Quaternary deposits.

9 ALLOSTRATIGRAPHY

9.1 Background

The sedimentary record may be viewed as being composed of units that are bounded at the top and bottom by non-depositional or erosional surfaces (unconformities) from the scale of thin beds to the scale of continental sedimentary cover (Miall 2016). Sediments are deposited when there is sufficient supply and accommodation space for it; otherwise, there will be a gap (unconformity; Catuneanu et al. 2011). Unconformities are also produced and extended back in time by the removal of previously emplaced rock by erosion. The processes of sediment deposition and erosion operate at various tempos and at spatial scales ranging from ripples to continents, which is reflected in the resultant sediment units and their bounding unconformities. The significance of unconformities and associated missing time are well illustrated by a chronostratigraphic cross-section (‘Wheeler diagram’), in which the vertical dimension is drawn with a time scale instead of a thickness scale, making time gaps become readily apparent (Fig. 13) (Virtasalo et al. 2007).

Allostratigraphy is a descriptive stratigraphic approach aimed at subdividing depositional successions into unconformity-bounded units in a hierarchical manner. A sediment unit bounded above and below by significant unconformities is formally recognised as a synthem in the International Stratigraphic Guide (Salvador 1994) and as an allostratigraphic unit in the North American Stratigraphic Code (NACSN 2021). The term synthem has not been adopted by the stratigraphic community, whereas allostratigraphic units (allounits) are widely used. The basic allostratigraphic unit is the alloformation. An alloformation may be completely or only partly divided into allomembers, or it may have no allomembers. Alloformations may also be grouped into an allogroup.

Regional unconformities have long been used for defining natural subdivisions of the stratigraphic record (e.g., Playfair 1802, Blackwelder 1909). The allostratigraphic approach has been easiest to apply in the context of fluvial Quaternary deposits, where unconformities between different terrace deposits are well developed and the different terrace elevations have made the delimitation of the units relatively easy (e.g., Zuchiewicz 1988, Autin 1992, Straffin et al. 1999). In Quaternary glaciogenic deposits, allostratigraphy has been used in mountainous regions, where morphology has again helped the delimitation of the allostratigraphic units (e.g., James et al. 2002, Hughes et al. 2005, Hughes 2010). In offshore studies, where seismic and acoustic profiles clearly reveal the unconformities, the allostratigraphic approach has also been applied (e.g., Hiscott & Aksu 2002, Rijsdijk et al. 2005, Virtasalo et al. 2005, 2007, 2014).

Stratigraphic classification based on the allostratigraphic approach begins by identifying unconformities that are unambiguously recognisable in sediment cores or exposures. Adequate documentation of the unconformities is critical, and publications need to include good-quality images of the recognised unconformities and the immediately underlying and overlying sediments. Indeed, allostratigraphic classification criteria are similar to lithostratigraphic criteria in that they are both descriptive and can be studied visually. A number of sites need to be investigated in order to recognise unconformities of a local extent and regional unconformities that have a larger spatial extent. Because significant unconformities are often associated with changes in sediment density, they are usually traceable in seismic-acoustic and other geophysical sub-bottom profiles, such as ground-penetrating radar profiles, which greatly facilitates studying the lateral extent and geometry of allostratigraphic units. The allostratigraphic approach may also be used for glacial and glacially influenced sediments that typically are frequent in unconformities and show high lateral lithological variation, whereas lithostratigraphic units defined in such deposits either have a restricted lateral extent or incorporate substantial lithological heterogeneity, which complicates their unambiguous definition and recognition at the regional scale (Räsänen et al. 2009).

Descriptive allostratigraphic units are fundamental building blocks of any depositional succession (Miall 2016), and as such, are useful for different interpretive stratigraphic approaches, such as (glacial) sequence stratigraphy and architectural element and land system schemes. Classical sequence stratigraphy is concerned about relative sea-level changes in marine settings (e.g., Catuneanu et al. 2011), and is less suitable for glacial and glacially influenced depositional successions. Instead, glacial sequence-stratigraphic models consider the ice-margin position, differential glacio-isostatic rebound and local water-level changes as additional controls on sediment accommodation (Brookfield & Martini 1999, Powell & Cooper 2002). In addition, hierarchical architectural element and land system schemes are useful interpretive approaches to the complex sedimentary cover of former glaciated regions (Hughes 2010, Slomka & Eyles 2015). It should be noted that one interpretive approach may be more suitable than others at a particular scale of study, and more than one interpretive approach may be applied to the same allostratigraphic division, as long as they all serve a purpose.

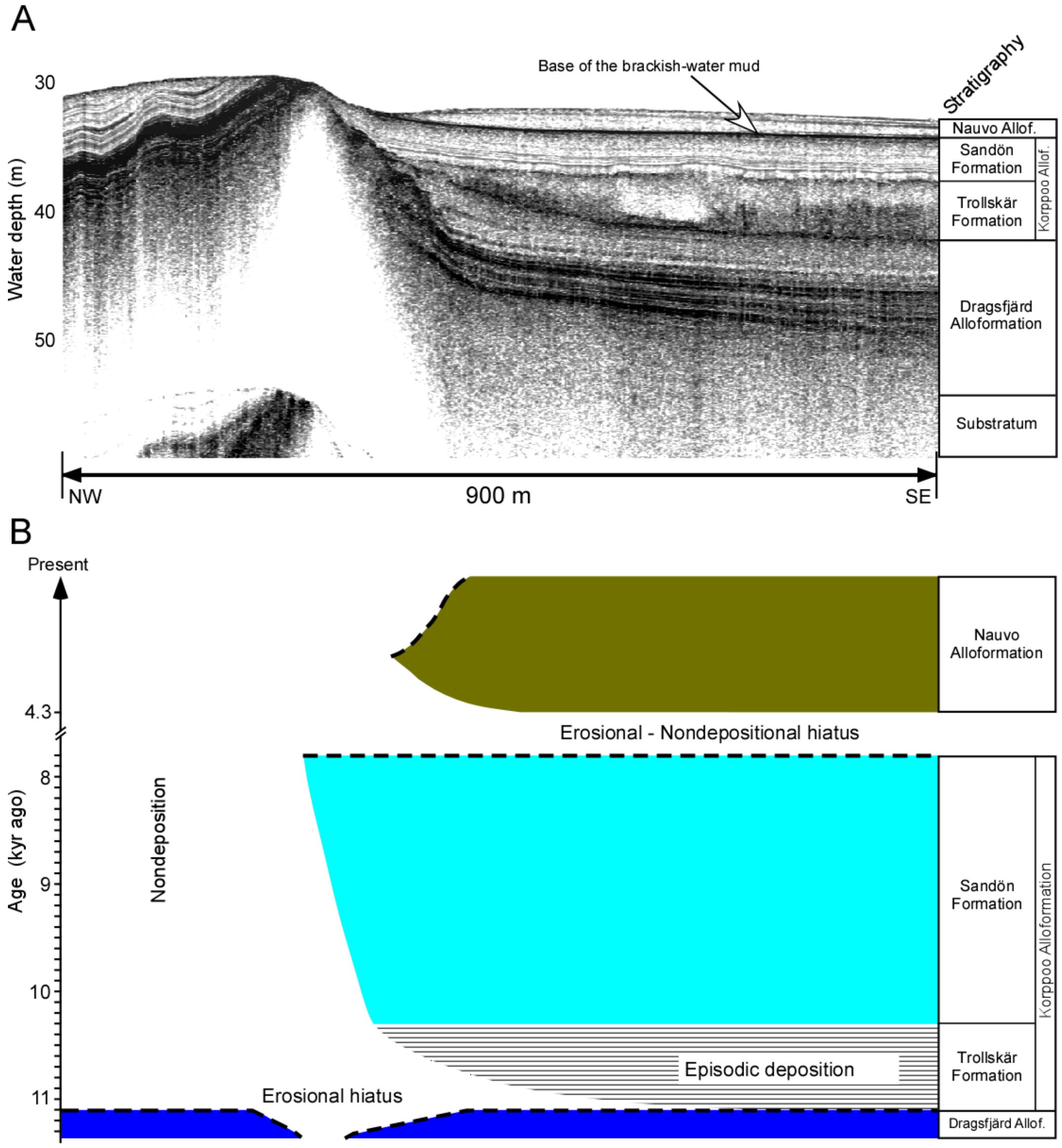


Fig. 13. A) Seismoacoustic sub-bottom profile (12 kHz pinger) and stratigraphic units after the CUAL approach from the Archipelago Sea in the northern Baltic Sea Basin. B) Corresponding Wheeler diagram with time on the vertical axis. Modified from Virtasalo et al. (2007). Stratigraphic units after Virtasalo et al. (2010).

9.2 Application of allostratigraphy to Quaternary deposits in Finland

The allostratigraphic approach has mainly been used for the allostratigraphic division of Weichselian deglacial and post-glacial Baltic Sea Basin sediments. The areas where this approach have been successfully applied include the Archipelago Sea area (northern Baltic Sea) (Fig. 13) (Virtasalo et al. 2005, 2007, 2010), offshore areas at the Gulf of Riga (Tsyrulnikov et al. 2012), the western Gulf of Finland (Virtasalo et al. 2014, 2019), the Ångermanälven river estuary (Hyttinen et al. 2017), and the Bornholm Basin (Jensen et al. 2017). For example, Virtasalo et al. (2016) demonstrated that the unconformable base of the brackish water mud is a basin-wide marine flooding surface, which was caused by glacioeustatic ocean-level rise and the mid-Holocene transgression of the world ocean to the Baltic Sea Basin ca. 8 ka ago. Studies carried out using the allostratigraphic approach indicate that local stratigraphic studies, when combined, will potentially result in the recognition of unconformities that have local, regional and basin-wide significance.

The allostratigraphic approach has also been applied to glacially influenced strata on the eastern coast of the Gulf of Finland, where till beds and organic-rich lake deposits are separated by unconformities (Räsänen et al. 2009, 2015). These unconformities serve as the primary (allo)stratigraphic subdivision criteria, whereas lithostratigraphic units can be used for complementing lithostratigraphically mappable features in the allostratigraphic framework where useful (Räsänen et al. 2009, 2015, Virtasalo et al. 2007, 2014).

