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Stratigraphic framework in Finland – formal classification and practical guidance

Juha Köykkä, Antti E. K. Ojala and Timo Tarvainen (eds)

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This volume is a revision of stratigraphic procedures and nomenclature in Finland. The articles provide practical guidance on the appropriate use of geological unit terminology in the Fennoscandian Shield area and Finnish perspectives on stratigraphy as a science. The first article by Kohonen et al. discusses the stratigraphic challenges typical for Precambrian shield areas, with the main emphasis on litho-based classifications. The authors present novel ideas regarding the efficient use of lithodemic units in map database structures. Additionally, the authors propose a new approach related to regional chronostratigraphic nomenclature. The second article is a completely revised edition of the 'Guidelines and procedures for naming bedrock units in Finland', with Juha Köykkä as the corresponding author. This new version aims to offer practical advice on the use of different bedrock unit classification systems in Finland, providing an update and revision of Strand et al. (2010). It also describes the current status regarding how various aspects of regional geology are covered by parallel but distinctly defined unit classifications. The final article by Lunkka et al. is the "Stratigraphic framework for the classification of Quaternary deposits in Finland". This paper introduces practices for the mapping and classification of superficial Quaternary deposits in Finland. It is not a formal stratigraphic guide or a stratigraphic code (Salvador 1994), but aims at introducing applicable approaches and practices through which different classifications have been and are currently applied to benefit both scientific interests and more applied research in Quaternary geology.

Keywords: bedrock, deposits, stratigraphy, Precambrian, Quaternary

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PREFACE

The establishment and management of geological bodies larger than a single observation point or outcrop creates a need for the identification of *geological units*. The classification, naming and correlation of these units and the description of their spatial and temporal relationships collectively constitute the science of *stratigraphy* (Salvador 1994).

Precambrian, dominantly Paleoproterozoic and Archean, bedrock units within the Fennoscandian Shield are covered by a thin veneer of Quaternary superficial deposits. The Precambrian bedrock is characterized by rock assemblages consisting of medium to high-grade metamorphic units, intruded by plutonic igneous rocks in various stages. The applicability of the formal *lithostratigraphic* approach is restricted for plutonic rocks, but also for gneissic and other highly metamorphic rocks without reliable control of the superposition of the mapped lithological units (e.g., Easton 2009, Pratt et al. 2023). The classification of Quaternary deposits in Finland encompasses similar challenges in lithostratigraphy, but for different reasons. The establishment of meaningful and mappable glacial and interglacial units is challenging due to their insufficient lateral continuity and connectivity, which in Finland has led either to a surface lithology-based mapping approach or, more recently, to the application of less formal systems, such as morpho-lithogenetic classification (see Palmu et al. 2021 and references therein). The regional classification of Quaternary deposits in the Fennoscandian Shield area and its surroundings 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). For the reasons above, in the Finnish research tradition, the application of formal stratigraphic procedures and nomenclature (Salvador 1994) has been limited in both Precambrian and Quaternary geology.

The present revitalization, or renaissance, of stratigraphy and other science-based geological classification systems has a close connection to the emerging applications of information technology and map data architecture (Ahtonen et al. 2021). The national databases of geological information and the underpinning data models greatly benefit from both defined classification concepts and the hierarchical structure of stratigraphic schemes. Furthermore, regional geology in the Fennoscandian Shield area is loaded with colloquial and informal terminology and site-specific names, and their inconsistent and overlapping use is one the major reasons for confusion and misunderstanding in scientific communication. Geological units constitute the most fundamental building blocks in geological mapping and description, and appropriate and accurate scientific terminology related to these should thus be essentially expected.

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Stratigraphic framework in Finland – formal classification and practical guidance
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Geological Survey of Finland, Bulletin 418, 6–36, 2024

STRATIGRAPHY OF PRECAMBRIAN ROCKS IN FINLAND: A REVIEW WITH EMPHASIS ON THE APPLICATION OF LITHODEMIC UNITS, REGIONAL CHRONOSTRATIGRAPHIC NOMENCLATURE AND MAP DATABASE MANAGEMENT

by

Jarmo Kohonen[1]), Juha Köykkä[2)] and Perttu Mikkola[3)]*

Kohonen, J., Köykkä, J. & Mikkola, P. 2024. Stratigraphy of Precambrian rocks in Finland: a review with emphasis on the application of lithodemic units, regional chronostratigraphic nomenclature and map database management. *Geological Survey of Finland, Bulletin 418*, 6–36, 11 figures and 5 tables.

The characterization, definition and classification of geological units and their correlation with geological time comprise one of the oldest branches of geology: *stratigraphy*. Systematic and hierarchical classification schemes for the different geological units largely define the structure of the *data model,* the framework underlying any digital map database and regional geological map compilation. This article reflects on the experience gained by the Geological Survey of Finland (GTK) during a reconstruction of the national map data architecture. We describe how different geological units have been used in the arrangement of the Precambrian rock bodies and present alternative options for the further development of (1) litho-based unit classification, (2) other geological unit types and their spatial representation and (3) chronostratigraphic nomenclature in Finland. This is a complimentary contribution related to the 2nd and revised (2024) edition of the '*Guidelines and procedures for naming bedrock units in Finland*'.

Lithodemic classification has been found functional in the naming of various nonstratiform rock bodies. However, problems have appeared in the systematic characterization of lithodemes. We discuss the combined use of lithostratigraphic and lithodemic classifications and present insights into the improved applicability of the lithodemic system. The benefits of independently defined, overlapping geological units, such as deformation units and alteration units, are described and their increased use is recommended.

General nomenclature referring to geological age is essential in scientific communication. To improve the inconsistent and insufficiently defined chronostratigraphic nomenclature, we introduce new regional time-stratigraphic scales for the (Paleoproterozoic) Karelian formations and Svecofennian rocks in Finland. Regarding the Meso- and Neoproterozoic rocks, the use of system and Period names of the International Chronostratigraphic Chart (ICS) is suggested and definitive abandonment of the obsolete traditional names Jotnian, postJotnian and subJotnian is proposed.

Keywords: bedrock, chronostratigraphy, database, lithodemic units, Precambrian

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1 INTRODUCTION

Stratigraphy is one of the most traditional and fundamental branches of geology. Research has been carried out for generations, and the stratigraphic classification categories have been developing step by step over time. The narrow meaning of the term stratigraphy is expressed as '*a branch of geology concerned with the study of rock strata and stratification*'. The broader definition is '*the science dealing with all rock bodies forming the Earth's crust and their organization into distinctive, mappable units based on their inherent properties'* (condensed from Salvador 1994, p. 137). In this article, the terms '*stratigraphy*' and '*stratigraphic*' (e.g., stratigraphic nomenclature, stratigraphic unit) are used in a meaning broader than the obsolete narrow definition, but still not encompassing all possible geological units (for details, see 2.2 below). For conciseness, the key references are presented in the text as abbreviations: Salvador 1994 (International Stratigraphic Guide), NASC 2005, 2021 (North American Stratigraphic Code; North American Commission on Stratigraphic Nomenclature 2005, 2021).

The stratigraphy of the Finnish bedrock has not been a popular topic, and the latest comprehensive stratigraphic summary is several decades old (Simonen 1986). Since then, however, major steps forward have been taken. Milestones include the application of formal lithostratigraphy (e.g., Laajoki et al. 1989, Laajoki 1991), the introduction of lithodemic units (Laajoki & Luukas 1988) and experiments in Precambrian sequence stratigraphy (e.g., Strand & Laajoki 1999). This activity was remotely related to the worldwide 'slow revolution of stratigraphy' (see Miall 2016) and the increased application of a sedimentological approach and basin analysis to stratigraphic studies. In 2006, the Stratigraphic Commission of Finland was founded and, some years later, the Precambrian Subcommission launched the first edition of the national guidelines for naming Precambrian geological units (Strand et al. 2010). The latest profound contribution is a discussion on the relationship between dated events and the traditional stratigraphic nomenclature of 'Karelian formations' (Hanski & Melezhik 2012).

The establishment of a nationally coherent and internationally compliant system of geological units is a major systemic, educational and technological challenge for the Finnish geoscience community, and especially for the coordinating agency, the Geological Survey of Finland (GTK). The application of stratigraphic nomenclature is not uncomplicated in Precambrian terrains dominated by gneissic rocks. Additionally, the transformation of heterogeneous and fragmentary legacy information, published as map sheets, their explanations and peer reviewed articles, to a harmonized system of stratigraphic units has been a demanding task.

Currently, the status of stratigraphic nomenclature in Finland is two-fold: the geological units are arranged into a GTK database, whereas the time-based nomenclature is utterly inconsistent. The mixed use of the formal chronostratigraphic nomenclature suggested by the International Union of Geological Sciences (IUGS, e.g., Paleoproterozoic, Ediacaran) and the regional, in part poorly defined and tradition-based nomenclature (e.g., Kalevian, Svecofennian, Jotnian, Vendian) forms a major source of conceptual confusion. Another challenge is the inconsistent usage of the currently diverse tectonostratigraphic and lithotectonic nomenclature in Finland. This article focuses on the classification of Precambrian rock bodies at the national level. The objectives are to clarify the principles underlying the present national (GTK) map database and the linked digital lexicon of geological units (FinstratiKP database). In the following sections, we (1) review the status of the bedrock stratigraphy in Finland, (2) reflect on practical experiences regarding the application of the national guidelines and (3) make proposals concerning the stratigraphic nomenclature in Finland. This article is a complimentary contribution related to the revised 2nd edition of the "*Guidelines and procedures for naming bedrock units in Finland*" elaborated by the Precambrian Subcommission of the Stratigraphic Commission of Finland (Kohonen et al. 2024, this volume).

2 APPLICATION OF STRATIGRAPHIC CLASSIFICATIONS

2.1 Stratigraphy: an anachronism or a flexible tool kit for modern data management?

Stratigraphy has a history. After the primary idea of a uniform 'time-based' stratigraphy became obsolete in the middle of the 20th century, the biostratigraphic, lithostratigraphic and chronostratigraphic categories were consequently separately defined and formalized. The parallel categories removed many theoretical problems related, for example, to diachronic unit boundaries and the relationships between geochronology and chronostratigraphic units. The different classification categories also substantially improved the applicability of stratigraphy by increasing flexibility. The downside was the increasing number of names and terms. Furthermore, many proposed new stratigraphic approaches, such as tectonostratigraphy, allostratigraphy and sequence stratigraphy, still lack formal recognition by the International Commission on Stratigraphy (ICS), and their unclear status has created some uncertainty and deepened the division between the different 'stratigraphic schools'.

The wrestling between the 'formalist' and 'pragmatist' views on stratigraphy has a long history. Famously, P.D. Krynine stated: *"Stratigraphy represents the complete triumph of terminology over facts and common sense"* (cf. Folk & Ferm 1966, p. 853). Ever since, certain scepticism regarding 'geological book-keeping' has prevailed, and basin analysts and oil exploration professionals have especially been inclined towards a sequence-based, genetic approach largely corresponding to the 'modern stratigraphy' of Miall (2013, 2016). Miall (1984) also presented an ultimately critical comment on traditional stratigraphy: "*The main emphasis was on formation and group and member names, and more names. There is no excuse for the continued use of such an approach.*" Domestic dissenting views have also been presented. For example, Hanski & Melezhik (2012) worried that the lithostratigraphic method was resulting in "*a plethora of local stratigraphic names, whose correlation is cumbersome and difficult to manage*."

To simplify, criticism of the stratigraphic method has had three main points: 1) The stratigraphic units basically do not represent genetically meaningful 'sequences' useful in basin analysis (e.g., Miall 1984, Sloss 1988). (2) The strong stratigraphic tradition, with rules, formal procedures and categories, restricts the emergence of new ideas and approaches. In an academic research climate, therefore, formal stratigraphy has been regarded more as a restriction of innovative case-by-case writing rather than a vital element of the scientific method and fundamental part of appropriate science language. (3) Different regions have different traditions in the classification and naming of geological units. The internationally formalized stratigraphic categories and rules do not always meet the practical needs of geological mapping. This is one main topic of the present article.

Modern information technology provides unseen possibilities to analyse and visualise rock bodies. Easy access to data and appropriate quality control in the forward modelling processes can only be achieved by systematic arrangement of the data stored in information systems. Therefore, the 'information age' has re- established the need for globally harmonized classification systems. The interoperability and exchange of machine-readable geoscience information is based on shared concepts, data models and related vocabularies. The IUGS Commission for the Management and Application of Geoscience Information (CGI) globally coordinates the work on data sharing, standards and best practices in geoscience information management.

To summarize, there are diverse, and even fundamentally different, viewpoints on formal stratigraphy (Fig. 1). Most map data management professionals see the value of defined stratigraphic categories as part of their data models, and the national geological mapping agencies, such as GTK, need a consistent and hierarchically arranged system of geological units to fulfil their basic role in storing, organizing and sharing geological data. In addition, a systematic procedure for naming various types of geological units guides our decisions about how these units should be established and correlated. Geology is a global science. Geological units do not respect political boundaries, and today, the geological units in our maps, models and databases are still largely built on the principles of stratigraphic classification. All international collaboration, from cross-border projects to global initiatives, is fundamentally based on the framework of shared stratigraphic concepts.

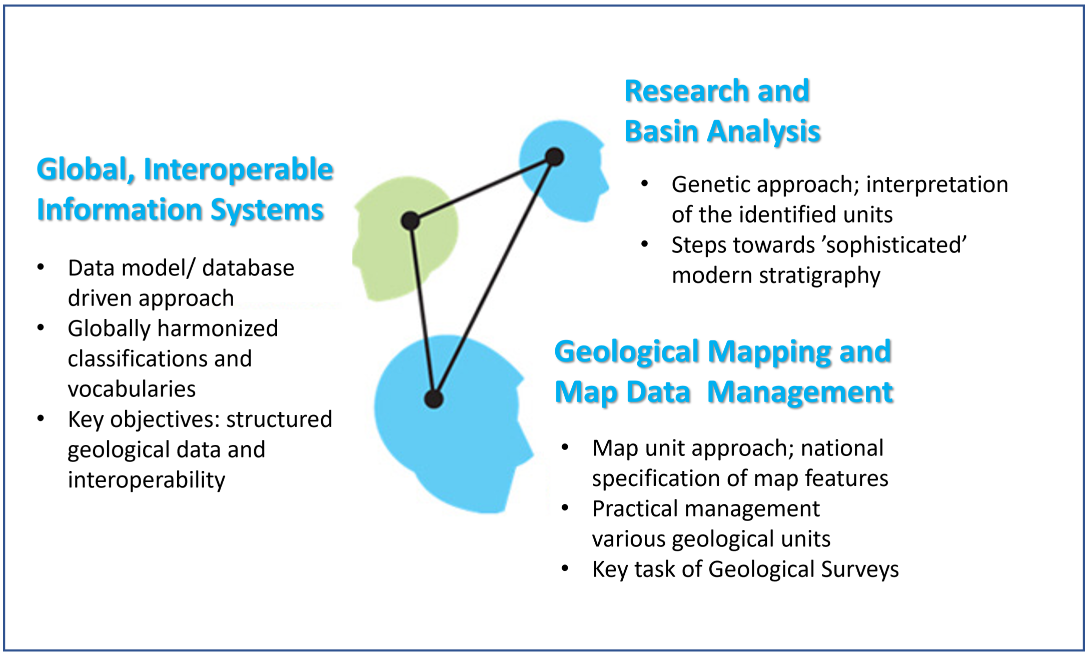

Fig. 1. Different viewpoints on stratigraphy and the applicability of stratigraphic classification categories depend on the purpose of the activity.

2.2 Geological unit classification: theory and practice

There are two main application areas for geological unit classifications: (1) the traditional use case in the management of mappable units and (2) the design of data models and construction of map databases. Regarding the first point, today we still need tools to designate and unambiguously communicate the lithological, structural, geochronological and other aspects of rock bodies. From the latter perspective, the potential of stratigraphy and other defined classification systems lies in their capacity to manage different aspects of geology in a systematic way. Geological units provide the most essential tool to characterize rocks, describe relationships between rock bodies and to arrange these into hierarchical structures.

In the International Stratigraphic Guide (Salvador 1994, p. 137), the definition of '*stratigraphic unit*' is all- encompassing and would basically cover nearly all types of geological units. Thus, the conceptual difference between the terms '*geological unit*' and '*stratigraphic unit*' is not distinct, and some key references (e.g., NASC 2005, 2021) apply the terms synonymously. Alternatively, 'geological unit' can be considered as a concept broader than 'stratigraphic unit'. In the GeoSciML scheme and related vocabularies, the types of '*geological units*' [Geologic Unit] are differentiated based on their defining lithological, stratigraphic or other physical properties, and the [Geologic Unit Type] makes no implication for required properties or cardinalities. The GeoSciML vocabulary (CGI; see Table 1) currently recognizes 13 main types of geological units without any division into 'stratigraphic' and 'non-stratigraphic' classifications.

It appears that the most significant difference between the stratigraphic and other classification categories is the 'degree of formality'. The formally defined classifications, such as lithostratigraphy, have globally defined systems with agreed procedures (e.g., Salvador 1994), whereas the rules for some other classifications (e.g., lithotectonic) are still in their infancy. For terminological clarity, and to foster the application of an innovative approach to unit classification, we suggest that in the division of bedrock units in Finland, only the formal (ISSC; see Table 1) and other internationally recognized classification categories (lithodemic, pedostratigraphic) be considered as '*stratigraphic*'. Accordingly, a '*stratigraphic unit'* is a geological unit established by applying the rules of a stratigraphic classification scheme (stratigraphic category). Tectonostratigraphic classification forms a special case (see 3.3 below) defined in the Norwegian guide (NCS, see Table 1) and is commonly used in all the

Scandinavian countries. However, wider international recognition of tectonostratigraphic units is largely lacking.

In principle, the classification of a '*geological unit*' can be based on any of the many properties and attributes that the rocks possess. However, and as emphasized in the Salvador (1994), the clear definition of a geological unit is of paramount importance. All geological units should be established according to a defined classification system, and all the used unit classification systems must be based on clearly defined properties (characteristic for the system). The unit boundaries may or may not coincide with those based on another unit classification. The applied units can be based on well-established stratigraphic categories, other defined geological unit types (see CGI in Table 1) or, alternatively, on a new or regionally defined classification scheme (e.g., the lithotectonic provinces of Finland; Kohonen et al. 2021).

Table 1. Relationships between geological units (recognized by CGI), formal categories of stratigraphic units (defined by ISSC), widely recognized categories of stratigraphic units (NASC and NCS) and the unit categories included in the guides of Sweden and Finland. Note the similar approach of all Scandinavian countries.

Geologic units	**Stratigraphic units**				
(1) Recognized by CGI	ISSC / ISG	NACSN / NASC	NCS	SWE guide	**FIN guide**
Allostratigraphic unit	*Unconformity-bounded unit* (**Formal category)**	Recognized			
Alteration unit					
Biostratigraphic unit	**Formal category**	Recognized			
Chronostratigraphic unit	**Formal category**	Recognized	Recognized	Included	Included
Geomorphologic unit					
Geophysical unit >Magnetostratigraphic unit	Magnetostratigraphic. polarity unit (**Formal category)**	Recognized	Recognized		
Lithogenetic unit >Artificial ground >Excavation unit >Mass movement unit					
Lithologic unit					Included
Lithostratigraphic unit	**Formal category**	Recognized	Recognized	Included	Included
Lithodemic unit		**Defined**	Recognized	Included	Included
Lithotectonic unit >Deformation unit					Included
Pedoderm					
Pedostratigraphic unit		Recognized	Recognized		Included
Polarity chronostratigraphic unit					
(2) Not recognized by CGI					
Tectonostratigraphic unit			**Defined**	Included	Included

CGI (Commission for the Management and Application of Geoscience Information; GeoSciML vocabularies; status 01/2022)
ISSC (International Subcommission on Stratigraphic Classification; International Stratigraphic Guide, Salvador, A. 1994)

NACSN (North American Commission on Stratigraphic Nomenclature; North American Stratigraphic Code 2005)

NCS (Norwegian Committee on Stratigraphy, Rules and recommendations for naming geological units in Norway, Nystuen, J. P. (ed.) 1989) SWE Guide (Guide for geological nomenclature in Sweden, Kumpulainen, R. 2017)

FIN Guide (Guidelines and procedures for naming bedrock units in Finland. (2nd edition). Kohonen, J., Köykkä, J. & Strand, K. (eds) 2024)

Stratigraphy is basically an internationally formulated procedure to describe, classify, name and correlate geological units. The ambitious objective of stratigraphy, 'apply locally – connect globally', creates the need to discuss the applicability of stratigraphic procedures on three different levels: global, regional and local.

The usefulness of a globally defined linkage between chronostratigraphic and geochronological units and the importance of the International Chronostratigraphic Chart (Cohen et al. 2013) cannot be questioned. The International Stratigraphic Guide (Hedberg 1976, Salvador 1994, Murphy & Salvador 1999) is another example of valuable coordination by the IUGS International Commission on Stratigraphy. However, regarding the international coordination on unit classification schemes, the rather conservative position of the ISSC (see Table 1) is challenged by both the increasing application of genetic approaches (e.g., 'modern stratigraphy', sequence stratigraphy) and the needs of information systems and data models (e.g., NADM C1, GeoSciML).

The practical applicability of strictly formal stratigraphy for highly metamorphosed and severely deformed rocks is a relevant question (see Pratt et al. 2023 and references therein). These rocks do not conform to the Law of Superposition and, furthermore, the lateral continuity of the rock units is in many cases limited. This has seriously restricted the use of formal lithostratigraphy in Precambrian terrains worldwide. The challenges with Precambrian chronostratigraphy are also universal and are caused by the limited number of units with precise isotopic ages and poor time resolution.

The International Stratigraphic Guide (Salvador 1994) acknowledges the different needs in different geological environments by allowing the use of informal unit classification categories, recognizing the need for regional chronostratigraphic scales and encouraging the compilation of national guides. However, balancing regional and national needs between the international standards and the practical needs of mapping programmes and related information systems is not an easy task. The compilation of the national guide (Kohonen et al. 2024, this volume) and the experience gained during the implementation of the national map database have raised the following major challenges:

(1) Precambrian shields with folded high-grade gneisses typically represent mid-crustal sections and a geological environment very different from well-exposed mountain ranges or large sedimentary basins with continuous, stratified rock units. Consequently, different mapping traditions and stratigraphic approaches have evolved in geologically different areas. The Finnish approach is described in the 'national guide' (Kohonen et al. 2024, this volume) and discussed in this article.

(2) There are fundamental problems in the systematic management of intrusive, highly tectono- metamorphic and altered or metasomatic rock bodies. Those rock bodies are of varied origins, and the present lithological properties of the 'composite-genesis rocks' may reflect a long history of successive events. The generation of consistent nomenclature and informative attributes for the corresponding geological units is not a simple, straightforward task.

(3) 'Mappable unit' is a key concept in stratigraphy (e.g. Salvador 1994), and the traditional approach is tuned to 'normal, regional-scale mapping'. In the past, the minimum size of a map unit was largely determined by the scale of the printed map product. In digital mapping, there is basically no limitation for the scale (the scale of the portrayal can be selected). The transitions between different resolutions obviously stretch the conceptual limits of a 'mappable unit', and a geological unit in general.

(4) The boundaries of chronostratigraphic units are in the tangible Precambrian rock record rather imaginary. Many features, such as the relationship between geochronological, chronostratigraphic and diachronic unit boundaries, are challenging to comprehend, and their application is further complicated by error limits of millions of years in isotopic age determination. Time in relation to Precambrian stratigraphy is discussed in Chapter 4.

3 CLASSIFICATION AND NOMENCLATURE OF BEDROCK UNITS IN FINLAND

3.1 Background

3.1.1 Drivers for the change

The technology-driven change in Finland from printed map sheets to map databases has been described in Ahtonen et al. (2021). The new technology was soon followed by new legislation based on the European INSPIRE directive, and presently, public domain map information must be harmonized with INSPIRE (2013) data models and accessible in a machine-readable format. This fundamental change was reflected in all work processes and information management, but also in the growing importance of conceptual-level modelling of map information (e.g., NADM-C1, INSPIRE data model). Presently, the international data models, largely based on the IUGS-ICS recommendations, provide the primary reference for the planning of map data infrastructures, and 'geological unit' is one of the key concepts in these models. In general, the hierarchical, taxonomic systems of defined data, such as stratigraphic units, are ideal elements of digital databases.

Nevertheless, the roots of stratigraphy are in geological mapping ('*mappable units*'), and even in Finland, the transition from mapping lithological (rock type-based) units to lithostratigraphic (e.g., Silvennoinen 1972, Laajoki 1991) and lithodemic (Laajoki & Luukas 1988) units started well before the emergence of digital mapping. However, the nationwide, systematic approach to the use of litho-based stratigraphic units is rather recent (cf. Luukas et al. 2017) and the method is still partly unconsolidated. Compared to rock type-based lithological units, the application of stratigraphic units provides many advantages: (1) the use of entities larger than solitary rock type-based map units streamlines the management of national map data, (2) stratigraphic units allow for the assignment of meaningful attributes regarding their age, origin and tectonic setting and (3) unexposed subsurface bodies can be correlated with defined surface units.

To summarize, the main challenge is that the national map data architecture needs to be both compliant with internationally defined data models and suitable for storing geological information produced and used in Finland. The system, and related data model, would ideally include all relevant geological units, whether stratigraphic or not, and still reflect the key principles of the systematic stratigraphic approach. Ultimately, the requirements are set by the needs of different research activities, from regional geology to mineral exploration and engineering geology. Thus, the applied classification systems must be fit for the purpose: the main point cannot be the traffic rules themselves, but the resultant organized and smooth flowing traffic arising from these rules. From this starting point, some flexibility is needed in the application of formal stratigraphic categories to digital map data management.

3.1.2 Traditional stratigraphic nomenclature: burden or blessing?

The geological literature of Finland and the Fennoscandian Shield has a long history and, as a result, the legacy information contains a rich flora of stratigraphic nomenclature in part burdened by a long tradition rather than reflecting formal scientific language with well-defined terminology. The nomenclature is largely inherited from times, nearly a century ago, when the difference between lithostratigraphy and chronostratigraphy, especially in the Precambrian, was not recognized. Many of the traditional names are still in use, and in most cases, the usage and content has transformed far beyond their original meaning. Poorly defined but widely used traditional stratigraphic names, such as Sariola/Sariolian, Jatuli /Jatulian, Kaleva/Kalevian, have been used in eastern and northern Finland to name sedimentary facies, chronostratigraphic units and lithostratigraphic groups (see Sederholm 1897, 1932, Meriläinen 1980a,b, Simonen 1980, Laajoki 1986, Hanski et al. 2001, Ojakangas et al. 2001). Examples of other obsolete names include Jotnian, Svionian and Bothnian.

Traditional nomenclature can illuminate the research history and constitutes a part of the stratigraphic heritage, but the unpleasant fact is that the precise meaning of these names is currently unclear. This has resulted in their utterly inconsistent use, and the appropriate use of the traditional names is a tricky issue. Salvador (1994) emphasizes the importance of explicit procedures in naming but, on the other hand, suggests that the well-established and traditionally used unit names should be preserved. Ideally, the best scientific practice would be the abandonment of all the traditional names, but in reality, this would never happen. Recommendations for the future use of the traditional names are given in Chapter 4.2.

3.2 Litho-based units

The identification of rock unit boundaries (lithological units) is the primary task in regional mapping. These lithological units may evolve by definition and naming into stratigraphic units. All litho-based geological units (1) are defined by their composition (lithology, rock type), (2) have boundaries against the adjacent rock units and (3) have or do not have a unit name. It is essential to see the difference between the terms *map unit*, *lithological unit* and *stratigraphic unit*. A map unit is any area defined on a map (e.g., ore potential domain), whereas a lithological unit is a map unit defined by the rock type. A stratigraphic unit is a geological unit defined on the basis of a lithostratigraphic, lithodemic or, rarely, pedostratigraphic classification scheme (Fig. 2). All proper stratigraphic units have a name as the *unique identifier of the unit* (e.g., Harju formation, Väärälä granodiorite), whereas lithological units are labelled by a *generic* rock name (e.g., sandstone, gabbro, granite). A stratigraphic unit may be represented by one or several lithological map units (Fig. 2).

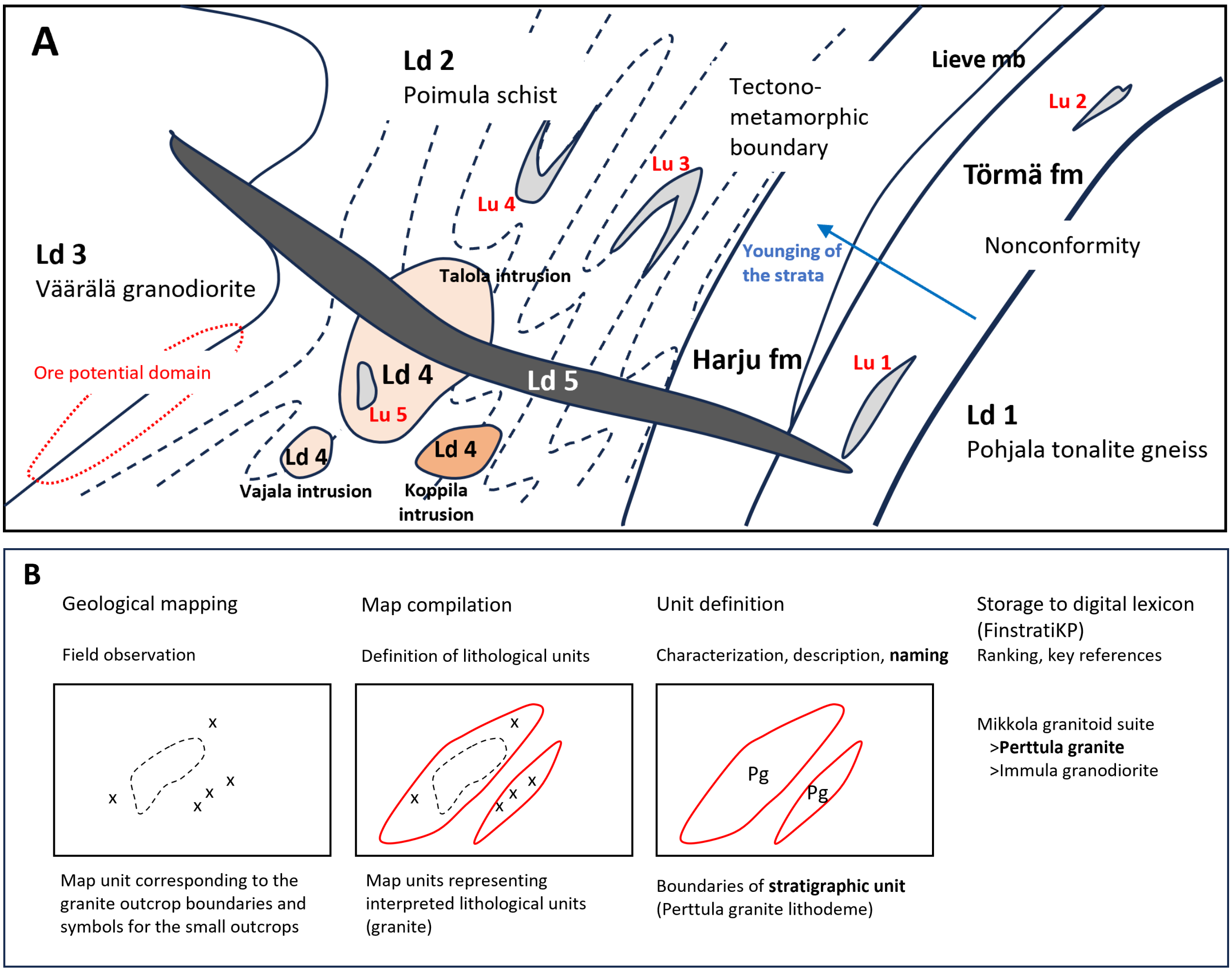

Fig. 2. A) Relationships of lithostratigraphic formations (fm), tectono-metamorphic lithodemes (Ld 1, Ld 2) and intrusive lithodemes (Ld 3, Ld 4, Ld 5). Ld 4 (Ahvenkoski granite lithodeme) comprises four litho-based map units and three intrusions (intrusive bodies). Lithological units (Lu1–Lu5) are independent of stratigraphic classification and nomenclature. B) The evolution path of a geological unit (an imaginary lithodemic unit 'Perttula granite' as an example). For further information see "*Guidelines and procedures for naming bedrock units in Finland*" (Kohonen et al. 2024, this volume).

3.2.1 Lithostratigraphy sensu lato

According to the national guidelines (Kohonen et al. 2024, this volume), the application of lithostratigraphic, lithodemic and pedostratigraphic categories in the naming of lithological units is complementary. Essentially, this means one system of non-overlapping units utilizing three different classification schemes. Accordingly, all the primary rank units are either formations or lithodemes or, in a few cases, paleosols. This type of combined lithostratigraphic-lithodemic approach has been called 'lithostratigraphic (*sensu lato*) nomenclature for Precambrian rocks' (Easton 2009).

For stratigraphic classification, lithological units are divided into two main groups: (1) *stratiform* rocks comprising layered supracrustal successions and (2) *nonstratiform* rocks including intrusive, highly tectono- metamorphic or pervasively altered rocks. Stratiform rocks conforming to the Law of Superposition are classified according to the *lithostratigraphic* scheme. The pedostratigraphic units (paleosols) of weathering origin are comparable to a formation. The relative age of the units is an essential part of the lithostratigraphic method. The applicability of lithostratigraphic classification (*sensu stricto*) does not depend on the degree of metamorphism but on superposition only. Where control to unit superposition is lost, the stratiform rocks are classified by the *lithodemic* scheme, similarly to nonstratiform rocks (Fig. 3). In folded and metamorphosed bedrock, regionally undisputable confidence in superposition is in many cases challenging to achieve. Altogether, this means that the choice between the lithostratigraphic and lithodemic approaches in the classification of deformed supracrustal units must be carefully considered case by case.