10 HYDROSTRATIGRAPHY

10.1 Background

As summarised by Brodaric et al. (2018), hydrostratigraphy is concerned with the identification of the hydrogeological role (aquifer or aquitard) of shallow and deep subsurface lithostratigraphic units based on their hydrogeological properties. Aquifers are permeable and allow easy groundwater flow, while aquitards have a low permeability that impedes groundwater flow. An aquitard overlying an aquifer generally leads to confined conditions in the underlying aquifer. In modern scientific hydrogeological research, hydrostratigraphic units are roughly synonymous with hydrogeological units defined within a hydrogeological conceptual model. Despite the evolution of the hydrogeological ontology in the last decade, hydrostratigraphic units have retained their role in the description of groundwater systems and their numerical modelling as distinct volumes of earth material that serve as containers for subsurface fluids.

The two main types of hydrostratigraphic units, aquifers and aquitards, are distinguished by the facility of groundwater flow within these volumes. The boundaries of hydrostratigraphic units may depart from those of lithostratigraphic units, since these boundaries are based on hydraulic properties controlling the potential or actual ability to store or move water, whereas lithostratigraphic units are defined on the basis of material types, notably based on grain size. Hydrostratigraphic units often regroup lithostratigraphic units playing the same role (aquifer or aquitard). The conversion between lithostratigraphic units (sediment properties) and hydrostratigraphic units (hydrogeological properties) thus generally involves a generalization leading to a smaller number of units, as several lithostratigraphic units can form a single hydrostratigraphic unit playing the role of either an aquitard or aquifer based on their hydraulic properties (Fig. 14).

In a hydrogeological conceptual model, hydrostratigraphic units are combined to represent aquifer systems within a large framework, which are made up of collections of aquifers and aquitards. Aquifer systems can be made up of rock units, granular (sediments) units or a combination of both, depending on their geological contexts. In the context of buried valleys above bedrock, aquifer systems can be composed of sediment successions of overlapping units that have been laid down in different depositional environments, leading to a succession of aquifers and aquitards. For example, sediments deposited in channel fills or deltaic environments that have similar hydraulic properties may be grouped into the same hydrostratigraphic unit (Heinz & Aigner 2003, Klingbeil et al. 1999). Such a context is typical for repeatedly occurring ice-marginal sediment successions, where the consecutive ice-margin oscillations leave behind thin diamicton facies (<10–50 cm) overlapping random gravel, sand and/or silt lithologies. These stacked sediment packages can be defined as aquifer- or aquitard-type hydrostratigraphic units, depending on their hydraulic properties (Fig. 14).

Depending on the scale of the aquifer system considered, hydrostratigraphic units are scalable, and in a wider context, this type of scalability follows a hierarchical approach in which sediments, landforms and landscapes fit together using depositional processes and external controls in the environment (Walker 1992). The definition of hydrostratigraphic units is a multidisciplinary activity and involves an iterative process among geologists and hydrogeologists. This process allows the creation of a new type of data set based on traditional Quaternary maps but also geological models, which are the basis for the definition of hydrostratigraphic units within hydrogeological conceptual models. The implementation of hydrogeological conceptual models is the basis for the development of numerical groundwater flow models. An example of Quaternary geological data used within a hydrogeological conceptual model in Finland is presented in Figure 14.

10.2 Application of hydrostratigraphy to Quaternary deposits in Finland

Mapping of surface morpho-lithogenetic (MLG) units also allows the 3D modelling of subsurface hydrostratigraphic units (Fig. 14, Table 4). The modelling process and the system incorporates the general sediment classification principles explained in Chapter 4. Nevertheless, the unique role of genetic deposit types (GTD) must be highlighted. GTDs are conceptually derived from landforms, lithology and depositional conditions to outline the geometry component from sparse and in some areas non-existent geological and/or geophysical data. Informally mapped lithofacies or facies associations (see Chapter 3.1) are a part of the process to constitute three-dimensional architectural elements for the modelling of Quaternary deposits.

The practical modelling process is demonstrated at two different scales that are used in the subsurface modelling and hydrogeological modelling of Quaternary geology in Figure 14. In the modelling continuum, superficial geology map information

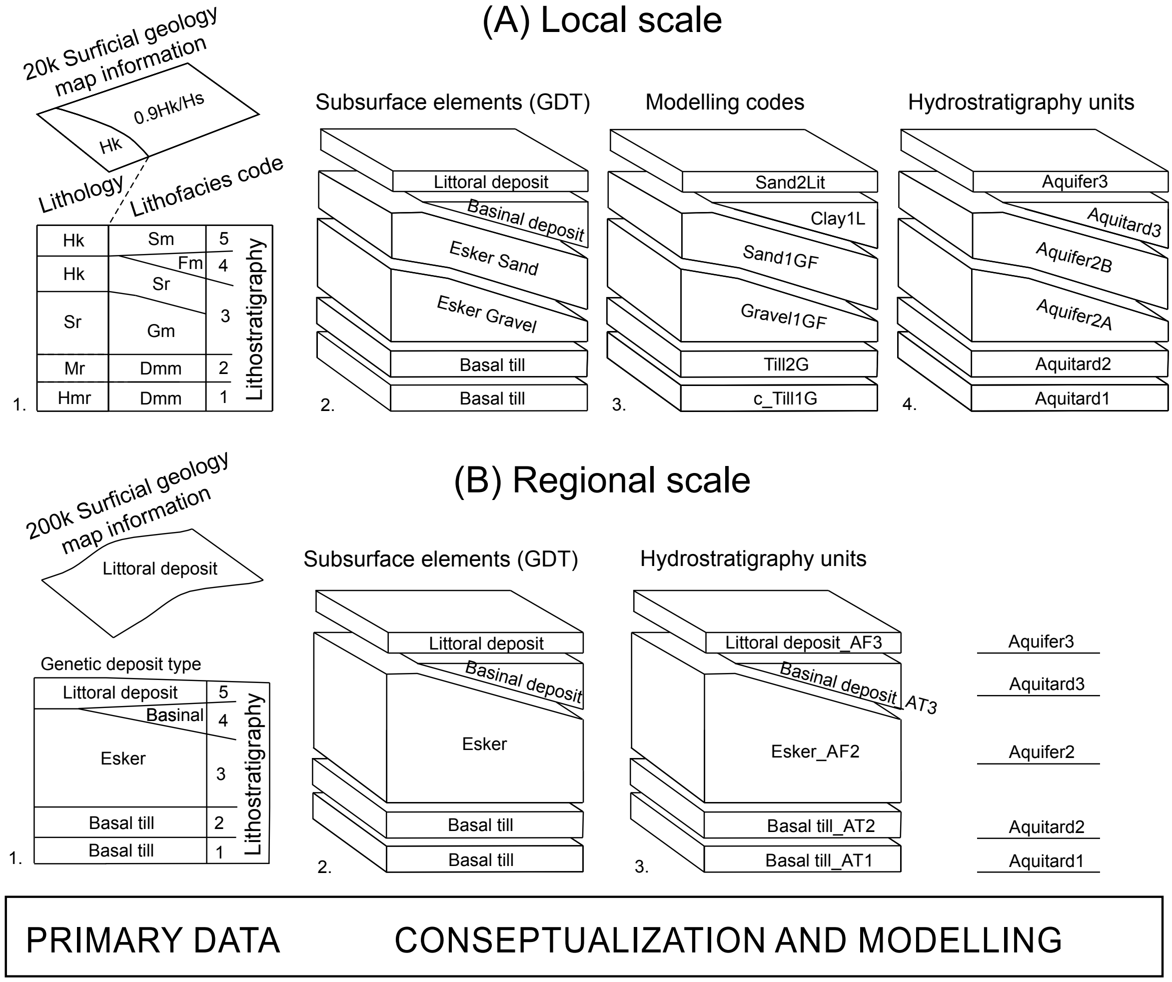


Fig. 14. Subsurface Quaternary deposit and hydrostratigraphic 3D modelling approach adopted by the Geological Survey of Finland (GTK). Principles of the coding system are presented in (A:3) and Table 4. The hydrostratigraphic conceptual model consists of alternating aquitard and aquifer couplets, with Aquitard 1 as the lowermost unit, followed by Aquifer 1, although this is not represented in the figure. A) Local scale: (1.) Scale 1:20 000 (i.e., 20k) superficial (surficial) geological map data provides information on surface lithology, while subsurface data obtained from borehole logs and exposures provides lithostratigraphic data on sediment texture (lithology) and lithofacies. (2.) Subsurface sedimentary elements are derived from sediment lithology and the three-dimensional geometry of sediment facies and facies associations (see Fig. 2 in Chapter 3) obtained from geological and geophysical data. (3.) The modelling operates in the coding system following the morpho-lithogenetic and lithological classification presented in Table 1. (4.) Hydrogeological modelling based on hydrostratigraphic units (aquifers or aquitards) is derived from model codes (units) and based on their hydraulic conductivity (K-value). B) Regional scale: (1.) In the regional approach, superficial geology map data (1: 200 000, i.e., 200k) and the surface MLG units are defined. (2.) Subsurface elements (GDT) are often generalized from local-scale GTDs, or they are derived from regional-scale Quaternary map data to form hydrostratigraphic units (3).

(lithology), GTDs and their outer margins (polygons) and cross-sectional data (unit top and bottom boundaries) are transferred to the subsurface deposit mapping. All this, together with general understanding of the inferred depositional conditions and processes, is central to the emerging conceptual model. Practical 3D modelling follows the conceptual model according to the rules set out above to form subsurface Quaternary geological and hydrogeological data. It should be noted here that hydrogeological modelling has a two-way role in subsurface modelling, as it often redefines the dimensions of modelled subsurface elements via inversion techniques that are run by *in situ* hydraulic tests and/or groundwater flow model calibration.

Table 4. Subsurface modelling coding system.

Prefix **Optional code extension**	**Sediment type (Lithology)** **Mandatory field**	**Genetic deposit type** **Mandatory field**
Gravel (g)	Peat	Holocene (H)
Sand (s)	Gyttja	Aeolian (A)
Silt (si)	Till	Fluvial (F)
Clay (c)	Gravel	Littoral (Lit)
	Sand	Lacustrine (BL)
	Silt	Marine (BM)
	Clay	Glaciofluvial (GF)
	Anthropogenic	Ice marginal (IM)
		Glacigenic (G)
		Unknown (U)

11 GEOCHRONOLOGICAL METHODS IN THE QUATERNARY

11.1 Background

A number of geochronological methods are applicable to date Quaternary sediments at large, and also sediments deposited in glacial environments (e.g., Walker 2005, Jull 2018) (Fig. 15). Radiometric methods (such as ^{14}C, ^{230}Th, ^{210}Pb, ^{40}K – ^{40}Ar, U–He, ^{137}Cs, and cosmogenic nuclides ^{10}Be, ^{26}Al and ^{36}Cl) are based on the radioactive decay of unstable naturally occurring isotope systems. Radiative dosimetry methods (OSL, TL, IRSL, ESR dating) are based on natural radiation damage in a silicate mineral (quartz and feldspar) during sediment burial. Both radiometric and radiative dosimetry methods yield numerical ages. In addition to these dating methods, there are so-called relative and age equivalence, as well as incremental methods such as varve counting, paleomagnetic dating, dendrochronology, tephrachronology and lichenometry, which can be tied to the present day or radiometrically obtained numerical ages to give absolute ages for sediment sequences or materials that are subjected to age determinations. Annual ice layers are also used for dating the top part of ice cores (e.g., the Greenland NGRIP core). However, the global standard age models (e.g., the MIS system or GI system) for ice cores and marine sediment cores are mainly based on wiggle matching of ice core proxy data to the Earth's orbitally driven insolation time series and also on magnetic and absolute age determinations. The so-called amino-acid racemisation method and litho- and biostratigraphy are also used for dating purposes, but being relative, these methods must be confirmed by other dating methods.

The most common dating methods used in Finnish Quaternary geology are undoubtedly the radiocarbon dating and varve dating methods, which have been widely used for dating Holocene and Late and Middle Weichselian sediments (e.g., Sauramo 1923, Hyvärinen 1975, Ojala et al. 2012). The OSL, TL and IRSL, as well as cosmogenic nuclide dating methods are important dating methods for studies on glacial environments and have also commonly been used in Finland during the past decades to date siliciclastic sediments, boulders and bedrock surfaces (Cuzzone et al. 2016, Sarala et al. 2022). Recently, Kalliokoski et al (2023) introduced the first comprehensive Holocene tephrochronological

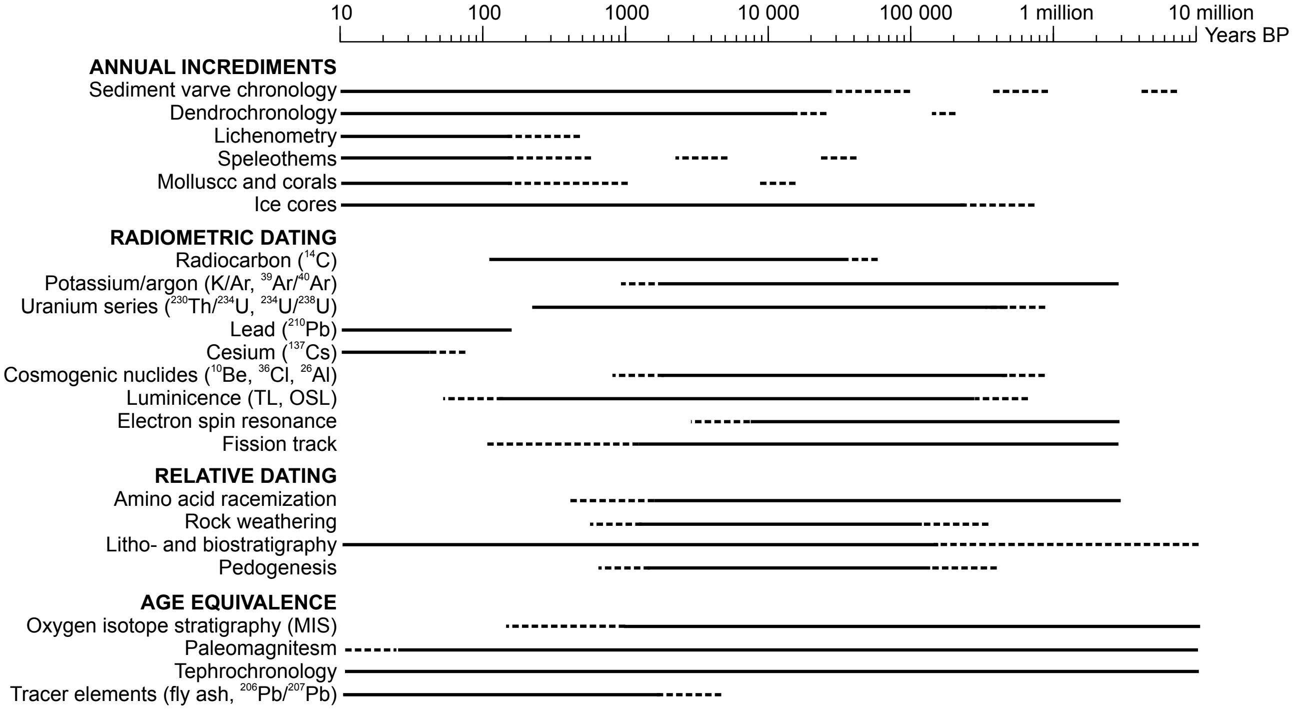


Fig. 15. The ranges of different Quaternary dating techniques typically applied in glaciated terrains (modified after Walker 2005).

framework for Finland, indicating an excellent potential for using tephrochronology in Finland and linking intercontinental environmental paleoarchives. Here, we only introduce the basic principles and applications of the most commonly used methods for dating Finnish Quaternary sediments.

11.2 Radiocarbon dating

11.2.1 Background

The radiocarbon dating method (^{14}C method) provides age estimates for materials containing carbon that has originated from living organisms. An age could be estimated by measuring the amount of the radioactive carbon isotope ^{14}C present in the sample and comparing this amount to an internationally used reference standard (Walker 2005). Radiocarbon dating is widely used in Quaternary geology, and it is one of the most important dating methods to provide age estimates for samples that contain natural organic remnants and organic-rich sediments using normal dating procedures up to around 50 000 years BP (e.g. Reimer & IntCal Group 2020).

Carbon (C) has three different isotopes, ^{12}C (98.9%), ^{13}C (1.1%) and ^{14}C, the amount of which is roughly only one atom in a million atoms. Carbon isotopes ^{12}C and ^{13}C are stable, but isotope ^{14}C, radiocarbon (^{14}C), is an isotope that is unstable and weakly radioactive. Carbon isotope ^{14}C and positrons (e^+) are continually being formed in the upper atmosphere by the effect of cosmic ray neutrons (n) on nitrogen isotope ^{14}N atoms (Eq. 1). Carbon isotope ^{14}C is rapidly oxidized in air to eventually form carbon dioxide (Eq. 2), which enters the global carbon cycle. Plants and animals assimilate ^{14}C via photosynthesis from carbon dioxide throughout their lifetimes (Eq. 3). They stop exchanging carbon with the atmosphere when the living organisms die, and the ^{14}C content of plants and animals starts to decrease due to radioactive decay (eq. 4). Radiocarbon dating is essentially a method designed to measure residual radioactive ^{14}C left in natural organic samples obtained from biota.

$$n + {}^{14}N \rightarrow {}^{14}C + e^{+} \qquad (Eq.\ 1)$$
$${}^{14}C + O_2 \rightarrow {}^{14}CO_2 \qquad (Eq.\ 2)$$
$$6H_2O + 6{}^{14}CO_2 + UV \rightarrow 6O_2 + {}^{14}C_6H_{12}O_6 \qquad (Eq.\ 3)$$
$$C\text{-}14 \text{ decay equation: } {}^{14}C \rightarrow {}^{14}N + e^{-} + \gamma \qquad (Eq.\ 4)$$

The half-life of ^{14}C is 5730 ± 30 yrs and the limit of detection of ^{14}C activity is eight half-lives, which means that the theoretical upper limit of the ^{14}C dating method is around 50 000 yrs. Samples giving ages over this limit are normally referred to as having 'infinite ages' (expressed as >45 000 radiocarbon years BP). In practice, ages over 40 000 radiocarbon years are considered finite ages unless special techniques such as isotopic enrichment are attempted, which might extend the age to about 45 000 radiocarbon yrs (e.g., Reimer & IntCal Group 2020). The remaining ^{14}C in the sample can be calculated as follows:

$N = N_0 e^{-\lambda t}$ (Eq. 5)
$(\ln (N/N_0) = -\lambda t)$ (Eq. 6)
N = number of remaining ^{14}C isotopes left in a sample
N_0 = number of atoms in an original sample (at the time t=0 when the organism died)
λ = decay constant

The decay constant λ defines the rate of decay. The commonly used term half-life ($t_{1/2}$ = 5730 ± 30 yrs) (Godwin 1962), which is the time for one-half of the remaining ^{14}C radionuclide atoms to decay, is related to the decay constant λ as follows:

$$t_{1/2} = \ln 2/ \lambda$$

This means that after 5730 years, only half of the initial ^{14}C radionuclide atoms in the original sample (N_0) remain, after two half-lives (after 11 460 years), a quarter of ^{14}C atoms remain, and so forth. Conventional radiocarbon ages are calculated using the half-life and are reported, for example, as 5000 ± 50 yrs BP (POZ-20063), where the age, a laboratory-specific estimate of the error in the age (1σ or 2σ confidence level) and the laboratory code are listed. BP stands for "before present", referring to the number of years before CE 1950 (CE = Common Era, i.e., BC (before Christ).

An obtained ^{14}C age in radiocarbon yrs BP is not the same as the calendar age of the sample, mostly because the proportion of ^{14}C in the atmosphere is not constant and has varied over the past 50 000 years. There are several prerequisites that must be known, determined or assumed before an obtained radiocarbon age can be translated into a calendar age with reasonable precision. Two of these prerequisites, the half-life of ^{14}C and natural levels of present ^{14}C, are known precisely enough. However, assumptions have to be made of the ratio between ^{14}C, ^{13}C and ^{12}C in different carbon reservoirs (atmosphere, biosphere, freshwater, marine water). It also has to be estimated whether complete and rapid mixing of ^{14}C has taken place in these reservoirs. In addition, it must be also considered whether the initial ratio between different carbon isotopes has been altered prior to or after the death of the organism.

11.2.2 Error sources of ^{14}C dating

Several factors can affect the accuracy of radiocarbon dating (e.g., Walker 2005):

1. Contamination is the main source of error, where there is an addition of older or younger carbon to a sample. Older carbon residues from weathered (carbonate) rocks derived in depositional basins can especially contaminate lake sediments, yielding too old ages for the samples dated. An addition of younger carbon can result, for example, from the downward penetration of roots or humic acids into peat, limnic mud or/and soil profiles and lead to too young ages. Contamination can also occur in field sampling and in laboratory procedures. The contamination of old and young carbon can cause major errors in radiocarbon dating results.