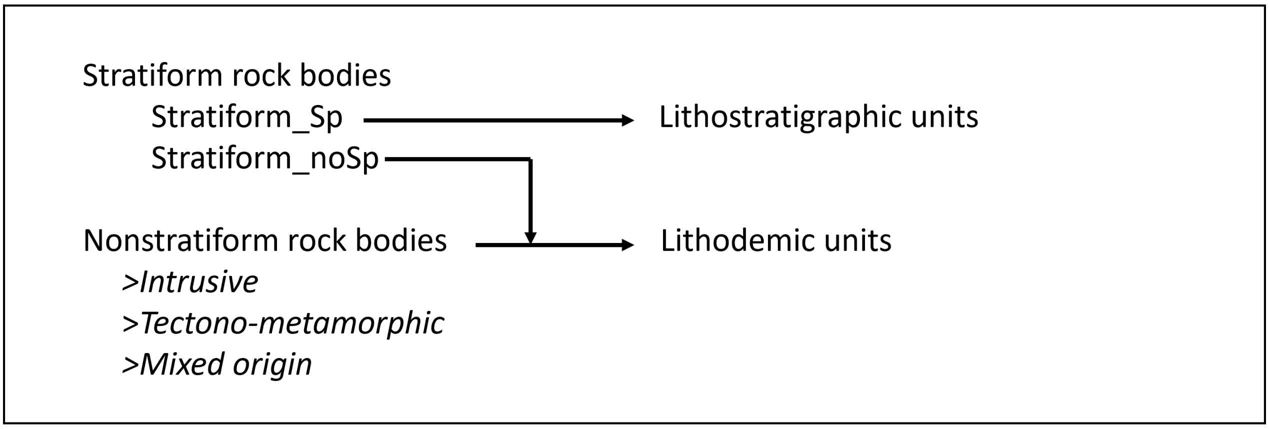

Fig. 3. Litho-based stratigraphic classification of stratiform and nonstratiform rock bodies in Finland. Stratiform_Sp and Stratiform_noSp refer to successions conforming and not conforming to the Law of Superposition, respectively. Origin-based classes of nonstratiform rock bodies are modified from Gillespie & Leslie (2021).

It is important to note that lithostratigraphic and lithodemic classifications are fundamentally different, and the crucial role of the applicability of the Law of Superposition the regarding their distinction has recently been emphasized by Maxeiner et al. (2024). Lithostratigraphic units are always based on the lithology of the protoliths and other inherent properties characteristic for the type section, whereas lithodemic units are solely based on the observed rock type. The formal requirements for the establishment of a lithostratigraphic formation are strict and include a complete type section (location and description of the stratotype or reference section) and a description of the primary nature of the upper and lower boundaries (e.g., Kohonen et al. 2024, this volume). In poorly exposed Finnish terrain, such perfect, continuous sections are uncommon. Furthermore, nearly all rocks show tectono-metamorphic overprinting. In practice, all the fairly well-exposed stratiform units with assumably reliable superposition have been classified as formations. Lithostratigraphic nomenclature has been successfully applied to Mesoproterozoic sedimentary rocks (Satakunta fm; Pokki et al. 2013), Paleoproterozoic (Karelian) supracrustal successions in eastern and northern Finland (e.g., Laajoki 1991, Kohonen & Marmo 1992, Köykkä et al. 2019, 2022), some well-preserved Svecofennian rocks (e.g., Kähkönen 1989, Nironen & Luukas 2017) and in a few cases to Archean supracrustal rocks (e.g., Papunen et al. 2009, Sorjonen-Ward 1993).

However, most of the Finnish bedrock is characterized by different types of granitoids (e.g., 'Central Finland granitoid complex', Nironen 2005) and terrains of lithologically complex and highly metamorphic rocks. The lithodemic approach provides the best available option (see Easton 2009) for the stratigraphic classification of those rock bodies. A lithodemic unit is a defined body of predominantly intrusive, highly deformed and/or highly metamorphosed rock (NASC 2005, 2021). This definition apparently excludes hydrothermally altered and/or metasomatic rocks, impact-origin rocks and cataclastic rocks. However, we cannot see any fundamental reason why these lithological units would not be named as lithodemes.

3.2.2 Issues in the application of lithodemic units

The litho-based unit boundaries may be depositional, intrusive, metamorphic, tectonic or metasomatic in origin and sharp, gradational or sheared in appearance, or undefined. Both the nature of the unit boundaries and the discernability of superposition are judged by the corresponding mapping geologist. When there is a lack of clear guidelines, the selection of the classification scheme is not always obvious, and some inconsistency occurs. Increased attention is suggested in the characterization of lithodemic unit boundaries in general, and especially in frontiers where a regional metamorphic gradient transects the rock units and lithostratigraphic and tectono-metamorphic lithodemic units come into contact (see Fig. 2A). These boundary zones are typically geologically complex, but their description would justify and explain the changing classification scheme.

Nonstratiform rocks comprise a highly diverse assemblage of rock bodies of varied origins and, except for the plutonic rocks, their rock names are even more heterogeneous and unsystematic (Fig. 4). Therefore, the creation of hierarchies in the lithodemic system and the consistent application of genetic attributes for lithodemes is problematic and distinctly different from lithostratigraphic formations.

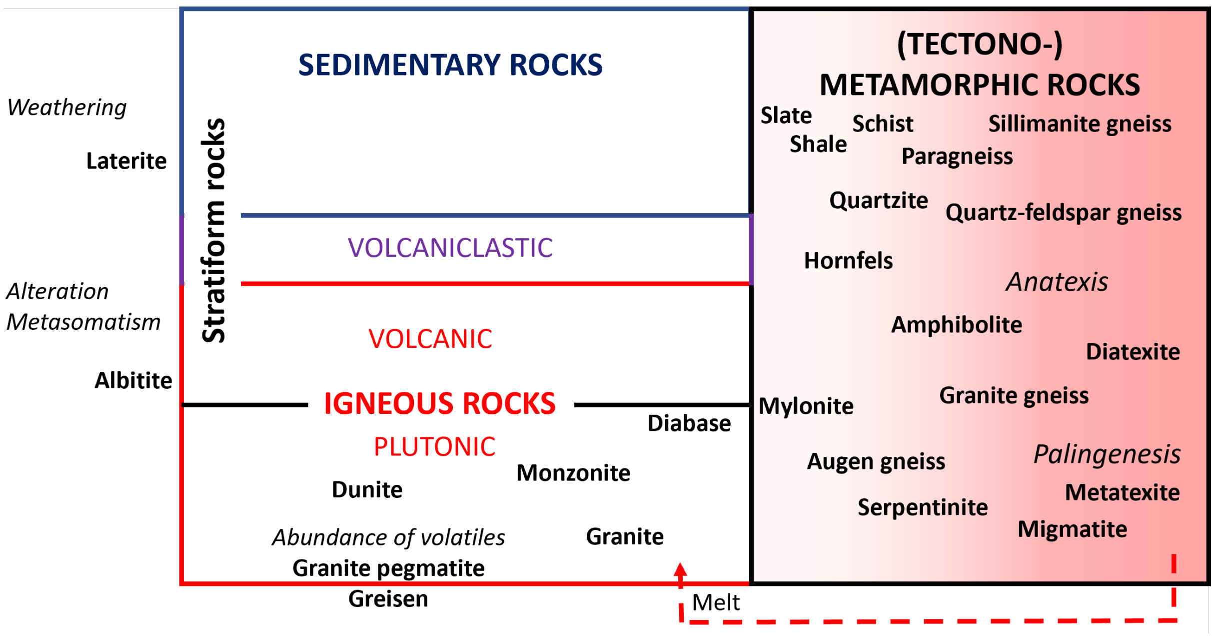

Fig. 4. Spectrum of nonstratiform and tectono-metamorphic rock names. Several processes affect the composition and texture of the composite-genesis rocks, successively in many cases. Consistent, systematic classification of the corresponding rock names and corresponding lithological units is challenging. Migmatites with a high melt fraction make even the distinction of plutonic and metamorphic rocks blurred.

The rock names for intrusive (plutonic) rocks are derived from the mineral composition or modal composition. For other nonstratiform rocks or 'composite-genesis rocks' (cf. NADM SLTT 2004), the rock type, and the derived lithodemic unit name, may be derived from the protolith (e.g., quartzite), metamorphic (e.g., hornfels) or 'tectono-metamorphic' (e.g., schist, mylonite, augengneiss) texture, 'mixed-origin' (e.g., migmatite, impact breccia) rocks or even features of intensive epigenetic alteration origin (e.g., greisen, metasomatic albitite). The present lithological properties of metamorphic rock bodies may reflect a long history of successive events after their deposition or emplacement. In many cases, these overprinting diagenetic, metasomatic (alteration) and tectono-metamorphic features dominate and determine the rock type (Fig. 4), and accordingly, the name of the lithodeme. Thus, there are some features presently reducing the applicability and information value of lithodemic geological units:

1. The simple, all-inclusive classification based on mappable lithological units and their descriptive rock names practically means that 'apples and oranges' presently go into the same basket. For example, the intrusive 'Someplace dunite' with primary mineral composition and the metasedimentary 'Someplace sillimanite gneiss' are very different rocks. Their only common denominator is that they are presently nonstratiform mappable units and thus lithodemic stratigraphic units (Fig. 3). Informative attributes for those lithodemic units would certainly not be similar.
2. A related problematic point is that the mapped rock types represent various and completely different rock classification schemes without consistency. This causes inherent inconsistency in the lithodemic nomenclature. The use of standard rock classification would have two major advantages: (1) increased consistency of lithic terms in lithodemic nomenclature and (2) an increased capability of database queries by [rock name].
3. Both the presentation and management of successive rock-forming processes, such as deposition, regional metamorphism and post-metamorphic alteration, is not supported by the simple lithodemic classification. This reduces the information content of bedrock map databases predominantly based on lithodemic units.

3.3 Units based on bounding surfaces

Some unit classification systems are based on the *physical limits of the material unit*, not the material of the unit (Table 2). Examples are fault-bounded *tectonostratigraphic* units and units bounded by depositional unconformities. In the Finnish Caledonides, the tectonostratigraphic approach (Lehtovaara 1986, 1989) was adopted from neighbouring Norway and Sweden, having a strong tradition in tectonostratigraphy. Luukas & Kohonen (2021) presented a provisional division of different *thrust-bounded units* in Finland. The aim of their informal fault-bounded units is to enable the portrayal, management and communication of structural features dominating the present configuration of the lithostratigraphic and lithodemic units. Thrust-bounded units, such as Kittilä and Outokumpu *allochthons* and the Kainuu *thrust stack* with several *thrust sheets* (see Luukas & Kohonen 2021 and references therein), have significantly aided the description of the Paleoproterozoic thrust belts in northern and eastern Finland. It is important that the boundaries of the different geological units are defined separately. The boundaries can and do coincide, but the boundary of a litho-based unit should not conform to the thrust-bounded unit boundary where a lithological difference has not been observed.

Table 2. Classifications based on the bounding surface of the unit used in Finland.

Nature of the bounding surface	Tectonic (detachment)	Depositional (unconformity/ sequence boundary)
Classification scheme Unit ranks	**Tectonostratigraphic** Nappe system / nappe complex - >Nappe >>Thrust sheet	**Unconformity-bounded** Synthem
Other informal units Subdivision	Allochthon >Thrust sheet	(Sequence stratigraphy) (System tract)
	Thrust stack, duplex, thrust block	

Laajoki (1990, 1991) introduced the concept of *tectofacies*, corresponding to supracrustal successions formed during a specific long-lasting tectonic phase and bounded by major unconformities. Basically, the units of the approach share most features of a *synthem*, a diachronous, *unconformity-bounded stratigraphic unit* (see Salvador 1994). *Sequence stratigraphic* interpretations of unconformity-based units in eastern Finland have also been envisioned (e.g., Strand & Laajoki 1999, Strand 2005). However, sequence stratigraphy in Finland will hardly develop to map unit classification but remains a deductive method of basin analysis.

3.4 Lithotectonic units

Lithotectonic units are defined on the basis of the assumed tectonic evolution, origin or structural features (Kohonen et al. 2024, this volume). The definition of a lithotectonic unit is broad and subcategories can be grouped under the main category. Lithotectonic classifications have emerged as a response to the need for a systematic and consistent nomenclature for tectonic provinces (or domains), crustal blocks and orogens. Examples of different applications (e.g., Raymond 2018, Stephens 2020, Nemeth 2021) are accumulating, but no internationally well-established classification schemes are presently available. In Finland, Kohonen et al. (2021) proposed a classification scheme that builds on a combination of the lithotectonic approach and the province classification of Australia (Raymond 2018). The classification (named LT-FIN) introduces three classes of lithotectonic units: crustal province, tectonic province and structural province (for details, see Kohonen et al. 2021). The harmonization of the nomenclature is challenging for many reasons: (1) the units are typically 'conceptual' rather than mappable, (2) the tectonic terms typically have a close link to the applied tectonic concepts, (3) the competing tectonic models generate different units and (4) systematic lithotectonic approaches are in their infancy and new ideas flourish.

3.5 New perspectives on the classification of geological units in Finland

3.5.1 How many unit classification schemes are needed?

The bedrock of Finland offers many challenges in the sensible classification of geological units. The classification of metamorphic rocks is complicated by features such as: (1) complex folding obscuring the superposition of units and development of tectono-metamorphic fabric obscuring the protolith, (2) several successive processes (e.g., epigenetic alteration>deformation>peak metamorphism>deformation and retrograde metamorphism), (3) severe deformation resulting in tectonic contacts between the units and the disruption of rock bodies and (4) anatexis and migmatization. As a result, lithological units with indistinct boundaries, low lateral continuity and poorly defined age relationships are mainly mapped. Therefore, a detailed description of the relationships between all kinds of geological units is not a realistic objective.

The parallel use of different classification categories with overlapping map units is one tool in the arrangement of different geological features. This is approved and encouraged by the Salvador (1994), stating that "*stratigraphic units* [distinct entities] *based on one property will not necessarily coincide with those based on another*." Currently, three independently defined categories (see Kohonen et al. 2024, this volume) have been used: (1) lithostratigraphic-lithodemic units (or lithostratigraphic *sensu lato*), (2) thrust-bounded units (or tectonostratigraphic *sensu lato*) and (3) lithotectonic units (provisional). In our experience, the parallel use of lithostratigraphic (*sensu lato)* and thrust-bounded units has clarified the map portrayal and significantly simplified the regional description of thrust belts. Lithotectonic units are rather conceptual tectonic-scale domains defined by properties related to their interpreted tectonic history. The other potentially applicable classifications include deformation units (structural units), alteration units, metamorphic units and, possibly, lithogenetic units.

Principally, the basis of each classification category must be clearly defined so that units can be established independently of other categories. How many types of geological units are needed depends on the geological circumstances and on the selected approach. The more features we present as map units, the more classifications are needed. However, the approach always incorporates both geological units and the unit attributes (Fig. 5).

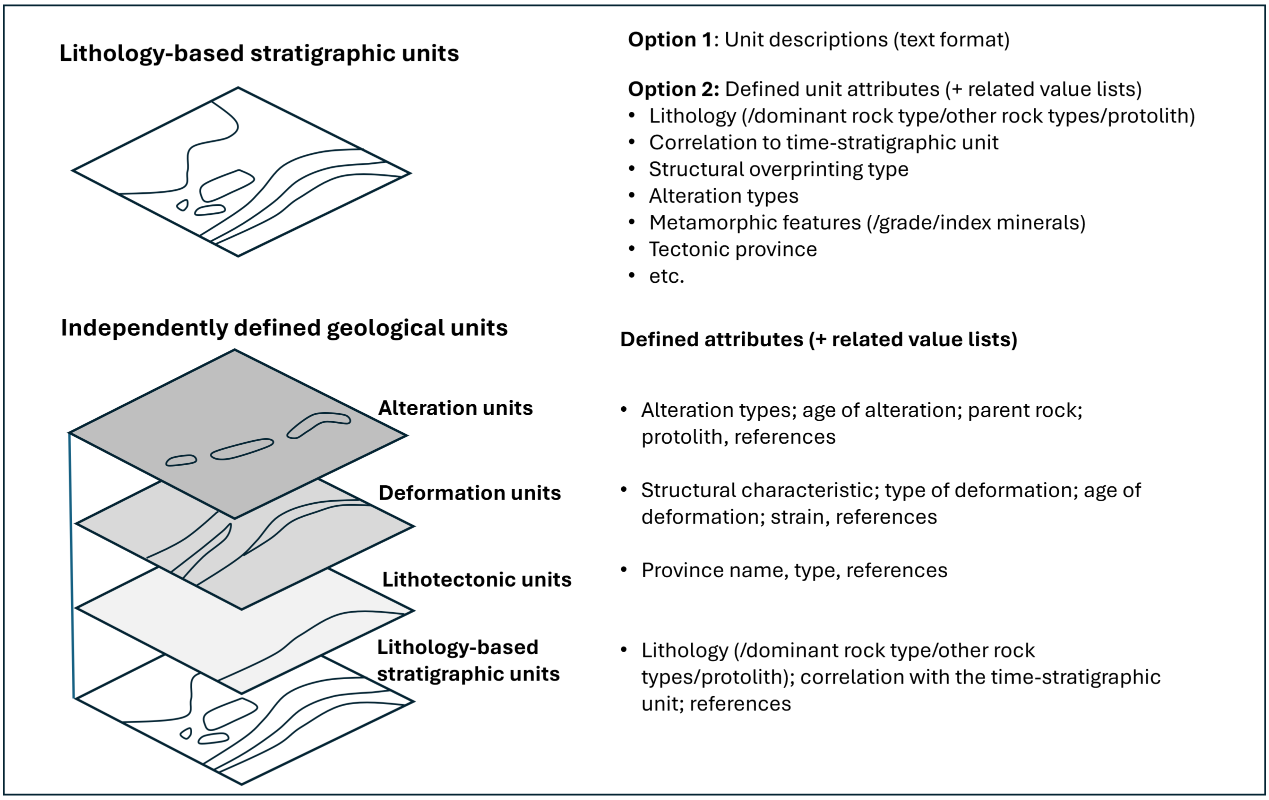

Fig. 5. Comparison of systems with (1) stratigraphic units (above) and (2) examples of independently defined overlapping geological units (below). The simple solution is the use of stratigraphic units with traditional text format descriptions. In more structured databases, the management of the attributes is one major challenge. The application of overlapping, independent units simplifies the database structure but increases the number of spatial datasets.

3.5.2 Benefits of overlapping geological units

Problem with composite-genesis rocks

Traditionally, geological mapping has focused on present, observed rock types and the corresponding lithostratigraphic and lithodemic units. This means that many important features, such as different alteration units and boundaries between high-strain and low-strain zones, are not typically included in the mapping procedure. However, in many cases, the descriptive lithological term in the name of a lithodeme is based on the overprinting fabric (e.g., schist, gneiss) or the final metasomatic mineral composition (e.g., albitite) (Fig. 6). Composite-genesis rocks have been defined (NADM SLTT 2004) as products of more than one rock-forming process. They are not purely igneous or sedimentary and include metamorphic rocks, mylonitic and cataclastic rocks, altered/metasomatic rocks and impact-origin rocks, but not weathering products or soils. The management of successive rock-forming processes that result in composite-genesis rocks, from deposition, or intrusion emplacement, to regional metamorphism and further to hydrothermal alteration, is presently not ideally supported by the lithodemic approach. In the following, we discuss the potential benefits provided by deformation units, alteration units and metamorphic units.

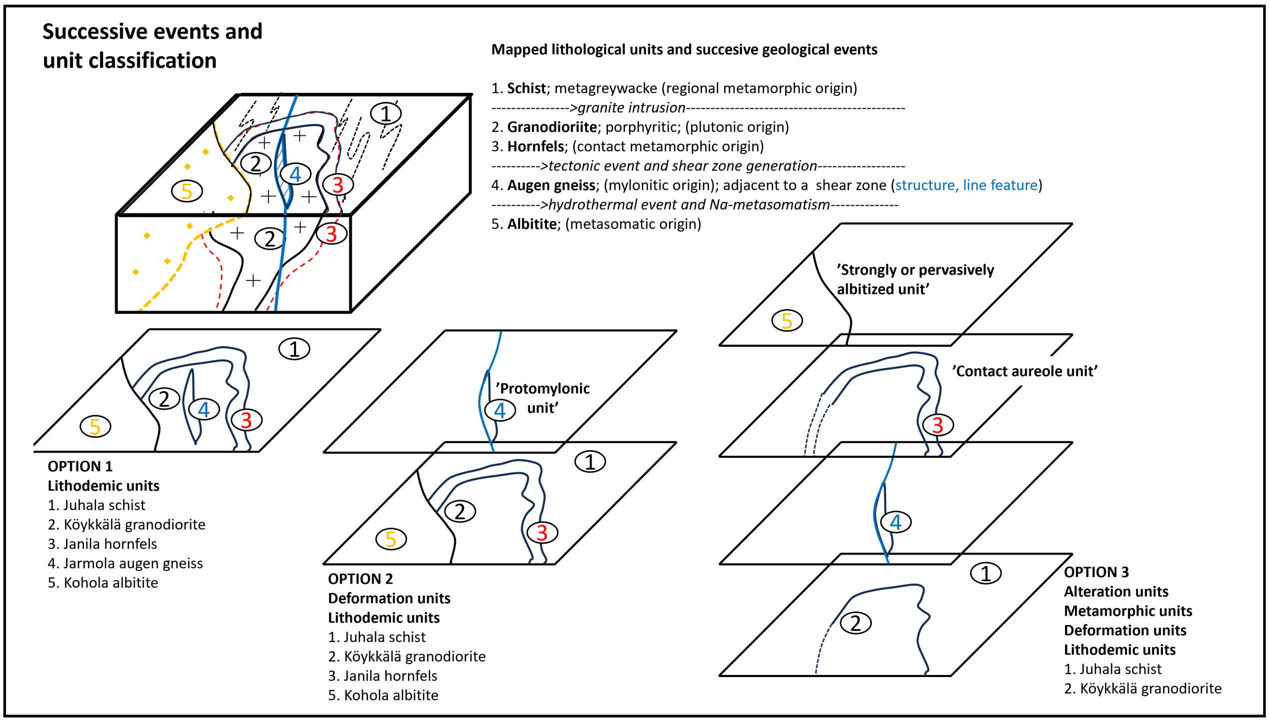

Fig. 6. Schematic diagram addressing the successive origin of mapped lithological units. The unit boundaries are intrusive, metamorphic, tectonic and metasomatic in origin and sharp, gradational or diffuse in nature. Option 1 incorporates *lithodemic units* of varied origins. In Option 2, the overlapping *deformation unit* showing an augen-gneiss texture with K-feldspar porphyroclasts is separated and connected with other structural features (lines, points). Option 3 also involves overlapping *metamorphic units* and *alteration units*. The units are possible to connect thematically to other metamorphic (e.g., index minerals, metamorphic facies boundaries) and alteration (e.g., areas of patchy alteration, alteration observation points) map features. The alternative options (2 and 3) also support unit characterization and description according to the genetic type of the unit.

Structural units

CGI vocabulary (GeoSciML v2016.01) defines a *deformation unit* as follows: "Lithotectonic unit defined by deformation style or characteristic geologic structure observable in outcrop." The fundamental idea is to describe the distribution of deformation independently of litho-based units. Structural domains and subdomains typically define map units with characteristic structural features different from the adjoining units. Major shear zones forming a mappable unit and high strain rock units, such as augen gneiss (see Fig. 6), can be incorporated. In highly tectono-metamorphic Precambrian terrains, structural features may dominate the geological map over the primary (depositional, intrusive) features. Even so, the application of *deformation units* (or 'structural units') has not been conventional in Finland. The establishment of deformation units with hierarchies, such as subdomain <domain <subprovince <province (see Kohonen et al. 2021), would significantly aid the portrayal of geological features, such as shear zones, and support tectonic modelling at all scales (e.g., Lahtinen et al. 2022).

Alteration units and metamorphic units

Alteration units may cover large areas, such as albitite in Figure 6, but alteration and metasomatic features more commonly occur as patches within a certain area. These areas would ideally be mapped as alteration units. The recognition and characterization of regional alteration features is of primary importance for mineral exploration. Hölttä & Heilimo (2017) defined national-level metamorphic units, and further development of the classification system is worth considering. This would allow the definition of units based, for example, on the presence of different index minerals, contact metamorphic features and, most importantly, multiple overprinting metamorphic features, such as Archean metamorphism overprinted by retrograde Paleoproterozoic metamorphic features.

To conclude, many unit classification conventions have been inherited from the era of printed maps. The printed map has serious restrictions in the portrayal of different map unit types overlapping each other, and structural and metamorphic features have thus been presented by symbols. In digital map databases, this restriction has been wiped away, and in theory, the way is open for an unlimited number of overlapping, independent unit themes (Fig. 5) and their portrayal as transparent layers. However, the use of overlapping units increases the number of map unit polygons and complicates the management of the spatial data. An alternative option in the management of the most important post-genetic features is the addition of appropriate attributes for the lithostratigraphic and lithodemic units or a combination of these two approaches.

3.5.3 Adjustment of the lithodemic classification

Different lithological units have different origins, and their dominant lithological properties reflect their entire genetic history: 'Someplace dunite' originated through the fractional crystallization of magma, whereas 'Someplace sillimanite gneiss' is a high-grade metamorphic rock with a sedimentary or uncertain protolith and 'Someplace migmatite' manifests partial melting of the rock body. One fundamental idea in the application of geological units (see 3.1.1) is to provide meaningful and important attributes related to their age, origin and tectonic setting. The management of lithodemes as one group, independent of their origin, works well in the management of units and their 'free text' descriptions (see Fig. 5 and Table 4 in Easton 2009). However, in more advanced, structured map databases, the applicability of lithodemic units can be substantially improved by grouping (Fig. 7).

A descriptive set of lithogenetic attributes for the different lithodeme types (Fig. 7) is certainly not the same. For example, the attribute 'suggested protolith' is highly relevant for most composite-genesis lithodemes but not for the intrusive ones. A broad discussion of attributes is not within the scope of this article, but some examples of genetic attributes are presented in Table 3 to highlight the diversity and to address the potential benefits of the postulated subdivision of lithodemes.

The nomenclature of lithodemes is presently heterogeneous. The primary reference (NASC 2005, 2021) includes the names Killarney Granite, Duluth Gabbro, Manhattan Schist, Adamant Pluton and Skaergaard Intrusion. Easton (2009) provides examples such as Pardo Granite, Ardoch Lithodeme (kya-grn-mus gneiss) and Davis Lake Lithodeme (syenogranite gneiss). Gillespie et al. (2008) proposed intrusive lithodeme names emphasizing a

Intrusive lithodemes
- >Plutonic
- >Subvolcanic/dyke

Tectono-metamorphic lithodemes
- >Regional metamorphic
  - >>Migmatitic
- >Contact metamorphic
- >Mylonitic
- > Cataclastic

Other composite-genesis lithodemes
- >Hydrothermally altered/metasomatic
- >Impact origin

Fig. 7. Suggested subdivision of lithodemes.

combination of the rock type and the geometry of the rock body (e.g., Wallow Crag Gabbro Plug, Rae Crags Granite Intrusion). Regarding the names of lithodemic units, it appears that we need to sharpen the distinction between the *rock type* (of a sample or an outcrop) and the *lithology* of a rock unit. The rock type refers to a rock name based on the observed mineral composition or texture, whereas lithology refers to the rock association within the defined unit. The rock name and the lithic term of a unit is in many cases the same (e.g., 'granite', 'serpentinite') and in some cases generalized (e.g., 'schist' representing bio-mus-q schists and q-fs schists). In addition, the terminology used in the description of three-dimensional rock bodies (e.g., intrusion, pluton, dyke, sill, laccolith, batholith) and especially their appropriate and consistent use in lithodemic nomenclature is necessary to consider.

In Finland, most lithodeme names currently combine, according to the recommendation of NASC 2005, a geographic term with a lithological term (Sorsakoski granite, Akkala quartzite). The genetic groups (Fig. 7) would also consolidate the selection of lithological terms used in the naming of lithodemes. For all the groups, specific rock classification schemes are available and reference to the used classification should always be given (e.g., rock classification used by GTK). However, rock names and rock type classifications are outside the scope of this article.

Lithodeme is a lithologically characterized geological unit. In the digital lexicon, names indicating the lithology and rank would be most informative

Table 3. Examples of potential lithogenetic attributes for different types of stratigraphic units.

	Origin class	Rock class	Examples of lithogenetic attributes
LS unit	Stratified supracrustal (by default)	**Sedimentary**	Environment of deposition (e.g., alluvial, submarine fan)
		Igneous>Volcanic	Type of eruption (e.g., subaerial lava flow, pyroclastic fall, submarine pillowed)
		Sedimentary-volcanic (mixed)	
PdS unit	Pedologic horizon	Regolith	Weathering type (e.g., kaolinitic, lateritic) Parent rock
LD unit	Intrusive	**Igneous**>Plutonic	Form (e.g., batholith, stock, laccolith, sill) Petrogenetic class (e.g., A-type granite)
		Igneous>Subvolcanic, dyke	Form (e.g., dyke, sill, subvolcanic intrusion)
	Tectono-metamorphic	**Metamorphic** >Granoblastic, foliated, gneissic, migmatitic	Type of metamorphism (e.g., regional mm, contact mm, palingenetic) Protolith
		Tectonic, mylonitic, cataclastic	Type of dominant fabric Protolith
	Other composite genesis	Metasomatic, altered	Alteration type Parent rock or protolith
		Impact metamorphic	Type (shocked, breccia, impact melt)

(e.g., Sorsakoski granite lithodeme) in making a distinction from unranked lithological units, such a granite body near Tavikoski casually named ‘Tavikoski granite’. Where the unit is highly heterolithic and challenging to describe concisely, names such as Telkkämäki lithodeme would be most convenient. Finally, the lithodeme names are primarily identifiers, and perfect consistency between the descriptive lithological term in the unit name (‘schist’) and the actual rock names in the description (e.g., biotite-muscovite schist with interbeds of carbonaceous schist and carbonate rock) is not required.

Suite is a rank and consists, by definition, of lithodemes of the same class (e.g., intrusive, tectono-metamorphic). Unnamed lithological map units can also be linked to a suite. Examples of names include the Idaho Springs Metamorphic Suite, Tuolumne Intrusive Suite and Cassjar Plutonic Suite (NASC 2005), and in Finland the Rapisevankangas gneiss suite (Laajoki & Luukas 1988) and Heinävesi suite (Mikkola et al. 2022). In the NASC (2005, 2021), names consisting of a geographic term, an adjective denoting the fundamental character of the suite and the rank term are suggested. In Finland, descriptive three- or four-partite names would be most informative (e.g., Heinävesi plutonic suite, Koli gabbro sill suite, Kittilä metamorphic suite). The most typical adjectives would be ‘intrusive’, ‘plutonic’ and ‘metamorphic’, but mylonitic suite, metasomatic suite and impact rock suite may also be useful in Finland. Finally, we consider that the descriptive value should be preferred over the formality, and names where the fundamental character is self-evident are thus acceptable (Rautalampi granitoid suite, Koli gabbro sill suite).

Complex, the unranked lithodemic unit, is defined as an assemblage or mixture of rocks typically of two or more genetic classes (NASC 2005, 2021). Complexes are extensive units comparable to suites or supersuites and are widely used in the Precambrian unit nomenclature. NASC (2021) specifies three types (volcanic complex, structural complex, intrusive complex) but does not restrict the use of other types.

Examples of Precambrian complexes include the Devils Lake Structural Complex, Glamorgan Gneiss Complex (Easton 2009) and, in Finland, the Jormua ophiolite complex (Kontinen 1987), the tectono-metamorphic complexes in eastern Finland (e.g. Piiparinmäki complex, Kalpio complex; Laajoki & Luukas 1988, Laajoki 1991), the Tohmajärvi volcanic complex (Ward 1987) and Lentua TTG complex (Hölttä et al. 2012). Migmatite gneiss complex would an appropriate term for large, complex migmatite units consisting of high-grade gneisses, migmatites and intrusive granites.

Compared to lithostratigraphy (*sensu stricto*), the lithodemic hierarchy is flat (lithodeme<suite< supersuite) and the fundamental unit (lithodeme) has no lower ranks (Table 4). However, the resolution of the system is adjustable without any lower ranks. For example, the Sorsakoski granite (lithodeme) consists of three lithological map units: granite, quartz-monzonite and diorite (Mikkola et al. 2024), and all of these rock units are included in the description of the lithodeme. For more resolution, the granite and quartz-monzonite could be named as individual lithodemes. Furthermore, the use of lower ranks would create a vast number of lithodemic unit names and obscure the difference between a rock unit (lithological unit) and a stratigraphic unit. Thus, any subdivision of a lithodeme into lower ranks is not suggested.

Table 4. Proposed practice for the management of lithodemic and lithological units. Only the named lithodemic units (bold) would be included in the digital lexicon (GTK FinstratiKP).

North American Stratigraphic Code	**Current practice** in the GTK map database	**Proposed** for the GTK map database and FinstratiKP digital lexicon
Supersuite >Suite >>Lithodeme (>>Unnamed lithological unit)	Supersuite >Suite >> Lithodeme (named) >>Undefined lithodeme (corresponding to an unnamed lithological unit)	**Supersuite** >**Suite** >>**Lithodeme** (named, characterized) >>>Unnamed lithological map unit >>Unnamed lithological map unit
Complex (unranked)	*Complex* (unranked)	***Complex*** (unranked)

In summary, the presently used lithostratigraphy *sensu lato* in Finland is the best solution for litho-based stratigraphic units at the national level. The lithodemic classification can be developed by subdivision into genetic classes and by the attachment of new unit attributes. Descriptive three- or four-partite names with a flexible naming convention would, as such, increase the information value of the lithodemic units. Finally, it is important to note that too ambitious objectives and complicated data models may reduce the main strengths of the lithodemic system, the ease of application and a kind of informality.

3.5.4 'Mappable unit' independent of resolution

'Mappable unit' is a key concept incorporated in the definition of stratigraphy (Salvador 1994). The concept involves two components: (1) the units represent distinct entities and (2) the map units can be portrayed (on a printed map or in a digital map service) at 'normal mapping scales'. However, the meaning of the term 'mappable' is not fully unambiguous and may become even obsolete in the digital management of geological units. Unit 'mappability' obviously depends on the selected resolution ('mapping scale'). The management of digital geological map data at different resolutions and the transitions between these compilations is one major challenge. The minimum sizes of map units (polygons) are defined separately, for example, for local (ca. 5k to 20k), regional (ca. 50k to 200k) and national (ca. 500k to 2M) scale compilations. In principle, this allows the use of rather small map units where appropriate. Nevertheless, we acknowledge that the establishment of very small geological units is not wise. For clarity, and to avoid an excess of stratigraphic names, we suggest that stratigraphic unit boundaries should primarily be defined at the resolution used, and explicitly defined, for regional maps in Finland. In the digital lexicon, a stratigraphic unit (e.g., Someplace granite) has a name, description, and defined boundaries that are possible to portray at the regional mapping scale.

However, the location of the unit is a more complicated issue. The correlation of map units (or subsurface rock bodies) of any size with the defined stratigraphic units (in digital lexicon) should not be restricted. Basically, an unlimited number of spatial objects can be linked to the unit by a shared unit ID, and the number of linked objects can be different at different resolutions (Fig. 8). This type of 'map database for the future' with several resolutions would have some major advantages: (1) functional zoom-in portrayal of map data in digital map services and (2) map data updating (based on new detailed information) without any generalization and related loss of information. The multiresolution approach would plausibly have a major impact on map database structures: spatial information (polygon boundary line coordinates or X-Y-Z coordinates) of an unlimited number of spatial objects would be linked to the geological unit, separately for each resolution.