2. Isotopic fractionation is another potential source of error that causes different carbon isotopic proportions in samples compared to that of the atmosphere. In general, all biological pathways in the terrestrial realm have a tendency for preferring the lighter isotope ^{12}C to be taken up, while ocean water and marine organisms prefer to absorb isotope ^{14}C. The marine reservoir effect, i.e., differences in radiocarbon isotope proportions in ocean waters used by marine organisms to build their skeletal parts, has to be considered while dating marine organisms. Different photosynthesis pathways of plants also affect the carbon isotopic proportions. The effect of isotopic fractionation can be assessed and corrected by defining the $^{13}C/^{12}C$ ratio of a sample and comparing this ratio with the international PDB standard (belemnite carbonite from the Cretaceous Peedee Formation in South Carolina, USA). The $\delta^{13}C$ value (Eq. 5) provides a measure for the isotopic fractionation of a sample.

$$\delta^{13}C = [(^{13}C/^{12}C)_S / (^{13}C/^{12}C)_{STD} - 1] \times 1000‰ \qquad (Eq. 7)$$

where $(^{13}C/^{12}C)_S$ = the C-13 and C-12 isotope ratio in the sample and $(^{13}C/^{12}C)_{STD}$ = the C-13 and C-12 isotope ratio in the standard.

$\delta^{13}C$ values of terrestrial wood, peat and plants using the C_3 photosynthesis pathway are normally around -25‰, marine plants around -15‰ and atmospheric CO_2 -8‰. Each per mille difference from -25‰ represents approximately 16 years in age estimation.

3. Atmospheric variation in the $^{14}C/^{12}C$ ratio is the third source of error in radiocarbon dating. It is nowadays well known that the production of ^{14}C (see Eq. 1) has not been constant through time. There are many reasons for the fluctuations in ^{14}C production, with perhaps the main influence being modulation of the cosmic ray flux due to changes in Earth's geomagnetic field and /or the intensity of solar activity (e.g., Stuiver et al. 1991). Therefore, the radiocarbon yrs BP measured from a sample do not represent true calendar years, as noted above, and radiocarbon ages have to be calibrated using calibration curves to yield calibrated radiocarbon ages (abbreviated as cal yrs BP or cal BP = calibrated or calendar years before the year CE 1950) (Fig. 16). The calibration curves are based on comparing radiocarbon ages with the known variation in the atmospheric $^{14}C/^{12}C$ ratio constructed from annual records such as tree rings, varved lake sediments, speleothem and marine sediment (e.g., U-Th-dated corals) records. The recent IntCal20 northern hemisphere radiocarbon calibration curve covers the time span between 0 and 55 000 cal PB (Reimer & IntCal Group 2020). The dendrochronological part of the IntCal20 northern hemisphere radiocarbon calibration curve covers ca. 13 910 cal BP, and the older part of IntCal20 comprises floating tree-ring chronologies, lacustrine and marine sediments, speleothems and corals back to ca. 53 970 cal BP, with marine reservoir-corrected Cariaco Basin data providing an extension of the curve to 55 000 cal BP (Reimer & IntCal Group 2020, Heaton et al. 2020a,b).

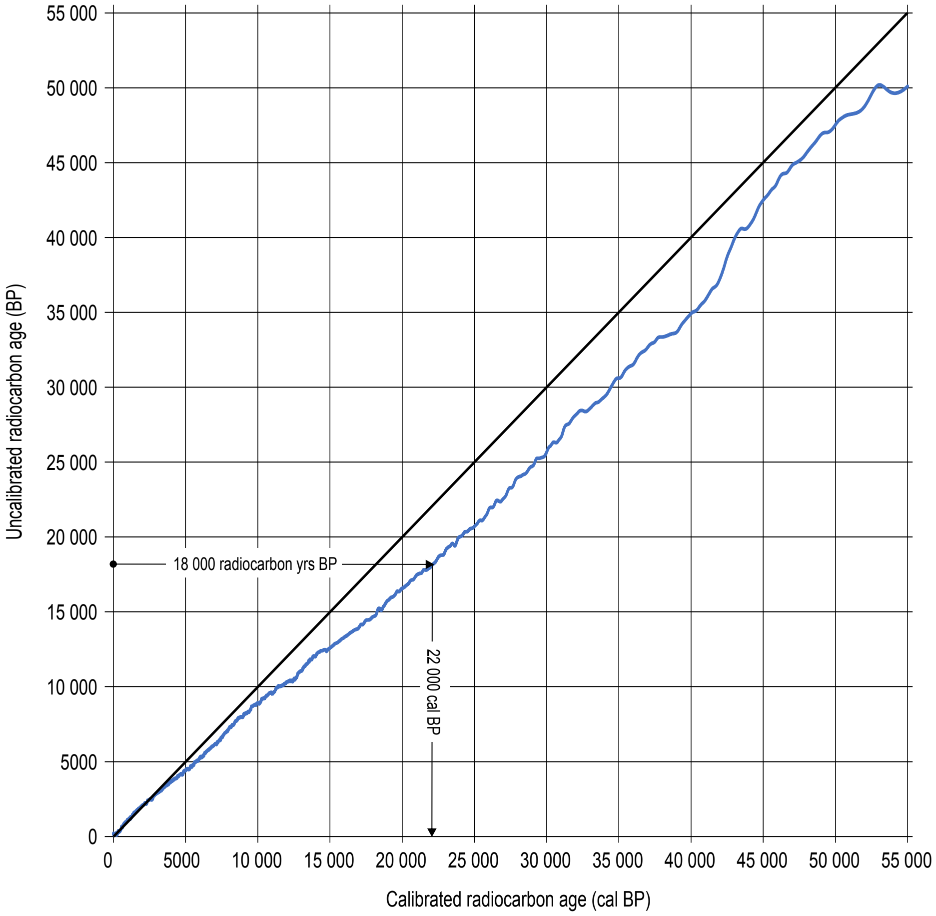


Fig. 16. The Northern Hemisphere calibration curve INTCAL20 (http://www.intcal.org/), showing the relationship between uncalibrated radiocarbon ages (yrs BP) and calibrated radiocarbon ages (cal BP), the latter representing calendar years before the year CE 1950 (Reimer & IntCal Group 2020). An example is given for the calibration of a radiocarbon measurement of 18 000 years, which is calibrated to ca. 22 000 cal BP using the CALIB Radiocarbon Calibration program (http://calib.org/calib/).

11.2.3 Techniques and datable materials

Three principal techniques are used to measure the ^{14}C content of any given sample: gas proportional counting, liquid scintillation counting and accelerator mass spectrometry. The accelerator mass spectrometry (AMS) method is the most modern radiocarbon dating method and provides an efficient way to measure the radiocarbon content of a sample. In this method, the content of the isotope ^{14}C is directly measured relative to the isotope contents of ^{12}C and ^{13}C present in the sample. The method enables the number of carbon atoms present in the sample and the proportion of the carbon isotopes to be counted.

In two other methods, mainly used prior to the invention of the AMS method, emitted beta particles produced during the radioactive decay process are counted. In the gas proportional counting method, the carbon sample is first converted to carbon dioxide gas before measurement is carried out. Gas proportional counting counts the beta particles emitted by a given organic sample. The liquid scintillation counting technique is based on adding a scintillator to a sample that is in a liquid form. This scintillator produces a flash of light when it interacts with a beta particle, and based on these flashes of light, beta particles are registered. Further details of these techniques are presented, for example, in Walker (2005).

Most organic materials in various geological samples can be radiocarbon dated. Wood, such as fossil trees and twigs, plant macrofossils, charcoal and peat from originally terrestrial realms are best suited for C-14 dating. Physical and chemical pretreatments should be carried out on these materials to remove possible contaminants before they are subjected for dating. In addition, error sources should be considered and calibration of C-14 ages to calibrated ages performed when assessing the true age of a sample. A number of calibration programs are available, such CALIB (http://calib.org/calib/calib.html) (Stuiver & Reimer 1993) and Oxcal (https://c14.arch.ox.ac.uk/oxcal.html), in which radiocarbon ages can be calibrated to calibrated radiocarbon years.

11.3 Luminescence dating

11.3.1 Background

Thermoluminescence (TL), optically stimulated luminescence (OSL) and infrared stimulated luminescence (IRSL) dating methods are based on the luminescence phenomenon and are widely used to date Quaternary sediments (e.g., Jull 2018). These methods measure how much time has elapsed since quartz and/or feldspar minerals in a sediment deposit or archeological remain/sample were last exposed to daylight or heated to a few hundred degrees Celsius. The luminescence phenomenon is based on the ability of quartz and feldspar to accumulate electrical charges in their lattice and release the energy of this charge as photons (light) once submitted to an external stimulus (e.g., Preusser et al. 2008). During the past two decades, OSL has been most commonly used method to date Pleistocene and Holocene quartz-rich minerogenic sediments (sand and silt) that often lie in between the above till sequences.

Sediments in glacial and non-glacial environments are transported by wind, water, ice and gravity. If sediments are exposed to sunlight during transportation, they will be zeroed (i.e. bleached, meaning the removal of trapped electric charge due to exposure to light/heating) of any previously acquired luminescence signal (Fig. 17). Once sediments containing quartz and feldspar minerals are deposited and subsequently buried, natural radioactive decay from surrounding rocks and minerals in the depositional environment start to accumulate energy in the buried quartz and feldspar minerals (Fig. 17). The number of trapped electrons (energy) accumulated into their mineral lattices is proportional to the time the sediment has been buried and the radioactive dose they receive per unit of time in their depositional environment. This is known as the dose rate (D_R).

For dating purposes, the so-called paleodose, i.e., the amount of absorbed energy accumulated in mineral lattices during burial, is estimated. In a laboratory, the natural luminescence signal of a sample is compared with applied artificial irradiation doses (heat in the TL method and visible light in the OSL and IRSL methods) to obtain the equivalent dose (D_E). All methods to measure the equivalent dose (D_E) involve measuring the response of samples to radiation treatment. This also requires measurements of the luminescence intensity emitted by a sample after it is given a series of known laboratory doses. The equivalent dose (D_E), expressed as energy per mass of mineral ($1\ J\ kg^{-1} = 1\ Gy$ (Gray)), is simply an estimation of the true *in situ* paleodose during sediment burial. To define the age of a sample, a dose rate (D_R) has also to be measured. The dose rate (unit Gy/1000 years, commonly expressed in geology in Gy/ka) is simply the amount of energy absorbed by a mineral, which can be used as a natural dosimeter per unit time and mass. The amount of energy absorbed results from naturally occurring radiation in both the sample and its environment. These measurements can be performed during sampling in the field or from the sample itself in the laboratory.

The luminescence age of a sample can be determined by dividing the equivalent dose (D_E) by the dose rate (D_R) (Fig. 17). The equivalent dose measurements have changed from the thermoluminescence (TL) and multiple-aliquot techniques of the 1970s to 1990s (Wintle 2008) to single-aliquot and ever smaller aliquot methods particularly developed for optically stimulated luminescence (OSL) and infrared stimulated luminescence (IRSL) dating (Mahan et al. 2023). The single-aliquot regenerative dose (SAR) protocol (Murray & Wintle 2000) is the preferred method for quartz and feldspar luminescence dating. In this protocol, the natural signal (Ln) and luminescence signal from a series of regenerative doses (Lx) are measured from individual aliquots or grains. A fixed test dose is given and measured after each Ln and Lx measurement to determine the sensitivity change between measurements. After this, the sensitivity-corrected natural signal is interpolated onto the so-called dose response curve (DRC). The DRC is basically obtained from luminescence intensity values emitted from the sample after a series of known laboratory doses are given. This is essentially a calibration method completed for each aliquot measurement. Where the natural signal (Ln) falls on the dose response curve determines the value of D_E. Multiple measurements of D_e are combined through statistical techniques to obtain the final paleodose value, which is used in age determination.

The maximum age range of the standard OSL method using quartz is 100–200 ka when the saturation levels (i.e., the point in the DRC where a higher laboratory dose does not produce a linear luminescence signal) are around 100–200 Gy and dose rates 1–2 ky/ka. However, older OSL ages, verified from independent chronometers, have also been obtained using improved techniques and in low natural dose environments (e.g., Rhodes 2011, Ankjærgaard et al. 2013, Ellerton et al. 2020). Luminescence dating with feldspar can potentially range up to over 500 ka, because feldspar has higher saturation levels than quartz, despite the higher dose rate.

The standard OSL method on quartz is most commonly used to date Quaternary clastic sediments, excluding till, in Finland. Hitherto, this OSL method has offered the best opportunity to date fluvial and glacifluvial sediments that lie between till strata and relate to warmer interglacial and interstadial phases in the Fennoscandian Ice Sheet area. Recently, Sarala et al. (2022) established an OSL database (version 1) for Finland, in which most of the OSL ages published in Finland are listed. The database will be regularly updated in the future. For good summaries of luminescence dating methods, applications and the interpretation of luminescence results, see, e.g., Wintle (2008), Preusser et al. (2008), Rhodes (2011), Smedley & Wintle (2018) and Mahan et al. (2023).

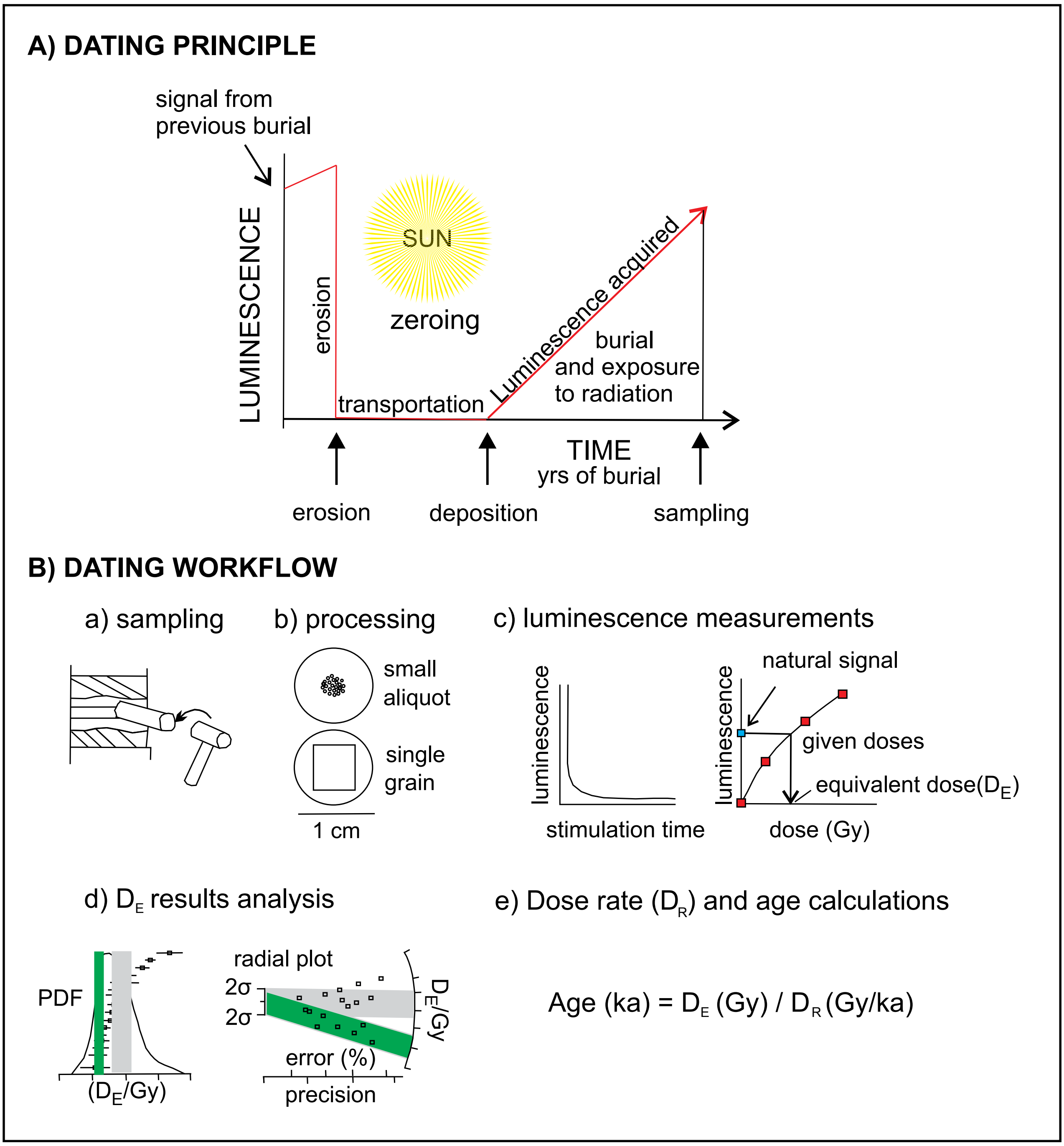


Fig. 17. A) The basic concept of luminescence dating: Sediment eroded and transported by wind, water, ice and/or gravity can be exposed to sunlight and zeroed (bleached) of any previously inherited luminescence signal. After transportation, sediment is deposited and subsequently buried. Once buried, sediment it is not exposed to light but to low levels of natural radiation in the surrounding sediment and bedrock. As time passes, quartz and feldspar minerals accumulate a luminescence signal as ionizing radiation excites electrons within parent nuclei in the crystal lattice. A certain proportion of the freed electrons become trapped in the quartz or feldspar crystal lattice defects, and the number of trapped electrons increases over time and is dependent on the time sediments including quartz and feldspar minerals have been buried. B) Dating workflow showing the main steps of the luminescence dating procedure: a) sampling of suitable sorted sediments in the field (mainly siliclastic sand and silt) for luminescence dating, b) processing of sample material aliquots/single grains for measurements, c) luminescence measurements (e.g., a natural signal and a response curve) defining the equivalent dose (D_e), d) the statistical analysis of the equivalent dose (D_e) measurements and e) dose rate (D_r), and age calculations (ka = thousand years). Modified after Ritternour (2018).

11.3.2 Error sources and uncertainty

There are a number of error sources and uncertainties in luminescence dating. Luminescence ages have a minimum uncertainty of 4–5% at best. The errors causing uncertainty are mainly systematic errors in both the dose rate and equivalent dose estimations (Wallinga & Cunningham 2014). In reality, random and systematic uncertainty in determinations of the equivalent dose rate (D_E) value related to laboratory instrumentation, measurement protocols, the sediment bleaching history, and the sedimentological and geological setting are much higher than 5%.

In practical luminescence sampling, the sampling site and sediments suitable for sampling need to be carefully selected and the deposition environment fully understood. The key issue is to assess whether the sediment that will be sampled has been exposed to light and thus bleached during its transport and deposition. Such an interpretation of the sedimentary environment requires knowledge of sedimentology, which helps to interpret the environmental controls on bleaching. This is particularly important when sampling is carried out from sediments deposited in glacial environments, where glaciofluvial/-lacustrine/-marine sediments are normally transported with minimal or no exposure to light and where the sedimentation rate is high in often turbid water. It also has to be acknowledged that in all environments, including glacial environments, around 50% of deposition may occur in total darkness (e.g., Rhodes 2011). An optimal depositional environment in a glacial setting where the likelihood of complete bleaching is high would be, for example, shallow water sandur braidplain and glaciofluvial delta topset environments. Luminescence characteristics, i.e., the bleaching rate and residual signal levels, also have an effect on bleachability and on residual signal levels. Studies have demonstrated, for example, that quartz eroded from bedrock and deposited in many of the glacial sub-environments at or close to the ice margin typically have a low OSL sensitivity, i.e., are poorly bleached, whereas quartz that has been reworked and re-cycled during its depositional history is often well bleached (e.g., Rhodes 2011).

Another potential dating uncertainty relates to the error in the dose rate (D_R) calculation, which is normally ±5–10%, with random and systematic errors being related to instrumentation and environmental effects (e.g., Mahan et al. 2023). The main environmental uncertainties are due to assumptions of a) secular equilibrium in the U and Th decay chain, b) the conversion factors in D_R calculations from radionuclide concentrations, c) the degree of beta and alpha attenuation related to grain size and d) the level of internal radioactivity of grains (particularly in the case of feldspars). Cosmic and gamma rays affect samples close to the ground surface, and the burial depth of a sample therefore has to be considered when estimating D_R. The greatest uncertainty affecting D_R is, however, related to the estimation of the sediment's interstitial water content at the time of burial (e.g., Mahan et al. 2023). It is in some cases very difficult to estimate the water content of sediment during the sediment's entire burial history. For example, every 1% increase in water content by weight (water/dry sediment) increases the age by about 1%. This implies that if the estimated water content of a sample differs on average by 5% from the true water content, for a luminescence age face value of, for example, 100 ka, the error will be 5 ka simply from using the wrong water content estimate.