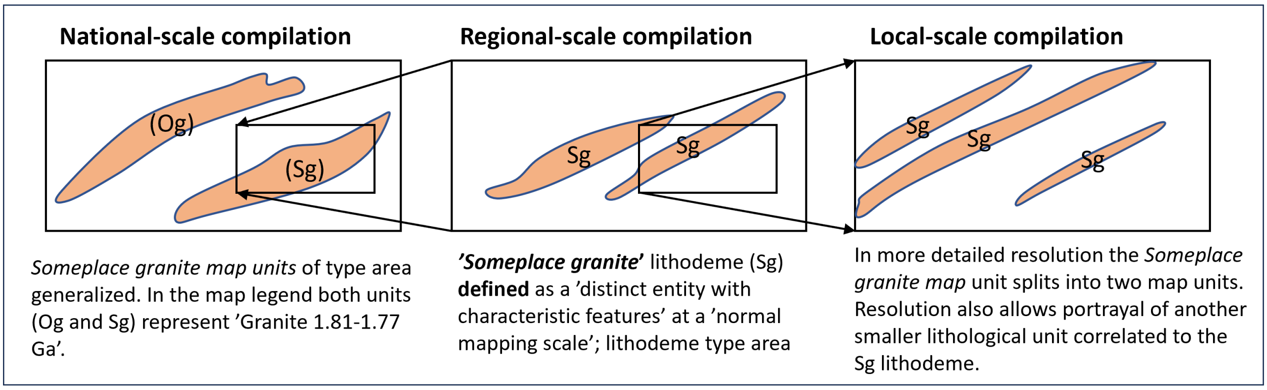

Fig. 8. The fractal nature of granite bodies within a migmatite belt. The size of a 'mappable unit' depends on the selected resolution (regional vs. local scale). *Someplace granite* (Sg) and *Otherplace granite* (Og) constitute part of the *Fineplace granitoid suite*. The national-scale compilation is based on age group classification, and the lithodemic name can be attached as an attribute. The link between the map units and the defined lithodemic unit (Sg) can be retained at all resolutions, despite the different polygon boundary line coordinates.

4 CORRELATION WITH TIME: CHRONOSTRATIGRAPHY IN THE PRECAMBRIAN OF FINLAND

The diachronic nature of most lithological boundaries has been understood since the formulation of 'Walther's law' (cf. Walther 1894, Middleton 1973). The same point was formulated by Wheeler (1964) as follows: "*Time as a stratigraphic dimension has meaning only to the extent that any given moment in the Earth's history may be conceived as precisely coinciding with a corresponding worldwide lithosphere surface and all simultaneous events either occurring thereon or directly related thereto*." Thus, time is both the most fundamental and the most difficult constraint in stratigraphy, and especially so in the Precambrian (see reviews by Altermann et al. 2012, Miall 2016, Shields et al. 2022).

Chronostratigraphy deals with the rock record, geochronology with geological age. These two classifications tend to be inherently blurred, because the same names are used for both. Geochronometry is the branch of geochronology referring to the quantitative measurement of geological time. The boundaries of geochronological units (e.g., period, epoch) and the corresponding chronostratigraphic units (system, series) are defined and updated globally (https://stratigraphy.org). All the Mesoproterozoic and older geochronological-chronostratigraphic unit boundaries are currently based on Global Standard Stratigraphic Ages (GSSA), and these age boundaries do not correspond to any specified reference points in the rock record. Where more resolution in the division of Archean and Proterozoic is needed, the Geon concept of Hoffman (1990) and the informal Precambrian epochs presented in the INSPIRE data model (Asch et al. 2009) are worth considering.

Nonetheless, by definition, a chronostratigraphic unit includes all rocks formed during a specific interval of geological time, and the units are bounded by isochronous horizons. These two aspects combined bring in both theoretical and practical issues regarding Precambrian chronostratigraphy. First, how can we apply chronostratigraphy, even theoretically, when there is no defined linkage between the time and the stratum? A more practical question is related to Precambrian geochronometry. Error limits for age determinations of Precambrian rocks are typically millions of years and sometimes tens of millions. Consequently, the delineation of accurate chronostratigraphic boundaries (formal or informal) in the Finnish bedrock is not a realistic idea, and the 'chronostratigraphic method' is limited to the correlation of litho-based units and geochronological-chronostratigraphic units.

In practice, radiometric dating is the only tool available in Finland for the correction and correlation of the observed stratigraphic relationships. In addition to the traditional igneous rock crystallization ages, an increasing number of detrital zircon ages and metamorphic age patterns provide improved constraints on the bedrock evolution of the Fennoscandian shield. The internationally defined formal geochronological-chronostratigraphic names are used in Finland as attributes of geological units. However, in scientific communication, both the formal (e.g., Archean, Paleoproterozoic) and informal (e.g., Jatulian, Svecofennian, Riphean) geochronological-chronostratigraphic nomenclature is widely, and utterly inconsistently, in use. The clarification of these useful, but poorly defined, informal names and the underpinning concepts is one objective of this contribution.

4.1 Archean

In the International Chronostratigraphic Chart, the Archean Eon has not been subdivided beyond the Era-Erathem level. In Finland, the formal names (e.g., Mesoarchean, Neoarchean) and their internationally defined age boundaries are in common use, and no regional schemes for the Archean geochronological record have been presented. Thus, going forward, usage of the IUGS Era and/or Erathem names in the subdivision of the Archean time and rock record in Finland is suggested when found informative and appropriate.

4.2 Paleoproterozoic

Regarding the Paleoproterozoic Era, in the GTK databases, correlation with the formal Paleoproterozoic geochronological units (e.g. Rhyacian, Orosirian) has been used (see Luukas et al. 2017), but in scientific articles, the use of these period-system names has been limited. The challenge in the application of formal, *globally defined chronostratigraphic scales* is that the unit boundaries do not correspond to the widely agreed mainlines of geological evolution and to regionally observable 'events'. Therefore, *regionally defined time-stratigraphic scales* are justified and provide a useful time-bound nomenclature of Proterozoic rocks in Finland.

4.2.1 Time-stratigraphy of Karelian formations in eastern and northern Finland

Salvador (1994) recommends the preservation of traditional, well-established names (Chapter 3.B.3.g.) where possible and allows the use of regional chronostratigraphic scales (Chapter 9.E.). The ages of regionally recognizable, sufficiently dated events form the foundation for an applicable regional time-stratigraphic scale. However, it important to note that chronostratigraphic scales are of two fundamentally different types: (1)) scales based on the recognition of a Global Boundary Stratotype Section and Point (GSSP; see ICS ICC https://stratigraphy.org/ICSchart/ChronostratChart2023-09.pdf) and scales defined by the Global Standard Stratigraphic Ages (GSSA) having no corresponding rock sequences. The GSSP type is not applicable in the Precambrian of Finland for several reasons: (1) very few of the potential events are recorded by a dated stratiform rock body, (2) most of the dated rock units are not widespread, (3) many of the suggested 'events' are indistinct and nearly impossible to date accurately (e.g., Lomagundi-Jatuli isotopic excursion) and (4) the age determination limits of error are typically rather large.

Karelian formations refer to the Paleoproterozoic successions deposited nonconformably on the Archean basement and occurring in the eastern and northern parts of the Fennoscandian shield. Hanski & Melezhik (2012) re-introduced the traditional stratigraphic names by re-defining these as informal, event-based periods/systems: *Sumian* (2505–2430 Ma), *Sariolian* (2430–2300 Ma), *Jatulian* (2300–2060 Ma), *Ludicovian* (2060–1960 Ma) and *Kalevian* (1960–1900 Ma). The lower boundaries are based on the age of the gabbronorite intrusions (Sumian and Sariolian), the timing of the onset and termination of the Lomagundi-Jatuli isotopic excursion (Jatulian and Ludicovian) and the age of crosscutting relationships of a mafic dyke swarm (Kalevian) (Fig. 9, Table 5; for details, see Hanski & Melezhik 2012).

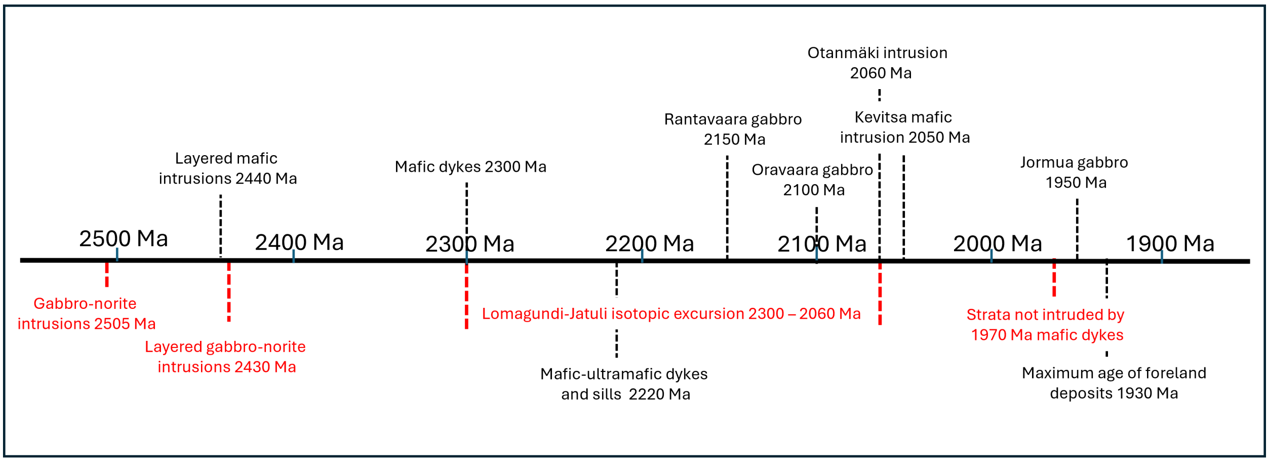

Fig. 9. Events that have potential for application in the time-stratigraphy of Karelian formations. The events proposed by Hanski & Melezhik (2012) are shown in red. Dated intrusions are according to data in Huhma et al. (2018). The commencement of orogenic foreland deposition (1930 Ma) is estimated on the basis of the presented detrital zircon ages (e.g., Lahtinen et al. 2010).

Our proposal for a regional time-stratigraphic scale of Karelian formations in Finland is modified from the profound proposal of Hanski & Melezhik (2012) but also influenced by some selected events (Fig. 9) and the IUGS Chronostratigraphic Chart (Table 5). It is of paramount importance to see that the proposed scale divides geological time and has no direct correspondence to the tangible rock record. To underline the distinction between the regional stratigraphic nomenclature presented in Table 5 and the formal, globally- agreed IUGS chronostratigraphy, we systematically use the term 'time-stratigraphy' in connection with the proposed regional scale. In our proposal, the scheme of Hanski & Melezhik (2012) has been adjusted by two pragmatic modifications: both Jatulian and Kalevian periods/systems have been divided into two parts. In addition, the lower boundary of the Sumian is set to the internationally defined Archean–Proterozoic boundary (2500 Ma). The *Lower/Upper Jatulian boundary* nearly corresponds to the age (2220 Ma) of the differentiated gabbro-wehrlite intrusions (Hanski et al. 2010, Huhma et al. 2018). The definition of the Ludicovian and Kalevian periods is ambiguous, and different proposals regarding the appropriate boundaries have been presented (e.g., Köykkä et al. 2022, Lahtinen et al. 2023). The *Lower/Upper Kalevian boundary* is here set by the estimated maximum age of the orogenic sediments within the Karelian succession (Fig. 9)

All time-stratigraphic scales defined by stratigraphic ages, including the IUGS Chronostratigraphic Chart for the Paleoproterozoic and our proposal in Table 5, are seldom ideal to apply in a certain area. However, the proposed scale provides one uniform and rather applicable framework for the correlation of rock bodies and geological time. For example, the 2220 Ma mafic dykes and sills, and associated distinctive magnetic anomalies, have been used in the division of successions for decades (e.g., Kohonen & Marmo 1992, Korsman et al. 1997). In addition, the informal name 'Upper Kalevian' has been conventional in eastern Finland since the 1990s (cf. Kontinen 1987, Laajoki 2005, Kontinen et al. 2006), referring to the assumed age of the orogenic metasedimentary rock units within the foreland.

Table 5. Regional time-stratigraphic scale for the Karelian formations.

Proposed*		Hanski & Melezhik 2012		IUGS Chronostratigraphic Chart (System/ Period) 2019	
System/Period (informal)	Numerical age	System		Orosirian	2050 – 1800 Ma
Upper Kalevian	1930 – 1900 Ma	Kalevian	1960 – 1900 Ma		
Lower Kalevian	1960 – 1930 Ma				
Ludicovian	2060 – 1960 Ma	Ludicovian	2060 – 1960 Ma		
Upper Jatulian	2200 – 2060 Ma	Jatulian	2300 – 2060 Ma	Rhyacian	2300 – 2050 Ma
Lower Jatulian	2300 – 2200 Ma				
Sariolian	2430 – 2300 Ma	Sariolian	2430 – 2300 Ma	Siderian	2500 – 2300 Ma
Sumian	2500 – 2430 Ma	Sumian	2505 – 2430 Ma		

*Informal, regional time-stratigraphic scale for the Karelian formations in Finland; the proposal has been communicated within the Precambrian Working Group of the Stratigraphic Commission of Finland.

4.2.2 Time-stratigraphy of Svecofennian rocks in western and southern Finland

The roots of the name '*Svecofennian*' are in the crustal evolution of the Fennoscandian shield (e.g., Simonen 1980, Gaál & Gorbatchev 1987). The *Svecofennian orogeny* (ca. 1930–1770 Ma; Lahtinen et al. 2005, 2023), *Svecofennian domain* (Gaál & Gorbatchev 1987) and *Svecofennian crustal province* (Kohonen et al. 2021) refer to the orogenic phase and the resulting domain of continental crust with a Svecofennian age, respectively. The orogenic phase has previously been subdivided into early Svecofennian (1.91–1.86 Ga) and late Svecofennian (1.83–1.80 Ga) (Saalmann et al. 2009, Nironen & Mänttäri 2012), separated by an intraorogenic period (Bergman et al. 2008, Lahtinen & Nironen 2010, Nironen 2011, Väisänen et al. 2012). Nonetheless, the oldest rocks within the Svecofennian Crustal Province are around 1.93 Ga (Huhma et al. 2011), and a protocrust with an age of up to 2.0 Ga has been envisaged (e.g., Lahtinen et al. 2005).

For simplicity and consistency, we propose an informal, time-stratigraphic subdivision into Lower, Middle and Upper Svecofennian (Fig. 10). In a geochronological sense, the division refers to the indistinct stages of tectonic evolution within the present Svecofennian crustal province (see Kohonen et al. 2021). The Lower Svecofennian (1930–1900 Ma) corresponds to the early, poorly known crustal evolution. The Middle Svecofennian (1900–1860 Ma) is the period of major crustal growth during and after the collision and subsequent lateral accretion to the Archean Karelia craton. The Upper Svecofennian (1860–1800 Ma) was characterized by the intra-orogenic stabilization phase, the following continued crustal growth in southern Finland and, finally, waning of the orogeny (e.g., Nironen 2017). It should be noted that the regional time-stratigraphic scales for the Archean and Svecofennian crustal provinces reflect the separate histories of the Archean Karelia craton and the Proterozoic crustal domain prior to their tectonic amalgamation at ca. 1900 Ma (Fig. 10).

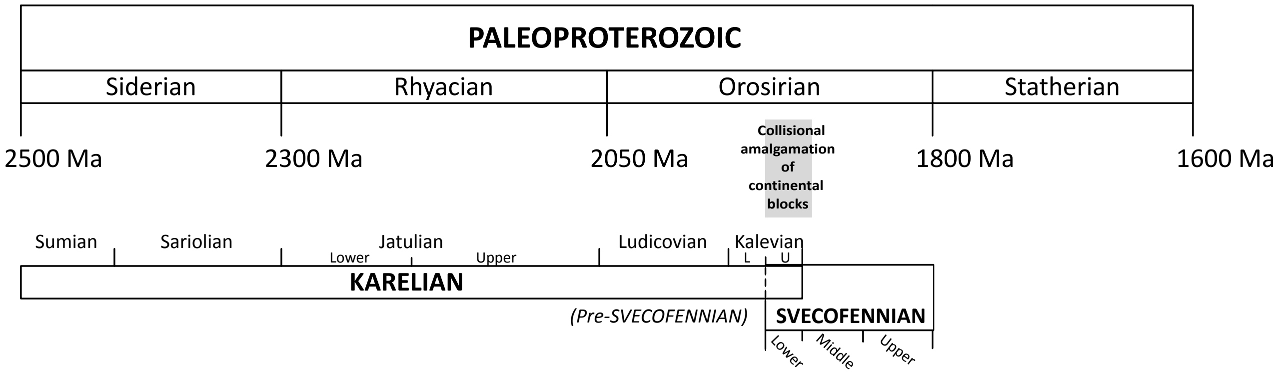

Fig. 10. Formal geochronological/chronostratigraphic scale (IUGS) in comparison to the proposed regional time-stratigraphic scales. Note the overlap (1930–1900 Ma) of the proposed regional time-stratigraphic scales.

4.2.3 Summary of the Paleoproterozoic

The event stratigraphic approach of Hanski & Melezhik (2012) both established a regionally applicable time-stratigraphic scale for the Karelian formations and provided an elegant way out of the conceptual tangle with the traditional stratigraphic nomenclature (see 3.1.2 above). Ideally, the suggested time- stratigraphic unit boundaries are tied to events recorded in rock bodies, and the connection between the boundaries and the tectonic history of Fennoscandia is the fundamental underpinning idea. However, the 'event stratigraphic' nature of the presented regional time-stratigraphic scales can also be questioned. Most of the proposed events are not widespread within the shield or are rather poorly dated. The proposed boundaries will probably change with advancing research and the recognition of well-defined events. However, the proposal defines the time-stratigraphic meaning of the nomenclature used in the scales. Consequently, and to avoid further confusion, any lithostratigraphic connotation of the traditional Karelian nomenclature (e.g., Jatuli/Jatulian, Ludicovi/Ludicovian) should be avoided.

The problematic points of the overall time-stratigraphic scheme (Fig. 10) for the Paleoproterozoic are: (1) the dependence on a tectonic paradigm assuming collision at ca. 1900 Ma and (2) the related overlap of the Karelian and Svecofennian scales. In fact, the proposal can be seen as one uniform scale: Karelian 2500–1930 Ma (with subdivision) and Svecofennian 1930–1800 Ma (with subdivision). Accordingly, all the intrusions (1930–1800 Ma) and all the structures linked to the collisional orogeny must be considered as 'Svecofennian', also within the Archean crustal province. Two notes are needed, however: (1) Possible future identification of Proterozoic crustal domains or rock units within the present Svecofennian crustal province with ages >1930 Ma should not be regarded 'Karelian', but the Svecofennian scale needs to be revised accordingly. (2) The 'orogenic' sedimentary rock units within the Archean crustal province (Upper Kalevian, 1930–1900 Ma) can basically be considered as Lower Svecofennian. However, Upper Kalevian is still found useful as a time-stratigraphic name (or 'alias name') for many reasons. Firstly, these rocks constitute an integral part of the Karelian succession and have been known as 'Kalevian' for more than a hundred years. A sudden, fundamental change in nomenclature would create more confusion than clarity. Secondly, the timing of the collision and the subsequent lateral accretion is not accurate (ca. 1920–1890 Ma) and, plausibly, the collision was diachronic. Furthermore, the geological evolution from Karelian continental margin to collisional foredeep, foreland basin system, subsequent basin inversion and the development of a foreland fold-and-thrust belt (cf. Kohonen 1995) is complex and not sufficiently resolved.

For these reasons, the time-stratigraphic classification of collision-related deposits across the Raahe–Ladoga cryptic suture is a complicated task. This issue and the distinction of the *Upper Kalevian* and the *Svecofennian* greywackes has been discussed by Kontinen & Sorjonen-Ward (1991), Lahtinen et al. (2015, 2023) and Mikkola et al. (2022). Furthermore, the stratigraphic relationships between the pre-orogenic (Ludicovian to Lower Kalevian; see Fig. 10) and orogenic, largely allochthonous (Upper Kalevian) rock units is also found challenging within the Archean crustal province (e.g., Kohonen 1995, Lahtinen et al. 2010).

Regardless of these potentially problematic issues, this proposal clarifies the Proterozoic time-stratigraphic and geochronological nomenclature in Finland. The published scheme provides a terminological reference for many commonly used stratigraphic names and aids general communication concerning major geological units in Finland. However, the best way to serve international readers would be to provide the boundaries, e.g., Ludicovian (2060–1960 Ma), or parallel use with the International Chronostratigraphic Chart (IUGS-ICS) according to the following examples: *Ludicovian* (early Orosirian) or *Svecofennian* (Orosirian).

4.3 Mesoproterozoic and Neoproterozoic

Compared to Archean and Paleoproterozoic rocks, the volume of Mesoproterozoic and Neoproterozoic rocks in Finland is minor. The main components are (1) the 'Mid-Proterozoic' (late Paleoproterozoic to Mesoproterozoic) anorogenic granites and associated mafic rocks and (2) the local occurrences of Meso- to Neoproterozoic cover on the Svecofennian crystalline basement.

The age determinations of 'Mid-Proterozoic' anorogenic granites and associated mafic rocks are abundant (e.g., Rämö & Haapala 2005), whereas the age constraints of the supracrustal cover rocks are sparse. The diabase dykes and sills crosscutting the sandstones of the Satakunta formation (cf. Pokki et al. 2013) have been dated at ca. 1270 Ma (Suominen 1991). The Mesoproterozoic age of the Muhos formation (for a description, see Simonen & Kouvo 1955, Solismaa 2008) is plausible but uncertain (Kohonen & Rämö 2005). The applied time-stratigraphic nomenclature has typically been a mixed combination of ICS-IUGS Erathems, the influence of Russian classification schemes and the legacy nomenclature inherited from the first part of the last century.

The name *Riphean* (Fig. 11) has been, and still is, in common use in Russia, including the eastern part of the Fennoscandian Shield. It was also part of the older international geological timescales and constitutes part of the General Stratigraphic Scale of Russia (e.g., Puchkov et al. 2014). The history of the obsolete 'Jotnian nomenclature' in Finland has been summarized in Simonen (1986). The name Jotnian was proposed by Sederholm (1897) for all the post-orogenic (i.e., post-Svecofennian) rocks in Finland. 'PostJotnian' was introduced by Ramsay (1909) for the diabases truncating the 'Jotnian' sandstones. The name 'subJotnian' was first used by Högbom (1909), and the concept has included an idea of an exhumed peneplain preceding the deposition of 'Jotnian' sandstones (for details, see Lidmar-Bergström 1996).

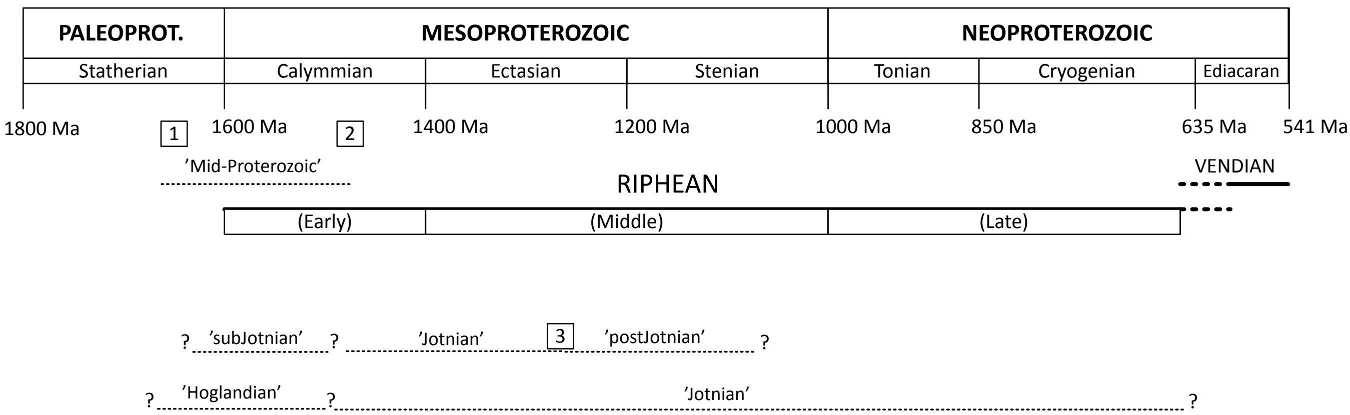

Fig. 11. Formal geochronological/chronostratigraphic scheme (IUGS) in comparison to the Riphean and Vendian. The scheme of Sederholm (1927; lowermost) and the obsolete division of the 'Jotnian' are shown for comparison. Boxes 1 and 2 point to the ages of the oldest and youngest intrusions of the 'mid-Proterozoic' anorogenic magmatic province (Rämö & Haapala 2005), and box 3 to the age of the diabase crosscutting the Satakunta sandstone.

To conclude, *Riphean* is a defined time-stratigraphic concept (corresponding to Era/Erathem). However, the resolution provided by *Riphean* (1600–650 Ma) is minimal, even compared to the formal (IUGS) Erathems (Fig. 11). The names *Jotnian, postJotnian* and *subJotnian* are problematic for many reasons: (1) They were established in times when stratigraphy was in its infancy and the distinction between time-based and litho- based categories was not developed; (2) Proper definitions are lacking and the geochronological boundaries of the division have never been presented; (3) Currently, names with an ending '-ian' are preferred for time-based units; (4) Prefixes such as 'sub-' and 'post-' are not appropriate in time-stratigraphic nomenclature. Amantov et al. (1996) pointed out the descriptive nature (i.e., a diabase cutting the sandstone) of the names 'Jotnian' and 'postJotnian' and questioned their connection to any time-based classification. We consider that the scientifically apt use of these traditional names is not possible, and their further use in any stratigraphic connection is not feasible. Furthermore, compared to the Riphean and Jotnian, the formal (IUGS-ICS) chronostratigraphic scale provides both better resolution (Mesoproterozoic divided into periods/systems) and an internationally recognized reference.

The number of Neoproterozoic strata in Finland is minor, but the name *Vendian* deserves a brief review. The Vendian System and Period were established from drill core sequences on the Siberian platform (Sokolov 1952, Sokolov & Fedonkin 1984). The name (Vendian) has been widely used internationally, but it was never adopted by the Subcommission on Precambrian Stratigraphy. The upper boundary is defined by the onset of the Cambrian and the proposals for the lower boundary have varied between 650 and 600 Ma (Fig. 11). The General Stratigraphic Scale of Russia (Ver. 1993, see Zhamoida 2015) sets the boundary at 650 ± 20 Ma. In 2015, the *Ediacaran* System/Period (635–541 Ma) was included in the ICS international chronostratigraphic chart (see Cohen et al. 2013), and it has rapidly replaced *Vendian* in international use. In Finland, the use of Ediacaran is recommended.

Finally, we suggest that (1) IUGS Era/Erathem and period/system names are used for the Meso- and Neoproterozoic rocks in Finland and (2) the obsolete names Jotnian, subJotnian and postJotnian should be abandoned and no longer used in a stratigraphic context.

5 SUMMARY AND FINAL REMARKS

Systematic classifications and related nomenclature are needed to reduce ambiguity in communication and correlation but not least to enable digital, structured datasets of interpreted geological information, casually referred to as map data. Stratigraphic units form the backbone of geological map databases, but stratigraphic nomenclature is also in everyday use in scientific communication. For example, 'the lower Jatulian Herajärvi Group of the Höytiäinen belt' (for belts and other geological region names, see Kohonen et al. 2021) concisely communicates the lithostratigraphic unit, the suggested time correlation and the location.

We see that the combined use of lithostratigraphic and lithodemic units provides tools for flexible description and attribution of the observed lithological units and sufficient reference to the field by type sections and type areas. The use of lithodemic units has been found to be a convenient and uncomplicated method in the management of the heterogenous lithological units and in rearranging legacy map data of different ages and variable resolutions. However, the all-inclusive nature of the classification means that lithodemes are very heterogeneous and their informative attributes are different. This causes a need to consider their division into subclasses according to the origin (e.g., intrusive, metamorphic). One substantial threat is the plethora of stratigraphic names. The risk can be reduced by avoiding too small lithodemes, pointless naming of lithological units and unnecessary upper rank names. We suggest that only litho-based units with defined characteristics and related references deserve a stratigraphic status and related unit name.

Innovative ways of combining the application of stratigraphic and other unit classifications would enable the storage of geological information in its all richness. However, the practical applications must be demand-driven, steered by common sense and fit for the purpose. For example, research papers presently introduce plentiful nomenclature of tectonic blocks, provinces, orogens and crustal domains. Both the understanding and management of these rather conceptual geological units would be supported by a classification system including definitions and the criteria for their characterization. On a more concrete level, the systematic use of deformation units, such as structural domains, would improve both the mapping process and the information value of geological map data.

As pointed out by Hanski & Melezhik (2012), any geological discussion is cumbersome without general nomenclature referring to geological age. The proposed regional time-stratigraphic names provide a good basis for improved terminological consistency. Nevertheless, the ultimate key point is to realize that in the Precambrian, we *correlate* rock bodies with the geochronological units (Period or Era). In correlation, reference to a defined chronostratigraphic-geochronological scale (formal or informal) should always be provided. In the rock record, the chronostratigraphic systems and their boundaries are conceptually abstract, unreal features. For example, a mapped lower contact of the locally lowermost quartzite unit correlated with the Jatulian period ('Jatulian quartzite') is a boundary between rock units and definitely not the lower boundary of the Jatulian system.

In principle, all geological units of different resolutions and purposes, from tectonic interpretation to engineering geology, are basically possible to manage as parts of one modular information system supported by an advanced data model. In practice, however, the planning of a map database means balancing between capability and applicability. Sophisticated, complex systems with many parallel classifications and large numbers of attributes for each unit type are complicated to construct and laborious to maintain, whereas very simple systems lack the capacity to describe various features of Precambrian rock bodies. The core of a map database is a conceptual data model, and other parts of the system are the digital lexicon, the spatial system (for coordinate management), map feature catalogues, attribute lists (with definitions) and vocabularies (and derived 'value lists'). Decisions regarding the application of geological units affect all these components, and the challenge cannot be addressed by a national stratigraphic code or guidebook alone. The issues related to the appropriate and beneficial application of geological units can only be tackled by developing good scientific practices, practical level recommendations, training and professional case-by-case decisions on the organizational level .

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GUIDELINES AND PROCEDURES FOR NAMING BEDROCK UNITS IN FINLAND

(Fully revised 2nd edition)

by

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The Stratigraphic Commission of Finland (SCF) was established in 2006 and the first edition of *Guidelines and Procedures for Naming Precambrian Geological Units in Finland* was published in 2010. The Precambrian Subcommission of the SCF and the Geological Survey of Finland (GTK) have jointly developed the bedrock geological nomenclature in Finland, and this revised edition provides a summary of the current practices and recommendations. This guide presents the principles of the classification of geological units, the procedure for the naming of formal and informal units and advice for the application of the different classifications. Special emphasis has been placed on: (1) the combined use of lithostratigraphic and lithodemic units and (2) the classification of tectonic/structural bedrock units of Finland.

Effective communication in geosciences requires accurate and internationally consistent terminology and nomenclature. The emergence of networked and interoperable data systems and information services has underlined the need for hierarchical classification systems and globally harmonized vocabularies. On the national level, the best practices can be obeyed by creating internationally compliant information infrastructures and by enforcing appropriate scientific procedures. The principles and recommendations presented in this guide provide one practical step towards structured geological data and unambiguous nomenclature of geological units.

Keywords: bedrock, lithostratigraphy, stratigraphic units, lithodemic units, tectonostratigraphic units, sequence stratigraphy, chronostratigraphy, nomenclature, guidelines, Finland

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PREFACE TO THE REVISED 2024 EDITION

The first edition of this guide appeared more than ten years ago in 2010, resulting from collaboration between the Stratigraphic Commission of Finland (SCF) and the Geological Survey of Finland (GTK). The background information and the contributors can be found in the preface of the first edition. Since the 2010 edition, there have been significant developments in the management of geological map data in Finland. This revised 2nd edition has largely benefitted from the experience gained at GTK regarding the compilation of the seamless, national map database. One lesson learned is the need to clarify the relationship between the formal stratigraphy and the practical management of different geological map units. In 2019, the SCF formulated a procedure for the approval of formal stratigraphic units in Finland. GTK is currently maintaining a digital lexicon (FinstratiKP) for the management of all the bedrock units in Finland.

Globally, a significant change is that the different classification systems and derived nomenclature are increasingly forming a part of our information infrastructure. International initiatives, such as the European infrastructure for spatial information (INSPIRE) and the global data transfer standard for geological data (GeoSciML), are transforming our working environment and provide unseen opportunities for shared geological information. The related vocabularies are developing to international standards, and the national agencies responsible for geological information need to adapt to this change, including globally interoperable systems and compliance with the INSPIRE directive and related national legislation.

This guide, produced by the Precambrian Subcommission of the SCF, is intended to be both authoritative and helpful in explaining the stratigraphic method for practicing geologists. The main emphasis is still on the application of different classification categories and recommendations in naming the bedrock units in Finland. Compared to the first edition, the guide is more concise and practical, and attempts to provide pragmatic advice on the designation and naming of geological units. To fulfil the purpose of supporting the harmonization of the geological nomenclature and related practices, the guide would ideally be widely applied by the Finnish geological community. One of the notable changes is that this guide is now applicable to all bedrock units in Finland, without any specific emphasis on “Precambrian” geology. By design, this guide is meant to be an evolving document. Both the evolution of stratigraphy and changing means of information management may cause a need for revisions in the future.

In 2022, during the compilation of the guide, the members of the Precambrian Subcommission were: Prof. Kari Strand (chair; University of Oulu), Dr Jaana Halla (University of Helsinki), Prof. Juha Karhu (University of Helsinki), Dr Jarmo Kohonen (GTK), Dr Juha Köykkä (GTK), Dr Raimo Lahtinen (GTK) and Dr Markku Väisänen (University of Turku). The editors appreciate the collaboration within the Subcommission and are grateful for all the contributions to the manuscript. L. Wickström and E. Lehtonen are thanked for reviews of the manuscript and their constructive comments and improvements.

Espoo 01.02.2024

Jarmo Kohonen, Juha Köykkä and Kari Strand
Editors of the revised 2024 edition

1 INTRODUCTION

1.1 Background

Geological knowledge, such as scientific articles, reports, maps and models, builds on common concepts expressed by the language of geoscience. The spectrum of geological units has developed with the tradition of geological mapping, and the description and definition of different units still forms the basis for the field-based research process. To support a common understanding and consistency, geological units need to be named and classified according to the accepted international and national guidelines and stratigraphic codes. An increasingly important application area is the design of geological information systems and related data models. The search for information with modern information technology tools can be highly improved by consistent classification systems and shared vocabularies.

The Stratigraphic Commission of Finland (SCF) was founded in a constitutive meeting held on 27 February 2006 under the Finnish National Committee for Geology. The role of the SCF is to provide guidance on stratigraphic nomenclature and procedures in Finland. The development of stratigraphic procedures and management of the geological units is elaborated in close collaboration between the Geological Survey of Finland (GTK) and the SCF (Fig. 1). The increasing importance of stratigraphy, and geological classification systems in general, is due to the following reasons:

- National and international efforts to harmonize geological information;
- The establishment of geological databases requires defined, hierarchical classification systems;

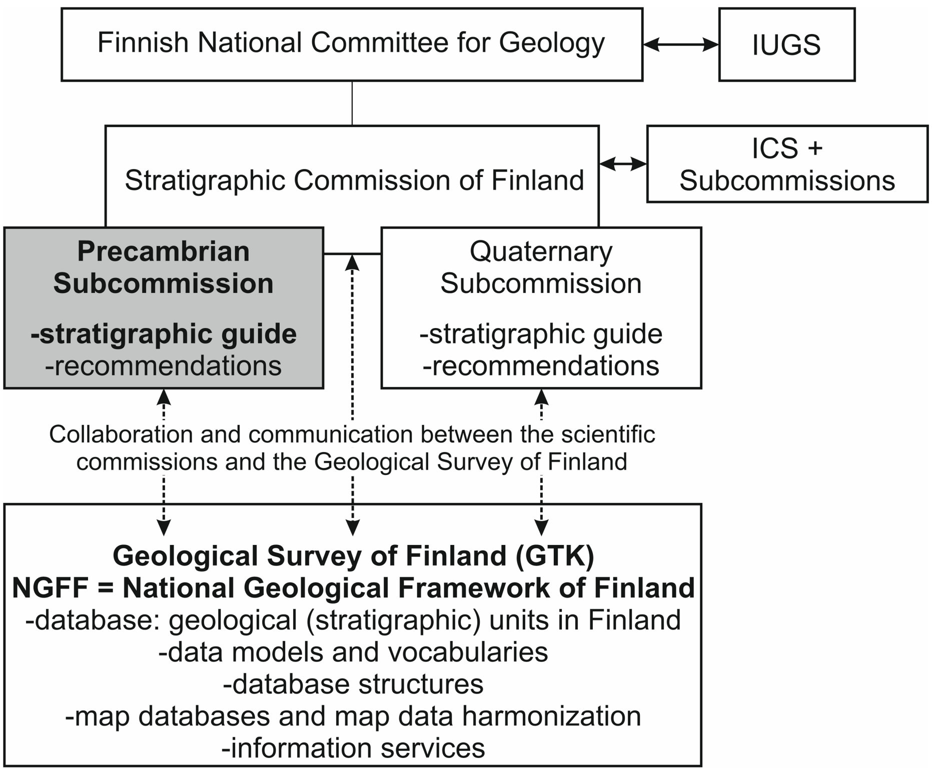


Fig. 1. The roles of the Stratigraphic Commission of Finland and the Geological Survey of Finland in the development of stratigraphic procedures and databases.

- In the global working environment, data exchange and interoperability are no longer only necessary for leading scientists, but for everybody working in the broad field of geology.

The established stratigraphic classification systems (e.g., International Stratigraphic Guide, Salvador 1994) evidently have limitations when applied to bedrock terrains (see Hattin 1991, NASC 2005, Easton 2009). Especially challenging are the intensely and multiply deformed complexes consisting of metamorphic and plutonic rock assemblages. As a result, a formal lithostratigraphic approach has not been applied in most parts of the rock record in Finland. Nevertheless, novel stratigraphic concepts developed by the international stratigraphic organizations and documented by the International Union of Geosciences (IUGS), the International Commission of Stratigraphy (ICS) and the North American Commission on Stratigraphic Nomenclature (NACSN) have opened new insights into the application of stratigraphy.

1.2 Purpose of the guide

'*Guidelines and Procedures for Naming Bedrock Units in Finland*' communicates how modern stratigraphy is best applied in Finland and forms the backbone for the work of the Precambrian Subcommission of the SCF. This guide was compiled to: (1) support consistent geological unit nomenclature in Finland, (2) assist regional geologists and other geoscientists in practical stratigraphic problems related to complex, metamorphic terrains and (3) facilitate the development of the national geological unit database (digital lexicon). This guide provides practices and standard procedures for defining and naming the bedrock units. It is not a formalized stratigraphic code but attempts to meet the practical needs of geologists studying the bedrock of Finland. The guide also serves as a proxy to more formal and advanced stratigraphic information. Several stratigraphic guides or codes are available for international (e.g., Hedberg 1976, Salvador 1994, Murphy & Salvador 1999, NASC 2005) and regional (e.g., NCS 1989, Kumpulainen 2016) usage. These editions, together with the IUGS CGI (GeoSciML) vocabularies, have been used as the principal references. For conciseness, the key references are presented in the text as abbreviations: **ISG 1994** (International Stratigraphic Guide; Salvador 1994); **NASC 2005** (North American Stratigraphic Code; North American Commission on Stratigraphic Nomenclature 2005); **NCS 1989** (Rules and recommendations for naming geological units in Norway; Norwegian Committee on Stratigraphy, Nystuen, J. P. (ed.) 1989); and **CGI** (IUGS CGI GeoSciML vocabulary https://cgi.vocabs.ga.gov.au/vocab/). To avoid unnecessary overlap with the established international editions, the technical procedures and general rules are not included in full detail.

The key terms are presented in *italics*. When a definition is not provided in the text, the ISG 1994 glossary (pp. 106–142), the main reference for each classification category (see Table 1), the IUGS CGI (GeoSciML) vocabulary and the Glossary of Geology (5^{th} revised edition; Neuendorf et al. 2011) are the suggested terminological sources. It is noted that following the principal references (ISG 1994, NASC 2005) and the 'standard' vocabulary by the CGI, the short spelling 'stratigraphic' (instead of stratigraphical) is used, whereas the long spelling for the more general words (geological, lithological) is retained.

1.3 Stratigraphic procedure and management of geological units in Finland

The management of geological units in Finland incorporates three fundamental roles: (1) the provision of stratigraphic advice and a knowledge base, (2) ownership of the digital lexicon, maintenance of the defined units and the development of related systems and services and (3) ownership of the formal process (see Fig. 1). The first role, handled by the SCF, includes the monitoring of international development, participation in the ICS subcommissions and national communication on stratigraphy. The second role is played by GTK, the national authority responsible for geological information and databases. GTK develops and maintains the digital lexicon of bedrock units (FinstratiKP database) and is thus authorized to insert units and manage the system. In practice, GTK gathers nomenclature from published scientific articles, reports and maps. The third role, final approval of the formal stratigraphic units, is again the responsibility of the SCF.

2 CLASSIFICATION OF GEOLOGICAL UNITS

2.1 Geological unit and stratigraphic unit

In the most traditional form, stratigraphy is essentially an organized description of stratified rocks (the stratum). However, the stratigraphic method has evolved towards the systematic arrangement of all the rock bodies of the Earth's crust. Nowadays, stratigraphy is the science of the rock record, concerning the characteristics, boundaries (2D and 3D) and attributes of rock bodies (e.g., distribution, form, geochemical properties, age, lithological composition) and, in some cases, also involving the interpretation of geological units.

The term *geological unit* (or *geologic unit*) denotes a volume of rock that has defined boundaries, characteristic features and, generally, a name as an identifier. There is no universally recognized definition for a geological unit, and the following is adapted from NADM-C1 (North American Geologic Map Data Model Steering Committee 2004): *A body of earth material distinguished from adjoining material on the basis of content (lithologic or fossil), inherent attributes, physical limits, geologic age, or some other property or properties. Commonly used properties include composition, texture, included fossils, magnetic signature, radioactivity, seismic velocity, and age. Sufficient care is required in defining the boundaries of a unit to enable others to distinguish the material body from those adjoining it [NACSN 1983]. A geologic unit is a part of the solid Earth that is identified by its geologic characteristics, has definable, locatable boundaries, and is persistent in time. Excludes non-material, temporal units.*

The denotation of and difference between the terms 'geological unit' and 'stratigraphic unit' is not distinct. Some key references (e.g., NASC 2005) use stratigraphic unit synonymously with geological unit. The INSPIRE vocabulary (INSPIRE 2013) defines a geological unit as follows: *A volume of rock with distinct characteristics. Includes both formal units (i.e. formally adopted and named in an official lexicon) and informal units (i.e. named but not promoted to the lexicon) and unnamed units (i.e. recognisable and described and delineable in the field but not otherwise formalised).* The CGI vocabulary (http://cgi.vocabs.ga.gov.au) currently recognizes 19 types of geological units (Fig. 2). Some of these units do not have a direct connection to the rock record (such as some lithotectonic units) or are independent of the unit relationships (e.g., lithological units), and these units are not comprehended as stratigraphic units (*sensu stricto*). In this guide, 'geological unit' is a broader concept than 'stratigraphic unit'. Only the classification categories recognized by stratigraphic guides and codes are considered here as stratigraphic *sensu stricto* (see Fig. 3 and Table 1).

Geologic unit
- Allostratigraphic unit
- Alteration unit
- Biostratigraphic unit
- **Chronostratigraphic unit**
- Geomorphologic unit
- Geophysical unit
  - Magnetostratigraphic unit
- Lithogenetic unit
  - Artificial ground
  - Excavation unit
  - Mass movement unit
- **Lithologic unit**
- **Lithostratigraphic unit**
  - **Lithodemic unit**
- **Lithotectonic unit**
  - Deformation unit
- Pedoderm
- **Pedostratigraphic unit**
- Polarity chronostratigraphic unit

Fig. 2. Geological unit categories, as defined by the IUGS Commission for Geoscience Information (CGI) Geoscience Terminology Working Group (status 1/2022). Unit types are differentiated based on their defining lithological, stratigraphic or other physical properties. The classifications considered in this guide are in bold.

A *stratigraphic unit* is a geological unit that is recognized by applying a stratigraphic classification scheme (stratigraphic category). Stratigraphic units based on one property (according to the selected category) will not necessarily coincide with those based on another. Therefore, it is essential that different terms are used for each named unit so that the units can be distinguished from each other. A clear definition of a stratigraphic unit is of paramount importance.

The identification, characterization and definition of geological units is part of the geological research process. Geological units are generated in the description of stratigraphic columns (stratotypes of a succession), in geological mapping (map units) or as a result of interpretation based conceptual modelling (e.g., lithotectonic units). Geological units form a basic component of most geological maps or models, and the map area or model volume is most typically composed of geological units. Therefore, a meaningful unit is mappable, has defined boundaries and is geologically significant. In this guide, good practices in application of the established classification categories are encouraged, but new innovative ways to define and classify are not excluded. However, the new systems need to be documented, comprehensible and sufficiently explicit to enable users to distinguish rock bodies that are included in a class from those that are not.

2.2 Categories of unit classification

Rock bodies may be classified according to many different inherent properties. Each classification needs its own distinctive nomenclature. The categories of unit classification are of two principal types: (1) material categories defined on the basis of physical properties and (2) categories expressing or related to geological age, which can be divided into material units that formed within a specific time span.

The classification of geological units supports the description of both successions (type sections, stratotypes) and geometries (e.g., map units, volume units of a 3D model) of rock bodies. The parallel use of various classification categories opens views to the different aspects of stratigraphy and improves the effective communication of geological information. The fundamental objective of the classification schemes is to promote the unambiguous characterization of observed rock bodies. Ideally, a code with classification categories improves the distinction between observable features (reproducible data, such as stratotypes) and inferences or interpretations.

2.2.1 Stratigraphic classification categories

The **material categories** (e.g., lithostratigraphic, lithodemic, tectonostratigraphic and sequence stratigraphic) are based on the content or physical limits of rock bodies. The composition and related characteristics (e.g., texture, structure) or different physical, chemical or biological contents or properties of rock serve as the basis for distinguishing and defining the fundamental formal units. The material-based, tangible units are distinguished either by their lithological characteristics or by the nature of their bounding surfaces.

- *Lithostratigraphic units* are based on the lithological properties and stratigraphic relationships of rock bodies conforming to the Law of Superposition.
- *Lithodemic units* are based on the lithological properties of rock bodies (typically non-stratified).
- *Biostratigraphic units* are based on the fossil content of rock bodies.
- *Tectonostratigraphic units* are bodies of rocks bounded above and below by tectonic detachment *surfaces.*
- *Sequence stratigraphic units* are based on interpreted depositional stacking patterns and their bounding surfaces controlled by cyclic base-level changes (mainly relative or eustatic sea-level changes).
- *Unconformity-bounded stratigraphic units* are bodies of rocks bounded above and below by *surfaces* representing significant discontinuities in the stratigraphic succession.
- *Allostratigraphic units* are bodies of rocks bounded above and below by *surfaces* representing significant geological discontinuities. This category of the NASC 2005 largely corresponds to the unconformity-bounded category of the ISC 1994, but is more generic by definition.
- *Magnetostratigraphic units* are based on the specified remanent magnetic properties of rock bodies. The upper and lower limits of a *magnetopolarity unit* are defined by boundaries marking a change in polarity.
- *Pedostratigraphic units* (geosols) are bodies of rocks that consist of one or more buried pedological horizons developed by weathering in one or more lithostratigraphic, lithodemic or allostratigraphic units.

The **categories based on geological age** express material units that formed within a specific time span. For these types of units, characterizing collective names are given, such as the Siderian

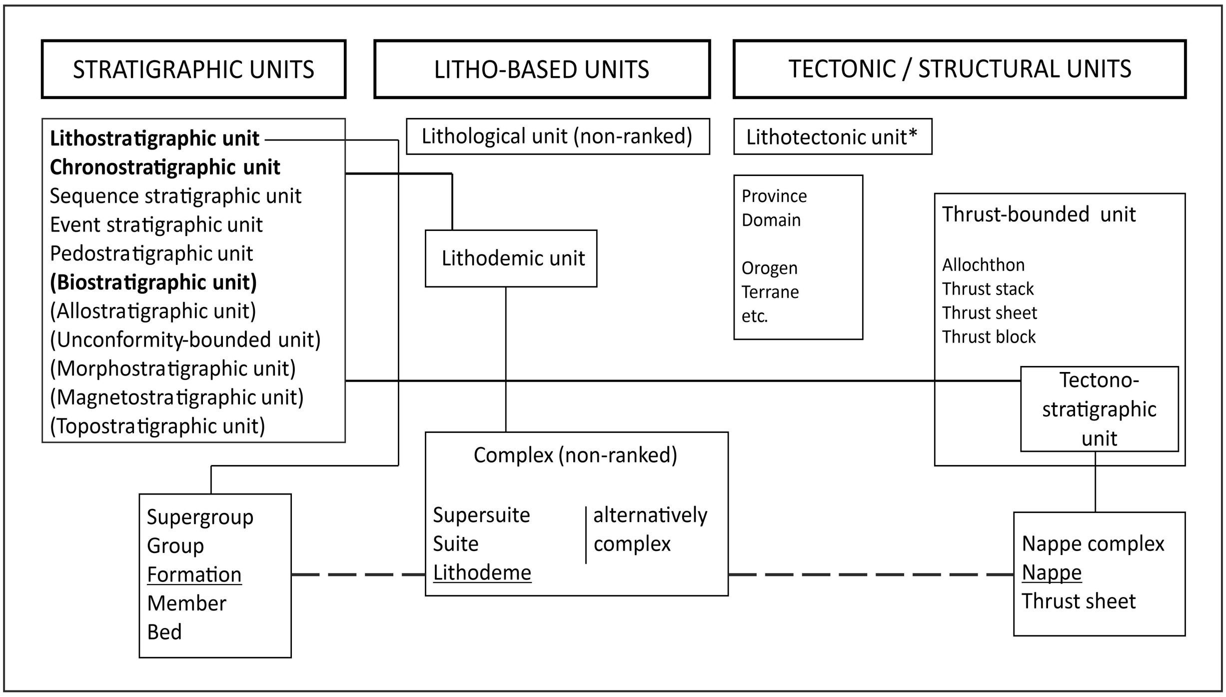
System (chronostratigraphic unit) corresponding to the Siderian Period (geochronological unit).

- *Chronostratigraphic (time-stratigraphic) units* are based rock bodies deposited in the same period of time.

Geological time plays a vital role in stratigraphy, and geochronological units correspond to the time spans of chronostratigraphic units. However, geochronological units divide geological time and not bodies of rocks. Therefore, geochronological units are excluded from this guide (for the International Geologic Time Scale and the International Chronostratigraphic Chart, see the ICS website: http://www.stratigraphy.org).

The concept of *event stratigraphy* was first proposed by Ager (1973) for the recognition, study and correlation of the effects of significant physical events (e.g., marine transgressions, volcanic eruptions, geomagnetic polarity reversals, climatic changes) or biological events (e.g., extinctions) on the stratigraphic record of whole continents or even of the entire globe. In bedrock geology, boundaries placed at "key events" in the stratigraphic record have been suggested as a new basis for chronostratigraphic division (e.g., Bleeker 2004, Altermann et al. 2012).

Geological units can be arranged (Fig. 3) in three main groups: (1) stratigraphic *(sensu stricto)*, (2) litho-based and (3) tectonic/structural. Lithostratigraphy represents a litho-based stratigraphic classification. Following the Swedish example (Kumpulainen 2016, Andersson et al. 2023), lithodemic units are primarily related to the litho-based group. However, the category has close ties to lithostratigraphy, and can also be understood as a stratigraphic category (see NASC 2005). Despite the name of the category, tectonostratigraphy is not recognized by ISG 1994 or NASC 2005, and here, the category is considered as a tectonic/structural classification scheme. In Figure 3, the tectonostratigraphic units are loosely coupled with the proper stratigraphic categories, however.



*Before any application of lithotectonic units, the corresponding categories, their ranks and classification rules shall be defined.

Fig. 3. Summary of geological units. The most formal stratigraphic categories are in **bold**; the categories and units not considered in this guide are in parentheses; the principal ranks of a category are underlined (modified from Kumpulainen 2016).

2.2.2 Geological unit classification in Finland

Each country and geological region has a unique research tradition and heritage concerning the geological units and their usage. The emphasis of this guide is on classification categories, which are widely used in bedrock geology and also applied in Finland (Table 1). The less relevant categories, such as biostratigraphy and magnetostratigraphy, have either been omitted or are only briefly mentioned.

For information on optional categories, detailed procedures and international examples, the reader can turn to ISC 1994, NASC 2005 and, regarding tectonostratigraphy, NCS 1989.

Table 1. Geological unit classifications included to this guide (X; most significant in bold) and their recognition in the international references. The main reference for each category is also indicated (color cells).

Classification	**Unit definition based on**	**Recognized (X) or mentioned (+) in**						
		This guide	IUGS*		Regional/national stratigraphic guides/codes**			
		SCF	ISSC	CGI	NACSN	UK	NCS	Sweden
Lithostratigraphic	Lithology, stratigraphic relationships	**X**	X	X	X	X	X	X
Lithodemic	Lithology	**X**	+	X	X	X	X	X
(Lithological, non-ranked)	Lithology	+		+				
Sequence stratigraphic	Stacking pattern, bounding surfaces	X	+	+		X		+
Unconformity-bounded	Bounding unconformity surface	+	X	+		+		
Chronostratigraphic	Geological age	**X**	X	X	X	X	X	X
Pedostratigraphic	Pedological horizon (paleosol)	X		X	X		X	
Event-stratigraphic	Rare, identifiable geological events	+	+			+		+
Magnetostratigraphic	Magnetic characteristics	+	X	X	X	X	X	+
Isotope stratigraphic	Isotope characteristics	+	+			X		
Tectonostratigraphic	Bounding detachment surfaces	X				+	X	X
Lithotectonic***	Variable; specified in classification rules	X		X				+

*International Union of Geological Sciences; ISSC (International Subcommission on Stratigraphic Classification; ISG 1994); CGI (Commission for the Management and Application of Geoscience Information; GeoSciML vocabularies; status 01/2022)

** NACSN (North American Commission on Stratigraphic Nomenclature; NASC 2005); UK (United Kingdom; Rawson et al. 2002. Stratigraphic Procedure. Geological Society, London, Professional Handbook); NCS (Norwegian Committee on Stratigraphy, Nystuen, J. P. (ed.) 1989); Sweden (Kumpulainen 2016, Andersson et al. 2023).

***Before the application of lithotectonic units, the corresponding categories, their ranks and classification rules should be defined

In this guide, four principal categories of geological units are presented to support the classification of the bedrock of Finland (Table 1). The conventional classification schemes are divided into groups (the principal categories are in **bold**):

1. Geological units based on material content
- (Lithological)
- **Lithostratigraphic**
- **Lithodemic**
- Pedostratigraphic (paleosols)

2. Geological units based on the physical limits of the material unit
- **Tectonostratigraphic**
- Sequence stratigraphic

3. Categories based on various specified tectonic and/or structural properties of the material unit
- Lithotectonic

4. Categories based on geological age
- **Chronostratigraphic** (or time-stratigraphic)

The *lithostratigraphic and lithodemic units* are fundamental and the most important in the division of bedrock bodies. Thus, the related principles have priority when approaching the definition and management of geological units of the Finnish bedrock. Lithodemic classification can be seen as a complementary system for classic lithostratigraphy, and these principally different classifications are mostly not applied independently (see Chapter 4.1).

In highly metamorphic and complex folded terrains, like most of the bedrock of Finland, *lithological (lithologic) classification* is usually the first approach in geological mapping. After defining the type section or type areas, *lithostratigraphic and/or lithodemic units* are established and named. However, in detailed and applied studies, when the genetic relationships of the rock units are not the main focus, typically only lithological units have been used. The CGI vocabulary defines a *lithologic unit* (a subclass of a geologic unit) as: "*Geologic unit defined by lithology independent of relationships to other units. Denotes a 'kind' of rock body characterized by lithology, e.g. basaltic rocks".* Lithological units are not named, ranked and designated, and are not therefore part of the nomenclature of geological units. Thus, lithological units are not considered any further in this guide and are presented in parentheses in the list above and in Table 1.

Tectonostratigraphic principles are applicable in areas where thrusting has resulted in prominent and mappable detachment surfaces. *Sequence stratigraphy* focuses on the relationships between the architecture of the depositional units and cyclic changes in a base level, where the different depositional trends can be studied and analysed at variable scales. Sequence stratigraphy is essentially a basin analysis method, and it has been applied in some studies on the bedrock of Finland (see Chapter 6.1). *Unconformity-bounded units* are briefly considered in Chapter 6.2. *Lithotectonic units* have emerged as a response to the problematic management of conceptual tectonic-scale units and boundaries. The units are specified on the basis of structural or deformation features, mutual relations, origin or historical evolution. The challenges of bedrock *chronostratigraphy* are presented and considered in Chapter 7.3.

Furthermore, some less conventional methods may also have potential in stratigraphic studies in Finland. *Magnetostratigraphy* covers all aspects of stratigraphy based on remanent magnetism (paleomagnetic signatures). Four basic paleomagnetic phenomena can be determined or inferred from remanent magnetism: polarity, the dipole-field-pole position (including apparent polar wander), the non-dipole component (secular variation) and field intensity. The apparent polar-wander paths provide supporting information for the interregional, and even global, correlation of bedrock units (e.g., Mertanen & Pesonen 2005, Pesonen et al. 2012, 2021, Salminen et al. 2021). However, it is not a principal method for the identification and naming of geological units in Finland. The use of carbon, oxygen or strontium isotopes (*isotope stratigraphy*) in correlating strata has been a promising method, especially in Cenozoic deposits. In bedrock research, isotope methods provide a potential tool when used with other stratigraphic information or for correlation (e.g., Karhu 1993, 2005). Nevertheless, these categories and approaches are not considered any further in this guide.

3 GENERAL PRINCIPLES AND PROCEDURES FOR DEFINING AND NAMING GEOLOGICAL UNITS

3.1 Definition of geological units

Stratigraphy is a global subject, and conformity with internationally established terms and practices is therefore important. ISG 1994 provides detailed procedures for the establishment of formal stratigraphic units and a glossary of stratigraphic terms. Naming specifies an individual geological unit having a spatially defined location, boundaries and associated geological properties and attributes. Therefore, the name preferably contains both a geographical and a geological component. The unit name is the fundamental identifier, which shall be unique for a formal unit and ideally so for all the named geological units. The applied unit classification system (and possible rank) needs to be specified. Preferably, the source of the geographical name is explained (e.g., National Land Survey of Finland base map or topographic map; sheet and year), if not self-evident. The use of the same geographical name for two or more different units, even of different categories or ranks, is not recommended, but exceptions regarding established names are acceptable.

Different stratigraphic categories can be applied in the same area, but the terminology of the categories must never be mixed. For example, the combined use of the lithostratigraphic and lithodemic categories is conventional, but a lithodeme cannot be placed within a group. Similarly, a formation can be described within a nappe, but the formations cannot be included in the subdivision of a nappe or nappe complex.

The establishment of a formal geological unit requires the publication of adequate characterization in a recognized scientific medium, and publication is suggested for all new stratigraphic units. In naming a unit, the priority in the publication of a properly proposed, named and defined unit should be respected (see ISC 1994, p. 23). Names in long traditional use will thus have preference over other suggested names if there is no justified reason for discarding the principle of priority. The procedures for the establishment and naming of stratigraphic units of different categories are provided in Chapters 4–7.

The name is the unique unit identifier, and the unit nomenclature needs to be nationally maintained. The stratigraphic lexicon of Finnish bedrock units (FinstratiKP database of GTK) is in practice the tool for the management of geological units, where the names, characteristic features and, most importantly, references to original research can be accessed. New units, changes in the name or rank of a unit and unit abandonment may be proposed in writing to GTK (see Appendix 1 for the procedure).

3.2 Formal and informal units

The international guides (ISC 1994, NASC 2005) recommend the usage of formal units. The importance of formal geological units is in forming a stable, well-documented collection of the most significant rock records. Only geological units having a stratigraphic rank (Fig. 3) can be accepted as formal units.

A new formal unit must be described and defined appropriately, and the intent to establish or designate it must be specific. *Formal stratigraphic units* shall sufficiently correspond to the requirements of the category of classification (see Chapters 4 and 5). Formal units are proposed, named and defined according to the guidelines presented in Chapters 4.4 and 5.2. In practice, a formal unit is established when the research with appropriate characterization is published or via the formalization of an informal unit. The status and record of all formations can be accessed via the digital national lexicon (GTK FinstratiKP). The formally defined stratigraphic units are essentially persistent and protected against change without a new formal procedure. Thus, an injudicious or premature establishment of a formal unit may turn out as inexpedient. The procedure for the final approval of formal names is presented in Appendix 1.

A named geological unit not fulfilling the requirements of a formal stratigraphic unit or pending approval is always *informal*. Informal nomenclature is found useful in bedrock stratigraphic work, when the applicability of formal lithostratigraphy is restricted (e.g., Easton 2009 and references therein) and the age constraints are limited. Even though the usage of formal nomenclature is encouraged, it is emphasized that the appropriate characterization of geological units, whether informal or formal, is important for cumulative geological knowledge. Nevertheless, no geological unit should be established unless the new unit serves a clear purpose.

Informal units form a major part of the bedrock stratigraphic nomenclature in Finland. There are different kinds of informal units. Some units of geological significance may, for various reasons, be difficult to characterize according to the formal requirements. An informal status is advisable where the unit is only known in an area having a very limited extent. In practice, an informal unit is created when it is designated, founded when its study, including the description of the named unit, is published and, finally, established when incorporated into the (digital) national lexicon (see Figs. 4 and 7). Informal names are, in principle, not protected against change by the stability provided by proper formalization, but the priority of the name also applies to informal nomenclature. Obviously, there cannot be any formal procedures for informal units. However, it is recommended that the description, characterization and definition of informal units should follow the suggestions of this guide when possible and appropriate.

3.3 Redefinition, revision and abandonment

Redescription means the correction of an improper description, whereas *redefinition* may include major changes to a description and a change in the lithological designation (see NASC 2005). For example, igneous rocks originally defined as quartz monzonites can be re-classified as granites, or the descriptive part of the unit name (e.g., shale) can be replaced by another descriptive term (e.g., marl) without changing the original proper geographical term in the unit name. Minor *revision* is defined here to include changes in map unit boundaries and minor hierarchical changes (formation/member ranks; suite/lithodeme ranks). The hierarchical rank of a geological unit can be changed without any changes to the definition or geographical part of the name.

Major *revision* involves (1) all justifications of the stratotype or the definition of the unit, (2) changes in the category or (3) major changes in the unit's rank or boundaries. Where the unit is divided (i) into two units of different ranks, the original name cannot be used for both units as a whole and for a part of it, and where it is divided (ii) into two or more units having the same hierarchical rank, the original names should not be used for any of the new units. Any formally approved names should not be modified without strong and well-documented reasons. An established geological unit can be abandoned or rejected when it is (i) improperly defined, (ii) equivalent to a previously formally defined unit or (iii) defined in the wrong category, or does not otherwise fulfil the requirements of the nomenclature or definition rules. A unit may also be abandoned if it proves inappropriate (e.g., very small or not recognizable or mappable beyond the type area). The abandoned names are retained in the lexicon.

For practical reasons, GTK has a mandate to manage informal units, as well as the re-description, re-definition and minor revision of formal units in the digital lexicon (GTK FinstratiKP) and in spatial map databases. Major revision and abandonment of a formal unit follows the procedure described for the approval of a new formal unit (see Appendix 1).

3.4 Correlation

Correlation, the demonstrated correspondence of separated parts of a geological unit in some defined property or relative stratigraphic position, is one fundamental objective of stratigraphy. A suggested correlation, and information on which it is based, is an essential part of an ideal unit description. *Lithocorrelation* links together units with a similar lithology and stratigraphic position, or the sequential or geometric relations of lithodemic units. In geological mapping, the distinction of individual formations (as mappable units), geological units with a regional extent and major stratigraphic divisions is all based on correlation at different scales: between the sections and rocks (formations), between the key areas (regional map) and, finally, between the regions (e.g., nation-scale map). Under the Finnish conditions of limited bedrock exposure, a mappable unit seldom forms one observable entity but is represented by geographically separated outcrops, and correlation is typically aided by geophysical maps. *Chronocorrelation* refers to a correspondence between the age and chronostratigraphic position of a geological unit. Once the lithostratigraphic, lithodemic and tectonostratigraphic units have been established, there is a need to correlate them by age with one another and with the global chronostratigraphic scale. The different methods of calibration and correlation, such as biostratigraphy, sequence stratigraphy, event stratigraphy and isotope stratigraphy, are described and discussed in Rawson et al. (2002). In the bedrock geology of Finland, isotope geological geochronometry is by far the most important method of chronocorrelation. The results typically indicate age estimates for the crystallization of igneous rock or the minimum/maximum depositional age of a supracrustal succession.

4 LITHOSTRATIGRAPHY

4.1 Combined use of lithostratigraphic and lithodemic units

The establishment of adequately characterized lithological units and their correlation at all scales forms the core of the lithostratigraphic method. According to the international guides (ISC 1994, NASC 2005), the establishment of formal units should be the primary target in stratigraphic work (see Chapter 3.2). The lithostratigraphic challenges of bedrock terrains have been tackled with lithodemic classification, which can be understood as an extension of the lithostratigraphic approach (e.g., Easton 2009, CGI classification scheme in Fig. 2). The combined application of lithostratigraphic, lithodemic and paleosol units in Finland is described and discussed in Kohonen et al. (2024, this volume). In practice, the use of the categories is complementary and exclusive: all the fundamental units are formations, lithodemes or paleosols. This type of combined approach has been called 'lithostratigraphic (*sensu lato*) nomenclature for bedrock units' (Easton 2009).

Naming the mapped lithological unit as a lithostratigraphic or lithodemic fundamental unit (formation/lithodeme) after the type locality is always the first step in unit designation (Fig. 4). In the combined lithostratigraphic–lithodemic method, it is essential to ensure that each lithology-based unit (distinct body of rock) can be classified as either lithostratigraphic or lithodemic. Where the body of rock lacks primary stratiform features or understanding of the superposition of units is missing, the use of lithodemic units is justified (see Chapter 4.6). The application of lithodemic classification is simple and convenient. However, lithostratigraphic classification should always be considered as the first choice for supracrustal rocks.

The primary objective should be the foundation of formal stratigraphic units, and the description and characterization of all units should therefore obey the formal lithostratigraphic/lithodemic procedure when applicable and appropriate. The semipersistent nature of informal units, both lithostratigraphic and especially lithodemic, is acceptable and practical when there are not conditions or rational reasons to establish formal units.

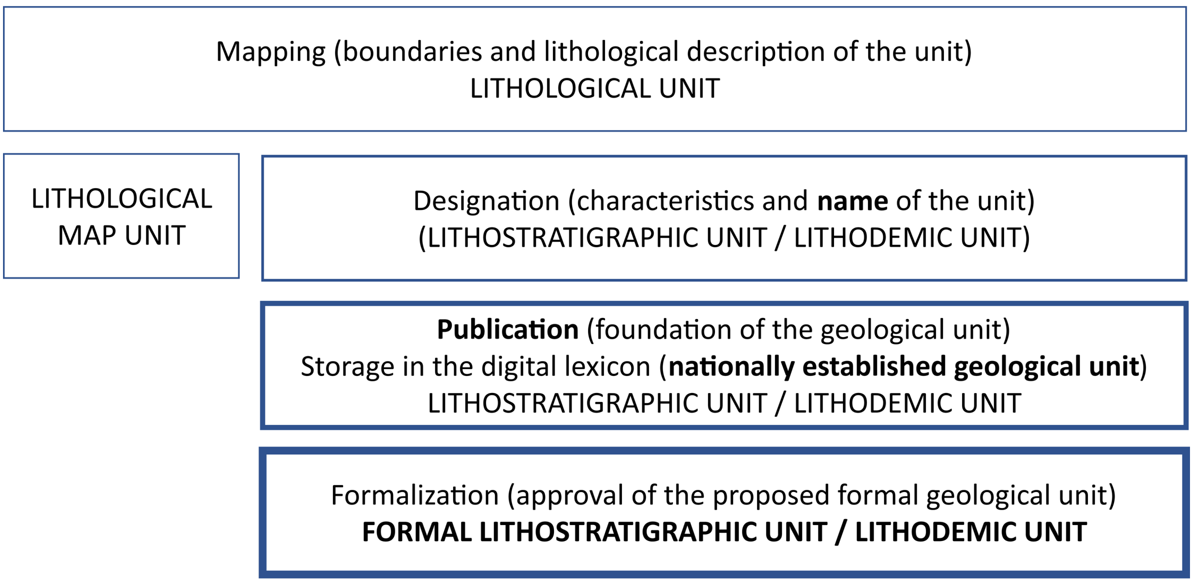


Fig. 4. The evolution of a geological unit from a map unit (top) towards a formal stratigraphic unit (bottom). Key steps of the process shown in bold.