All in all, luminescence dating techniques have proven to be analytically straightforward and sound, but potential errors may arise from false understanding and estimations of 1) bleaching during sediment transportation and deposition and 2) the water content history during the time of burial. A number of tests can be applied to detect incomplete bleaching, but water content estimates in many cases cannot be precisely defined. However, it must be borne in mind that in most of the sedimentologically well-known depositional environments from where samples are extracted, accurate estimates of the sediment water content percentage during the burial time are possible to make.

11.4 Surface exposure dating based on terrestrial cosmogenic nuclides (TCN)

Surface exposure dating techniques are a suite of dating methods that are used to date various types of geological events, ranging from lava flows to rock avalanches and cave development chronology. The terrestrial cosmogenic nuclide (TNC) method can be used to evaluate the exposure time of the rock (near)surface, to estimate erosion and weathering rates and to date the burial time of sediment. The method was first introduced for geological applications by Davis and Schaeffer (1955). In glacial environments, the TCN method is most often used to date the advance and retreat history of glaciers and ice sheets and glacio-isostatic land uplift, and it is also well suited to dating the bedrock erosion history of barren bedrock areas. The cosmogenic nuclide dating technique is based on the interactions between cosmic rays and nuclides formed in bedrock exposures or glacially eroded erratics (boulders) when exposed from underneath the ice sheets on terrain surfaces, and is used to determine the exposure history.

The primary cosmic rays include high-energy particles that interact with atoms in Earth's atmosphere, where a cascade of secondary cosmic particles form. This cosmic ray flux then absorbs into exposed rock surfaces and produces *in situ* terrestrial cosmogenic nuclides. The use of TCN as a dating tool is based on the known production rate of a specific cosmogenic nuclide, which enables the calculation of the rock's surface exposure age. The theory underlying the TCN method is described in detail in Gosse and Phillips (2001).

The method assumes a constant production rate of nuclides. However, the geomagnetic latitude, variations in the magnetic field, elevation (atmospheric pressure), sample density and the shielding of the sample during its history especially affect the production rate. To approximate the production rate of cosmogenic nuclides for a certain geographical area, different scaling models (e.g., Balco et al. 2008, the online calculators formerly known as the Cronus-Earth online calculator at http://hess.ess.washington.edu/math/v3/v3_cal_in.html) or onsite measurements of rock that has a well-known exposure history can be used (Borchers et al. 2016)

The most commonly used isotopes are ^{10}Be and ^{27}Al, but ^{36}Cl, ^{14}C, ^{3}He and ^{21}Ne have also been utilised for dating. Quartz (SiO_2) is the most frequently used medium for TCN surface exposure dating. Quartz is abundant in surface rocks, and when affected by cosmic rays, its isotopes ^{16}O and ^{28}Si are transformed to ^{10}Be (primarily originating from ^{16}O but also from ^{28}Si) and ^{26}Al (originating from ^{28}Si). Quartz-bearing rocks are typical in the crystalline bedrock of the Fennoscandian Shield, which makes TCN dating a potential tool to date the history of the Fennoscandian Ice Sheet (e.g., Rinterknech et al. 2004).

When interpreting TCN results, indications of the reburial of a sample and the possibility of inherited TCN concentrations should be taken into account. Measurements of two elements that have a constant production rate ratio but a different half-life can be used to evaluate interruptions in exposure, i.e., burial of the sample, for example, underneath glacial or other thick sediment cover after initial exposure (Fig. 18). ^{26}Al and ^{10}Be are a commonly used pair, as both can be measured from quartz. The commonly cited production rate ratio for ^{26}Al/^{10}Be is 6.75 (Balco & Rovey 2008). However, some more recent studies have suggested higher ratios (see, e.g., Borches et al. 2016, Corbett et al. 2017). If the erosion event to be dated has not been strong enough, the remaining surface typically shows inherited signals of cosmogenic nuclides that were produced when the surface to be dated was near the surface but not exposed. Cosmic rays penetrate more than 1 m beneath the rock surface. Inherited TCN concentrations are typical for weakly erosive areas, such as central Finnish Lapland (e.g., Darmody et al. 2008, Peltonen et al. 2024), and apparent TCN ages are old. However, the erosion and reburial of the sample can be approximated by combining two (Fig. 18) or three elements.

Typical applications for TCN dating include the dating of erosion surfaces (e.g., mass wasting earthquake, glacial plucking), but it is also used for determining the rate of weathering and erosion or the burial time of a surface. In Finland, cosmogenic isotopes have been used to estimate the deglaciation chronology of the Fennoscandian Ice Sheet (Rinterknect et al. 2004, Cuzzone et al. 2016) and the rate of weathering and glacial erosion (e.g., Darmody et al. 2008).

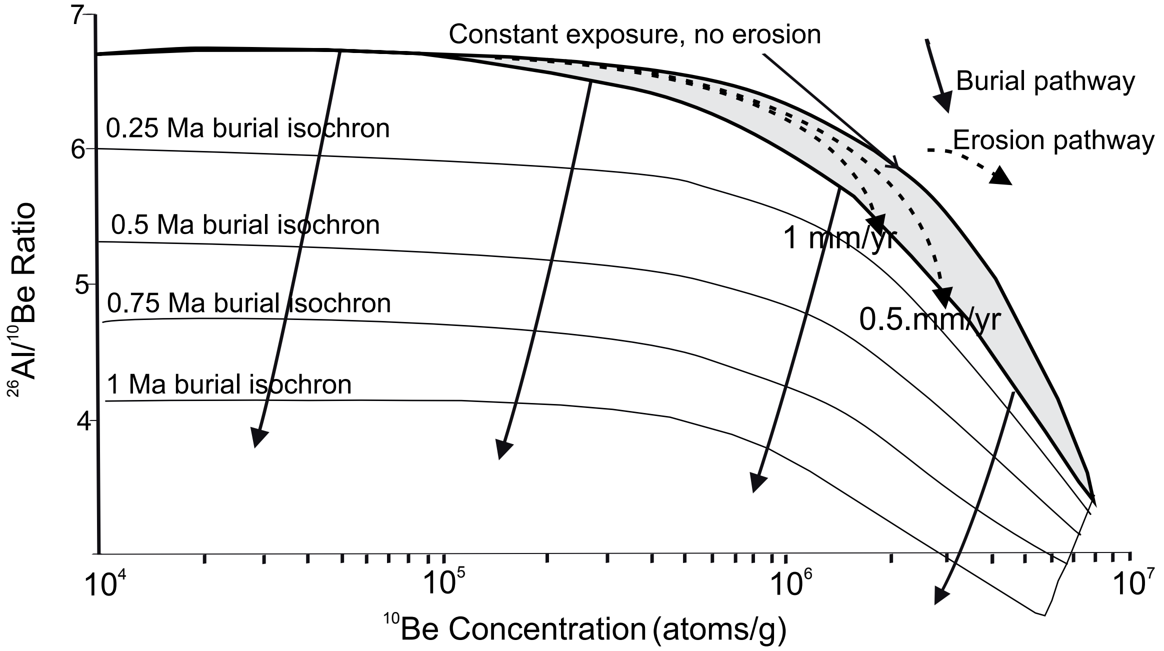


Fig. 18. The erosion rate and the reburial duration of a sample can be assessed by comparing the ^{28}Al/^{10}Be ratio with the ^{10}Be concentration. In the banana plot, the reburial trajectory is depicted as moving downward, due to the faster decay of ^{28}Al relative to ^{10}Be, and to the left, reflecting the loss of ^{10}Be nuclides. As the ^{10}Be concentration increases, the constant exposure line shifts downward, driven by the quicker decay of ^{28}Al. A higher erosion rate accelerates the decline of the ^{28}Al/^{10}Be ratio in comparison to the ^{10}Be concentration. The banana plot is adapted from Corbett et al. (2013).

11.5 Dating based on annual increments varves

Sedimentary varves in lacustrine and marine environments, ice cores, tree rings, speleothems and biogenic banded records, such as corals and bivalve shells, have distinct layered structures that make up sequences of seasonal laminae, annual varves or growth increments through time (Walker 2005, Zolitschka et al. 2015). Where there is sufficient understanding and evidence for the seasonal/annual formation of these archives, their structures can be used by means of chronological sequences for studies of the past climate and environmental change. These archives can provide either absolute, discontinuous or floating varve chronologies (Ojala et al. 2012) (Fig. 19). With absolute chronologies, an annual growth increments or depositional lamina is tied to the present day, allowing counting back in time and yielding continuous calendar-year chronologies. With floating chronologies, their chronological timeframe is also annual, but relatively anchored to a specific and precisely determined event, such as the deposition of tephra (Zillén et al. 2002, Kalliokoski et al. 2023) or a hydrological change within a basin (Sauramo 1918). The continuous and uninterrupted chronological framework gained through the counting of annual growth increments or depositional features is a major advantage of annually dated archives compared with radiometric dating methods that are based on discrete samples and interpolation between their dating results (Zolitschka et al. 2015).

In Fennoscandia, archives of annually laminated (varved) sediments and tree rings (dendrochronology) have been widely used as a basis for Late Pleistocene to Holocene chronologies (e.g., Sauramo 1929, Eronen et al. 2002, Ojala & Alenius 2005, Helama et al. 2008, Ojala et al. 2012). A multi-millennial tree-ring chronology for Finnish Lapland, extending back to 5634 BCE, is the longest conifer tree-ring chronology in Eurasia, but other tree-ring chronologies are also available from different parts of Finland (e.g., Helama & Lindholm 2003, Helama et al. 2008). The techniques and applications of measuring and examining tree-ring chronologies are presented, for example, in Walker (2005) and Eronen et al. (2002).