4.2 Lithostratigraphic units

4.2.1 General properties, rules and boundaries

Lithostratigraphic units are defined and distinguished on the basis of lithological characteristics and stratigraphic position (Fig. 3). The distinctive lithological characteristics may include features such as composition, texture, primary structures and colour. The units are commonly stratified and tabular in form.

A lithostratigraphic unit generally conforms to the Law of Superposition, and the application requires that even a deformed supracrustal succession has retained an observable time sequence of the beds and units. A high grade of deformation and metamorphism limits but does not necessarily restrain the use of lithostratigraphic units.
A *lithostratigraphic unit* has been defined as:

- A body of rocks that is defined and recognized on the basis of its observable and distinctive lithologic properties or a combination of lithologic properties and its stratigraphic relations (ISC 1994);
- A body of sedimentary, extrusive igneous, metasedimentary or metavolcanic strata that can be delimited by its stratigraphic position;
- A stratum or body of strata, comprising stratified rocks and superficial deposits (conforming to the Law of Superposition, i.e., sedimentary layers are deposited in a time sequence, with the oldest on the bottom and the youngest on the top), which are distinguished and defined based on lithological properties and stratigraphic boundary relations;
- A geological unit defined on the basis of observable and distinctive lithological properties or a combination of lithological properties and stratigraphic relationships. Denotes a particular body of rock. (CGI definition as a subclass of *geologic unit*).

Lithostratigraphic units are defined independently of the inferred geological history or the mode of genesis, and the all the units are diachronous in nature. The ranks are, in decreasing order, supergroup, group, formation, member and bed/flow, where formation is the fundamental unit. The guidelines for the characterization and naming of formations and other lithostratigraphic units are presented in Chapter 4.4.

The boundaries of lithostratigraphic units are placed at positions of lithological change, at distinct, sharp contacts or, at some selected arbitrary level, within zones of gradation. Both vertical and lateral boundaries are based on the lithological criteria that provide the greatest unity and utility. Unconformities, where objectively recognizable based on lithological criteria, are ideal boundaries for lithostratigraphic units.

Stratotypes (type sections) form the stratigraphic foundation by providing a link from the detailed description to a specified site in the field.

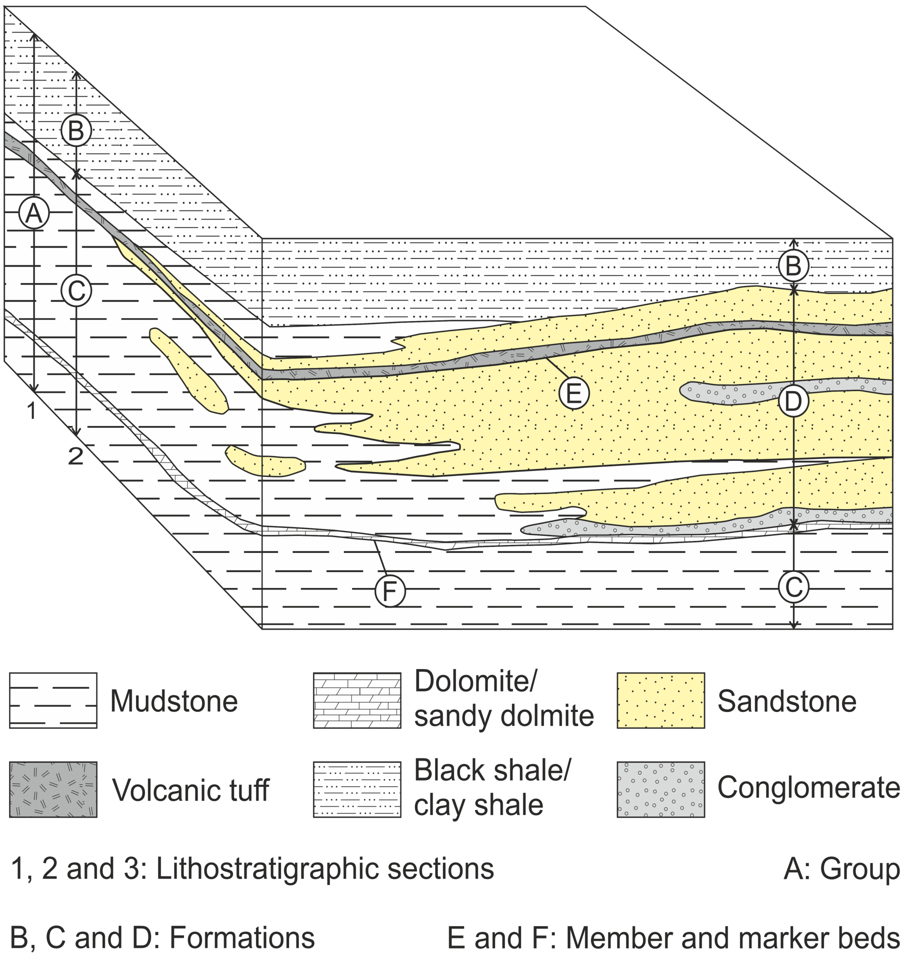


Fig. 5. Schematic illustration of the lithology-based designation of lithostratigraphic units (modified after NCS 1989).

4.2.2 Formation

A *formation* (*Formation*) is the fundamental unit in lithostratigraphic classification. Like all the lithostratigraphic units, a formation is identified by the lithological characteristics and the stratigraphic position. As the fundamental unit, a formation is the first unit to be designated, and the selected dimensions largely define the scale of the units within the area. Basically, the division into formations makes a distinction between the adjacent mappable units. Very large formations do not discriminate and, consequently, lead to a poor resolution of mapping. A formation must be mappable (or traceable in the subsurface) at a relevant, regional scale. In practice, this sets the lower limit for the dimensions of a formation. Therefore, the division into formations needs to be carefully considered and, before designation, comparisons with the formations of adjacent areas may provide examples of their dimensions. According to the general practice in Finland, a formation should be mappable at scales from 1:10 000 to 1:50 000, and the resulting map unit should be readable at a 1:100 000 map scale.

The stratigraphic relations, boundaries and position are part of the definition. Accordingly, when feasible, the formation boundaries preferably correspond to significant depositional change within the succession. The boundaries of a formation are set by lithological changes, however, and not by the depositional model.

Stratified volcanic rocks are comparable to sedimentary rocks and should be treated equally in the designation of a formation. An interbedded succession (e.g., sedimentary and volcanic rocks) and volcanic rock may be assembled into one formation, and the lower ranks can be used for further designation. The properties of a formation may change laterally. The changes in thickness, composition or metamorphic grade must be considered case by case. Suitable tools for these situations include, for example, presenting several sections through the formation, a change in the rank or category and the naming of a new unit. Laterally discontinuous bodies of similar rock, occurring at the same stratigraphic level, may be considered as the same formation.

4.2.3 The lower ranks: Member and Bed

A *member* (*Member*) is the unit ranked below a formation and is always a part of a formation. It is recognized as a named unit within a formation and it must show characteristics different from the adjacent parts of the formation. A formation does not need to be divided into members unless a useful purpose is served by doing so. Some formations may be completely divided into members, while others may have only certain parts designated as members, and still others may have no members. A member may extend laterally from one formation to another. The establishment of members is advantageous in the description of heterogeneous formations, and especially in cases when a rather thin unit bears specific value for the correlation or interpretation. A member, whether formally or informally designated, does not need to be mappable at the scale required for formations.

The lower rank of a member is a *bed* (*Bed*), except for volcanic flow rocks, for which the lowest rank is a *flow*. Members may contain beds and flows, but never other members. A bed, or beds, is the smallest formal lithostratigraphic unit of sedimentary rocks. A bed usually represents a single depositional event in a sedimentary succession. The designation of a bed or a unit of beds as a named lithostratigraphic unit should generally be limited to distinctive beds whose recognition is particularly useful. A key or *marker bed* is a thin bed of distinctive rock that is widely distributed. Individual marker beds may be traced beyond the lateral limits of a particular unit. A *flow* is a discrete, extrusive volcanic rock body distinguishable by texture, composition, the order of superposition, paleomagnetism or other objective criteria. A flow is usually a volcanic extrusive rock formed during a single eruption. Beds and flows are usually considered as informal units.

4.2.4 The upper ranks: Group and Supergroup

A *group* (*Group*) is a lithostratigraphic unit next higher in rank to a formation, always consisting of two or more associated formations of the same class of rocks. Groups are defined to express the natural relations of associated formations. They are useful in the compilation of regional-scale map legends and in wide regional correlations. In practice, groups typically represent major depositional units. A *supergroup* (*Supergroup*) is the highest lithostratigraphic rank, comprising two or more groups, having a natural vertical or lateral relationship with one another. Such units have proved useful in regional and provincial syntheses. Supergroups should only be named where their recognition serves a clear purpose. The upper rank units are named according to the general rules of naming (see Chapter 3.1) and the name combines a geographical name and the term “group” or “supergroup”.

Examples of application

Northern Finland: Orakoski, Palokivalo, Petäjäskoski, Matarakoski, Sattasvaara and Kumpu formations/Formations; Salla, Kuusamo, Kivalo, Sodankylä, Savukoskski and Kumpu groups/Groups (e.g., Lehtonen et al. 1998, Kyläkoski et al. 2012, Köykkä et al. 2019, Köykkä & Luukas 2021, Köykkä et al. 2022).

Eastern Finland: (1) Kainuu belt: Laanhongikko, Matinvaara, Paljakkavaara and Siikavaara Formations; Kurkikylä, Korvuanjoki and East Puolanka Groups of the (e.g., Laajoki 1991, Strand & Köykkä 2012); (2) Höytiäinen belt: Urkkavaara, Koli and Jero Formations; Kyykkä and Herajärvi Groups (e.g., Kohonen & Marmo 1992).

4.3 Lithodemic units

4.3.1 General properties, rules and boundaries

Lithodemic units are recognized and defined by their observable lithological characteristics. Basically, this denotes a mappable lithological unit with an attached identifier (the name), which allows lithocorrelation and attributes typical for a lithostratigraphic unit. Examples of such attributes are geochronological data, the estimated age and relationships with other rock units. The application of lithodemic classification supports regional description in areas where the relations between supracrustal and intrusive rocks are complex or where the supracrustal rocks have not retained primary unambiguous stratification. A unit may consist of several rock types; typical examples are different co-magmatic intrusions and migmatite complexes. The guidelines for the characterization and naming of lithodemic units are presented in Chapter 4.4.

A *lithodemic unit* has been defined as follows:

- A non-stratified body of intrusive, volcanic or highly metamorphosed and/or completely deformed rock (not conforming to the Law of Superposition) that mostly lacks primary depositional structures.
- A geological unit consisting of one or additional bodies of predominantly intrusive, plutonic or extrusive rocks and/or highly metamorphosed and deformed rocks, which are defined and distinguished on the basis of lithological characteristics. A lithodemic unit does not generally obey the fundamental principle of the Law of Superposition.

The contacts with other geological units may be sedimentary, extrusive, intrusive, tectonic or metamorphic (Fig. 5). The boundaries, vertical or lateral, of a lithodemic unit should be placed at the location of an observable lithological change. The boundary may be represented by a visible contact but also by a zone of gradation or interfingering. In practice, arbitrary and inferred boundaries cannot always be avoided.

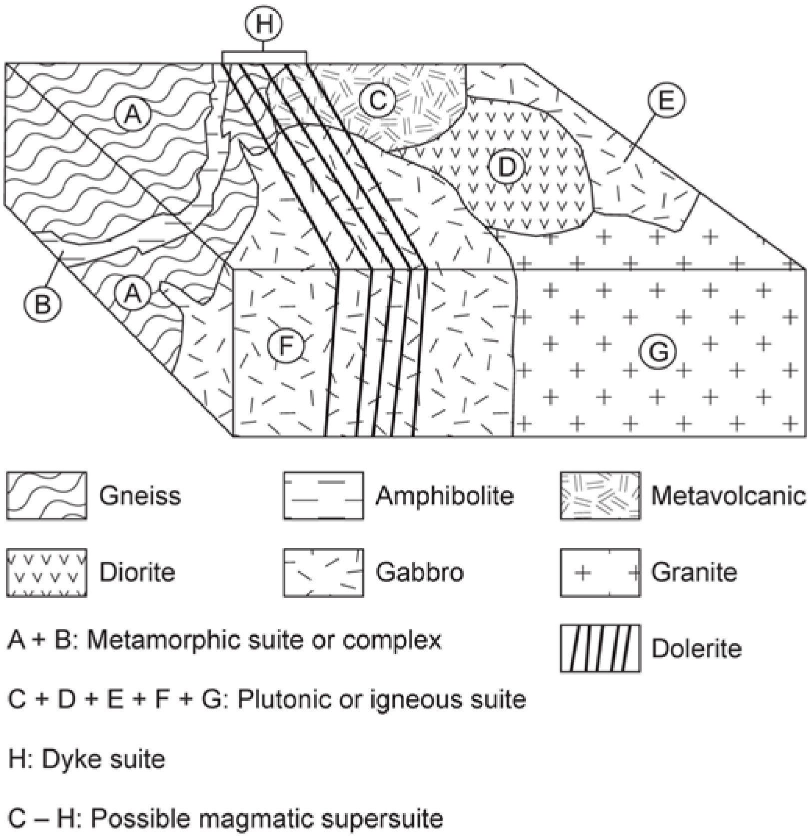


Fig. 6. Schematic illustration of the lithology-based designation of lithodemic units (modified after NSC 1989). Deformed and metamorphosed lithodemes form a suite or complex. The intrusive lithodemes comprise a plutonic suite or a dyke suite. Genetically related plutonic and dyke rocks can be grouped as a magmatic supersuite. (Modified from NCS 1989).

The lithodemic units are, in order of decreasing rank, *supersuite*, *suite* and *lithodeme*. A *complex* is a non-ranked lithodemic unit comparable to a suite or supersuite. The definition of a formal lithodemic unit (*Lithodeme, Suite, Supersuite*) should be based on an appropriate lithological description of the type area (see Chapter 4.4) and observations of the lateral and vertical variations and its contact relations with other rock units. The type locality (and possible reference localities) of a formal lithodemic unit should always be clearly defined. In Finland, formal lithodemic units should only be defined where the named unit is well established or another practical purpose for the formalization is presented.

4.3.2 Lithodeme

A lithodeme is a fundamental unit in lithodemic classification and nomenclature, and it is comparable to a formation (see Fig. 3). A lithodeme is mappable at the Earth's surface or traceable into the subsurface by using geological and/or geophysical methods. There are no lower ranks of a lithodeme. As a map unit, a lithodeme may enclose unnamed lithological units (see Kohonen et al. 2024, this volume).

A lithodeme may consist of (i) a single rock type, (ii) a mixture of two or more different rock types or (iii) a heterogeneous lithology, which in itself constitutes a separated unit that is distinct from adjoining or surrounding rock units. The different distinctive lithological characteristics may include mineralogy, textural features (e.g., grain size) and structural features (e.g., gneissic), and a lithodeme may change its character regionally. It may also be characterized by chemical, electromagnetic/magnetic, radiometric, seismic or some other physical properties derived from its lithological properties.

4.3.3 The upper ranks: Suite and Supersuite

A *suite* is the next higher in rank to a lithodeme. Formally, a suite consists of two or more associated lithodemes of the same class of rocks (e.g., metamorphic or igneous). In the map unit hierarchy, a suite is comparable to a group. A *supersuite* is the highest unit rank of the lithodemic category and is, as a map unit, comparable to a supergroup. A supersuite is always comprised of two or more suites.

4.3.4 Complex

An assemblage or mixture of two or more genetic classes (sedimentary, igneous and metamorphic) of rocks may be named as a *complex*. A complex is not a ranked lithodemic unit. As a map unit, a complex is commonly comparable to a suite or supersuite. A complex may be identified as an assemblage of diverse rock units and is typically used in bedrock areas where the mapping of each separate lithological component is impractical, difficult at ordinary mapping scales or provisional in nature. A complex may consist of two or more named lithodemes, lithostratigraphic units and/or unnamed lithological units. Where a named map unit consists of an assemblage of diverse types of a single class of rock, such as granitoids of an Archean terrane, terms such as metamorphic suite or plutonic suite should be considered as the first choice. NASC (2021) recognises three types of complexes (volcanic, intrusive, structural) but does not exclude use of other types of complexes. Tectonostratigraphic nappe complexes (Chapter 5.2) must not be confused with lithodemic complexes.

4.3.4.1 Volcanic complex

A *volcanic complex* refers to a site of persistent volcanic activity characterized by a diverse assemblage of different kinds of volcanic or metavolcanic rocks and related intrusions and their weathering products.

4.3.4.2 Intrusive complex

An "intrusive complex" differs from a "volcanic complex" in that it consists largely or entirely of intrusive rocks.

4.3.4.3 Structural complex

Tectonic processes may result in heterogeneous mixtures or disrupted bodies of rock in which some individual components are not mappable. Where the mixing or disruption is, without any doubt, due to tectonic processes, such a unit may be designated as a *structural complex*. Usually, a structural complex refers to an assemblage of two or more different kinds of rocks intermixed by tectonic processes, but may also consist of only a single class of rock.

Examples of application

Laajoki and Luukas (1988) applied, for the first time, the principles of lithodemic classification to the bedrock of Finland in the Salahmi-Pyhäntä area. For example, their Rapisevankangas gneiss suite consists of highly metamorphosed and deformed banded gneisses and mica schists divided into seven different lithodemes (e.g., Teerimäki biotite-plagioclase gneiss and Leppiperä quartz-feldspar gneiss).

In northern Finland, the supracrustal Mellajoki, Räväsjärvi, Haisujupukka and Sieppijärvi and Olostunturi suites comprise large areas in northern Finland of migmatitic arkose/mica schist, quartzite, paragneiss and amphibolite (Köykkä et al. 2019). The Kittilä suite covers an area of more than 2600 km^2 *in central Lapland and comprises several different volcanic-sedimentary lithodemes (e.g., Vesmajärvi mafic volcanic rock, Jänisvaara BIF, Uurrekarkia boninite, Nuttio serpentinite and Kivipurnuvaara conglomerate; see Köykkä et al. 2019, Bedrock of Finland 1:200 000).*

Examples of intrusive lithodemic units: Forssa gabbro (Hakkarainen 1994, Peltonen 2005), Koli sill suite (e.g., Vuollo & Piirainen 1992, Vuollo & Fedotov 2005, Vuollo & Huhma 2005), Penikat intrusion in the Tornio-Näränkävaara belt (see Alapieti & Lahtinen 1986, Iljina & Hanski 2005). A more complex example is the Akanvaara layered intrusion (see Mutanen 1997, Hanski & Huhma 2005).

One example of the 'full lithodemic hierarchy' is proposed for the rapakivi granites in SE Finland: Southern Finland rapakivi supersuite>Kymi rapakivi suite>Wiborg granite>wiborgite phase, and several informal supersuites are included in the GTK map database (Bedrock of Finland 1:200 000). However, in Finland, the term "complex" has commonly been used instead of "supersuite" for the large units consisting of two or more assemblages (suites or complexes) and having an assumed linkage to one another. Hölttä et al. (2012) classified the Finnish part of the Archean Province into nine different complexes: Ilomantsi, Lentua, Kuopio, Iisalmi, Rautavaara, Manamansalo, Kalpio, Siurua and Ranua. Other examples of application include the Nurmes gneiss complex (Kontinen 1991, Sorjonen-Ward & Luukkonen 2005), Suomujärvi complex (Evins et al. 2002, Sorjonen-Ward & Luukkonen 2005, Lapland granulite complex (Tuisku & Huhma 2006, Tuisku et al. 2006, Lahtinen & Huhma 2019), Central Lapland granitoid complex (Lahtinen et al. 2018) and Kemihaara and Naruska complexes (Tepsell et al. 2020). Informal names such as 'Tohmajärvi volcanic complex' and 'Pyhäsalmi volcanic complex' have been used in general descriptions without any detailed description of the rocks included. In Lapland, 'Vuotso complex' corresponds to parts of the structurally complex area formerly known as the Tana Belt. However, these units correspond rather well to the definition of a volcanic/structural complex (see 4.3.4.1 and 4.3.4.2 above).

4.4 Definition of lithostratigraphic and lithodemic units

4.4.1 Characterization

A designated new lithostratigraphic/lithodemic unit is characterized by information such as:

1. ***Name, category and rank;***
2. ***Location*** (with coordinates) of the type section (stratotype) or type area (if suitable);
3. Description of the unit, including: (i) ***a detailed description of the type section or type area***, (ii) characteristic features, (iii) ***nature of the unit boundaries***, including contacts, unit dimensions and shape (if possible);
4. The geological age, stratigraphic correlation and genesis (if possible);
5. ***Key references*** and historical background (if available).

There are several mandatory requirements for the formal units (shown above in ***bolded italics***). Furthermore, the definition, naming and establishment of new formal units, as well as their major revision or abandonment, requires publication in a recognized scientific medium.

4.4.1.1 Name, category and rank

The name of a unit consists of a geographical name referring to type section or type area (for the requirements of a geographical name, see Chapter 3.1) and a rank term and/or a descriptive term (<u>for naming details and examples, see Chapter 4.4.2 below</u>). The category and rank of a new or revised unit must be specific and follow the hierarchy presented in Table 2.

Table 2. Lithostratigraphic and lithodemic unit rank terms.

Lithostratigraphic Unit terms	Lithodemic Unit terms
Supergroup Group <u>Formation</u> Member (Lens, Tongue) Bed (Flow)	Supersuite Suite <u>Lithodeme</u>

4.4.1.2 Type section, type area and description of the unit

The description and definition should be so good that other geologists or scientists will also be able to recognize the geological unit and its characteristic features in the field. A type section (stratotype) or type area is a geological standard for a stratigraphic unit or boundary, and these should be sufficiently described, both geographically and geologically.

<u>A *type section* is the specific geographical location of a unit stratotype or unit boundary where the unit was first defined and named.</u> There are two kinds of lithostratigraphic stratotypes: (i) a unit stratotype and (ii) a boundary stratotype. These refer, respectively, to a type section for a stratified

geological deposit and to a specific point of a stratigraphic boundary. A type section may consist of several reference sections to demonstrate the areal extent or dimensions of the unit. A *type area* is the geographical area that encompasses the type locality of a stratigraphic unit. A detailed description of the type area, including the characteristic features of the named unit, is the main procedure in the definition of a lithodemic unit. The type area is ideally the place where the characteristic features of the unit are best observed. However, in the case of the well-established names of non-layered igneous rock bodies, the locality where the unit was originally defined and named may be preferred. The exact locality of the type area(s) and section(s) and the possible reference area(s) or section(s) of the units, e.g., formations and members, should be given in coordinates. These requirements also apply to named subsurface units, when the coordinates and other relevant information on the borehole are given.

In a unit description, the characteristic lithological features and nature of the unit boundaries should be emphasized. *Unit characterization* specifies the unique or specific features and attributes of the unit and serves as a key for both future recognition and correlation. The *unit boundaries* should be carefully recognized (see boundary stratotype above) and described. The boundary may be represented by a distinct contact between two different rock units or by a gradational or interfingered change between clearly different rock bodies. When the upper or lower boundaries of the unit have variable features, a covering description is essential. However, arbitrary and poorly defined boundaries are unavoidable in the bedrock geology of Finland. Where the unit boundaries are not exposed, their interpreted position may rely on other measured properties (such as magnetic, electromagnetic, seismic). In all cases, the nature of boundaries (observed, interpreted, inferred) should be indicated. The lateral dimensions, thickness variation and shape of the unit should be described or estimated (if possible). Finally, it is recommended that all different data on and samples of a formal unit should be stored in appropriate places for later examination.

4.4.1.3 Age, correlation and genesis

Lithostratigraphic and lithodemic units are not defined by inferred geological age or genesis. However, the age is an attribute of paramount importance, especially in bedrock geology. Therefore, all the available geochronometric age determinations or the interpreted/inferred chronostratigraphic information should be attributed to the lithostratigraphic and lithodemic units. The relations with the adjacent units, and the suggested stratigraphic correlation (litho- and chronocorrelation), should be included in the unit description. A correlation can be presented by referring to previous studies or in the form of attached tables, diagrams or any other relevant means. The presumed origin of a unit is preferably presented mainly by references, and long genetic speculations should not be included in the description.

4.4.1.4 Key references and historical background

Stratigraphic units are a result of geological research, and the full list of references is consequently essential. References to the articles defining, characterizing or describing a unit or its boundaries are mandatory. References to the history of the unit name or dissenting views concerning the position of the unit can be included. Extensive historical or regional reviews should not be included in unit descriptions.

4.4.2 Naming of formal and informal units

A new lithostratigraphic and lithodemic unit can be proposed as an informal or formal unit. A proposed formal unit should be characterized according to the requirements presented above (Chapter 4.4.1). Nevertheless, all units are, legitimately, informal before the formal approval process is completed. The formal status of a unit is indicated in name by capitalizing all words forming the name. Fulfilling all the requirements (ISG 1994) of a formal unit (e.g., lithostratigraphy: stratotype, unambiguity of unit boundaries) is mostly not realistic in the bedrock of Finland, and some tolerance and flexibility in application is needed. If the proposed formal unit serves a clear stratigraphic purpose and is characterized and defined appropriately, minor technical insufficiencies should not automatically exclude the formal status.

In all unit names (both lithostratigraphic and lithodemic), the lithological component should be a common and well-known rock name, such as gneiss or gabbro. A lithostratigraphic unit name consists of a geographical name and the appropriate rank term. In the informal names of formations and their lower ranks, a descriptive lithological term can be included between the two mandatory components. Examples of informal names include the Ukkola formation, Ukkola quartzite formation, Muijala dolomite member and Äijälä group. The corresponding formal names are the Ukkola Formation, Muijala Member and Äijälä Group. A formal group can be established where all the incorporated formations are formal units. The epithets lower/middle/upper are not allowed as part of a formal unit name (e.g., lower Tiksanoja Member vs. upper Tiksanoja Member). All the unit names include a lithostratigraphic rank term.

A lithodemic name principally combines a geographical name with a lithological and/or descriptive term and/or the appropriate rank term. The naming convention is less formal compared to lithostratigraphic units. Informal lithodeme name typically consists of (1) a geographical name with a lithological and/or descriptive term (e.g., Haukila quartzite, Särkilä gneiss, Lahnala gabbro sill) or simply (2) a geographical name with the rank term 'lithodeme' (e.g., Kalala lithodeme). The latter may be useful for very heterogeneous lithodemes or for lithodemes that are largely identified by geophysical features. Terms implying the rock genesis should always be avoided. The formalization of lithodemes needs to be considered with caution, particularly in cases where the supracrustal unit has the potential to be redefined later as a lithostratigraphic unit. Examples of formal names are such as Haukila Quartzite and Lahnala Gabbro Sill. The term 'formation' (or any other lithostratigraphic rank) should never be used in lithodemic nomenclature.

The name of a suite combines a geographical name and the rank term 'suite', with or without an adjective denoting the fundamental character of the suite. Examples of informal names include the Verkkola suite, Rysälä metamorphic suite, Koukkula intrusive suite and Siimala sill suite. The corresponding formal names are the Verkkola Suite, Rysälä Metamorphic Suite, Koukkula Intrusive Suite and Siimala Sill Suite. The name of a supersuite combines a geographical name with the term 'supersuite' (or 'Supersuite'). Only informal names are used for complexes, and the naming convention follows that of a suite (e.g., Venelä metamorphic complex, Airola migmatite complex). Finally, it is noted that the formalization of lithodemic units does not generate, as such, any major benefits, but in the case of well established names (e.g., Laitila Granite, Hyvinkää Gabbro) it is justified.

4.5 Paleosol as a stratigraphic unit

Indications of paleoweathering, or more formally, pedological horizons (see NASC 2005) represent products of soil development, which occurred subsequently to the formation of the underlying units. These horizons cannot be considered as lithostratigraphic or lithodemic units, but the involvement of pedostratigraphy is required. A *geosol*, the only pedostratigraphic unit, is defined as a buried, traceable, three-dimensional body of rock that consists of one or more differentiated pedological horizons. A geosol is a laterally traceable, mappable, geologic weathering profile that has a consistent stratigraphic position (NASC 2005).

Geosols are an important part of the stratigraphic record and have significance in correlation and even in paleoatmospheric studies. Marmo (1992) introduced the term *paleosol*, meaning a metamorphosed geosol, into the stratigraphic nomenclature of Finland. The description of a geosol (and a paleosol) should include a sufficient description of the material, based on features such as the colour, structure, chemical composition and mineralogy, and the nature of the unit boundaries. The lower boundary of a geosol (and a paleosol) is the lowest definite physical boundary of the horizon formed by pedogenesis, and the upper boundary is the top of a buried soil profile. Paleosols are named informally according to the type locality (e.g., Hokkalampi paleosol).

5 TECTONIC / STRUCTURAL GEOLOGICAL UNITS

5.1 Practice for establishing tectonic / structural units

Tectonic and structural units are not part of the classical stratigraphic portfolio (see Table 1 and Fig. 3). The classifications are variable and lack the stability of proper stratigraphic classification categories. However, the (semi)formal, 'Caledonian-style' tectonostratigraphy has a long tradition in Norway and Sweden. The term 'tectonostratigraphic unit' is used with two meanings in this guide: (1) tectonostratigraphic units (*sensu stricto*) corresponding to the NCS1989 classification and (2) tectonostratigraphic units (*sensu lato*) covering all kinds of thrust-bounded geological units in Finland. Tectonostratigraphic classification, as defined by NCS 1989 in Norway, is well defined and enables formal nomenclature.

Various lithotectonic divisions and classifications have gradually emerged (e.g., Sweden: Stephens 2020, Finland: Kohonen et al. 2021, Slovakia: Nemeth 2021), and these need to be considered as geological units. Luukas & Kohonen (2021) proposed a division for informal thrust-bounded units in Finland. Currently, internationally well-established lithotectonic classification schemes are not available. The description and characterization of all tectonic/structural units should correspond to the requirements presented in the classification scheme. Where lithotectonic units are used, the corresponding classification needs to be specified or defined (Fig. 7).

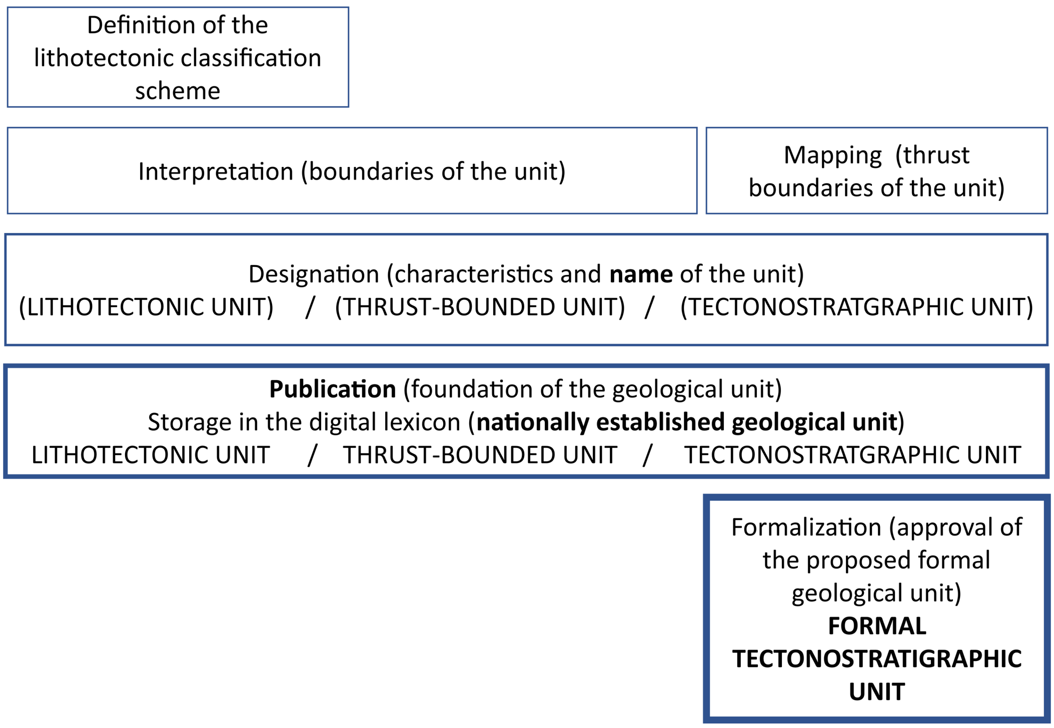


Fig. 7. Evolution of mapped (right) and interpreted (centre and left) structural / tectonic units from a map unit (top) towards a nationally established unit and further to a formal tectonostratigraphic unit (bottom right). For lithotectonic units, a classification scheme must be specified before the designation of new units (top left). The essential steps of the process are shown in bold.

5.2 Tectonostratigraphic units

5.2.1 General properties, rules and boundaries

Tectonostratigraphy is concerned with the stratigraphic division of geological units that are tectonically piled (Fig. 8) on top of each other (NCS 1989). The units are defined by their thrust boundaries and not by the lithology of the unit. The lower boundary is the floor thrust (sole thrust, basal detachment) and the upper boundary may be delimited either by the roof thrust or by an erosion surface. Thus, tectonostratigraphic classification fundamentally differs from lithostratigraphic and lithodemic classifications.

A *tectonostratigraphic unit* has been defined as follows:

A tectonostratigraphic unit represents a body of rock that (1) has been shifted or displaced along a thrust fault and (2) is located above or between the thrusts defining the boundaries of the unit.

A tectonostratigraphic unit may contain one or more lithostratigraphic or lithodemic units, but these should never be used as lower ranks of a tectonostratigraphic unit. It is important to make a distinction between the structures (e.g., fault, thrust) and the units defining the bounding structures. Not all thrusts bound a geological unit. The establishment of a thrust-bounded ('tectonostratigraphic') map unit is only justified when it simplifies the geological description and substantially aids the representation of the regional geology.

Tectonostratigraphy is not an internationally recognized stratigraphic category, and it is not included in ISG 1994 or NASC 2005. Tectonostratigraphic units (*sensu stricto*) are widely used in Scandinavia and recognized in the national stratigraphic guides (Norway: NCS 1989; Finland: Strand et al. 2010; Sweden: Kumpulainen 2016). In this guide, the nomenclature and procedures suggested by NCS (1989) are followed in the formal classification of tectonostratigraphic units.

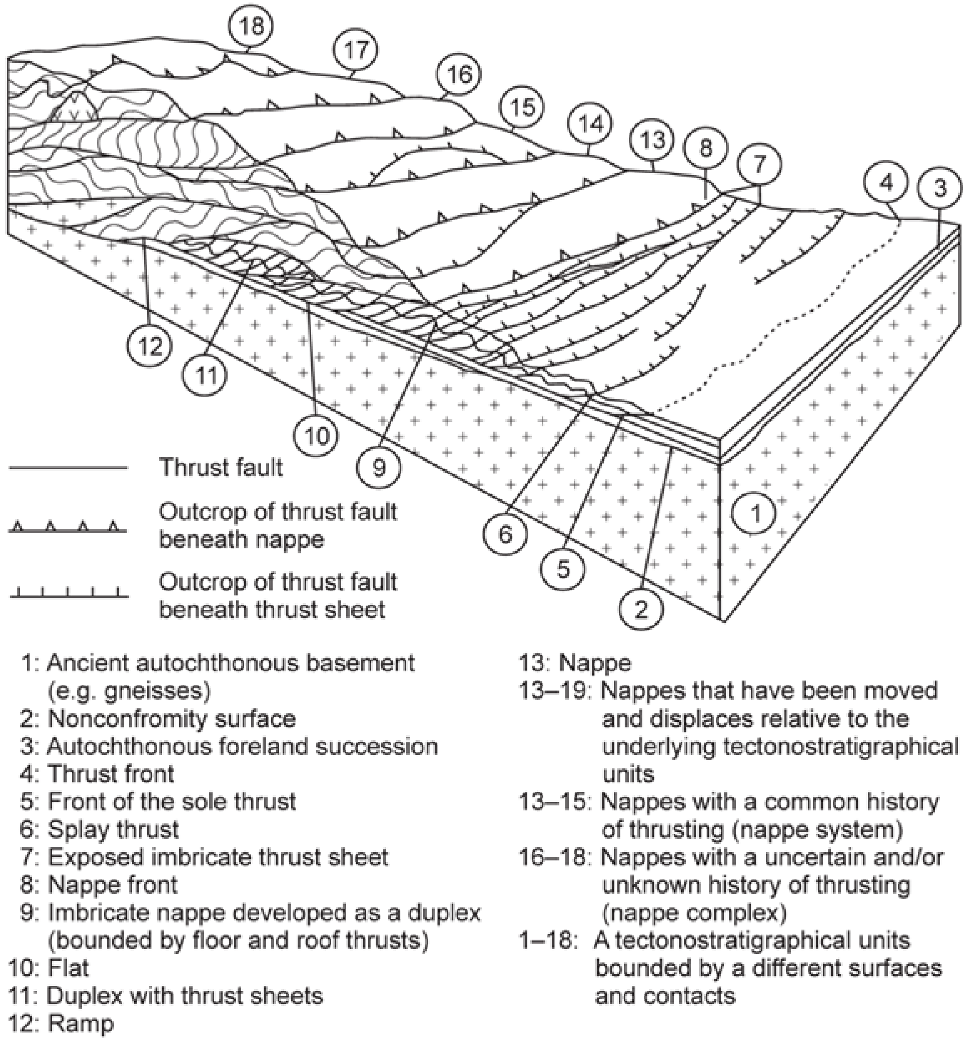


Fig. 8. Simplified schematic illustration of a foreland fold-and-thrust belt from the foreland (right) to the nappe region (left). (Modified from NCS 1989).

The designation of a new tectonostratigraphic unit should be supported by reference sections covering the bounding thrusts. The detailed description of the bounding faults is of paramount importance.

The description of a new tectonostratigraphic unit (nappe, thrust sheet) should include all necessary information, and for formal units, some items (indicated below in ***bolded italics***) are mandatory. An established new unit is characterized by information such as:

1. ***Name***, including the unit rank (or descriptive unit type for the informal units).
2. ***Location*** (with coordinates) of the type section or type area (if suitable).
3. Description of the unit, including: (i) ***a detailed description and names of the bounding thrusts***, (ii) other characteristic features, (iii) unit dimensions and shape (if possible).
4. Geological age, correlation and genesis (if possible).
5. ***Key references*** and historical background (if available).

The formal classification of tectonostratigraphic units (NCS 1989) would be applied when the thrust system is well established with published information, and where the major thrusts form the one primary basis for the rock unit division (e.g., Scandinavian Caledonides). In cases where the allochthonous nature of the unit is inferred, or the location and nature of the bounding thrust is poorly defined, the application of informal, descriptive *thrust-bounded units* is suggested.

5.2.2 Ranks of formal tectonostratigraphic units

The tectonostratigraphic units are, in decreasing order of the rank, *nappe system* and *nappe complex, nappe,* and *thrust sheet*, where nappe is the fundamental unit (NCS 1989). A nappe complex and nappe system have equal rank in a hierarchical classification (see Chapter 5.2.2.3 below).

5.2.2.1 Nappe

A *nappe* (*Nappe*) is the fundamental unit in tectonostratigraphic classification and nomenclature, and it is as a rank comparable to a formation or lithodeme (see Fig. 3). A nappe is a sheet-, slice-, wedge- or lens-shaped body of rock that has been moved and displaced, due to thrust faulting and/or sliding, a large distance in a horizontal or near subhorizontal (gently dipping) direction over the plane of separation along a thrust fault. A nappe is mappable at the Earth's surface and sometimes traceable into the subsurface by using geological and/or geophysical methods.

A nappe is defined and recognized by a tectonic thrust fault (floor thrust). The floor thrust and the nappe may, especially in multiply folded bedrock, be refolded or otherwise tectonically complicated. Therefore, the identification, systematic mapping and spatial representation of the early thrusts and related nappes may be difficult. Furthermore, in the deep levels of a thrust belt, the internal structure of a nappe is often complex and includes duplexes, other anastomosing shear zones, recumbent or overturned folds and thrust sheets of various dimensions and geometries.

5.2.2.2 The lower rank: Thrust sheet

A *thrust sheet* is the only lower rank of a nappe and comparable to a member of the lithostratigraphic classification system (see Fig. 2) representing a mappable unit within a defined nappe. The shape of a thrust sheet may vary (sheet, slice, wedge or lens), and there are no limitations for the size or the length of transport of a thrust sheet.

5.2.2.3 The upper ranks: Nappe system and nappe complex

A *nappe system* is a tectonostratigraphic unit next higher in rank to a nappe, and equivalent in rank to a nappe complex. It comprises two or more nappes, having a geometrical relation to one another. The movements and displacements of the distinct and individual nappes have taken place during the same deformation event. A nappe system may consist of several individual and distinct nappes and/or thrust sheets, which can be distinguished from one another by their content of lithostratigraphic, lithodemic and biostratigraphic units. The term nappe system should only be used when the movements and displacements of the individual nappes belong to the same deformation event and are well documented.

A *nappe complex* is a tectonostratigraphic unit next higher in rank to a nappe. Compared to 'nappe system', 'nappe complex' a less distinct term indicating that the displacements of the individual nappes represent different deformation phases or orogenies or that their relative ages are unresolved. A nappe complex may be comprised of two or more distinct nappes, but the term can also be used for complicated systems of inferred nappes or thrust sheets. Before naming a unit as a 'nappe complex', the options provided by the 'thrust-bounded units' (Chapter 5.2.3) need to be considered.

5.2.3 Informal thrust-bounded units

A thrust-bounded unit is a body of rock that has been displaced along a floor thrust and may be delimited uppermost by a roof thrust or the erosion surface. All thrust-bounded units may contain one or more lithostratigraphic or lithodemic units. The proposed terminology of thrust-bounded units (Luukas & Kohonen 2021) basically consolidated the common practice used in Finland.

5.2.3.1 Allochthon, thrust sheet (klippe, window)

An *allochthon* is a thrust-bounded unit underlain by an inferred decollement. The inferred amount of tectonic transport must be substantial (several kilometres, at least). A *thrust sheet* is the lower rank of a nappe but is also used as a descriptive term for any mappable volume of rock underlain by a thrust. A thrust sheet may form a part of a nappe, allochthon, thrust stack, imbricate fan or duplex. A *klippe* is an outlier (erosional remnant) of an allochthon (or nappe) and a *window* is an inlier surrounded by an overlying decollement at the present erosional level. Both of the terms are defined by the current land surface representing the extent of a map unit rather than a proper geological unit. 'Klippe' and 'window' are standard terms but should not be used in the nomenclature of geological units.

5.2.3.2 Thrust stack, duplex, thrust block

Not all thrusts are low-angle detachment zones, and the steeper fault zones may also delineate map units useful in regional description. *Thrust stack* refers to imbricated thrust sheet systems when the decollement is not identified, or the sole thrust is not a low-angle detachment; a typical example is a basement-involved foreland thrust system. A *duplex* is a thrust stack or a thrust sheet consisting of sigmoidal, smaller thrust sheets ('horses') between two larger-scale thrusts (e.g., Boyer & Elliott 1982). A *thrust block* is a special type of a thrust sheet, which is a relatively rigid, voluminous thrust-bounded body of rock. These are especially useful in the description of large-scale crustal features (for examples, see Luukas & Kohonen 2021). Finally, it is important to ensure that reverse faults, thrust faults and shear zones are geological structures, which do not automatically bound any geological unit. The Finnish bedrock is occupied by minor thrusts and reverse faults, and not all of these are meaningful in the sense of thrust-bounded unit boundaries.

5.2.4 Naming of formal and informal units

The formal and informal names for the tectonostratigraphic units are formed, according the general rules of naming (see Chapter 3), by the combination of a geographical name and a rank term or a descriptive term.

According to the procedure in NCS (1989), a proper tectonostratigraphic unit is defined and named according to the lower bounding thrust. The name combines a geographical term attached to the floor thrust (nappe, thrust sheet) or to the type area (nappe system and nappe complex) with the rank term. A thrust sheet must not be given the same geographical name as the nappe or the lithostratigraphic/lithodemic units within the nappe or thrust sheet. A nappe system or a nappe complex must not be given the same geographical name as a component nappe, or as any of the lithostratigraphic/lithodemic units in it.

A formal unit name is indicated by capitalized initial letters (e.g., Vaddas Nappe). In Finland, no formal names for nappe complexes have been suggested. The formal status requires the procedure described in Chapter 3.2. As an exception, where the unit names are adopted from an established formal nomenclature of the neighbouring countries (e.g., Finnish Caledonides), no re-approval by the SCF is needed. The informal thrust-bounded units are named by the combination of the geographical name of the type area and the descriptive term (such as 'thrust block' or 'thrust stack'; see Luukas & Kohonen 2021).

Examples of application

Lehtovaara (1986, 1989, 1995) and Lehtovaara & Sipilä (1987) applied the NCS 1989 tectonostratigraphic scheme to the Finnish Caledonides (e.g., Nalganas, Nabar and Vaddas Nappes) in the northwestern part of Finnish Lapland. In the Finnish bedrock, the repetition of strata by thrusts is probably much more common than currently recognized, and this is reflected by several examples of the tentative use of the term 'nappe', even without a sufficient description of the boundaries (e.g., Koistinen 1981, Laajoki 1991). Luukas & Kohonen (2021) provide both suggestions for the management of structural units and several examples of their practical usage. Another recent example is the Ylitornio nappe complex proposed by Lahtinen et al. (2019).

5.3 Lithotectonic units

5.3.1 General properties

A lithotectonic unit has been defined as follows:

- A body of rock distinguished and defined based on the specified tectonic or structural features and attributes;
- A geological unit defined on the basis of structural or deformation features, mutual relations, origin or historical evolution. Contained material may be igneous, sedimentary or metamorphic (CGI definition as a subclass of *geologic unit*).

Tectonic terms and related nomenclature are closely linked to the concepts and interpretations applied in their designation. Therefore, the harmonization of the nomenclature is challenging, and well-established classifications (or categories) with an internationally recognized status are not available. However, the published tectonic models, regional maps and general overviews include a plethora of 'crustal blocks', orogenic-crustal-structural 'domains', different kinds of 'provinces', 'terranes' and 'mobile belts', typically without any definition or other explanation. The nomenclature of these, typically extensive, geological units is needed, but systematic approaches are currently still in their infancy.

5.3.2 Classifications and subdivisions

The CGI vocabulary (v2016.01) recognizes only one subclass of a lithotectonic unit. A *deformation unit* is a lithotectonic unit defined by the deformation style or characteristic geological structure observable in outcrop. In Finland, Kohonen et al. (2021) proposed a classification scheme for three classes of lithotectonic units: *crustal province*, *tectonic province* and *structural province*. The provinces are characterized by a defined set of features and subdivided into subprovinces, domains and subdomains.

5.3.3 Obsolete terms: terrane, province and block

A *terrane* (or 'tectonic terrane'; 'suspect terrane'; 'exotic terrane') is an informal descriptive term for a fault-bounded body of rock characterized by a geological history different from that of the adjacent areas. The term was introduced by Irwin (1972) and finally established by Coney et al. (1980). The term has been used for (i) continental blocks bounded by suture zones and newly formed oceanic crust, (ii) nappes bounded by thrust faults, (iii) blocks bounded by regional transform faults, and (iv) pieces of the Earth's crust having complex and structurally composite fault surfaces. The key feature is that the terrane is found 'exotic' in comparison to the surrounding units. Presently, the term is ambiguous and partly overlaps with other terms such as allochthon, province, structural complex and tectonic block. *Terrane* must not be confused with the term "terrain", which is a general term relating to the physical features of the region or area.

International examples of the systematic classification of *provinces* are few, and the terminology is not well established. The Glossary of Geology (Neuendorf et al. 2011) provides the two following broad definitions: (1) A *province* is a large region with similar features or a history significantly different from the adjacent areas; (2) A *geological province* is an extensive region with a similar geological history throughout or similar structural, petrographic or physiographic features. A *block* (or fault block) is a fault-bounded unit that has been displaced as a single unit. <u>Without a detailed description, or a reference to a definition, the use of the general terms 'terrane', 'province' and 'block' is not suggested in the unit nomenclature of Finland,</u> and even in these cases, other naming options (such as structural province, crustal domain) are worth considering.

6 OTHER MATERIAL-BASED CLASSIFICATIONS

6.1 Sequence stratigraphy

6.1.1 General principles and unit boundaries

The lithostratigraphic classification of the sedimentary record remains the basic descriptive process for stratigraphic documentation because the extensive body of documentation is based on lithostratigraphy. However, the ultimate future goal is to develop stratigraphic frameworks based on sequence stratigraphy (Catuneanu et al. 2011). The method combines the insights of stratigraphic classifications and disciplines such as sedimentology, geomorphology, geophysics and basin analysis (cf. Catuneanu et al. 2009). The deductive sequence stratigraphic approach (see Embry & Johannessen 2017) defines the surfaces in terms of theoretical events on a base-level curve and builds a bridge between the identified boundaries and basin modelling techniques. Sequence stratigraphy is concerned with the large-scale arrangement of sedimentary strata, and the major factors that influence the unit geometries, such as sea-level change, contemporaneous fault movements, basin subsidence and sediment supply (see Rawson et al. 2002). Fundamentally, sequence stratigraphy deals with the sedimentary response to changes in the base level, and the depositional trends that emerge from the interplay of sedimentation (clastic input) and the accommodation space (available for sediments to fill).

Sequence stratigraphy is an approach to integrated stratigraphic analysis, dealing with the sedimentary response to changes in the base level, and the depositional trends that emerge from the interplay of sedimentation and accommodation space. Changes in the base level depend on the interplay of allogenic controls such as eustasy, tectonism and climate. The base level is therefore the link that synchronizes depositional processes across a sedimentary basin, bringing necessary coherence to the sequence stratigraphic model. This, in turn, means that sequence stratigraphy is an effective tool for correlation on a regional basis.

Sequence stratigraphy is not currently recognized as a stratigraphic category by any of the references given in Table 1. The units are defined by their boundaries, and the method shares some features of allostratigraphy (see NASC 2005), the definition of unconformity-bounded units of ISG 1994 and seismostratigraphy (cf. NCS 1989). The generic definition of a sequence corresponds to a full cycle of base-level changes (Fig. 9), and four main events are generally recognized:

I. Onset of forced regression (onset of a base-level fall in the shoreline)
II. End of forced regression (end of a base-level fall in the shoreline)
III. End of regression (during a base-level rise in the shoreline)
IV. End of transgression (during a base-level rise in the shoreline)

These four events control the timing of the formation of all sequence stratigraphic surfaces and systems tracts. Sequence stratigraphic surfaces (Fig. 9) define the unconformities due to the response to the main events. These serve in both the recognition of events and the division of the corresponding units. The process-based understanding of the origin of all genetic types of deposits and their bounding surfaces is fundamental to the success of the sequence stratigraphic approach. The integration of outcrop, core, well-log and seismic data affords the most effective application of the sequence stratigraphic method.

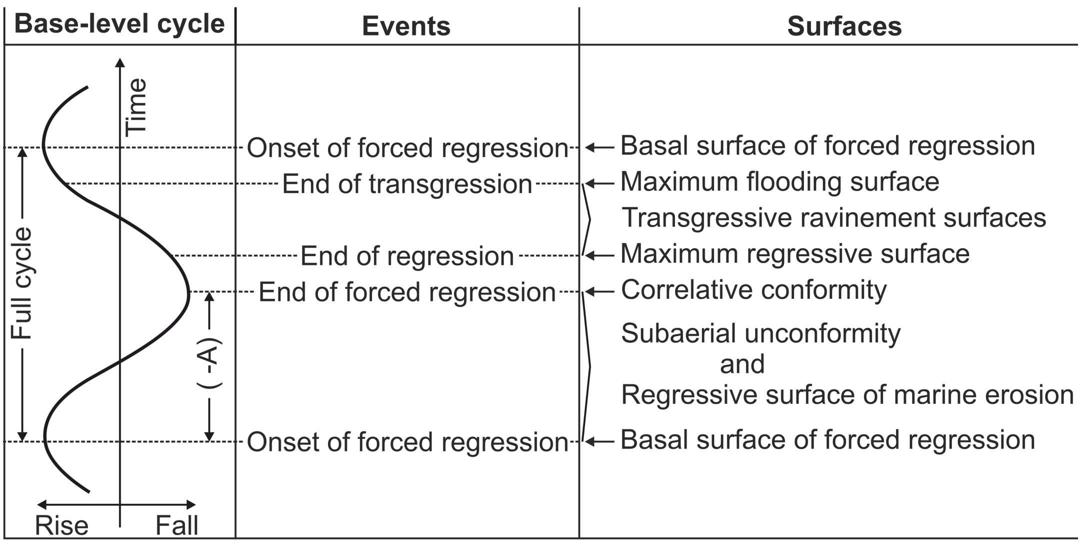


Fig. 9. Timing of the seven sequence stratigraphic surfaces relative to the four main events of the base-level cycle (modified from Catuneanu 2006). (Abbreviation: (–A) stands for negative accommodation)

The cyclicity of Proterozoic sedimentary rocks is still a rather crude concept, and the application of sequence stratigraphy to the Proterozoic rock record typically encounters difficulties due to poor preservation, tectono-metamorphic overprint and a lack of age determinations (Catuneanu 2006, Catuneanu et al. 2009). Nonetheless, the studies by Christie-Blick et al. (1988, 1995), Harris & Eriksson (1990), Jackson et al. (1990) and Catuneanu & Eriksson (1999) have demonstrated that the sequence stratigraphic approach can in principle be applied to the analysis of Proterozoic successions.

6.1.2 Units in sequence stratigraphy

The key concepts of sequence stratigraphic unit division are 'sequence' and 'systems tract' (Fig. 10). A full stratigraphic cycle, which starts and ends with the same type of sequence stratigraphic surface, delineates a 'sequence' (Catuneanu & Zecchin 2013), which typically includes two or more systems tracts. A *sequence* is a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Mitchum 1977). <u>A sequence corresponds to a full cycle of base-level changes</u>. It includes two stages of sediment-driven regression forming low-stand and high-stand systems tracts, an intervening stage of forced regression driven by a base-level fall generating a falling stage systems tract, and a stage of shoreline transgression, which relates to a transgressive systems tract. Each of these stages results in the formation of a particular genetic type of deposit, with characteristic stratal stacking patterns and sediment distribution within the basin. The definition of a sequence is independent of temporal and spatial scales. The relative importance of sequences is resolved via the concept of hierarchy. Higher-rank sequences may consist of two or more lower-rank sequences. A *parasequence* is a relatively conformable succession of genetically related beds or bedsets bounded by flooding surfaces or their correlative surfaces (Van Wagoner et al. 1988, 1990, Arnott 1995). Depending on the circumstances, these may be represented by transgressive ravinement surfaces, maximum flooding surfaces, maximum regressive surfaces, or facies contacts within the transgressive systems tract. Parasequences are commonly used to describe individual prograding lobes in coastal to shallow water systems, where evidence of flooding surfaces is easiest to demonstrate.

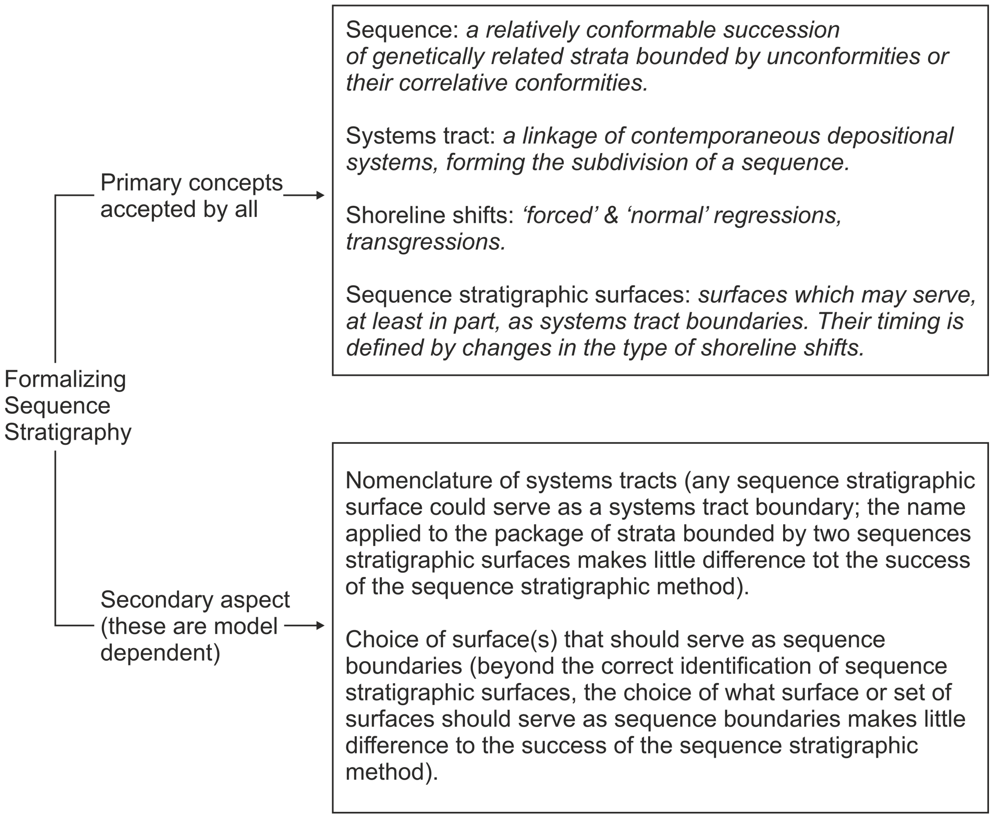


Fig. 10. Primary and secondary aspects in sequence stratigraphy (modified from Catuneanu 2006). Primary aspects are validated and generally accepted ('generic'). Secondary aspects are dependent on the model selected. The generic concept is the first step towards more formalized sequence stratigraphic units.

The mappability of the sequences, systems tracts and the bounding surfaces depends on the depositional setting and the types of data available for analysis (Catuneanu et al. 2009). In practice, the main methods of sequence stratigraphy in modern environments include the analysis of seismic reflectors and well-log signatures. In the study of ancient deposits (including bedrock successions), the facies analysis of outcrops, cores and interpretation of the unconformities are generally the only tools available. The achievement of time control via relative or absolute age determination is important in both cases. Conclusively, the application of sequence stratigraphic units may be useful in detailed studies with a genetic approach (e.g., paleosedimentology, basin analysis). However, the definition of any new geological unit must serve a clear purpose in stratigraphic work in Finland.

Examples of application

The basin analysis of the Kainuu belt (see Strand & Laajoki 1999, Strand 2005, 2012) provides examples of sequence stratigraphy applied to the Proterozoic rocks in Finland,

6.2 Tectofacies classification in Finland

Laajoki (1990, 1991) introduced the informal stratigraphic concept of *tectofacies* for "all the formations formed during a specific broad tectonic phase of the depositional-volcanic history of a basin or nearby basins." In fact, all the different tectofacies (Sumi, Sariola, Kainuu, Jatuli, Lower Kaleva and Upper Kaleva; Laajoki 1990) in the Kainuu belt are separated by major unconformities. Therefore, the concept of tectofacies shares features of a synthem, a diachronous, unconformity-bounded stratigraphic unit (see ISG 1994). However, without regionally identified unconformity surfaces, the unit (synthem) boundaries remain elusive.

Laajoki (2005) widened the perspective by stating that "in terms of sequence stratigraphy the tectofacies are related to Hubbard's (1988) megasequences." Even so, tectofacies cannot be considered as sequence stratigraphic units. In fact, the tectofacies concept appears to be primarily linked to the depositional megacycles derived from the basin evolution model of Kainuu (Laajoki 1991, 2005), and this has restricted the inter-regional application of the scheme.

7 CLASSIFICATIONS RELATED TO GEOLOGICAL AGE

7.1 Chronostratigraphic units

7.1.1 General properties, rules and boundaries

A chronostratigraphic unit has been defined as follows:

- A body of rocks that includes all rocks formed during a specific interval of geological time and only those rocks formed during that time span. Chronostratigraphic units are bounded by synchronous horizons. The rank and relative magnitude of the units in the chronostratigraphic hierarchy are a function of the length of the time interval that their rocks subtend, rather than of their physical thickness (ISG 1994);
- A body of rocks 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 (https://stratigraphy.org/guide/ 25.1.2022);
- A body of stratified rock that forms a material reference for all rocks formed during the same period of time;
- A geological unit that includes all rocks formed during a specific interval of geological time. CGI definition (a subclass of a *geologic unit*).

Chronostratigraphic units are based on the time of formation of the rock bodies and not on the material properties of the observed rock bodies. A unit includes all rocks formed during a specific interval of geological time and it comprises rocks with isochronous (time-parallel) lower and upper boundaries.

Chronostratigraphic classification provides a means of establishing the temporally sequential order of rock bodies. The principal purpose is to provide a framework for (1) the temporal correlation of the rocks in one area with those in another,

(2) placing the rocks of the Earth's crust in a systematic sequence and indicating their relative position and age with respect to the Earth's history as a whole, and (3) constructing an internationally recognized Standard Global Chronostratigraphic Scale (e.g., Grandstein et al. 2004).

The boundaries of the Phanerozoic stages, the lower boundary of the Ediacaran System and the corresponding geochronological units (age, period; see Table 3), are based on the recognition of a Global Boundary Stratotype Section and Point (GSSP; see Cohen et al. 2013; https://stratigraphy.org/ICSchart/ChronostratChart2023-09.pdf). In contrast, most Proterozoic (all Precryogenian) system/period boundaries, and all the Archean Erathem/Era boundaries are based on the geochronometric subdivision of geological time, and the boundaries defined by the Global Standard Stratigraphic Ages (GSSA) have no corresponding rock sequences. Therefore, the conceptual difference between the chronostratigraphic and geochronological nomenclature is easily dissolved in the bedrock geology.

Geochronological units are divisions of time, not tangible material units. A geochronological unit is not a stratigraphic unit but represents the time span of the corresponding chronostratigraphic unit. The difference is underlined by the subdivision of the units: chronostratigraphic units may be formally divided into Lower, (Middle) and Upper, whereas the corresponding geochronological units are divided into Early, (Middle) and Late. The names and boundaries of the all the chronostratigraphic, and corresponding geochronological, units are defined internationally by ICS (https://stratigraphy.org).

7.1.2 Ranking and nomenclature of chronostratigraphic units

The hierarchy of chronostratigraphic units, in order of decreasing rank, is eonothem, erathem, system, series and stage. In Proterozoic and Archean chronostratigraphy, system and erathem are the primary ranks. At any level in the hierarchy, an initial capital letter is used for each formal component of the name (e.g., Paleoproterozoic Erathem; Orosirian System). The use of lowercase initial letters implies an informal usage (e.g., 'lower Orosirian succession'; for details, see Grandstein et al. 2004).

Table 3. Rank terms of the chronostratigraphic category and the correspondence of the geochronological units (modified after ISC 1994).

Division of rock record (strata) into units based on their age	**Division of time** based on GSSP age or GSSA.
Chronostratigraphic Unit terms	**Geochronological Units**
Eonothem	Eon
Erathem	Era
System	Period
Series	Epoch
Stage	Age
(Chronozone)	(Chron)

7.1.2.1 Eonothem and Erathem

The highest unit rank is the *eonothem* and the next lower rank is *erathem*. The Phanerozoic Eonothem encompasses the Paleozoic, Mesozoic and Cenozoic Erathems. The Proterozoic Eonothem covers the Paleoproterozoic (2500– 1600 Ma), Mesoproterozoic (1600–1000 Ma) and Neoproterozoic (1000–542 Ma) Erathems. The Archean Eonothem is presently subdivided into Eoarchean (4031–3600 Ma), Paleoarchean (3600–3200 Ma), Mesoarchean (3200–2800 Ma) and Neoarchean (2800–2500 Ma) Erathems.

7.1.2.2 System

The unit of rank next lower to erathem is *system*. Rocks encompassed by a system represent a time span and an episode of the Earth's history sufficiently great to serve as a worldwide chronostratigraphic reference unit. The temporal equivalent of a system is a period. Presently, the Archean is not divided into systems. The Paleoproterozoic erathem encompasses the Siderian (2500–2300 Ma), Rhyacian (2300–2050 Ma), Orosirian (2050–1800 Ma) and Statherian (1800–1600 Ma) systems. The Mesoproterozoic erathem encompasses the

Calymmian (1600–1400 Ma), Ectasian (1400–1200 Ma) and Stenian (1200–1000 Ma) erathems, and the Neoproterozoic erathem encompasses the Tonian (1000–850 Ma), Cryogenian (850–630 Ma) and Ediacaran (630–542 Ma) systems. The Proterozoic–Cambrian boundary has been defined at 542 Ma by Amthor et al. (2003).

7.1.2.3 Series and Stage

A *series* is a chronostratigraphic rank below a system and is always a division of a system. A series commonly constitutes a major unit of chronostratigraphic correlation within a province, between provinces or between continents. Although many European series are increasingly being adopted for dividing systems on other continents, provincial series of regional scope continue to be useful. The temporal equivalent of a series is an epoch. A *stage* is a chronostratigraphic unit of smaller scope and rank than a series. It is most commonly of greatest use in intra-continental classification and correlation, although it has the potential for worldwide recognition. The geochronological equivalent of a stage is an age. For the nomenclature and boundaries of the Phanerozoic systems, stages and series, the International Chronostratigraphic Chart is referred to (https://stratigraphy.org/ICSchart/ChronostratChart2023-09.pdf).

7.1.2.4 Chronozone

A *chronozone* is a nonhierarchical, but commonly small, formal chronostratigraphic unit, and its boundaries may be independent of those ranked chronostratigraphic units such as system or stage. Although a chronozone is an isochronous unit, it may be based on a biostratigraphic unit (e.g., Cardioceras cordatum Biochronozone), a lithostratigraphic unit (Woodbend Lithochronozone) or a magnetopolarity unit (Gilbert Reversed-Polarity Chronozone). Chronozones may be of widely different time spans and, in theory, the extent of a chronozone is worldwide (for details of application, see ISG 1994).

7.2 Event stratigraphy

The term '*event stratigraphy*' was proposed by Ager (1973) for the recognition, study and correlation of the effects of significant physical events (e.g., marine transgressions, volcanic eruptions, geomagnetic polarity reversals, climatic changes) or biological events (e.g., extinctions) on the stratigraphic record of whole continents or even of the entire globe. Event stratigraphy can be defined as the organization and correlation of rocks on the basis of short-term, extraordinary phenomena, such as explosive volcanism, abrupt sea-level changes, climatic anomalies and meteorite impacts. The fundamental idea comes rather close to chronozones, marker beds and even to sequence stratigraphy (rapid eustatic changes).

Nevertheless, the effects of major events in the rock record may define truly synchronous horizons, and their correlation thus potentially leads to greater resolution and a more accurate chronostratigraphic scale, especially in the bedrock geology. The developments in Precambrian chronostratigraphy and the potential of various 'events' in the progressing definition of GSSPs has been reviewed by Altermann et al. (2012).

7.3 Application of chronostratigraphy and geochronology to the bedrock units of Finland

The Eonothem (Eon) and Erathem (Era) nomenclature is widely used in Finland. The application of the formally defined Proterozoic periods (e.g., Rhyacian, Orosirian) is not common in the literature, but the map data of GTK have been attributed accordingly. Furthermore, to improve the resolution of the map data of the Fennoscandian Shield, an informal subdivision to epoch level has been proposed (Asch et al. 2007, Luukas et al. 2017). The challenge with the Proterozoic period/system nomenclature is related to the globally defined boundaries not ideally corresponding to the observed age pattern and derived nomenclature used in Fennoscandia and in Finland. According to ISG 1994, the regional scales are acceptable: "*It is better to refer strata with accuracy to local or regional units than to strain beyond the current limits of time-correlation in assigning these strata to units of a global scale. Local or regional chronostratigraphic units should adhere to the same rules established for the units of the Standard Global Chronostratigraphic Scale.*"

In Finland, the regional classifications related to geological age are referred to as '*time-stratigraphic*' in order to avoid any confusion and to underline the global nature of the proper chronostratigraphic units. Regionally defined geochronological and corresponding time-stratigraphic (or 'event-stratigraphic') units are found appropriate when based on an established (scientifically published) scale. c All such time-stratigraphic units are informal and should not been mixed with the formal, internationally defined chronostratigraphic nomenclature. Finally, it is essential to note that in the bedrock of Finland, the chronostratigraphic (time-stratigraphic) boundaries are not possible to define in the field. Consequently, the application is limited to the correlation of the tangible material-based unit and the presumably corresponding time-based unit.

Examples of application

Event-stratigraphy basically attempts to identify natural events as a basis for time-based boundaries. Following this, Hanski & Meletzhik (2012) proposed an 'event-stratigraphic' (essentially time-stratigraphic) scheme for the (2505–1900 Ma) eastern and northern parts of the Fennoscandian Shield. Furthermore, the authors converted some legacy names (such as Jatulian, Kalevian) to the nomenclature of the proposed scale. Kohonen et al. (2024, this volume) developed the idea further and complemented the scale by including the Svecofennian evolution (2000-1800 Ma) in western and southern parts of Finland.

8 TERMINOLOGICAL COMMENTS

Misuse of the terms 'group' and 'supergroup'

Even the informal use of the lithostratigraphic rank terms 'group' and 'supergroup' for units not consisting of lower rank lithostratigraphic units is inappropriate.

Use of the term 'complex'

The word 'complex' is a component of various geological terms (e.g., intrusive complex, core complex, metamorphic complex). Regarding geological units, the definition of a lithodemic complex is presented in Chapter 4.3.4. Other uses of 'complex' are common and useful in general descriptive text (e.g., Archean basement complex). When the meaning is unambiguous and when not mixed with the defined nomenclature of geological units, this type of usage is part of conventional terminology and thus acceptable.