Varved sediments are sediment successions that represent a seasonal cycle of sedimentation and have been accumulated and preserved in sedimen-

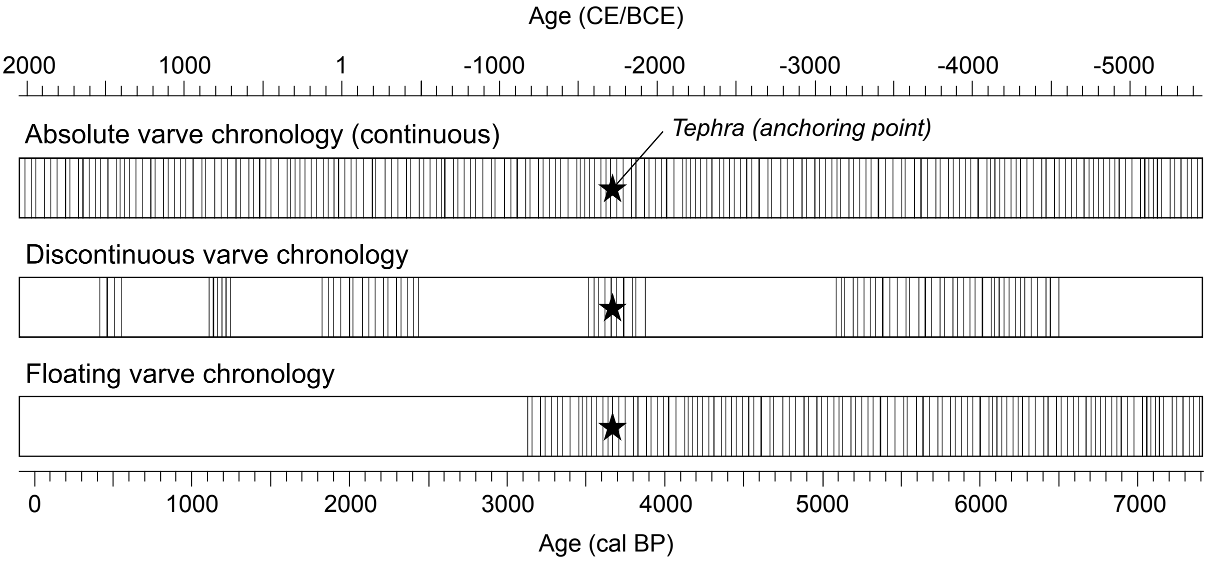


Fig. 19. Varve chronology is the use of varved sediment structures to establish ages in sedimentary sequences for dating and correlation. Varve chronology can be absolute, discontinuous or floating, and different varve chronologies can be matched using well-established anchoring points, such as identified cryptotephras (e.g., Zillén et al. 2002, Kalliokoski et al. 2023).

tary basins. A varve is a set of at least two or more seasonal laminae that can be identified visually and/or by content (biological, chemical, physical) and separated into distinct parts. The deposition of each lamina is often driven by the annual cycle of climate variability or pulses of periodic events, such snowmelt and runoff, calcite precipitation or algal blooms (Zolitschka et al. 2015, Schimmelmann et al. 2016). Varves have been described in proglacial, lacustrine and marine environments, and their formation and composition are governed by various climatological, hydrological, limnological and biological processes. Based on their genetic concept and laminae composition, varves are typically categorized into (i) clastic varves, (ii) biogenic varves and (iii) endogenic varves, although they rarely exist as pure end members, but rather as mixed varves of these three types (Zolitschka et al. 2015) (Fig. 20). A conceptual and idealised model for the varve formation process is a prerequisite for a varve chronology and applications of varve-related sedimentary data. The different approaches to demonstrate the annual nature of laminated sediments and to develop a process-related varve model are presented in Zolitschka et al. (2015).

Numerous sites with varved sequences and different varve types have been found and described in Finland (e.g., Sauramo 1918, Ojala et al. 2000). Proglacial varves reflect the seasonal fluctuation of glacial meltwater flow from continental ice sheets or smaller glaciers during deglaciation and have been used to compile classical varved-clay chronologies in Sweden and Finland (De Geer 1912, 1940, Sauramo 1918, 1929). Even today, these varve chronologies and varve thickness variations are applied as a basis for the rate of deglaciation, position of the retreating ice margin and the termination of the Pleistocene Epoch in the Fennoscandian Ice Sheet area. The varved-clay chronologies can be considered as floating ones. A clastic-biogenic (or clastic-organic) mixed varve type is frequently found in lacustrine environments in Finland and Sweden, which have been used as lacustrine chronological sequences in Holocene climate reconstructions (Renberg 1981, Tiljander et al. 2003, Zillén et al. 2003, Ojala & Alenius 2005). Biogenic lacustrine varves are also formed and preserved in a number of boreal lakes in Finland and have been used in Holocene climate and anthropogenic impact studies (e.g., Saarni et al. 2015, 2016, Salminen 2022). Lacustrine varve chronologies that are based on organic and clastic-biogenic varve types in Finland are mostly absolute and fixed to the deposition of the topmost varve on the sediment surface. The marine environment generally experiences higher energy levels than lakes, which hampers the deposition of continuous varved sequences, especially in shallow areas. Despite this, comparably long continuous clastic-organic varved sequences have been documented from the deep basins of the Baltic Sea (Burke & Kemp 2002) and in sheltered coastal sub-basins (Jokinen et al. 2015).

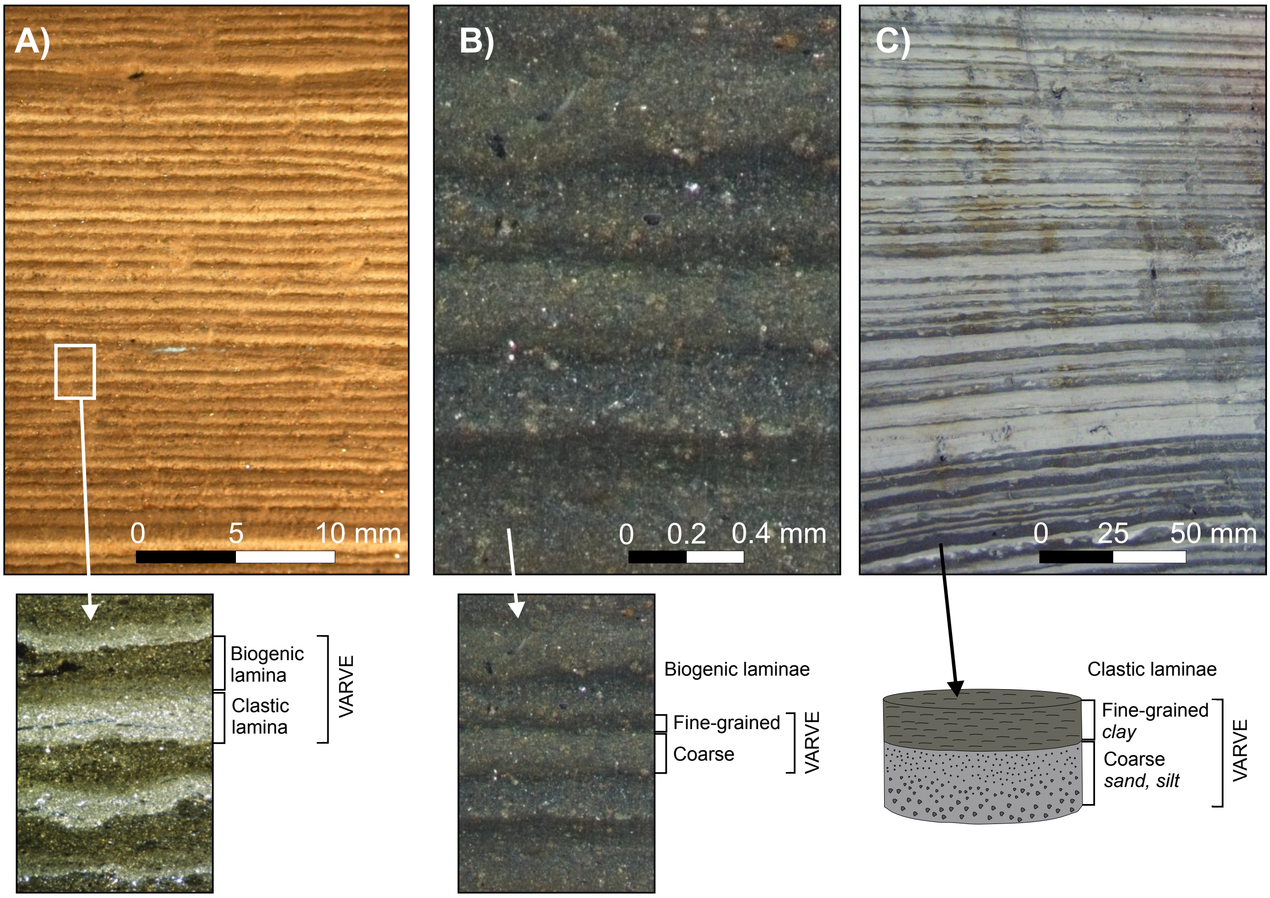


Fig. 20. Examples of the different types of varves: A) clastic-biogenic varves from Lake Nautajärvi, central southern Finland (Photograph: A. E. K. Ojala, GTK and University of Turku), B) biogenic varves from Lake Kallio-Kourujärvi, central Finland (Photograph: S. Saarni, University of Turku) and C) glaciolacustrine clay varves from Koria, southern Finland (Photograph: O. Hyttinen, Sitowise, Tampere).

The most important attribute of varved sequences is that they provide an inherent and continuous high-resolution timescale (varve chronology) for studies of climate and environment change. Varves are typically counted from the cleaned fresh sediment surface (or photographs), on epoxy-embedded sediment blocks or thin sections with thorough microscopic analyses combined with sophisticated digital image analysis techniques, or counting is based on elemental analysis by micro X-ray fluorescence (mXRF) spectrometry, Fourier transform infrared spectroscopy (FTIRS) or scanning reflectance spectroscopy in the visible spectrum (Zolitschka et al. 2015).

The longest uninterrupted varve chronologies in Finland extend from the present day to ca. 9850 cal BP (Ojala & Tiljander 2003), but their temporal extension is typically between 1000 and 5000 years (e.g., Saarnisto et al. 1977, Haltia-Hovi et al. 2011, Saarni et al. 2015, 2016). Like most annually resolved natural archives, such as ice cores and corals, every varve-based sediment chronology contains uncertainties and dating errors when extended thousands of years back in time. The reliability of established varve chronologies needs to be determined, verified and errors estimated in a multidisciplinary way. Of these, repeated varve counts on several cores and/or by different media and comparison with other independent dating methods are the most robust and widely used procedures (Zolitschka et al. 2015). Chronological errors associated with varve analysis and counting generally fall between ±1–3%, depending on the length of the sequence, as well as varve thickness and quality (Ojala et al. 2012). A well-established varve chronology enhances the scientific value of sedimentary archives by anchoring the wealth of paleoenvironmental information in an age–depth time series for multidisciplinary analysis.