Misuse of the term 'series'

The term 'series' has sometimes been used or applied to lithodemic and lithostratigraphical units, or to a sequence of rocks resulting from a succession of eruptions or intrusions. 'Series' is a formally defined chronostratigraphic term, corresponding to the geochronological term 'epoch', and should not be used for any other geological unit. In the informal Precambrian chronostratigraphy, '*system*' is the lowest rank, and no Precambrian geological unit name should not include the word 'series'. However, the words 'series', 'stage' and 'system' have been found useful in the description (e.g., layered series in the Narkaus intrusion; the early basin stages during the Jatulian) and, when confusion with chronostratigraphy is implausible, this usage is acceptable.

Names with ending '-ian'

According to the common usage, the names with the ending '-ian' (e.g., Devonian, Orosirian, Jatulian) are preferably used for chronostratigraphic (time-stratigraphic) or geochronological units. To support consistency and to avoid digressions, the ending is not suggested for any unit without a reference to a defined classification related to geological age.

Geographical geological names

Names referring to a geographical area or region in Finland (such as the Outokumpu area, the Kainuu belt and Central Finland granitoid area) and other geological geographical names (such as Fennoscandian Shield, the Russian platform, the Caledonian orogenic belt) are not part of the geological unit nomenclature. These region names are useful for many practical purposes, such as generalized maps and regional descriptions. The current region nomenclature, and its relationships with the lithotectonic terminology, has been summarized in Kohonen et al. (2021).

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APPENDIX 1

PROCEDURE FOR ESTABLISHING AND REVISING FORMAL STRATIGRAPHIC UNITS IN FINLAND

Accepted as a practice in the SCF (SSK *in Finnish*) meeting on 4.12.2019

Rationale:

- **The Geological Survey of Finland (GTK) maintains and develops the National Stratigraphic Database of Finland** (Finstrati). As the owner, GTK is authorized to develop the structure of Finstrati, guided by the operational needs of GTK and the development of GTK customer services.
- The charter of the Stratigraphic Commission of Finland (approved in the National Geological Committee of Finland meeting in 2006) states that **establishing and revising formal stratigraphic units is one key task of the SCF**.

Procedure for establishing formal units:

- GTK presents proposals for a formal unit status to the SCF. The original statement of intent may be presented by GTK or by a third party. The final GTK proposal must contain a due and clear description of the unit(s) in question and according to the requirements of the classification category.
- After submission to the SCF
  - The SCF asks the opinion of the Precambrian or Quaternary Subcommission; if needed, the Subcommission may request further information or a supplementary description of the unit.
  - The proposal seconded by the Subcommission is handed over to the SCF secretary.
  - The final decision is made in a meeting of the SCF.
- After SCF approval
  - GTK executes the required changes in the database.
  - GTK saves adequate documentation about the approval procedure in the information attributed to the unit.

ORIGINAL TEXT (IN FINNISH):

Formaalisten stratigrafisten yksiköiden muodostaminen ja hyväksyminen Suomessa

Hyväksytty käytännöksi SSK:n kokouksessa 4.12.2019

Lähtökohdat:

- *Geologian tutkimuskeskus (GTK) ylläpitää ja kehittää Suomen kansallista stratigrafian tietokantaa (Finstrati).*
- *GTK:lla on omistajan oikeus kehittää Finstratin rakennetta oman toimintansa ja asiakastarpeiden ohjaamana.*
- *Suomen Stratigrafian Komitean (SSK) perustamiskirjassa (hyväksytty Suomen Kansallisen Geologian Komitean vuoden 2006 kokouksessa) todetaan SSK yhtenä tehtävänä olevan muodollisten stratigrafisten yksiköiden hyväksyminen Suomessa.*

Menettelytapa formaalisten yksiköiden hyväksymisessä:

- *GTK tekee omasta aloitteestaan tai jonkin muun tahon aloitteen hyväksyttyään perustellun esityksen formaalin statuksen antamisesta. Perustelun tulee sisältää yksikölle / yksiköille riittävä kuvaus, joka täyttää kyseisen stratigrafisen luokittelun vaatimukset koskien yksikön määrittelyä.*
- *Esitys toimitetaan lausunnolle kvartäärin tai prekambrin työryhmään. Työryhmä voi tarvittaessa pyytää lisätietoja ja/tai edellyttää esityksen täydentämistä perustelluista syistä.*
- *Puollettu esitys toimitetaan SSK:n sihteerille ja esitys käsitellään SSK:n kokouksessa.*
- *GTK tekee SSK:n hyväksymisen jälkeen tarvittavat muutokset tietokantaan ja tallentaa yksikön tietoihin riittävän dokumentaation hyväksymismenettelystä.*

APPENDIX 2

LIST OF SUPPLEMENTARY INFORMATION IN THE WORLD WIDE WEB

CGI Vocabularies Register
https://cgi.vocabs.ga.gov.au/vocab/

GTK Map service – MDaE (Mineral Deposits and Exploration)
https://gtkdata.gtk.fi/mdae/index.html

North American Commission on Stratigraphic Nomenclature:
https://nacsn.americangeosciences.org/
http://www.agiweb.org/nacsn/code2.html

The Helsinki Term Bank for the Arts and Sciences (Tieteen Termipankki)
https://tieteentermipankki.fi/wiki/Geologia

The International Commission on Stratigraphy (ICS)
https://stratigraphy.org/
https://stratigraphy.org/guide/
https://stratigraphy.org/timescale/

The Stratigraphic Commission of Finland (SCF)
https://www.geologia.fi/2020/07/12/Suomen-stratigrafian-komitea-ssk/

STRATIGRAPHIC FRAMEWORK FOR THE CLASSIFICATION OF QUATERNARY DEPOSITS IN FINLAND

by

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Lunkka, J. P., Ojala, A. E. K., Kaakinen, A., Hovikoski, J., Kultti, S., Kuosmanen, N., Mäkinen, J., Palmu, J.-P., Putkinen, N., Sarala, P., Väliranta, M. & Virtasalo, J. 2024. Stratigraphic framework for the classification of Quaternary deposits in Finland. *Geological Survey of Finland, Bulletin 418*, 77–143, 20 figures and 4 tables.

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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CONTENTS

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, nonglacial 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

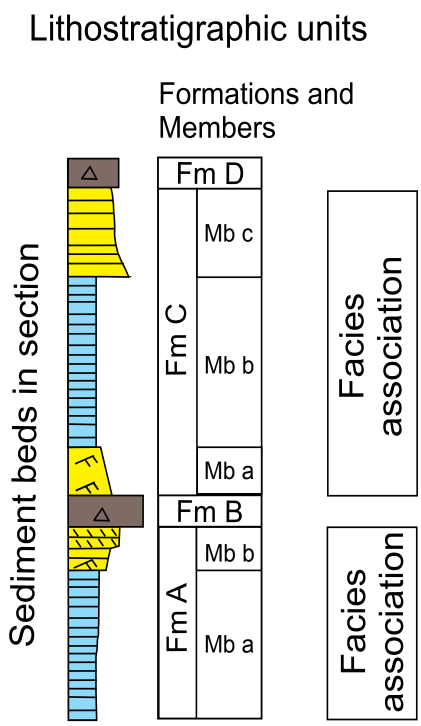


Fig. 1. Schematic presentation of a hypothetical sediment section in which the sediment beds of laminated silt and clay (blue), rippled, parallel and planar cross-bedded sand (yellow) and diamicton (grey) are lithostratigraphically divided into different formations (Fm) and members (Mb). The lithostratigraphic 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.

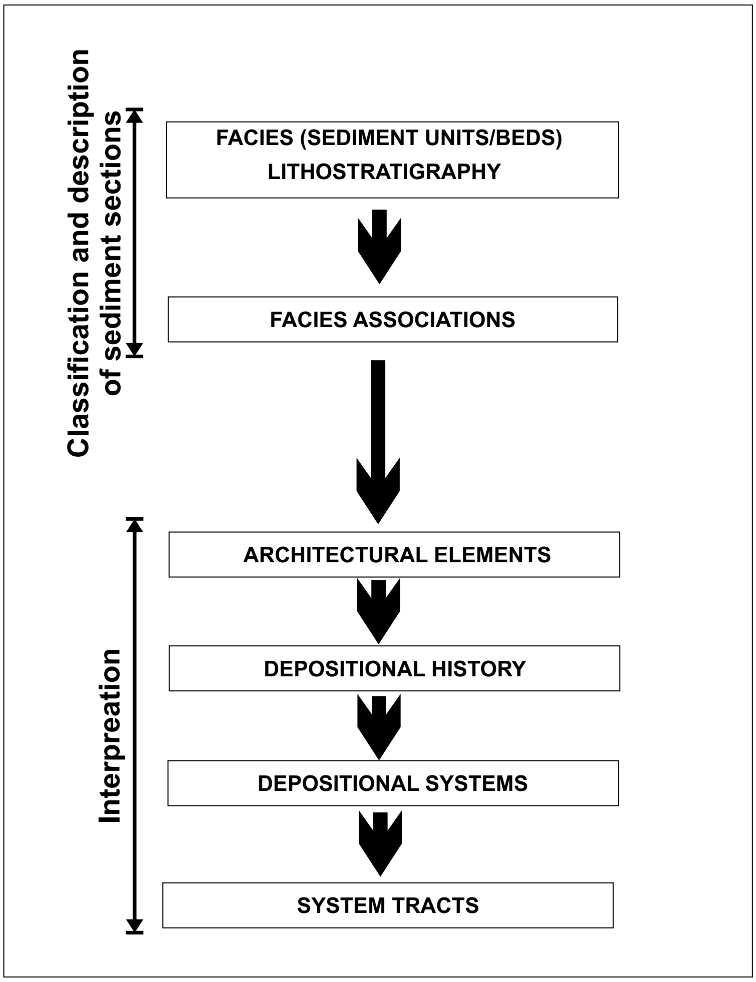


Fig. 2. Hierarchy to unravel depositional systems and system tracts. The lithostratigraphic description of sediment beds forming facies associations is the most important data for the interpretation of architectural elements and finally depositional systems and their evolution (highstand, lowstand and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

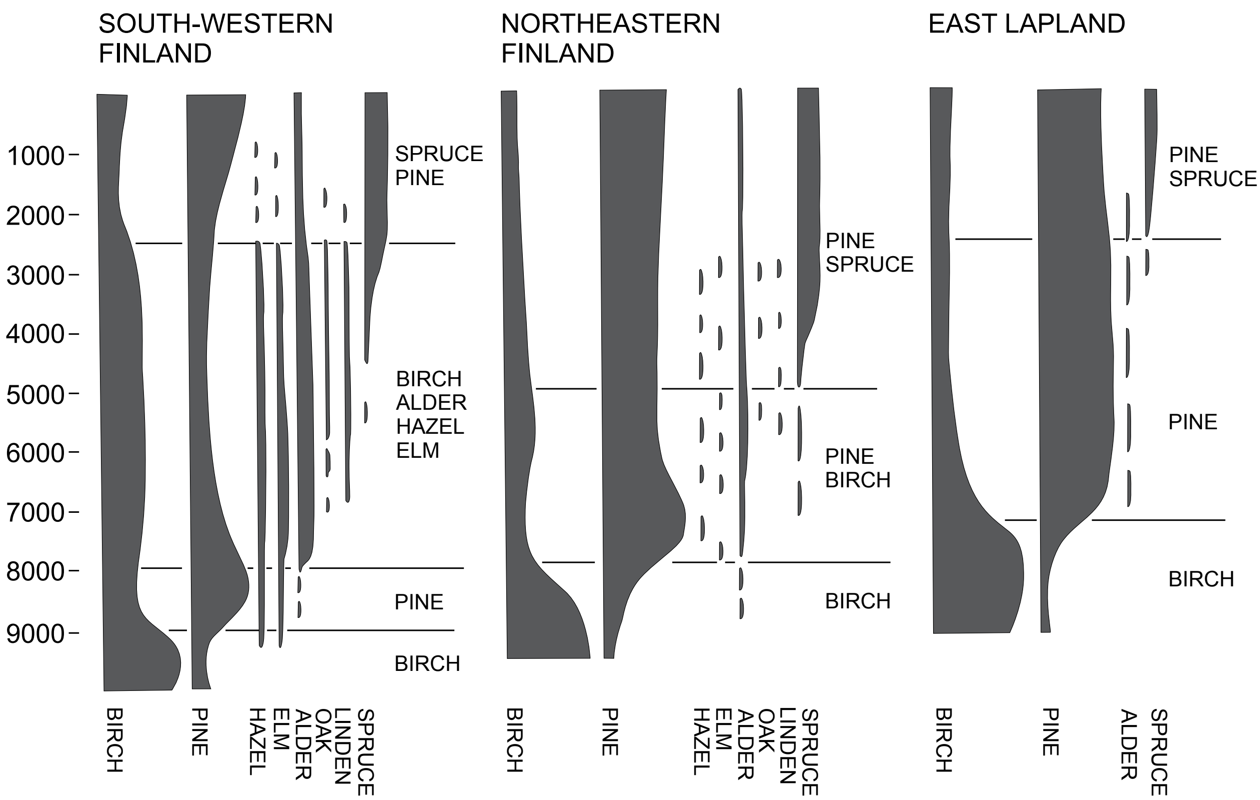


Fig. 4. Pollen stratigraphic biozones of southwestern Finland, northeastern Finland and eastern Lapland, and chronology from radiocarbon ages, modified after Hyvärinen (1986, according to Donner (1971) and Hyvärinen (1972)).

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.

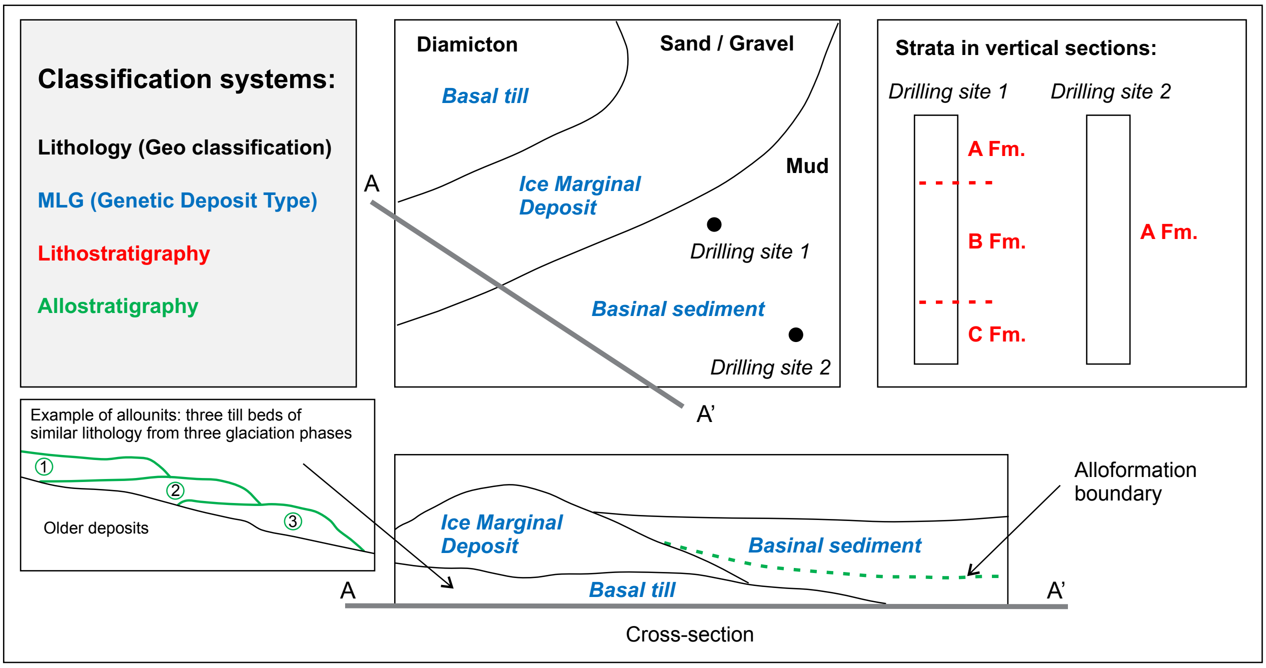


Fig. 5. Schematic illustration addressing the connections of different classification systems applied to the map view (top centre), vertical strata (top right) and geological cross-section (bottom centre). Note the colour coding (top left) for the classification systems.

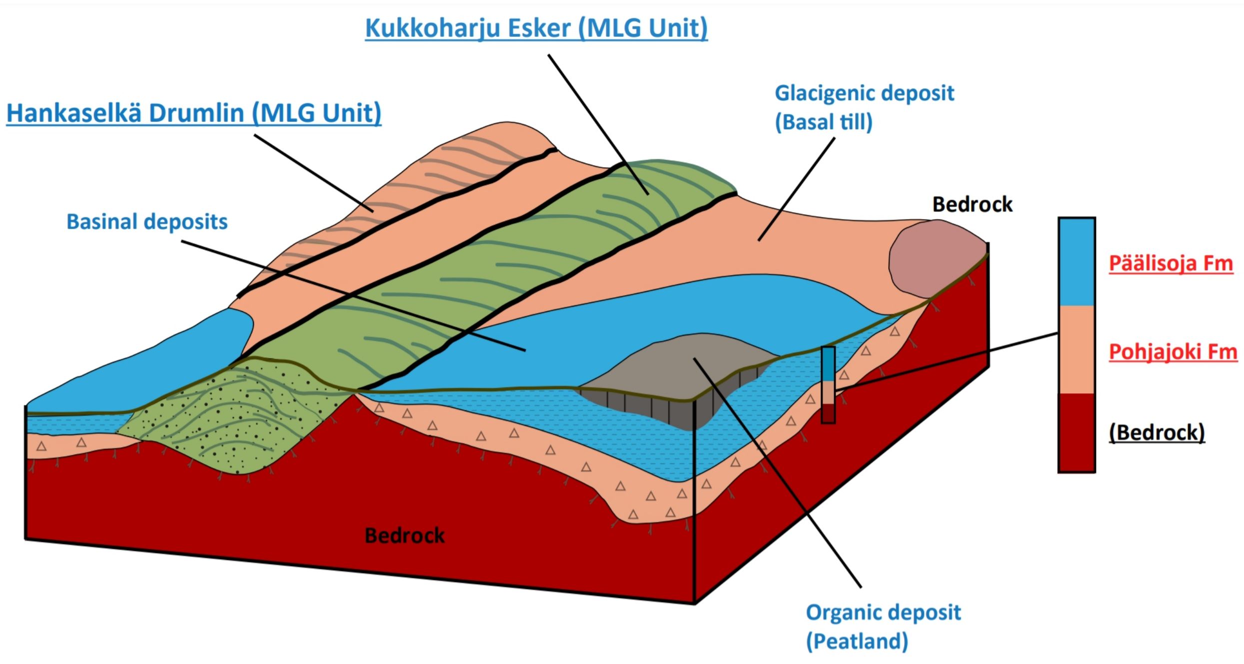


Fig. 6. Map units (top surface) classified by 'genetic deposit type' (blue text; see also Table 1) and their relationships with lithostratigraphic units (red text). The underlined geological units (see Table 2) will be included in the FinstratiMP lexicon database.

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).

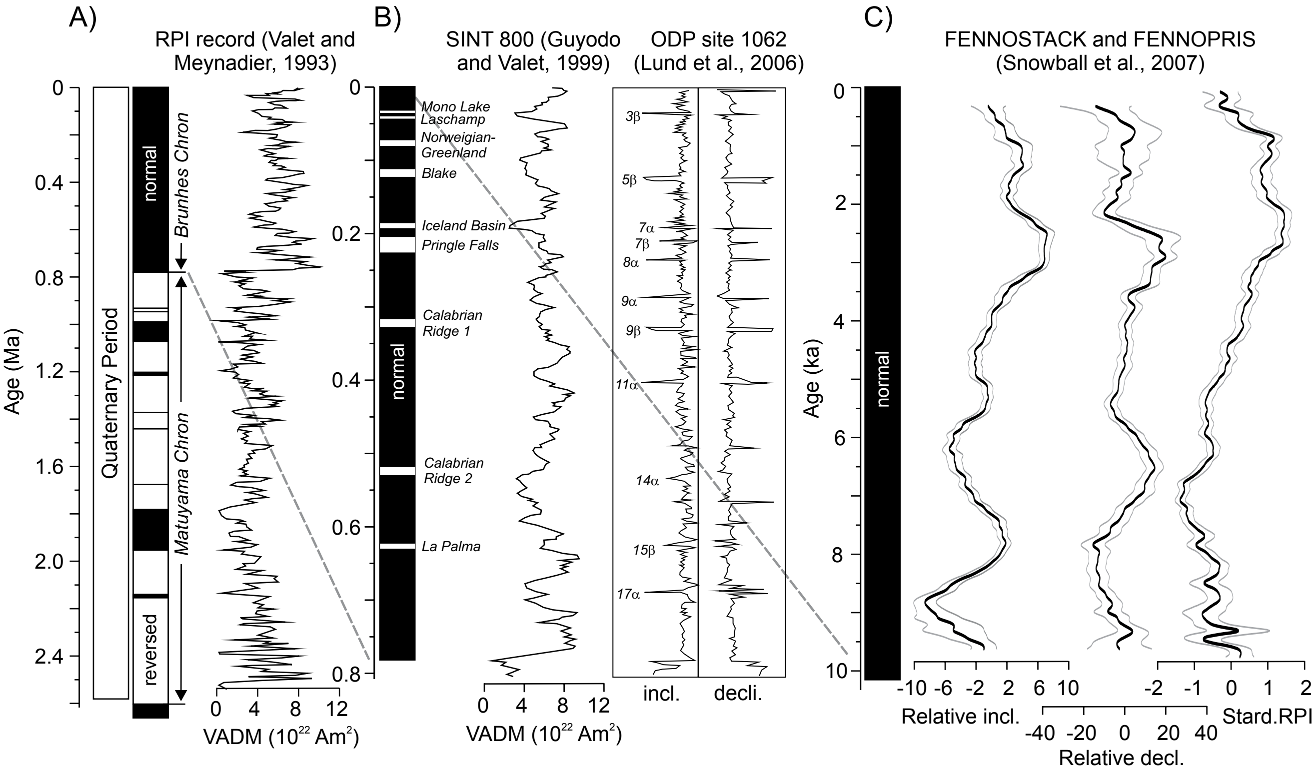


Fig. 7. Records of magnetic polarity A), geomagnetic excursions B) and paleosecular variation C) during the Quaternary Period. The Quaternary Period is characterized by the normal Brunhes and the reversed Matuyama chrons. Variations in Earth's magnetic axial dipole moment (VADM) are based on Valet and 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.

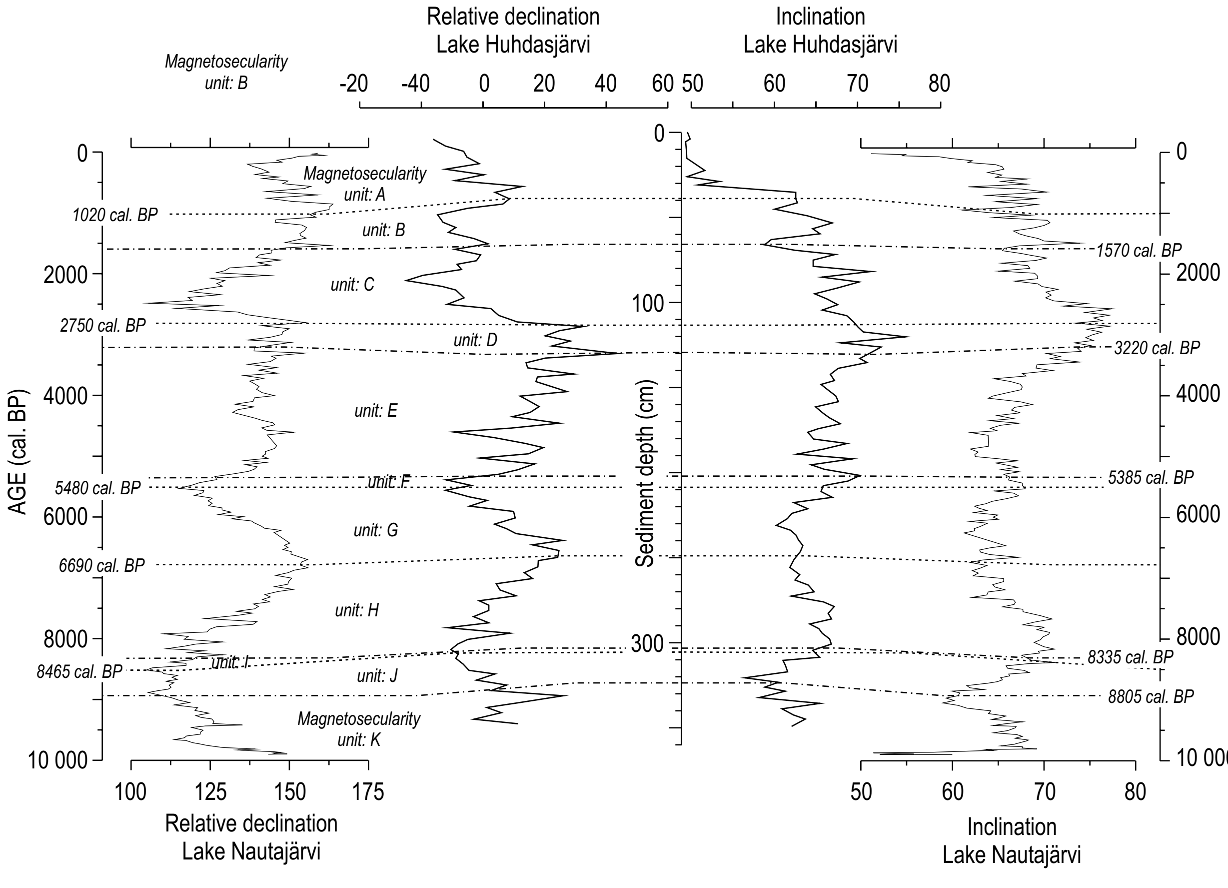


Fig. 8. A hypothetical example of magnetosecularity units A to K correlated between the accurately dated Lake Nautajärvi varved sequence from SW Finland (Ojala & Saarinen 2002) and the Lake Huhdasjärvi sediment core FID 60 A, SE Finland (Alenius et al. 2017). Subhorizontal lines indicate the paleosecular 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

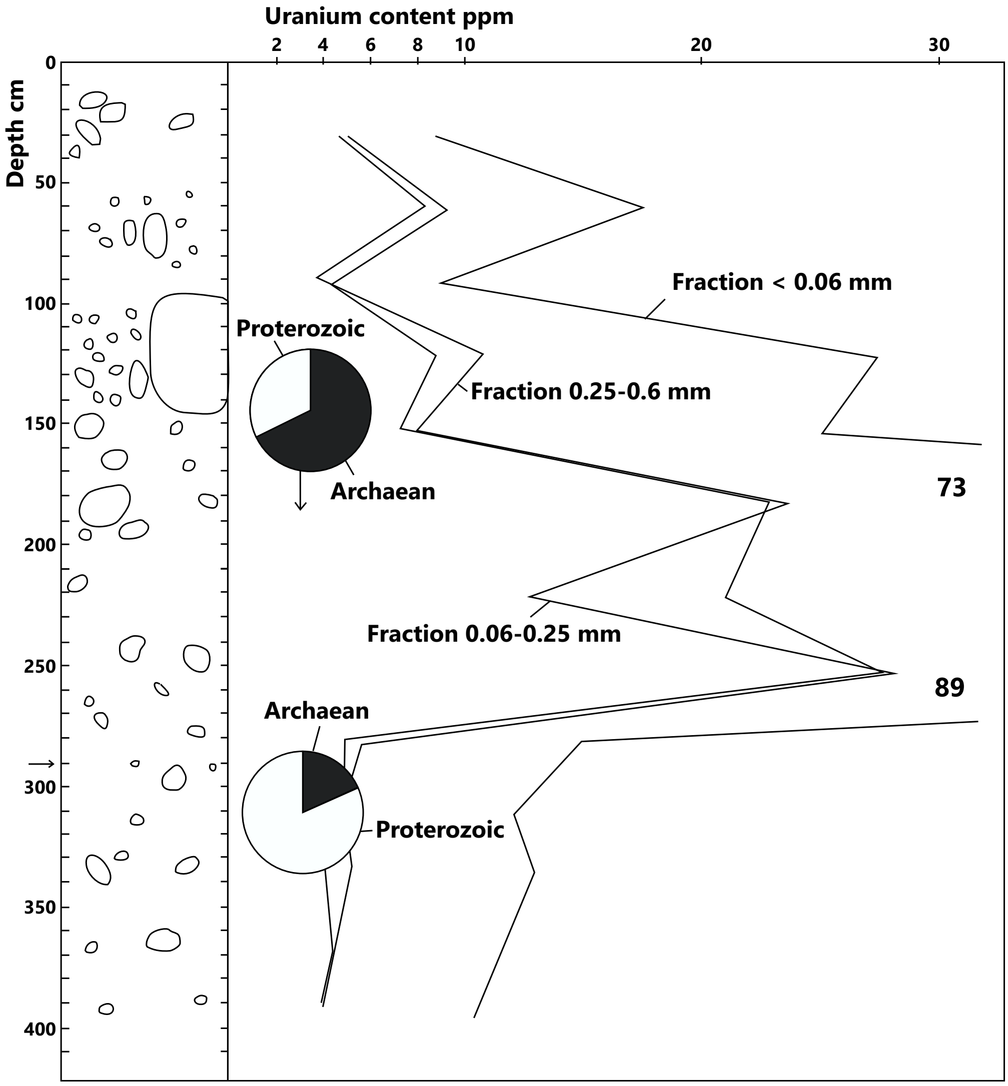


Fig. 9. An example of the use of chemostratigraphy to characterize different till units in southern Finnish Lapland. High uranium concentrations in the upper part of a till section indicate a much shorter transport distance and origin of till material compared to the lower part of the section. After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

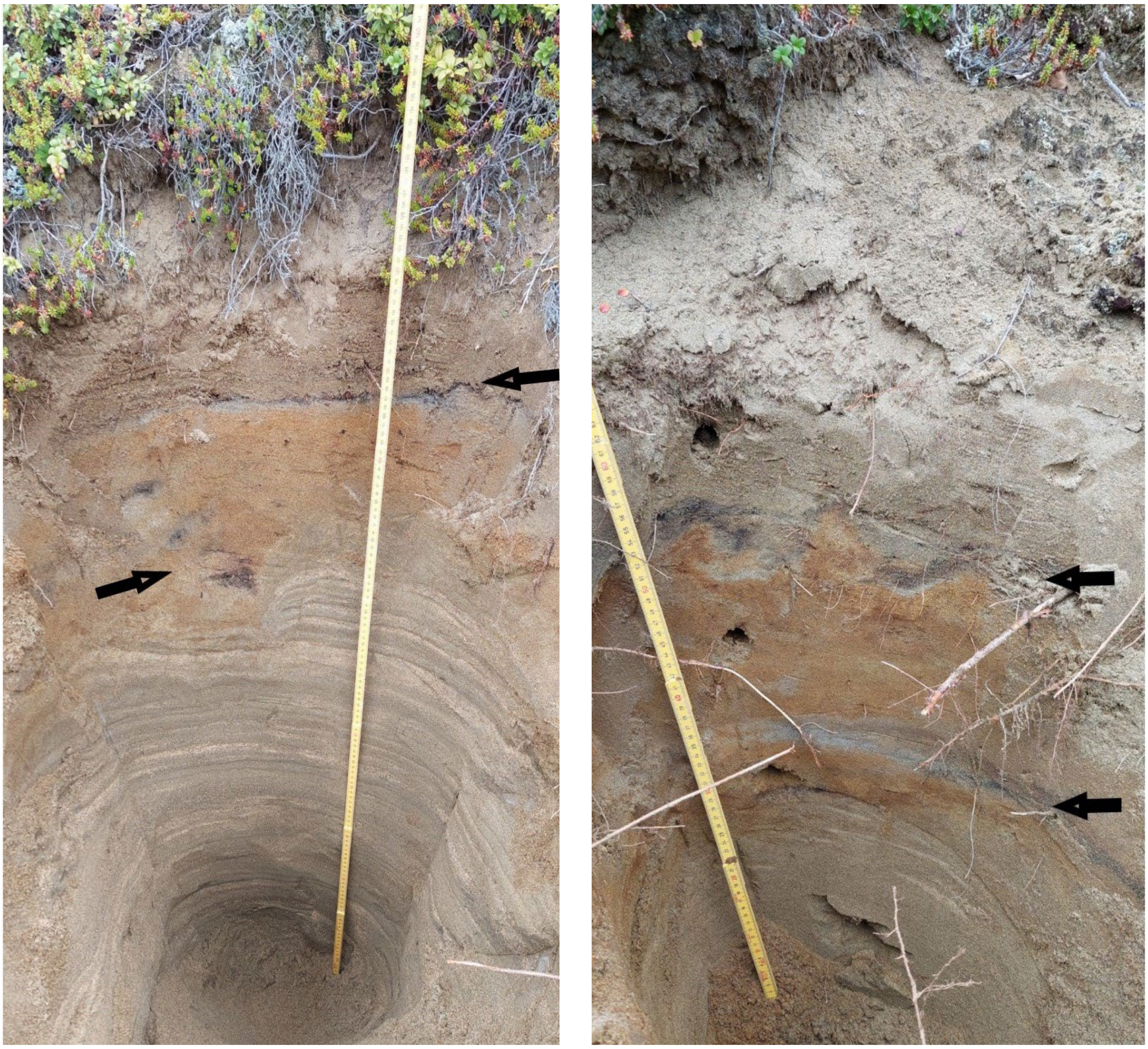


Fig. 10. Paleosols after forest burning (several black, organic-rich layers with underlying Podzol soil profiles, marked with black arrows) in dunes in the Kaamanen area, northern Finland (Photographs: P. Sarala, Oulu Mining School).