Late Pleistocene to Holocene varve chronologies have also been applied in validation and assigning ages to other (relative) sediment dating methods, such as dating based on paleosecular variation (paleomagnetic reference curves) (e.g., Ojala & Tiljander 2003, Snowball et al. 2007) and widely distributed tephra layers in the Northern Hemisphere (e.g., Brauer et al. 1999, Zillén et al. 2002, Wulf et al. 2013). In Japan, the 50 000-year-long varved record of Lake Suigetsu has demonstrated the potential for developing a terrestrial macrofossil-based radiocarbon calibration curve across the full range and detection limit of ^{14}C-dating (Bronk Ramsey et al. 2012).

12 SUMMARY

Formal stratigraphic practices are challenging to apply to sediments deposited in formerly glaciated terrains such as Finland. This is mainly because individual sediment units are thin and highly limited in their lateral extent. Therefore, instead of applying formal stratigraphic procedures, there are many informal practices to classify Finnish Quaternary deposits. The stratigraphic practices used for the categorisation have been and are at present mainly dependent on the nature of basic or applied research foci and the availability and development of technical devices to categorise different aspects of the Quaternary sediment strata and their three-dimensional entities.

The pre-Holocene sediment strata in Finland, as well as in other repeatedly glaciated areas normally lack long continuous sediment sequences and sediments, can also be deformed to various degrees and/or eroded. Therefore, stratigraphic correlation between different sections and areas or time correlation should not rely only on litho- and biostratigraphy if other means for correlation are more applicable. It is also advisable not to only use till units and their clast fabrics as marker beds for stratigraphic correlation, since till genesis and ice-flow direction patterns are diachronous and may differ greatly over long distances. Instead, organic beds that interlay till units and their biostratigraphic information (e.g., pollen), together with geochronological methods, should be preferred when all types of correlation schemes are made. It is equally essential that samples for independent age determinations are taken from suitable sediment beds in natural sections or boreholes. At present, the absolute dating methods applicable for organic and sorted clastic sediments include radiocarbon, thermoluminescence and TCN methods. The AMS radiocarbon dating method, when error sources are considered, has proven to be a reliable dating method for terrestrial organic material such as gyttja and peat, and especially for plant macrofossils, fossil wood and bones. Recent, INTCAL20 calibration curves (Reimer & IntCal Group 2020, Heaton et al. 2020b) for the Northern Hemisphere, covering the time period from the Holocene Epoch to the Late Pleistocene Middle Weichselian Substage, i.e., the past ca. 50 ka, have enabled more accurate age determinations for sedimentary units that contain organic beds. In addition to radiocarbon-based age determinations, clastic sediment units (mainly sand and silt) can be dated with luminescence dating methods.

The thermoluminescence dating method has been widely used in archeology, but also to date sand-rich beds sampled from geological sections. At present, the OSL method is the most widely used method in Finland and also elsewhere to date geological samples taken from sand and silt beds (Sarala et al. 2022). However, the error sources, such as incomplete bleaching and possible water content changes of the sediment beds during the burial time, have to be assessed and estimated when luminescence results are used. The OSL method can potentially date non-glacial, terrestrial sand and silt beds deposited in the age range between the Holocene Epoch and the Middle Pleistocene Late Saalian age (normally up to ca. 200 ka). In the Finnish context, the TCN method has mainly been used to date the last deglaciation chronology in Fennoscandia (e.g., Rinterknect et al. 2004, Cuzzone et al. 2016) and to estimate of weathering rate and glacial erosion rate (e.g. Darmody et al. 2008). In addition to specific sample site assumptions and an estimation of the nuclide production rate, it is important to consider the burial history of the surface to be dated, which helps in making assumptions about the inherited TCN concentrations.

Varve chronologies of clastic sedimentary varves deposited in a proglacial lake basin in front of a retreating ice sheet are used to establish timelines of deglaciation and correlation (e.g., De Geer 1912, Sauramo 1923). The correlation of individual varve records in glacial environments is generally based on the matching of the of varve thickness patterns that are similar for a set of varves or a single varve year across a limited region. They represent either floating timescales or timescales that are fixed to calendar years with other independent dating methods, such as radiocarbon dating or tephra chronology, thus providing an essential component of FIS deglaciation during the Late Weichselian and Early Holocene. Annually laminated sediments (varves) that cover the Holocene have been discovered in a large number of non-glacial lakebeds from many parts of the Fennoscandian Shield (Ojala et al. 2000, Zillén et al. 2003). These sediment sequences have been used to investigate multiple biological, physical and chemical climate and environmental proxies within a calendar year time scale. Many varved records provide a basis for understanding Holocene climate variability in Fennoscandia (e.g., Ojala & Alenius 2005, Giesecke et al. 2008, Saarni et al. 2016). Some varve chronologies have been cross-checked by radiocarbon dating, the most frequently used method to date Holocene lacustrine sequences in Finland, where potential sources of errors in ^{14}C dating have been highlighted (Ojala et al. 2019c). Carefully varve-dated lacustrine records in Finland and Sweden provide a basis for paleomagnetic dating using paleosecular variation (PSV) in the Earth's magnetic field (Ojala & Tiljander 2003, Snowball et al. 2007). These varve-dated master curves have then been applied to relatively date other sedimentary records used for palynological reconstructions or studies on settlement history (e.g., Alenius et al. 2017). Thus far, relative dating that leans on rapid geomagnetic excursions (geomagnetic 'jerks') has not been applied to date interglacial or interstadial sequences in the FIS area, although it holds some potential.

To establish a local Quaternary chronostratigraphy for Finland, it is important to use a combination of litho- and biostratigraphic approaches and absolute dating (or incremental dating / magnetostratigraphic techniques tied to absolute ages). During the past decades, considerable advances have been made in depicting a detailed, high-resolution Holocene stratigraphy for Finland using the combination of ^{14}C dating, biostratigraphic methods applied to lake (gyttja) and mire (peat) sediments, and varve- and paleomagnetic (PSV)-dated lacustrine records. Establishing a sound stratigraphy for the pre-Holocene has been challenging. However, there are a number of stratigraphically important sites in Finland where both organic units and clastic sorted sediment units occur, often interbedded with till units, in a single section or a borehole, and even within one sediment unit (see Fig. 3). These sediment successions should be used to establish stratotypes and type localities for different parts of Finland in order to construct a formal Pleistocene chronostratigraphy for Finland, and for its correlation with NW European and global Quaternary chronostratigraphies.

Mapping of Quaternary deposits and landforms has long been the focus of Fennoscandian geology. Due to the availability of 2-m-grid digital elevation models (LiDAR DEMs), glacial landforms can nowadays be mapped faster and in greater detail than ever before (e.g., Johnson et al. 2015). Modern mapping of Quaternary deposits and landforms is based on the MLG classification scheme, which has proven to be a useful approach to classify and map Finnish Quaternary deposits (McMillan 2005, Putkinen et al. 2017). The mapping of MLG units based on their (i) geomorphology, (ii) sediment composition and (iii) genetic interpretation has modernised Quaternary mapping in a more digital direction that can already be assisted by AI and machine learning techniques (e.g., Chandler et al. 2018). The resulting data can be implemented in practical approaches, such as hydrostratigraphy and engineering geological 2–3D modelling, but also have potential for significant advances in the development of new theories in glacial dynamics and geomorphology.

Allostratigraphy is a descriptive stratigraphic approach, which basically subdivides depositional successions into unconformity-bounded units in a hierarchical manner. It is an extremely useful stratigraphic tool and enables the rapid and unambiguous identification of deglacial and younger stratigraphic units in sediment cores from the Baltic Sea Basin. The bounding unconformities and geometry of the stratigraphic units can be traced in seismo-acoustic profiles basin-wide (Virtasalo et al. 2007, 2014, 2016). The unconformities also enable the correlation of the offshore sediment units with those currently on land (Ojala et al. 2018, Virtasalo et al. 2019). It is worth noting that allostratigraphic units should not be mixed with the classic Baltic Sea events, which were originally recognized based on mollusc finds on raised shores and later identified mainly on the basis of diatom analyses.

Sequence stratigraphy is a branch of stratigraphy that studies stratal stacking patterns and their stratigraphic relations (Catuneanu et al. 2011, Catuneanu 2017). It combines sedimentological and geophysical data sets with stratigraphic disciplines such as allo-, litho-, bio- and chronostratigraphy. The dominantly terrestrial and glacigenic Quaternary sedimentary record of Finland poses limitations to traditional sequence stratigraphic approaches. However, by examining the interplay between sedimentation and accommodation space development, we can gain valuable insights into the characterization and interpretation of (glacio)fluvial–(glacio)lacustrine depositional successions, in particular. This could be especially relevant in the case of the Salpausselkä ice-marginal complexes, whose evolution has been influenced by both the shifting ice-margin location as well as several lake-level changes. Subaquatic post-glacial sediments record a transition from glacially and lake level-influenced deposition to predominantly water level-controlled deposition, thereby approaching the traditional sequence stratigraphic setting.

Approaches to classify Finnish Quaternary deposits are many, ranging from traditional litho- and biostratigraphy to allo- and sequence stratigraphy. The MLG classification that has recently been introduced offers perhaps the most comprehensive approach to classify Finnish Quaternary deposits on land. Although the MLG classification scheme does not fulfil the requirements set by the formal stratigraphy, it is very applicable in fields of applied geology such as hydrogeology and provides the most complete picture of glacial and post-glacial sediments deposited during and after the Late Weichselian glaciation. In addition, the MLG classification approach yields valuable information on the dynamics of the Fennoscandian Ice Sheet during the last deglaciation. Stratigraphic evidence and absolute dating results demonstrate, however, that deposits older than the Late Weichselian exist in many areas throughout Finland. Sediment sequences that also include pre-Late Weichselian strata are best classified using litho- and biostratigraphic methods, aided by sequence and allostratigraphic approaches when applicable. In this task, it is most important to find suitable dating methods to date bio- and lithostratigraphically well-constrained sediment beds and define the local stratotype sections, through which the correlation between different areas is possible and a sound chronostratigraphy for Finland can be established.

The Finnish Stratigraphy Committee hopes that this comprehensive overview on various concepts regarding how to classify Quaternary deposits in Finland provides useful background and guidance for Quaternary scientists to carry out future stratigraphic work in various fields of basic and applied geology.

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