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)

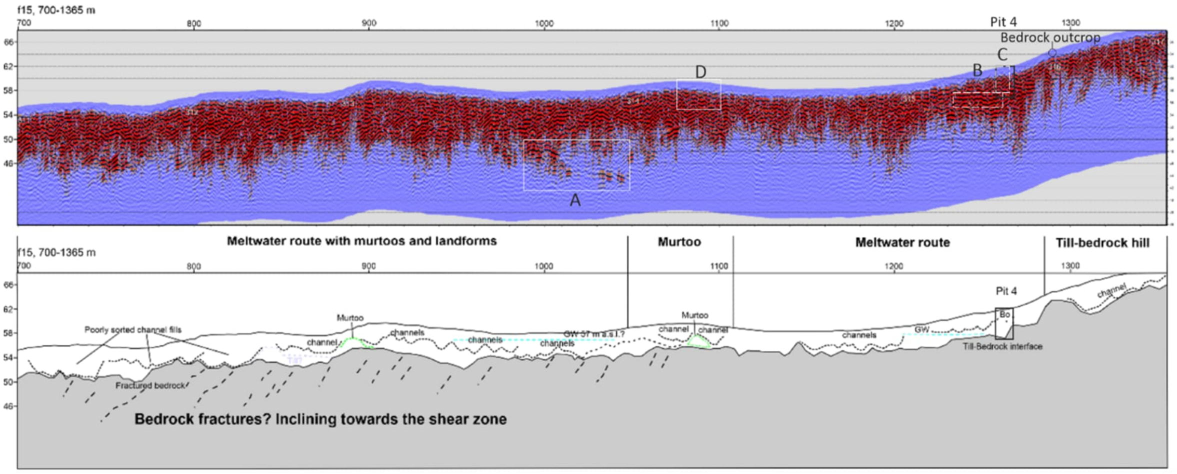
In Finland, the GPR and radar stratigraphy approach is commonly applied in the form of reconnaissance surveys (a continuous method), using a common-offset antenna configuration, where the separation of the transmitter and receiver antennae remains the same and the antennae are towed by foot, car, motor 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).



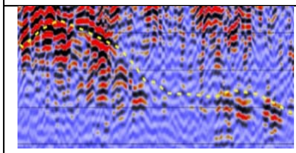
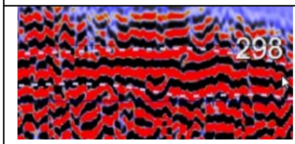
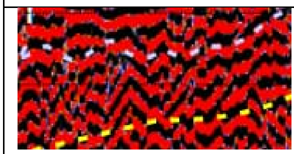
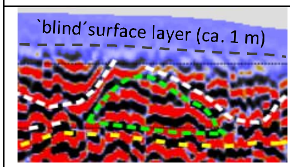
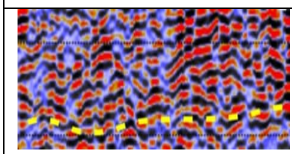
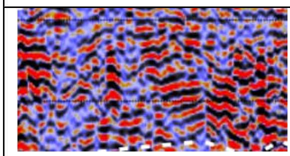
Radar facies	Characteristics	Lithology	Interpretation
 A (100 MHz)	Medium to high amplitude semi-continuous and undulating reflection (dashed line) within chaotic and downwards attenuated reflections containing numerous diffraction hyperbolas.	Crystalline bedrock, granodiorite or quartzdiorite	Bedrock with a major fracture (dashed line)
 B (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.
 C (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.
 D (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.
 E (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).
 F (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.

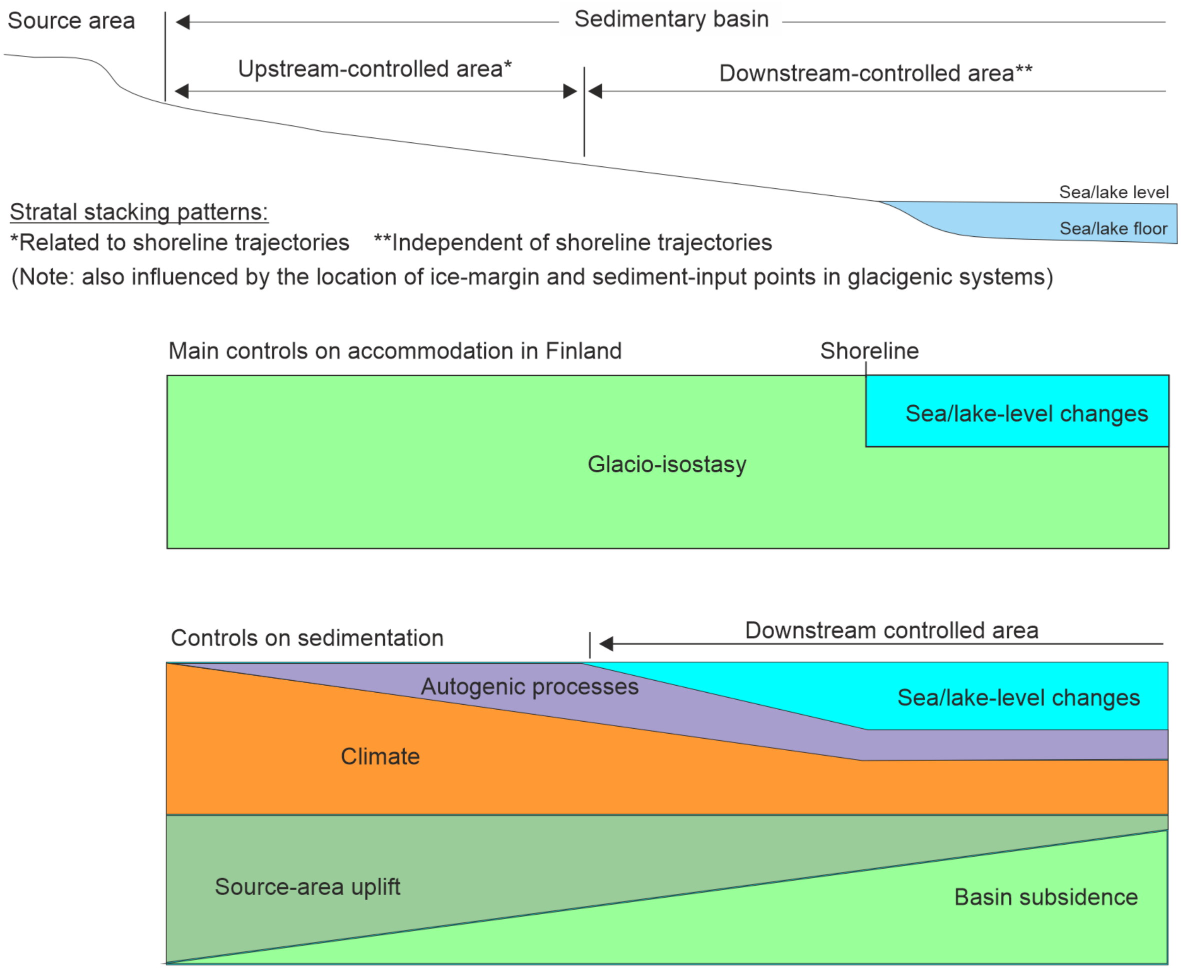


Fig. 12. Controlling factors of accommodation and sedimentation (modified from Catuneanu 2017; not to scale). Relative contributions of these controls may vary with the tectonic and depositional settings. In the Quaternary sedimentary systems of Finland, accommodation is mainly controlled by glacioisostasy 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.

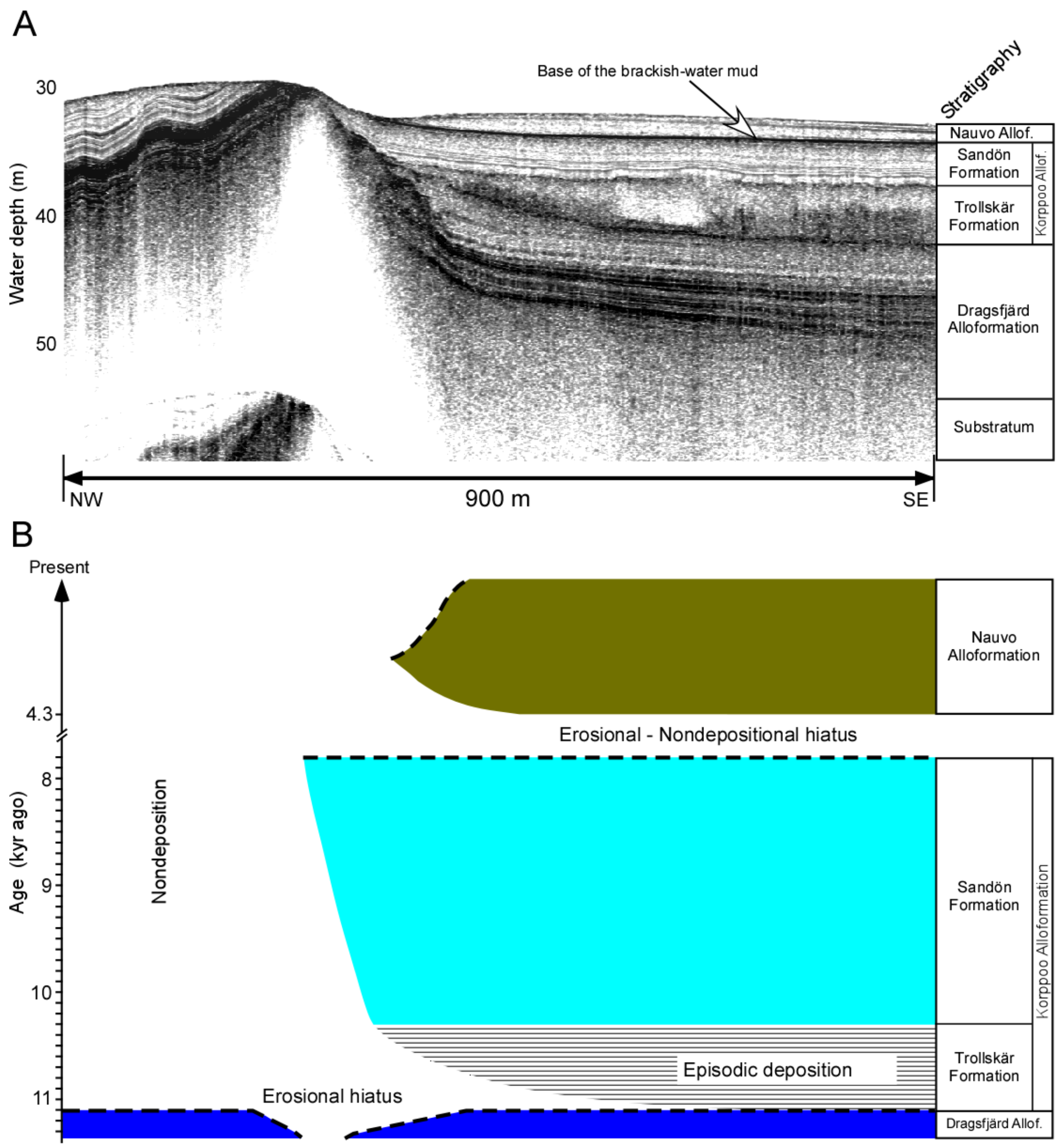


Fig. 13. A) Seismoacoustic sub-bottom profile (12 kHz pinger) and stratigraphic units after the CUAL approach from the Archipelago Sea in the northern Baltic Sea Basin. B) Corresponding Wheeler diagram with time on the vertical axis. Modified from Virtasalo et al. (2007). Stratigraphic units after Virtasalo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

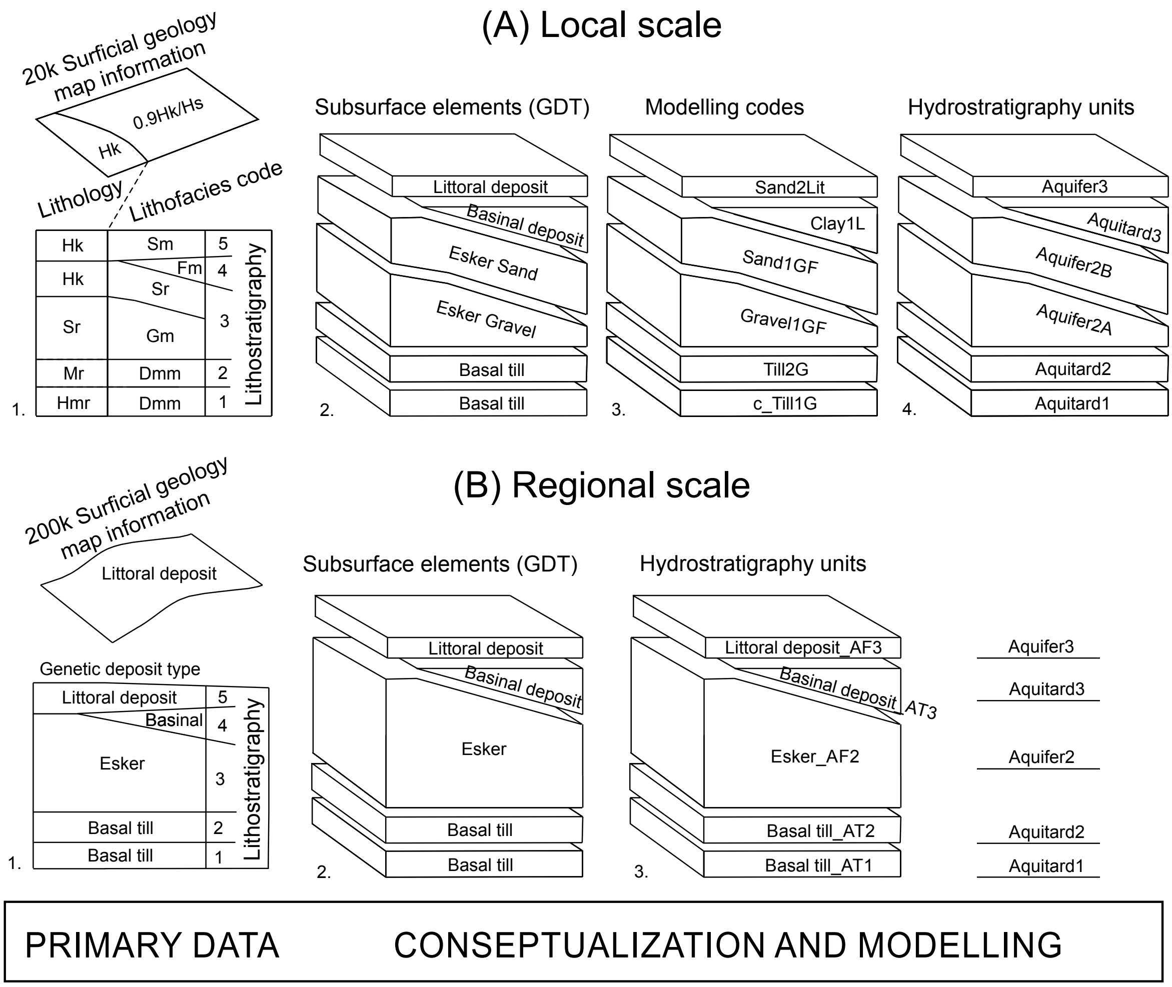


Fig. 14. Subsurface Quaternary deposit and hydrostratigraphic 3D modelling approach adopted by the Geological Survey of Finland (GTK). Principles of the coding system are presented in (A:3) and Table 4. The hydrostratigraphic conceptual model consists of alternating aquitard and aquifer couplets, with 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

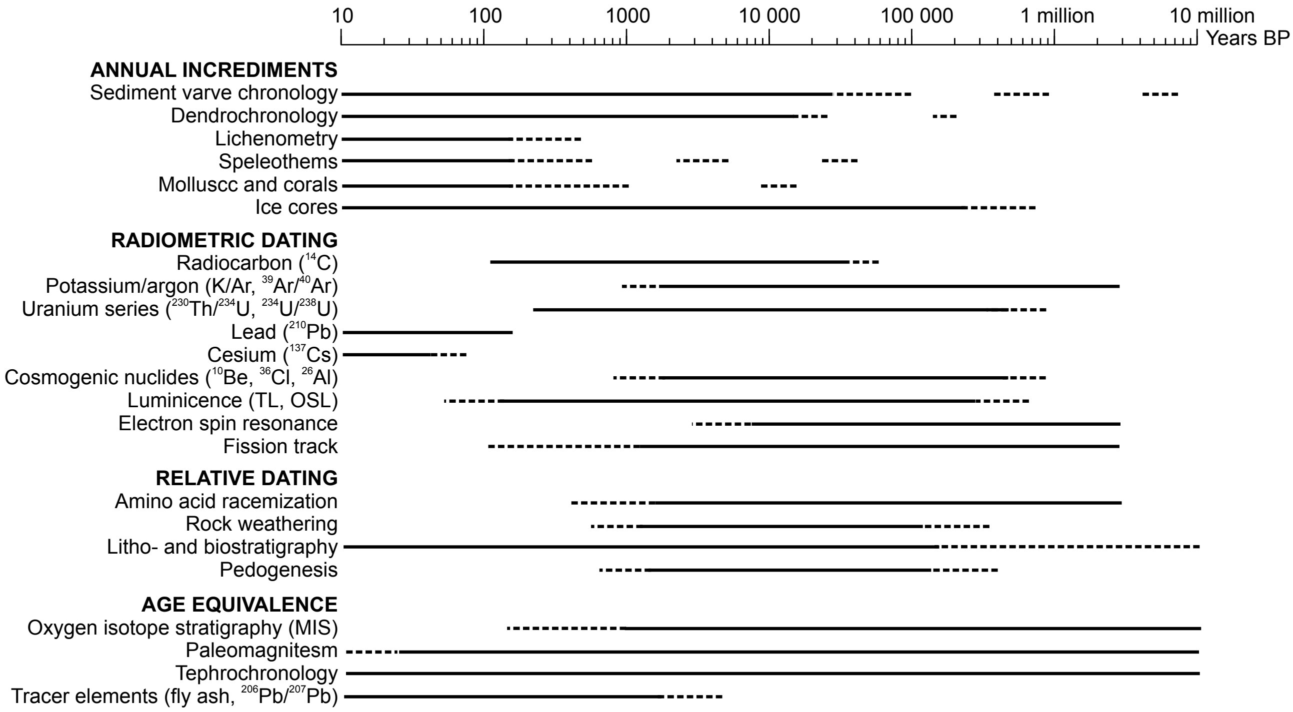


Fig. 15. The ranges of different Quaternary dating techniques typically applied in glaciated terrains (modified after Walker 2005).

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.

$$n + {}^{14}N \rightarrow {}^{14}C + e^+ \quad \textit{(Eq. 1)}$$

$$^{14}C + O_2 \rightarrow {}^{14}CO_2 \quad \textit{(Eq. 2)}$$

$$6H_2O + 6^{14}CO_2 + UV \rightarrow 6O_2 + {}^{14}C_6H_{12}O_6 \quad \textit{(Eq. 3)}$$

$$\textit{C-14 decay equation: } {}^{14}C \rightarrow {}^{14}N + e^- + \gamma \quad \textit{(Eq. 4)}$$

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.

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

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).

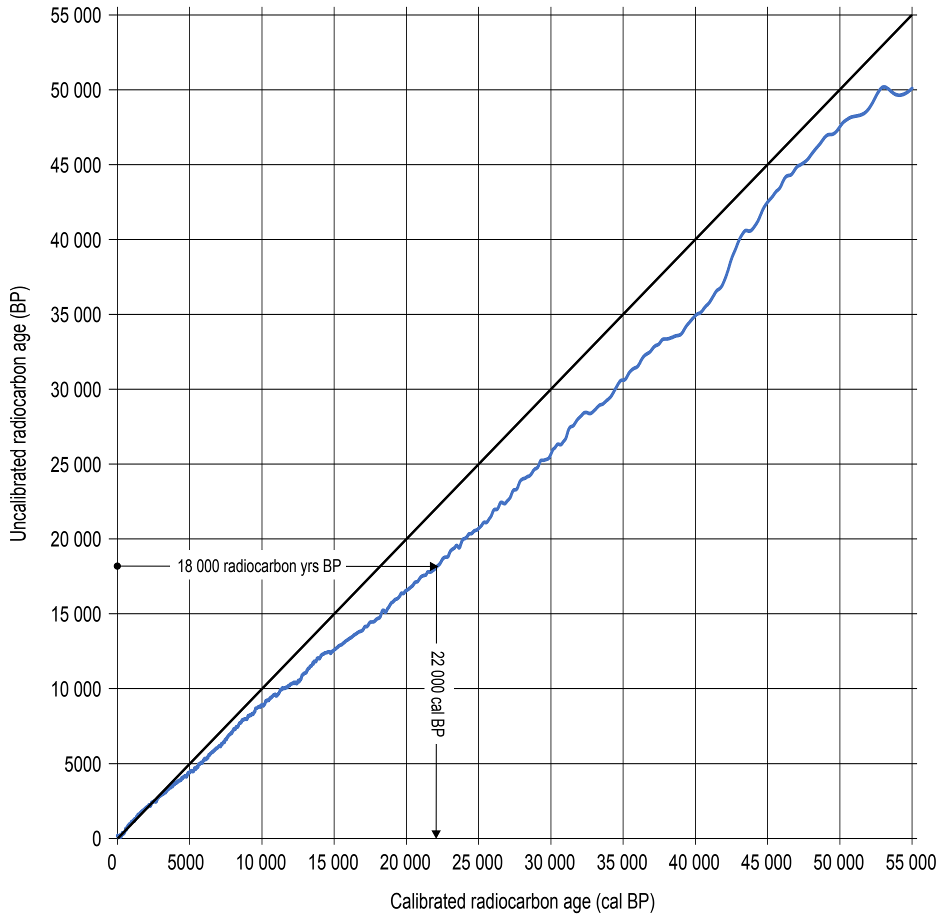


Fig. 16. The Northern Hemisphere calibration curve INTCAL20 (http://www.intcal.org/), showing the relationship between uncalibrated radiocarbon ages (yrs BP) and calibrated radiocarbon ages (cal BP), the latter representing calendar years before the year CE 1950 (Reimer & IntCal Group 2020). An example 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).

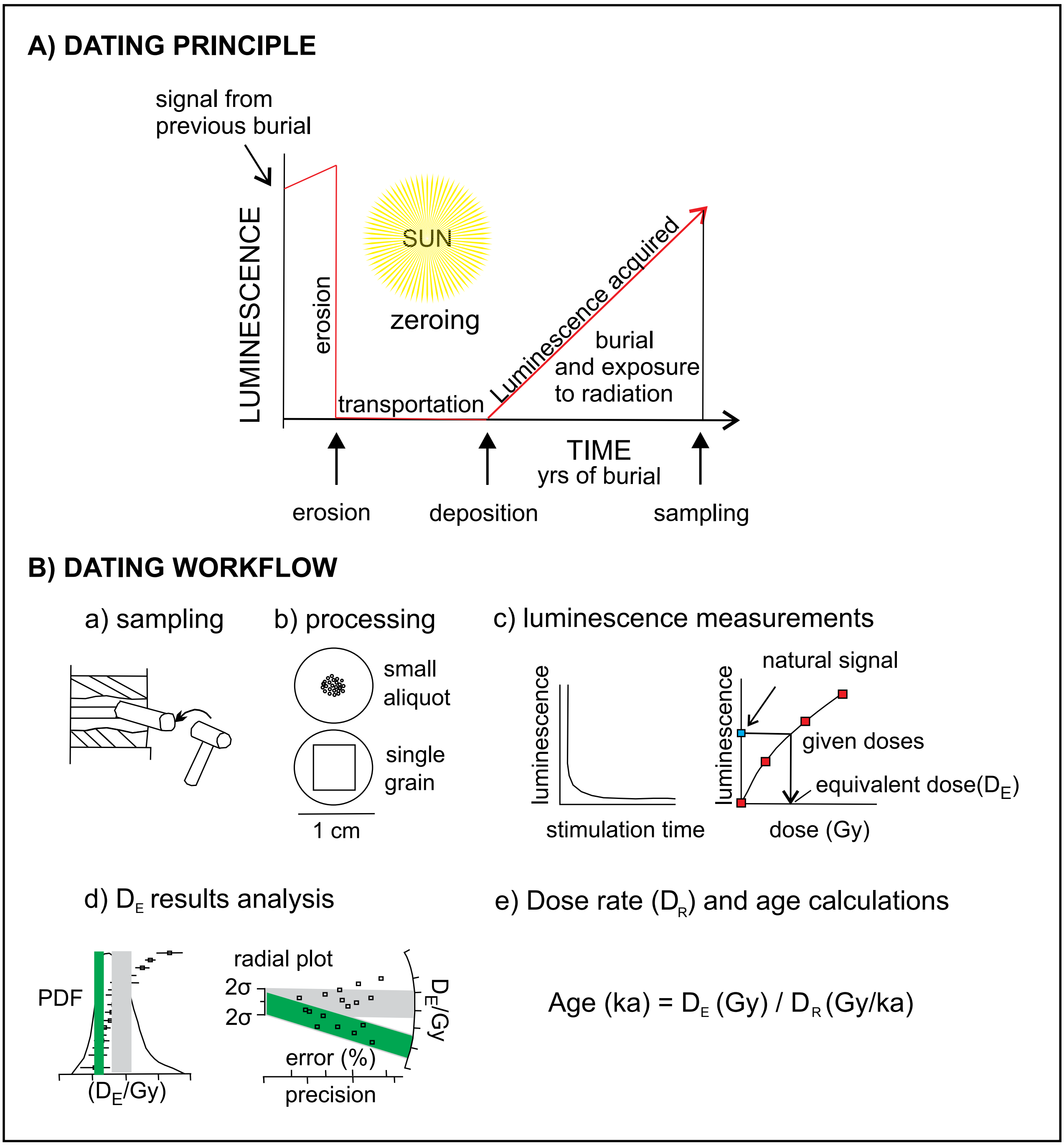


Fig. 17. A) The basic concept of luminescence dating: Sediment eroded and transported by wind, water, ice and/or gravity can be exposed to sunlight and zeroed (bleached) of any previously inherited luminescence signal. After transportation, sediment is deposited and subsequently buried. Once buried, 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).

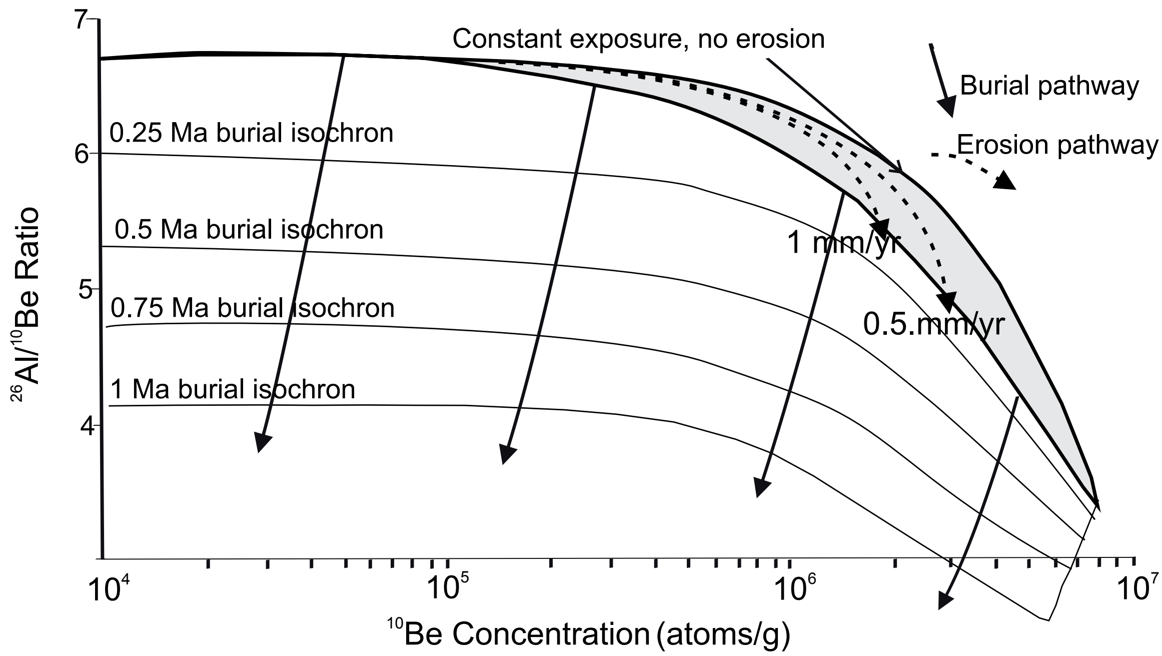


Fig. 18. The erosion rate and the reburial duration of a sample can be assessed by comparing the $^{28}Al/^{10}Be$ ratio with the ^{10}Be concentration. In the banana plot, the reburial trajectory is depicted as moving downward, due to the faster decay of ^{28}Al relative to ^{10}Be, and to the left, 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-

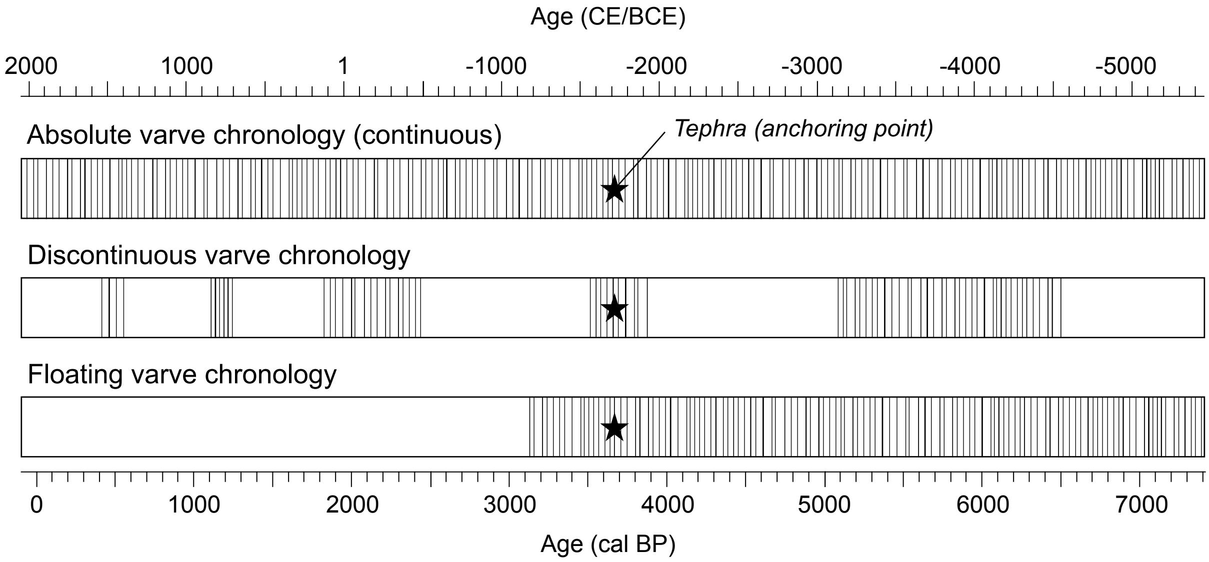


Fig. 19. Varve chronology is the use of varved sediment structures to establish ages in sedimentary sequences for dating and correlation. Varve chronology can be absolute, discontinuous or floating, and different varve chronologies can be matched using well-established anchoring points, such as identified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

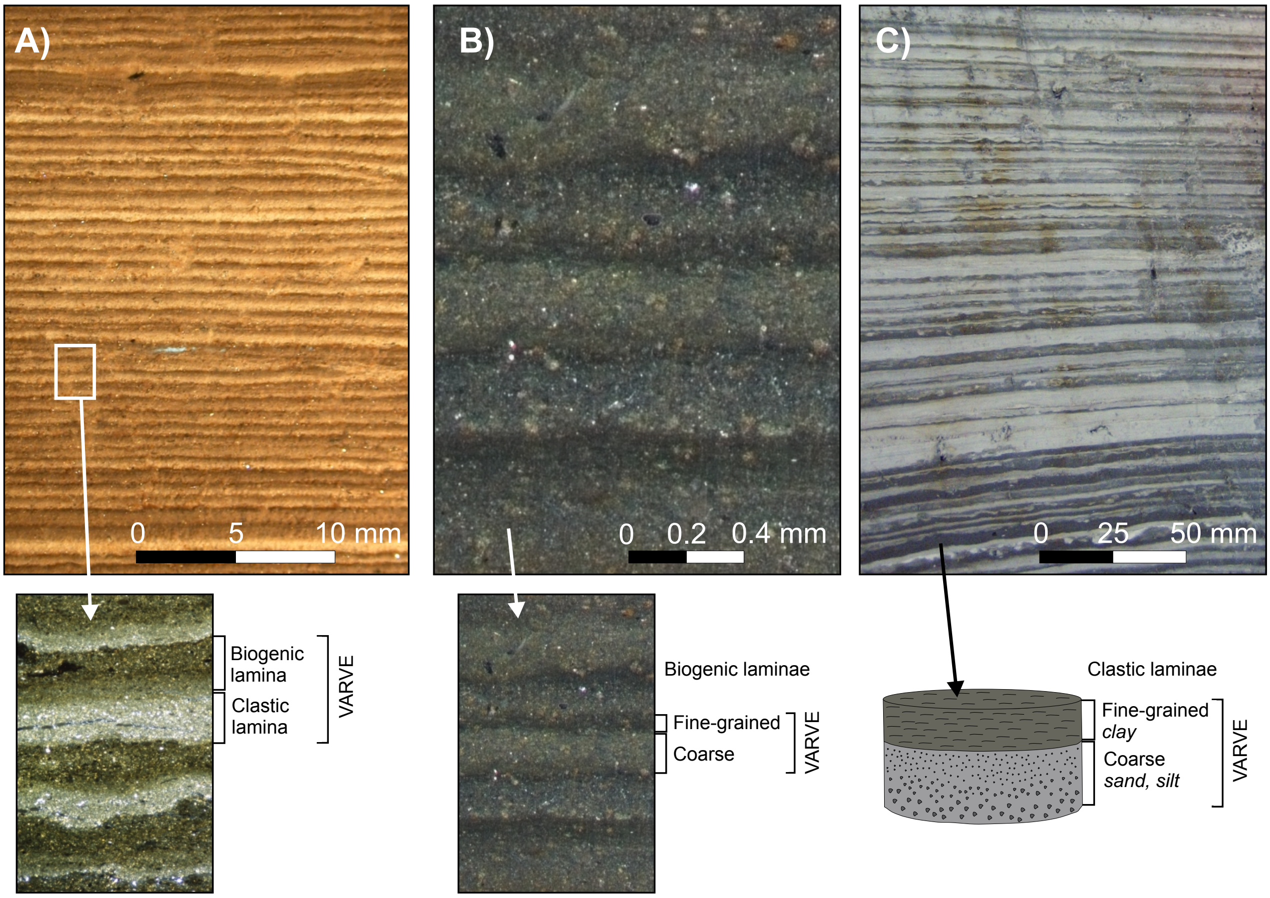


Fig. 20. Examples of the different types of varves: A) clastic-biogenic varves from Lake Nautajärvi, central southern Finland (Photograph: A. E. K. Ojala, GTK and University of Turku), B) biogenic varves from Lake Kallio-Kourujärvi, central Finland (Photograph: S. Saarni, University of Turku) and C) 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 postglacial 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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The present Special Issue of the Bulletin of the Geological Survey of Finland summarizes recent stratigraphic procedures and nomenclature in Finland related to bedrock units and superficial deposits. The three papers describe: (1) the stratigraphic challenges typical for Precambrian shield areas, (2) practical advice on the use of different bedrock unit classification systems in Finland, and (3) practices for mapping and classification of superficial Quaternary deposits in Finland. These papers provide a synthesis of the current stratigraphic framework in Finland.

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